ARCHITECTURAL ACOUSTICS

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BY

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PREFACE

Architectural acoustics is beginning to receive the attention it has long deserved. The past thirty years have been characterized not only by a remarkable growth in the scientific and technologic aspects of the subject, but also by a substantial expansion in the construction of buildings which have been designed in accordance with the newer knowledge of architectural acoustics. The outcome in some of these buildings has been highly satisfactory; in others it has been disappointing. This is typical of nearly all new developments in technology; and it is attributable, in the main, to an insufficient knowledge of the subject, to an imprudent choice of materials, or to an inadequate supervision of construction.

The following pages have been prepared in the hope that they will convey the pertinent facts of architectural acoustics to architects, builders, and all others who are interested in the design or construction of buildings. More specifically, the author has attempted (1) to set forth the fundamentals of architectural acoustics in a sufficiently comprehensive manner for all practical purposes — beginning with the most elementary facts and notions of acoustics, and developing from these the pertinent formulas and principles which should guide all good design; (2) to tabulate and describe the physical properties of materials and types of construction which are basic in the control of sound in buildings; and (3) to work out in detail problems of acoustical designing in all types of building in which acoustics should be considered.

Although the book is intended primarily as a reference work, it is believed that it also will be serviceable as a textbook for students of architecture. It is hoped therefore that the book will facilitate the organization of classes in architectural schools where acoustics is not at present a part of the curriculum. The architect's need for formal training in acoustics is certainly a basic one, and although the student of architecture may not master the subject of acoustics in a one-semester course, he will gain a working knowledge of the field which will enable him to meet intelligently the problems of acoustics which arise in the design and construction of buildings. In order to make the book more serviceable as a text, a number of problems and exercises have been included in an appendix.

The author has attempted to present the subject in such an elementary manner as will make the fundamental principles intelligible to the non-technical as well as to the technical reader; and although it has seemed desirable in a few instances to include derivations of formulas which necessitate some standard operations in calculus, the non-mathematical reader can pass over the formal steps in these derivations without losing a grasp of the fundamental principles. On the other hand, references are given for those who wish to pursue the theoretical or mathematical aspects of the subject.

The subject matter has been divided into three parts. Part I deals with the elementary facts of physical and physiological acoustics, and will contain but little new material for those who have had even a first course in acoustics. Part II presents the basic principles and data which should guide the acoustical design of buildings, and contains the main substance and the novel features of the book. For example, there are numerous tables on sound-absorptive and sound-insulative materials, many of which are published for the first time; there are new data on the effects of the shape of an auditorium and the location of absorptive materials upon reverberation time; and there are new recommendations concerning the optimal reverberation time and frequency characteristic for speech and music rooms. Part III deals with the specific and practical problems of design in school, church, and commercial buildings; in theatres and music buildings; in radio broadcast and sound-recording studios; and in all types of residential buildings.

The author is indebted to many of his colleagues for help and encouragement in the preparation of the manuscript. First of all, he wishes to acknowledge his gratitude to the many original workers who have published the results of their researches in acoustics, and especially to W. C. Sabine, F. R. Watson, P. E. Sabine, Harvey Fletcher, and C. F. Eyring, of the United States; to Hope Bagenal, Alex. Wood, A. H. Davis, and G. W. C. Kaye, of England; and to E. Meyer and E. Petzold, of Germany. All these men, and many others, have contributed largely to the accumulation of knowledge from which these pages were drafted. The author also wishes to acknowledge the kindness of the many manufacturers and distributors of acoustical materials who have permitted the publication of the results of tests conducted on their materials, and who have supplied the author with photographs of building interiors which have been designed or treated successfully for acoustics. Finally, he is indebted to Miss Charlotte J. Cox, who has exercised great care in typing the manuscript and arranging the tables on sound-absorption and sound-insulation.

Although the author has striven to eliminate all errors in the preparation of this work, he is aware that it is not inerrant. However, in spite of probable imperfections, the author wishes to make one significant claim; namely, that he is not presenting untried theories which are only of academic interest but that he has had occasion, in connection with the design and construction of numerous buildings, to test and verify the correctness of the fundamental principles set forth in the following pages.

VERN O. KNUDSEN.

March, 1932.

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CHAPTER I

INTRODUCTORY

1. Foreword. Until recently, acoustics has been the *bête noire* in the design of architectural interiors. Even in recent times the architect has not been entirely free from the mischief and distress which is attributed — often without warrant — to the uncontrolled conduct of this black animal. In fact, it is generally known that architects and builders await with considerable anxiety the outcome in the acoustics of the auditoriums which they build. Consequently, many people are yet of the opinion that acoustics is a dark and mysterious branch of learning, far beneath the dignity of a science or an art. And the results of the past would scarcely warrant a higher opinion.

Often the name *auditorium* clings to a room which is a marvel of structural engineering; which is perfectly illuminated, heated, and ventilated; which is provided with every comfort and luxury; which is a monument to architectural art and beauty; but which is so burdened with acoustical defects that the audition of music is reduced to a confusion of sound and the audition of speech is an utter impossibility. Builders and public alike have thought that the acoustics of an auditorium is non-predictable, and out of the realm of calculation in advance of construction, and that approval or condemnation must await the completion of the auditorium — in brief, that the outcome in acoustics is largely a matter of caprice or luck.

During the past thirty years much work has been done, especially in America, to correct this indefensible notion. Today, physicists, engineers, and architects in all civilized countries are being attracted in ever-increasing numbers to the important and fascinating problem of the acoustics of interiors. Already the contributions from these workers are raising architectural acoustics to the level of an exact science and an established art; and the architect who will design his buildings in accordance with what is already known about the behavior of sound in interiors can be assured that the outcome in acoustics will be satisfactory. This does not mean that every limitation to perfect acoustics has been removed. Indeed, there are certain limitations which make it impossible to design what might be called a perfect auditorium, but it is possible to calculate in advance of construction just what these limitations are, and to ascertain just what the outcome in the acoustics of any proposed building will be. Little by little these limitations are being overcome, and perhaps in some future day we shall be able to design and build an ideal auditorium for either speech or music.

It is hoped that in the present volume the fundamental principles of architectural acoustics can be presented in such a simple and useful manner that the architect will be able to design buildings which will be not only free from the common defects which in the past have ruined so many otherwise monumental buildings, but which will satisfy as nearly as is physically possible the highest and most rigorous requirements for the hearing of either speech or music. This is a big and an important task, and its successful fruition requires thorough training and skill in the fundamentals of acoustics.

2. Seeing and Hearing Compared. Seeing and hearing are man's most useful agencies in obtaining information about distant objects. The requisite conditions for good seeing are relatively simple and quite universally understood. An unobstructed view of the object, from a not too remote distance, and an adequate amount of diffused light, preferably daylight, illuminating the object are the necessary and sufficient requirements for good seeing. The problem of seeing and illumination in an auditorium is therefore a relatively simple matter which does not impose serious limitations upon the shape or the material used in the construction of the building. The necessary conditions for good hearing, especially in interiors, are not so simple, nor are they so universally understood. This difference between seeing and hearing depends largely upon (1) the great disparity in the velocities of propagation of light and sound, (2) the great disparity in the wave lengths or frequencies in light and sound, and (3) the amounts of radiant energy required for good seeing or good hearing. Light travels with a speed of 186,000 miles a second, which is nearly a million times faster than the speed of sound. Also, the wave length of sound is of the order of a million times longer than the wave length of light. Owing to the very great velocity of light and the *rough* surfaces of walls and ceilings, the separate visual impressions which come from a moving body are so quickly absorbed by multiple reflections within the interior of a room that there is sensibly no overlapping or confusing of the separate visual impressions. In the case of hearing in enclosures, however, owing to the relatively low velocity of sound and the *smooth* reflective surfaces of walls and ceilings, separate sounds of speech and music which follow each other in rapid succession die away so slowly that there is likely to be overlapping and confusing of the separate sounds. Such a confusion of sound is of course inimical to good hearing.

The wave length of sound, which varies from about one half inch to twenty feet, is comparable in length with the dimensions of many of the structural parts used in rooms, so that numerous unsuspected phenomena will result from the diffraction of sound. (These phenomena will be considered in Chap. II.) Finally, the energy content of speech and certain forms of music is so infinitesimally small that the means of conserving this energy to the best possible purposes often becomes a serious problem in auditorium design. Light energy, on the other hand, is both abundant and easy to supply.

It is apparent then that the acoustical properties in an auditorium are much more difficult to control than are the visual properties. Not only are they more difficult; they are more important, and unquestionably they merit the highest consideration of all factors which enter into the design of auditoriums. This, to be sure, is a utilitarian view, and may seem somewhat overstated to the proponents of classical or monumental architecture, but good acoustics need not require a sacrifice of monumental architecture although it may require a modification of past traditions.

3. Monumental Architecture. The utilitarian view, which places acoustics in the first rank in the design of auditoriums, requires that even monumental architecture be a composite art, based upon the highest esthetic standards of hearing as well as seeing. According to this view, an auditorium of monumental character will attain its true and highest dignity only when it composes forms and materials into such structures that will simultaneously satisfy the highest tastes of both the eye and the ear. Greenough stresses this idea in a letter to Emerson in which he expresses his views on architecture as follows: " Here is my theory of structure: a scientific arrangement of spaces and forms to functions and sites; an emphasis of features proportioned to their gradated importance in function. . . ."[1] The architect is correct in his insistence that this statement should read " A scientific and *artistic* arrangement of spaces and forms to functions and sites. . . . " But there is no reason here for a conflict between the scientific and artistic requirements. Art can always select from the scientifically correct those things which will embrace the requirements of both scientific rigor and artistic beauty. It has been stated that architectural acoustics probably will require certain changes in monumental architecture, particularly in the use of domed ceilings and curved walls, but the requirements for good acous-

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[1] Emerson's Essays.

tics are in no serious conflict with architectural form of good proportion and intrinsic beauty; and certainly forms which are an offense to the ear cannot forever claim the favor of the eye. In fact, it is probable that a new type of monumental architecture will evolve which will be more beautiful than any of the classical types of the past — a type which will adapt forms and materials to the highest functions, which will convey to all the senses, including hearing, an harmonious whole. This architecture of the future, which must satisfy the highest requirements of both utility and beauty, will be attained only through the fullest possible cooperation between scientist and artist — and it is indispensable that each have a thorough understanding of, and a sympathetic appreciation for, the other.

Before proceeding further with the development of the fundamental laws and principles of acoustics — principles which must be embodied in the architecture of the future — it will be advisable to outline briefly the historical development of architectural acoustics.

4. Evolution of the Auditorium. In the temperate climate of southern Europe the auditorium was of the open-air type, and was usually located favorably in a quiet site removed from the traffic and noise of the city.[2] The first auditoriums consisted only of a group of listeners standing around a speaker, all on a level or nearly level plane. The first step in the evolution of the auditorium consisted simply of elevating the speaker on a platform. This was followed by providing seats for the listeners and elevating the more remote seats. These early beginnings culminated in the well-known Greek and Roman open-air theatres, the ruins of which — remarkably well preserved — intrigue the interest and admiration of every modern traveler in southern Europe. Many of these theatres are so well preserved that it is possible to assess their merits and shortcomings from a study of the existing ruins. The outstanding merit of these antique theatres is attributable to the absence of surrounding walls and ceiling, which makes them free from such customary defects as echoes, reverberation, and delayed reflections. The sound which reaches the listeners is undistorted, and retains all the beauty and naturalness produced by the artist on the stage. But the outstanding defect also is attributable to the absence of surrounding walls and ceiling. Thus, all the sound energy which otherwise would be reflected from these bounding wall and ceiling surfaces is lost, and serves no useful purpose. This loss of reflected sound reduces the intensity of the sound reaching the more remote seats to the extent that the hearing of speech becomes very difficult or even impossible; and in the case of

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[2] A more complete account of the evolution of the theatre will be given in Chaps. XXII and XXIII.

music, the loss of energy, as well as the sustaining effect of the delayed reflections, impoverishes the richness and fullness of tonal quality. The arrangement of the seats in concentric semicircles around the stage and the steep slope of the seated area reveal the efforts of the Greeks and Romans to provide an adequate amount of sound energy for all listeners. The nature of the acoustical problems arising in these antique theatres and the progress which was made in the solution of the problems are recorded in the famous "Ten Books on Architecture" by Vitruvius, and will be presented in considerable detail in a subsequent chapter on open-air theatres. For the immediate purpose it is sufficient to note that the early Greek and Roman theatres were free from the modern defects of echo and reverberation, but that they were sorely in need of some means for strengthening the loudness of the speaker's voice.

As western civilization expanded to the less temperate climate of central and northern Europe it became necessary to enclose the auditorium with walls and ceiling. These enclosed rooms admitted the introduction of multiple balconies which served the double purpose of seating the audience near the platform or stage and accommodating a relatively large audience in a compact space. The proximity of the audience to the stage, together with the beneficial reflections from the walls and ceiling, provided a loudness of speech which was quite adequate in auditoriums seating fewer than about 2000 persons. The large audience in a relatively small space also provided a sufficient supply of absorptive material, a condition which is most essential for good acoustics in enclosed auditoriums. But not all auditoriums followed this course. Lavish tendencies in the design of civic and royal buildings, and especially in the design of Gothic cathedrals, resulted in vast enclosed spaces. (For example, the stone-surfaced interior of the Milan Cathedral, in the shape of a Latin cross, divided into five naves by 52 fluted columns, has a volume of about 7,000,000 cubic feet. The audience at a typical Sunday morning service may not number more than 1000 persons. Under this condition a powerful chord on the organ will reverberate in the cathedral for about eight seconds, and the spoken mass is an unintelligible confusion of sound.) The development of such spacious rooms, with interiors of stone or marble, and with accommodations for relatively small audiences, presented all sorts of acoustical difficulties. But these difficulties stimulated an interest in the study of acoustics which attracted a number of investigators in the nineteenth century. The investigations, with a few exceptions which will be mentioned later, centred almost wholly on the matter of form, leaving for the present century the important matter of materials.

5. Nineteenth Century Acoustics. The development of architectural acoustics in northern Europe began with a study of the numerous reflections of sound in enclosed spaces. Only meagre progress was made until the nineteenth century, when efforts were made to discover and design architectural forms which would favor a beneficial reflection of sound to the auditors. The problem was one of geometrical acoustics, limited almost solely to a study of the rays of reflected sound in a room, and the aim was to intensify by reflection the sound reaching the auditors. As a result, many buildings employed sounding boards, especially those of parabolic form, with the hope of directing an adequate amount of sound energy to the more remote listeners. But it was amply demonstrated that the use of these sounding boards or of specially designed surfaces above or behind the speaker was not sufficient to provide good hearing conditions in large churches or other auditoriums. The proper reflection of sound, or even an adequate supply of sound, was not and is not the entire remedy for the acoustical defects of modern buildings.

One of the first men to realize this fact and to express a more comprehensive view of the acoustical problem in an enclosed space was J. B. Upham, a doctor of medicine in Boston, Massachusetts.[3] Dr. Upham, at the early date of 1853, gave a rather lucid exposition of the phenomena of both reverberation and resonance in auditoriums — phenomena which are of the first rank in architectural acoustics. He realized that reverberation must be adequately suppressed, and that resonance must be carefully preserved. He conducted some experiments in the main apartment of the Boston Music Hall — a room 130 feet long, 78 feet wide, and 65 feet high. He observed the customary changes of reverberation as the soft scratch coat and the hard finish coat of plaster were applied to the walls and ceilings. He reported a measured time of reverberation[4] of 4.5 seconds before the seats and furnishings were installed. He further observed that the installation of upholstered benches, the laying of carpets in the aisles, and the hanging of curtains around the windows reduced the reverberation to a satisfactory condition. He continues: " Should it be required, on any occasion, to reduce still further this reverberatory property, it can (in the opinion of the writer) be readily and perfectly accomplished by the use of additional uphol-

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[3] J. B. Upham, "A Consideration of Some of the Phenomena and Laws of Sound, and Their Application in the Construction of Buildings Designed Especially for Musical Effects," Amer. Jour. of Science and Art, **65**, 215–226, 348–363; **66**, 21–33 (1853).

[4] He does not define *time of reverberation* but probably means the duration of audibility of some arbitrary source of sound such as a sung note or the note of an organ pipe.

stery, and the adoption of a simple contrivance of canvas, placed against the walls just below the cornice, which would not appreciably interfere with the resonance of the room nor mar, to any extent, its architectural beauty." His essay is concluded with the following pertinent plea for scientific work on this subject: " We here conclude our imperfect essay, ending as we began, with the regret that architects and scientific men have not honored with a more careful attention a subject so full of interest and so intimately connected with the welfare of Art, now almost universally known and appreciated."

The celebrated American physicist, Joseph Henry, in 1854 and again in 1856, submitted papers on the Acoustics of Buildings before the American Association for the Advancement of Science.[5] He discusses in a scholarly manner such important problems as the nature of speech and hearing, acoustics of open spaces, shape of enclosures, echoes, reverberation, and resonance. Many of his conclusions are based upon experiments and observations. His lucid understanding of the factors which affect reverberation is confirmed by the following: " It must be apparent, also, that the continuance of a single sound, and the tendency to confusion in distinct perception, will depend on several conditions; . . . first, on the size of the apartment; secondly, on the strength of the sound or the intensity of the impulse; thirdly, on the position of the reflecting surfaces; and fourthly, on the nature of the material of the reflecting surfaces." The effects of these four factors are then fully discussed in the light of physical theory and experimental demonstrations. On the nature of the reflecting surface he makes this significant remark: " A reflection always takes place at the surface of a new medium, and the amount of this will depend upon the elastic force or power to resist compression, and the density of the new medium. For example, a wall of nitrogen, if such could be found, would transmit nearly the whole of the wave of sound in air, and reflect but a very small portion; a partition of tissue paper would produce nearly the same effect. A polished wall of steel, however, of sufficient thickness to prevent yielding, would reflect, for practical purposes, all the impulses through the air which might fall upon it. . . . The striking of a single ray of sound against a yielding board would probably increase the loudness of the reverberation, but not its continuance." (This latter phenomenon he demonstrated with a tuning fork and sounding board.)

He then describes a new lecture room in the Smithsonian Institution which was constructed in conformity with his theory and experiments. The ceiling was kept low, the walls diverged in fan shape, and the rear

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[5] Joseph Henry, "Acoustics Applied to Public Buildings," Smithsonian Reports (1854 and 1856).

seats were well elevated. The oblique walls, the relatively large interior surface, broken with pillars, gallery and stair-screens, and the relatively large audience for the volume of the room, all contributed to a short reverberation in the room. The acoustical outcome was highly satisfactory.

Mr. T. Roger Smith, architect, in his book, " Acoustics of Public Buildings," which appeared in 1861, recognized the acoustical requirements for speech and music in the following significant words: " Music depends entirely upon the relations that subsist in pitch between different sustained sounds or notes, and upon the momentary impression of one note or chord resting in the memory of the ear when the next is sounded. It is not isolated notes, of however fine a quality, but the succession of such sounds or the blending them together that forms music; hence in all music there must be some relation between each note or chord, except the first of a passage and those that have gone before, and some recollection of them. In articulate speech, on the other hand, each syllable is a distinct concatenation of two or more sounds only, and though it may be combined with other syllables to make a word, yet it in no way depends upon them for its own completeness.

" Hence upon no music, however rapid, can the consequences of prolonging the impression of sounds beyond the time that they themselves actually last, exercise so injurious an influence as upon spoken words, where each syllable ought to be heard distinctly and separately, and where only the combinations of the letters that go to form single syllables could at all bear to be run together."

Roger Smith closes his discussion on the " obstacles and auxiliaries " with the following significant words: " It ought therefore to be our aim, not to make any building conspicuous for one excellence only, or to guard it against one defect, but rather to secure for it an equal proportion of every advantage within our reach, and to protect it from every possible mischance, esteeming no fault too small to be injurious, and no advantage so insignificant as not to be worth an effort, no matter how great a degree of excellence may be reasonably supposed to have been already secured."

Other investigators, notably Tyndall and Rayleigh, realized the necessity of controlling the reverberant sound in rooms by the use of sound-absorptive materials, but the generalized scientific work on this important problem of reverberation began in the last five years of the nineteenth century with Professor Wallace C. Sabine, of Harvard University. Sabine's work marked a new era in architectural acoustics which, at the present time, is exerting a profound and beneficial influence upon architecture.

6. Twentieth Century Acoustics. All the contributions to architectural acoustics before the work of W. C. Sabine were of a qualitative nature. Sabine was the first to commence a comprehensive and quantitative study of the subject, and since science and engineering are basically quantitative, it may be stated fairly that the science of architectural acoustics had its beginning with W. C. Sabine. In Sabine's paper in 1900 he set forth in simple but comprehensive language the requirements for good hearing in any auditorium, as follows: " . . . it is necessary that the sound should be sufficiently loud; that the simultaneous components of a complex sound should maintain their proper relative intensities; and that the successive sounds in rapidly moving articulation, either of speech or music, should be clear and distinct, free from each other and from extraneous noises. These three are the necessary, as they are the entirely sufficient, conditions for good hearing."[6]

It seemed to be apparent to Sabine that the third of these factors was the most important one in affecting the acoustical quality of a room, and he therefore devoted the major portion of his remaining days — some twenty years — to a quantitative study of the growth and decay of sound in an enclosure. His work was not only the beginning of a new branch of science to which contributions are now being made by men in all parts of the world, but his results were immediately applicable to architectural design. For example, his work on reverberation made it possible to calculate the time of reverberation in any room in advance of construction — and experience has shown reverberation to be the most important single factor in determining the acoustical outcome of any room. Already thousands of rooms have been designed in accordance with the theory developed by W. C. Sabine, and the results have been most gratifying.

Although numerous rooms were designed in accordance with the theory of W. C. Sabine immediately following the publication of his results, most architects were slow to recognize and apply his theory. Likewise, other scientific men were slow to follow his pioneer work, and it has been only during the past ten years that important contributions have been added to his findings. Today, architectural acoustics is receiving universal recognition as an indispensable branch of architecture and is attracting the attention of many architects and scientific investigators in university, private, and governmental laboratories. Besides, such industries as are related to the telephone, the radio, talking pictures, and the manufacture of acoustical materials, are making continued researches and contributions. The advent of sound pictures a few years

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[6] W. C. Sabine, "Collected Papers on Acoustics," 4 (Harvard University Press, 1922).

ago and the organization of the Acoustical Society of America in 1928 have been powerful agencies not only in popularizing acoustics but in developing fundamental theory and devices which have a profound and beneficial influence upon architectural acoustics. As a result, architectural acoustics is not only becoming a more complete and exact science, but because of its practical importance it is passing through an inevitable transition from a science to a branch of art and engineering. In this connection it should be emphasized again that architectural acoustics must satisfy the requirements of art as well as the requirements of exact science. It is very probable therefore that the future advances in architectural acoustics will result from a closer cooperation between artistic and scientific workers. This will be particularly desirable in connection with improvements in the design of music rooms.

7. General Survey of the Content and Treatment of the Text. Since this book is intended primarily for those who have had no special training in the theory of sound, it will be desirable to begin with a simple exposition of the first principles concerning the nature of sound. The student of architectural acoustics must have a good working knowledge of these first principles before he can obtain an adequate comprehension and appreciation of the fundamentals of architectural acoustics. Accordingly, the next chapter will be devoted to physical acoustics — the simple but rigorous laws which govern the behavior of sound in the external world, such as the generation of sound, its propagation, reflection, diffraction, refraction, transmission, absorption, and resonance. These are the phenomena which determine the behavior of sound in an enclosure, and consequently they constitute the logical beginning to the study of architectural acoustics.

Of equal importance is a knowledge of the nature of speech and music and of hearing. Both speech and music are forms of sound energy which are subject to the laws of propagation, reflection, refraction, absorption, transmission, and diffraction, and therefore it is of prime importance to know intimately the energy and frequency characteristics of speech and music. Since all these sounds must be received and judged by the sense of hearing, it is equally important to know the fundamental facts of hearing. These fundamental facts of hearing, and of the nature of speech and music, will be considered in Chaps. III and IV.

Since the reverberation and absorption of sound, the transmission and insulation of sound, and the amplification of sound, are among the principal properties which control the nature of sound in buildings, a rather detailed consideration will be given to these subjects in Part II of this book. Included in these chapters are tables of coefficients of absorption and coefficients of transmission, the two most important properties of materials which are needed in calculating the time of reverberation and the amount of insulation which will be provided by any proposed type of structure. In the last four chapters of Part II, the basic theory and the fundamental principles of architectural acoustics as applied to speech rooms and to music rooms will be developed. A thorough acquaintance with these first principles and the fundamental theory developed in Part II is indispensable to an understanding of the practical problems which arise in acoustical design. In Part III the practical problems of design in the acoustics of buildings will be considered. Here the architect will find examples of the application of the theory and principles of architectural acoustics to every type of building he is likely to encounter in building design, such as school buildings; office and commercial buildings; public buildings, such as municipal auditoriums, libraries, governmental buildings, and museums; churches — Roman Catholic, Protestant, Jewish, and Christian Science; theatres; music rooms; concert halls; opera houses; private residences; apartment houses and hotels; and radio broadcast and talking picture studios. Since speech or music and the control of noise are associated with almost every conceivable type of building, nearly every building which the architect is called upon to design has its own peculiar acoustical problems, and it is confidently believed that the theory and practical applications described in this book will enable the architect or engineer to find a satisfactory solution for most of the acoustical problems which arise in the design of buildings.

These problems are definite and can be solved in advance of construction. In general, the problem consists of (1) the adequate reduction of noise, and (2) the designing of interiors in which the voice or instrumentation is heard most satisfactorily — a condition which is realized by the proper design of shape and size of the interior; by the elimination of echoes, sound foci and delayed reflections; and by the proper control of reverberation and resonance. Both the theory and practice underlying these problems should be mastered before one is entrusted with the acoustical design of an architectural interior.

PART I

PHYSICAL AND PHYSIOLOGICAL ACOUSTICS

CHAPTER II

PHYSICAL ACOUSTICS — THE NATURE OF SOUND

8. Objective and Subjective Sound. The essential problem in the acoustical design of buildings consists of the most favorable adaptation of structural forms and materials to the established laws of objective and subjective sound. It is necessary therefore to possess a clear understanding of the basic principles of the objective sound — that is, the dynamical vibrations outside of the ear which make up sound waves — and also the subjective sensations resulting from the action of this objective sound upon the auditory apparatus with its associated nerve endings. In the present chapter, consideration will be given only to objective sound, that is, the external motions which characterize sound. Throughout this book the word **sound** will be used to denote the physical disturbance which could be sensed as sound if there were present a normal ear to hear it. It will be noted later that this limits objective sound to vibrations having a circumscribed range of amplitude and frequency. The phrase **sensation of sound** will be used to denote the subjective response to sound. The physicist and acoustician are interested primarily in objective sound; the psychologist primarily in subjective sound. There is no occasion for confusing the points of view of the physicist and the psychologist, although they overlap to a certain extent. Both points of view are required of the architect who would understand the problems of architectural acoustics, and the architect who possesses a comprehensive knowledge of both objective and subjective sound can readily apply this knowledge in adapting structural forms and materials to yield their utmost in acoustical quality. The following sections will introduce some of the more important facts of objective sound which are pertinent to the control of sound in buildings. These facts should be mastered thoroughly by the prospective student of architectural acoustics.

9. Production of Sound. When we ride in an automobile or teeter on a spring board we are aware of regular up-and-down motions which are called vibrations. Vibrations are set up in bodies which readily tend to return to their equilibrium or rest positions when they have been given a displacement. The most casual observations reveal that sound has its origin in vibrating bodies. The plucked string of a violin, the prong of a tuning fork hit gently with a soft mallet, the stretched parchment of a bass drum, or the paper cone of a radio loud speaker all present familiar demonstrations of vibratory motion of sounding bodies. The vibrations of the string, the tuning fork or the paper cone can be observed visually; the vibrations of the stretched parchment on the bass drum can be felt with the finger tips. The vibratory motion of a sounding tuning fork can be revealed in a spectacular manner by bringing a small suspended steel ball into contact with the vibrating prongs of the fork as shown in Fig. 1. The steel ball is driven away several inches by the impact of the vibrating prongs. Even after the sound of the fork has become so feeble as to be inaudible at a distance of a few feet, the force of vibration is sufficient to impart an appreciable blow to the steel ball. If the suspended ball be placed carefully between the prongs of a vigorously vibrating fork the ball is driven back and forth with such rapidity that it produces a sound similar to that of an electric bell or buzzer.

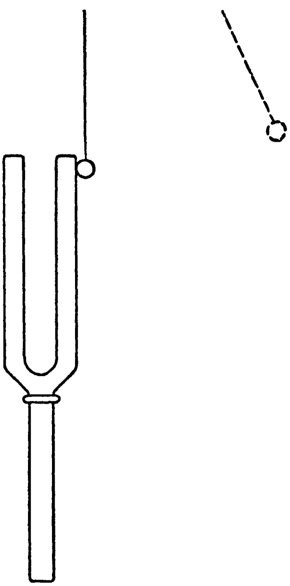

Fig. 1. Force of vibration exhibited by impacts of prongs of tuning fork against a suspended steel ball.

It may not be so obvious that sounds produced by organ pipes and other wind instruments have their origin in vibrating bodies, but it can be shown that the column of air within any one of these instruments is in a state of vibration. This vibration can be exhibited in the case of an organ pipe closed at one end with an elastic membrane. The vibratory motion of the membrane, and hence the column of air above it, can be felt with the finger tips, or the motion can be magnified and projected onto a screen by optical methods.

10. Propagation of Sound. Just as the generation of sound is produced by the vibrations of a body possessing inertia and elasticity, so the propagation of sound is produced by communicating these vibrations to any medium possessing the properties of inertia and elasticity, as air, or water, or steel. The propagation of sound is somewhat analogous to the propagation of a transverse pulse or wave along a stretched wire or rope. If a transverse disturbance be impressed upon a stretched elastic cord, as by hitting gently one end of the cord, the disturbance or deformation of the cord travels along the cord at a certain speed, and the form of the disturbance remains practically unchanged. The speed of propagation of the disturbance will depend only upon the mass per unit length and the tension of the cord. In fact, it can be shown by theory and proved by experiment that the speed of propagation is simply $\sqrt{T/m}$ where T represents the tension and m the mass per unit length of the cord. The propagation of sound through the air, or through liquids or solids, is more accurately exhibited by a special *wave model* which consists of a series of steel balls connected by spiral springs, as illustrated in Fig. 2. If ball 1 be given a displacement to the left, balls 2, 3, 4, etc., will be displaced successively in the same direction, that is, the disturbance imparted to ball 1 is propagated along the medium. After ball 1 has returned to the right, the other balls will follow in succession. Now if ball 1 be given a to-and-fro motion, this same motion will travel to the other balls, and the speed of travel will again be given by $\sqrt{T/m}$. In the case of a tuning fork vibrating in the air — an aggregate of discrete molecules coupled by elastic bonds — the molecules of air adjacent to the prongs of the fork are set into vibratory motion, and their motion is imparted to neighboring molecules which in turn impart the motion to more distant molecules. In this manner the vibratory motion is propagated away from the source with a speed which is determined by the density and elasticity of the air.

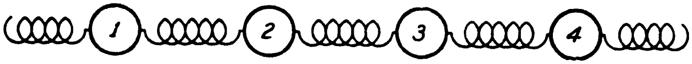

FIG. 2. Wave model of steel balls and spiral springs.

The necessity of a ponderable medium for the propagation of sound is shown by the following simple experiment: Suspend, by rubber bands, a small call-bell inside a bell jar which is attached to an exhaust or vacuum pump. When the jar is filled with air the bell can be heard distinctly if the jar be shaken. But if the air be well pumped out of the jar, the bell will not produce an audible sound even though the jar be shaken vigorously. If an exhaust pump is not available, the experiment can be performed by suspending the bell inside a flask containing some water. By boiling the water, all the air is driven from the flask and the space above the water is filled with steam or water vapor. In this condition the flask should be tightly corked. If the flask be shaken, the bell will be heard as well as when it was filled with air. But now let warm water, and then cold water, be poured over the flask so that the water vapor condenses. It will be observed now that the bell is no longer heard. Heating the water again will restore the water vapor, and with it the sound. The walls of the glass flask must be fairly thick for this latter experiment, or the force of the outside atmospheric pressure may break the flask. The experiment provides convincing proof for the necessity of a medium, such as air or steam or some other ponderable material, for the propagation of sound. In general, dense, elastic media, as wood, water or steel, propagate sound better than do rare, inelastic media, as gases, vapors or the atmosphere. Even a taut string is a good conductor of sound waves, as every boy has demonstrated with his " tin can and string " telephone. A simple demonstration of the conducting quality of string can be made by suspending a table fork or spoon from the middle of a string about three or four feet long, and bumping the fork or spoon against the edge of a table or chair when the two free ends of the string are held against the ears with the palms of one's hands. A clear, bell-like sound will be heard each time the fork or spoon makes impact against the table or chair.

The determination of the speed of sound in air has received the attention of physicists for nearly two hundred years. In 1738 the French Academy made some careful measurements of the speed of sound by firing cannon, first at one observatory in Paris and then at a station about seventeen miles outside of Paris. By measuring the elapsed time between the flash and the report — making measurements in both directions to compensate for any motion of the air — they found that the speed of sound in air is slightly more than 1100 feet per second. More precise experimental determinations indicate that at room temperature (20° C. or 68° F.) the speed is 1125 feet per second.[1] The speed is the same for all frequencies in the audible range, but increases slightly at supersonic frequencies. In a somewhat similar manner, the speed is constant for sounds of ordinary intensities, but increases slightly for very intense sounds. For all practical purposes, sounds of all pitches and of all loudness levels travel with the same speed. This is a fortunate circumstance, for if the speed changed appreciably with pitch or loudness, the music coming from a remote source would be badly distorted. The speed increases about thirteen inches per degree (Fahrenheit) rise of temperature, but does not vary with change of atmospheric pressure. It can be shown by a simple consideration of the thermodynamics of the propagation of sound in air that the speed is given by $\sqrt{\gamma P/\rho}$, where P is the pressure of the air, ρ is its density, and γ is a thermal constant which for air is 1.405. At a temperature of 20° C. or 68° F., and at sea level, P is 76 centimeters of mercury or 1,008,000 dynes, and ρ is 0.001205 gram per cubic centimeter. Hence, the speed of sound should be $\sqrt{\frac{1.405 \times 1{,}008{,}000}{0.001205}} = 34{,}300$ centimeters per second, or 1124 feet per second, which is in good agreement with that deter-

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[1] Based upon data given in International Critical Tables, vol. VI, p. 462.

mined experimentally. For purposes of calculation in this book the speed of sound in air will be assumed to be 1125 feet per second at a temperature of 20° C. or 68° F.

The speed of sound in air plays an important role in many of the fundamental problems in architectural acoustics, particularly in the phenomena of reverberation and echoes. The increase of speed with rise of temperature is one of the prime factors which produces the bending of sound rays in the atmosphere. This bending or refracting of sound waves affects slightly the distribution of sound reaching an audience, especially in an open-air theatre.

Sound travels much faster in liquids and solids than it does in air. For example, the speed in sea water is about 5000 feet per second; in wood it is about 13,000 feet per second along the fibres and only 4000 feet per second across the fibres; and in stone it is about 12,000 feet per second.

11. Physical Characteristics of a Sound Wave. A sound wave is characterized by the following properties: amplitude, frequency, wave form, and velocity (including direction) of propagation. The **amplitude** of vibration of a sound wave is the average maximal distance the individual vibrating particles, as the air molecules, are displaced from their equilibrium positions. Thus, referring to the model in Fig. 2, the amplitude is a measure of the to-and-fro displacements of the individual balls which are set into vibration. In general, the amplitude of a sound wave, especially in an enclosure, may vary from point to point in space. This variation, which results principally from the union of direct and reflected sound waves, is exhibited in Fig. 6. (See also Sec. 21.) The **frequency** of vibration of any vibrating source or medium is the number of complete to-and-fro vibrations which occur in a second. Thus, a tuning fork which vibrates at the rate of 512 complete vibrations or cycles per second produces a corresponding vibration in the surrounding air, which, if at rest with respect to an observer, will impress upon the eardrum of the observer 512 complete vibrations per second. The frequency is usually designated by a number followed by " cycles per second " or simply " cycles," which specifies the number of complete vibrations or cycles per second. Thus, 512 cycles describes a vibration having a frequency of 512 complete to-and-fro vibrations per second.

The **wave form** of a vibrating body is a graphical representation which is used to describe the precise nature of each complete to-and-fro vibration. The most elementary wave form or type of vibration is called a **simple harmonic motion**; it is the form of vibration which characterizes a pure tone, such as is approximated by the vibrations of a bowed or gently struck tuning fork. If a stylus on one of the prongs of such a vibrating fork make a trace of its motion upon a piece of smoked paper which moves by the stylus at a constant speed and at right angles to the motion of the stylus, the graphical record on the smoked paper will resemble the drawn curve shown in Fig. 3. Such a curve is called a sine or sinusoidal curve since it is the same type of curve as would be obtained from plotting, on rectangular coordinate paper, the sine of an angle against the angle itself. The sine curve in Fig. 3 gives the displacements of the vibrating tuning fork as a function of time, and it represents the *wave form* of a pure tone. Thus, a fork having a frequency of 512 cycles would make each second 512 complete sine curves like the four shown in Fig. 3. If the speed of the paper which is moved past the stylus on the prong of the tuning fork be known, the record furnishes a means of determining not only the *wave form* but also the frequency of vibration of the fork.

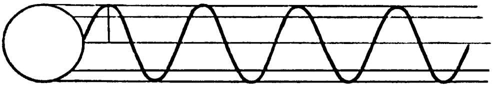

FIG. 3. Sine wave such as is generated by a tuning fork.

Closely associated with the concept of frequency are the concepts of period and wave length. The **period** is simply the reciprocal of the frequency, that is, it is the time required for a complete to-and-fro vibration of the vibrating source of sound. The **wave length** depends not only upon the frequency of vibration but also upon the speed of propagation in the medium. Thus, a fork having a frequency of 512 cycles will radiate into the surrounding air 512 condensations each second. After it has been vibrating, say, for one second, the first condensation will have been propagated away from the fork a distance of about 1125 feet, that is, the distance which sound travels in one second. But there will be 511 other condensations uniformly spaced between the fork and this first condensation; and therefore the distance between successive condensations will be 1125 ÷ 512, or 2.20 feet. This distance between two successive condensations, or the shortest distance between two portions of the propagated wave which are in the same phase of motion or condensation, is called the wave length of the sound wave. The wave length is proportional directly to the speed of propagation and inversely to the frequency of vibration. This is stated formally in the equation $c = nl$, where c is the speed of sound, n the frequency, and l the wave length.

The wave forms of musical notes are not so simple as those of the tuning fork. In general, each musical note is characterized by its own peculiar wave form. Thus, the wave forms of the sounds produced by a tuning fork, a violin, and an oboe are shown in Fig. 45, in Chap. III. These records are for musical notes of the same fundamental frequency and approximately the same amplitude of vibration, but it will be noted that they differ markedly in their manner of vibration, that is, in their wave forms. These wave forms are periodic, that is, they repeat at stated intervals, but they are called complex waves as distinguished from simple harmonic waves. It is possible to analyze complex wave forms, like those characteristic of the oboe or any other instrument, into simple harmonic vibrations. (See Sec. 15.) Further, these simple harmonic components usually form a **harmonic series,** that is, the component frequencies are integral multiples of the gravest or so-called fundamental frequency. This will be discussed more fully in Chap. IV.

The **velocity** of propagation of a sound wave includes both the *speed* and *direction* of propagation, that is, velocity is a vector quantity. The speed has been discussed in an earlier section. The direction of propagation is the direction of advance of the wave, defined more accurately by the normal or perpendicular to the wave front of the advancing wave. The direction of propagation of sound waves is a potent factor in connection with problems of localization of sources of direct or reflected sound waves, and also with problems of distribution of sound by means of electrical loud speakers.

It will be shown in the next chapter that amplitude, frequency, and wave form are the fundamental properties which determine the nature of speech and music, as well as all other types of sound, and that there are definite and well-known relations between these fundamental physical properties of a sound wave and the auditory sensations produced by them.

12. Relation between Amplitude of Vibration and Intensity of Sound. In acoustical measurements, it is convenient to speak of and measure the intensity of sound rather than the amplitude of vibration. The intensity of sound depends upon both the amplitude and frequency of vibration. The total energy possessed by a vibrating mass m, vibrating sinusoidally with an amplitude a and a frequency n, is $2m\pi^2a^2n^2$. It will be noticed that the total energy of vibration is proportional to the square of the amplitude and also to the square of the frequency; that is, proportional to the square of the product of amplitude and frequency. Consequently high-frequency vibrations have much smaller amplitudes of vibration than do equally intense low-frequency vibrations. The expression $2m\pi^2a^2n^2$ represents the total vibrational energy of a vibrating sound source having an effective mass m. In general, only a small part of this vibrational energy is radiated as sound, the remaining part being converted into other forms of energy, principally heat.

The pressure variations produced by a sound wave in air are proportional both to the amplitude and the frequency of vibration, and therefore the intensity of sound in air is proportional to the square of the pressure variation. The intensity of sound, as in a room, can be measured in terms of either the average energy of vibration per unit volume — as the number of microjoules per cubic centimeter — or the average rate of flow of sound energy through unit area — as the number of microwatts per square centimeter. Throughout this book, intensity will be used to designate the rate of flow of sound energy per unit area, and volume density will be used to designate the amount of vibrational energy per unit volume. It can be shown from a simple consideration of the flow of sound energy in such a medium as air that if p represent the root mean square value of the pressure variation, c the velocity of sound, and ρ the density of the air, then the rate of flow of sound energy per unit area, that is, the intensity I, is given by

$$I = \frac{p^2}{c\rho}. \tag{1}$$

If p be measured in bars (dynes per square centimeter), c in centimeters per second, and ρ in grams per cubic centimeter, I will be given in ergs per second per square centimeter. Since there are 10 ergs per second in a microwatt, it is necessary to divide the right-hand member of (1) by 10 in order to give I in microwatts per square centimeter. Hence, for sound waves in air at a temperature of 20° C. (68° F.), the intensity I, in microwatts per square centimeter, becomes $p^2/414$. The root mean square pressure variation in the air can be conveniently measured by diaphragm instruments, such as a calibrated condenser transmitter. Such an instrument is very useful therefore for measuring the intensities of sound in architectural interiors.

The rate of emission of acoustical energy from most sources of sound,[2] and the corresponding intensities in sound fields, is very small. Thus, the sound energy radiated by the average speaker in an auditorium is of the order of 25 to 50 microwatts. It would require therefore no fewer than 15,000,000 such speakers to generate a single horse power of acoustical energy. With such minute amounts of sound energy generated by the average speaker, the resulting intensity of speech in an enclosure is correspondingly small. Thus, the average intensity of unamplified speech in an auditorium is of the order of a thousandth of a microwatt per square centimeter. Such small amounts of acoustical power emphasize the delicacy of the problems of measurement which arise in architectural acoustics. Methods of measuring these feeble vibrations will now be discussed.

[2] The rate of emission of sound energy from a diaphragm (large in comparison with the wave length of the sound) having an area A and moving as a piston, is $2\pi^2 c\rho a^2 n^2$.

13. Measurement of Sound Intensity. Instruments for the measurement of sound intensity may be divided into two principal classes: those which utilize the velocity variations of the vibrations and those which utilize the displacement variations of the vibrations. In general, the pressure amplitude is proportional to either the velocity or the displacement, so that the intensity is proportional to the square of the measurements obtained by instruments which record either the velocity or displacement amplitudes. The magnetophone or telephone receiver, either of the electromagnetic or electrodynamic type, is the outstanding instrument in which the action depends upon the velocity of the diaphragm — that is, upon the rate of change of magnetic flux. The condenser microphone, of the type used in radio broadcasting and in sound studios, is the outstanding instrument in which the action depends upon the displacement of the diaphragm — that is, upon the rate of change of electrostatic capacitance. The condenser microphone is probably one of the most dependable instruments available for the measurement of sound intensity, and consequently it will be described in this section. It is not a power-indicating device, and therefore it does not measure the intensity directly. It is analogous to a high-resistance electrical voltmeter. It measures the alternating pressure in the air produced by a sound wave. A cross-sectional view of a condenser microphone is shown in Fig. 4. It consists essentially of a tightly stretched dia-

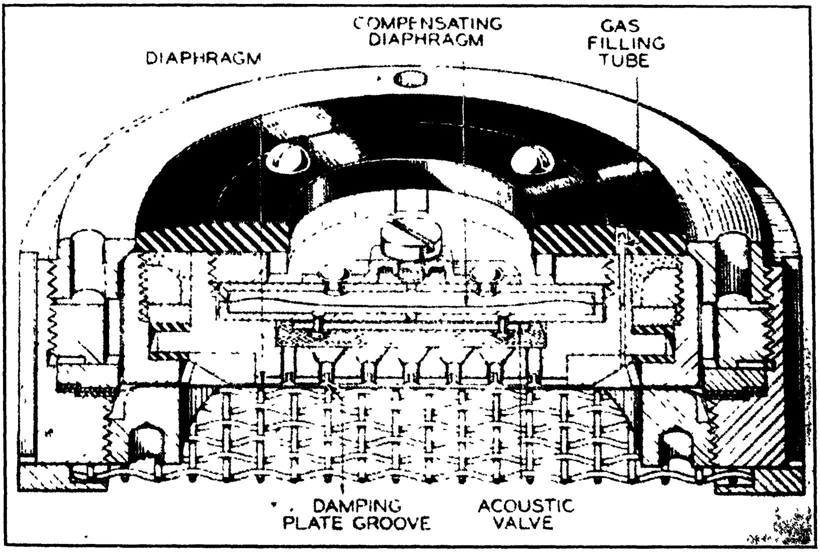

Fig. 4. Cross section of condenser microphone. (*Wente and Crandall.*)

phragm separated about 0.001 inch from a fixed steel plate. The sound waves exert a pressure upon the diaphragm which forces it into vibration. These vibrations alter the distance and consequently the electrostatic capacitance between the diaphragm and the fixed plate. Accordingly, the potential drop between the diaphragm and fixed plate, maintained by an external battery, is varied, and an alternating voltage is thus developed which is proportional to the pressure variations actuating the diaphragm. The voltage developed is exceedingly small — of the order of 3×10^{-3} volt per bar pressure against the diaphragm — but when suitably amplified by means of a vacuum-tube amplifier it is sufficient to operate a thermocouple and galvanometer. A circuit diagram of a typical measuring set utilizing the condenser microphone is shown in Fig. 5. The condenser microphone, as ordinarily used, is not an absolute instrument, but it can be calibrated by means of a thermophone, which does provide a means of making absolute measurements of intensity. The method of calibration is beyond the scope of this book, but the interested reader will find a description in Appendix A in " Speech and Hearing " by Harvey Fletcher.

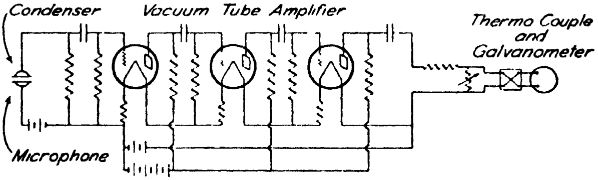

FIG. 5. Condenser microphone with amplifier and thermocouple for measuring intensity of sound.

Recently, an electrodynamic type of microphone has been developed by E. C. Wente and A. L. Thuras[3] which has all the advantages of the condenser microphone, and in addition has a higher sensitivity (9×10^{-3} volt per bar) and a wider and better frequency response, and is not so directional in its response. Further, it does not require a polarizing voltage, and it is not necessary to have an amplifier in close proximity to the microphone. It seems probable that the electrodynamic type of microphone will soon replace the condenser type.

Other instruments which are used for the measurement of sound intensity are the Rayleigh disc and the Webster phonometer.

14. Variation in the Intensity of Sound with the Distance from the Source. If a sound originate at a point in a homogeneous and an undisturbed medium, away from all reflecting and diffracting surfaces, the sound is propagated radially in all directions, and the wave front is

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[3] Jour. Acous. Soc., **3**, 48 (July, 1931).

spherical. Under such circumstances the intensity of the diverging sound varies inversely as the square of the distance from the source. If a sound wave be reflected by a large cylindrical " mirror " in such a manner that the sound spreads out with a cylindrical wave front, the intensity varies inversely as the distance from the source. Or, if a sound source be located at the focus of a large parabolic reflector, the sound is approximately reflected in a plane wave of constant amplitude, that is, the intensity does not vary with the distance from the source.[4] These last two instances of cylindrical reflection and parabolic reflection are ideal cases which are only approximated, but if the reflecting surface be very large in comparison with the wave length of the sound, the relation between intensity and distance from the source is approximately as stated for these ideal cases. Hence, the intensity of sound may die away with the inverse square of the distance, or inversely with the distance, or it may remain constant, depending upon whether the wave is spherical, cylindrical, or plane. In an enclosure, such as an auditorium, there may be combinations of these three types of sound propagation, but in most cases the reflecting surfaces are plane, so that most individual sound rays will diminish in intensity with the inverse square of the dis-

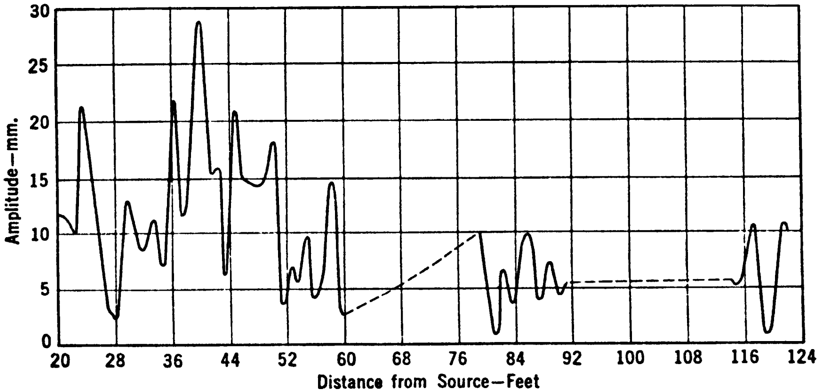

Fig. 6. Curve showing the variation of amplitude of vibration of sound with the distance from the source in a high-school auditorium. The source was a 256-cycle tone from a loud speaker. The detector was a Webster phonometer. The ordinates give the deflection readings of the phonometer. Source was located on front central part of stage. No measurements were made for the dotted portion of the curve.

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[4] This assumes that the sound energy of the wave motion persists as such and is not degraded into other forms of energy. It will be seen in the chapters on reverberation and absorption of sound that there is an attenuation owing to absorption in the air.

tance from the source. These reflecting surfaces in a room complicate the relation between intensity of sound and distance from the source, and in general the intensity falls off with the distance much less rapidly than would be required by the inverse square law. An example of the manner in which the intensity of sound depends upon the distance from the source in an auditorium is shown in Fig. 6.

15. Determination of the Wave Form and Frequency Components of Complex Vibrations. In the two following chapters the relations between wave form and the quality of speech or music will be discussed. It is important therefore that the reader be familiar with dependable and commonly used methods and apparatus for determining wave form. A number of instruments may be used for this purpose. Among the most dependable and practical instruments are (1) the condenser or electrodynamic microphone, with associated amplifier and oscillograph; (2) the phonodeik, developed by D. C. Miller; (3) the high-quality electric phonograph; (4) the equipment used by the motion-picture industry for recording sound on film.

The condenser microphone with the high-quality oscillograph is probably the most reliable equipment for the precise determination of wave form. The schematic arrangement of the apparatus is similar to that shown in Fig. 5, except that the thermocouple and galvanometer are replaced with the oscillograph. The sound to be recorded is picked up by the condenser microphone and converted into electrical waves. These electrical waves are amplified by a multiple-stage vacuum-tube amplifier and are then impressed upon the vibrating element of the oscillograph. The vibrating element is usually a bifilar suspension which vibrates as a loop between the poles of a powerful electromagnet. A tiny mirror on the vibrating element reflects light, by means of a suitable optical system, upon a sensitized film, which is propelled past the beam of light at a constant speed. The developed film then contains a record of the sound vibrations which acted upon the diaphragm of the condenser microphone. With a properly designed oscillograph it is possible to obtain faithful records of the types of vibration which comprise speech and music. Several of these records will be shown in the following chapter. A photograph of a magnetically damped oscillograph, developed by L. P. Delsasso, is shown in Fig. 7.

The phonodeik is fully described in D. C. Miller's book, "The Science of Musical Sounds." It consists essentially of a large receiving horn, a diaphragm, and a very delicate and sensitive optical system which projects the motion of the diaphragm onto a moving film, or onto a rotating mirror and screen for demonstrating to a group. The phonodeik introduces more distortion than the condenser microphone and oscillograph, but by making corrections for the distortion, the phonodeik can be used for the determination of the wave form of speech or music. There are in Dr. Miller's book many interesting photographic records of the wave forms which characterize different musical instruments.

The equipment which is used for making modern phonograph records also supplies satisfactory apparatus for investigating wave forms. This apparatus consists of a condenser microphone with a high-quality amplifier (see Fig. 5) and an electromagnetic cutter which cuts in the groove of a wax disc a record of the sound vibration picked up by the microphone. The wave form of this cut record can be examined microscopically, or, by means of a suitable electrical pick-up and optical system, the record of the motion may be projected upon a screen.

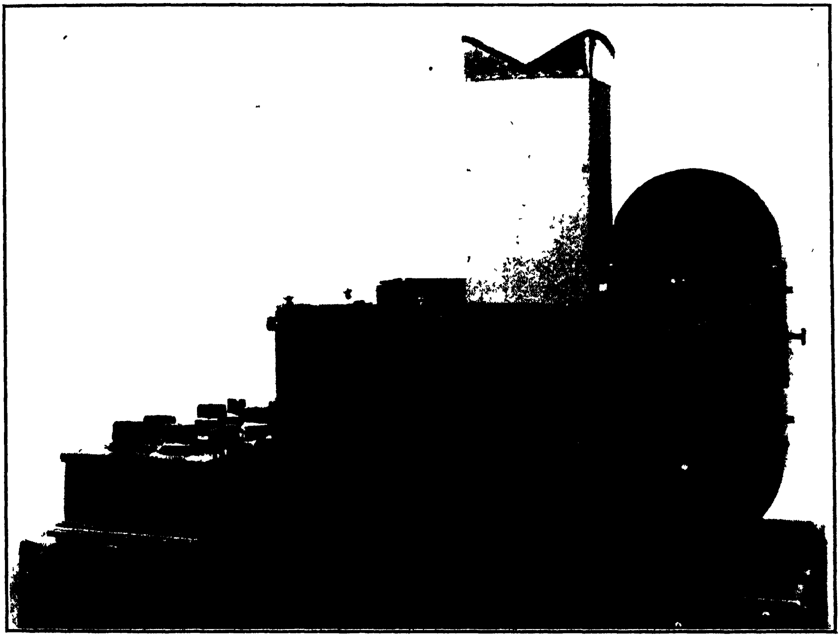

Fig. 7. Portable oscillograph for obtaining photographic record of sound vibrations. (*L. P. Delsasso.*)

The recently developed methods of recording sound on film, as used in the making of sound pictures, are all somewhat similar to the oscillographic method already described. The sound to be analyzed is picked up by a microphone, and is amplified with a suitable vacuum-tube amplifier. Two principal processes or methods are employed for recording these amplified electrical impulses upon film. The one method is known as the variable-area method and the other as the variable-density method. In the variable-area method, the recorder is similar to the oscillograph already described. The tiny mirror attached to this vibrator reflects light upon a very small slit, the image of which is sharply focused upon a film. As this tiny mirror is vibrated it effectively lengthens and shortens the length of the slit image on the film. Records obtained with such a device are illustrated in Fig. 8, which reveal wave forms of the sound produced by a bicycle bell, an orchestra, and a woman's voice. In the variable-density method, the amplified electrical vibrations are made to vary the width of a slit in a vibrating light shutter. The wire slit or shutter, which is normally 0.001 inch wide, opens and closes in accordance with the strength of the alternating current which actuates it. A constant source of light illuminates the slit, and the amount of light which passes through it is therefore proportional to the width of the slit, or to the strength of the electrical current operating the shutter. The light which passes through the slit falls upon a moving film which makes a variable-density record on the film similar to that shown in the upper part of Fig. 9. For comparison, a variable-area record is shown in the lower part of Fig. 9. The method just de-

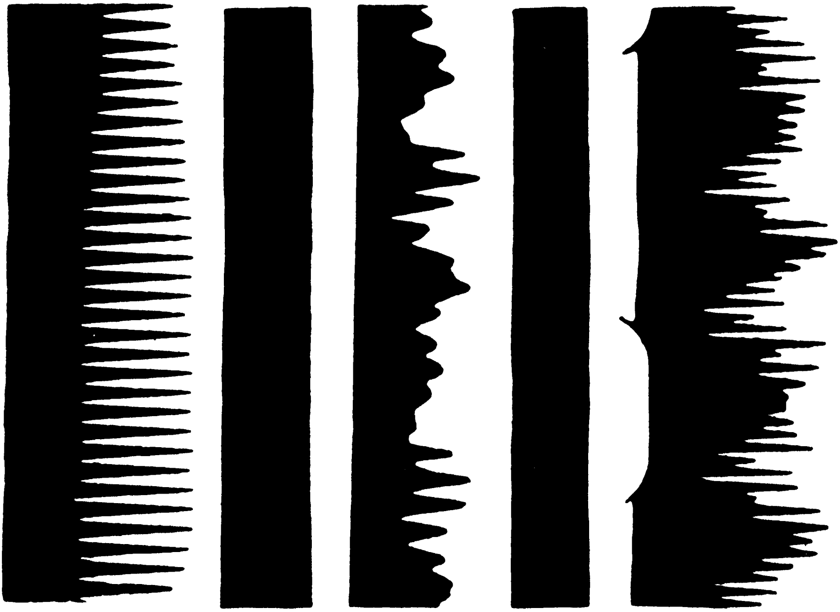

Fig. 8. Types of sound records made with R.C.A. Photophone — variable-area method. (*Townsend.*)

scribed is essentially that used by the Western Electric Company, and leased to many of the leading motion picture producers. The method used by the Fox Movietone Company produces a record similar to that just described, but in this method the light slit is of constant width, and the intensity of the light which illuminates the slit is proportional to the strength of the electrical current which operates the source of light — the Aeolight. The Aeolight is a gas-filled discharge tube which develops an amount of luminous energy proportional to the voltage impressed upon the tube.

The methods of recording sound on film just described furnish a number of simple and convenient means for investigating the wave forms of sound, but the use of such equipment is limited largely to the motion-picture industry.

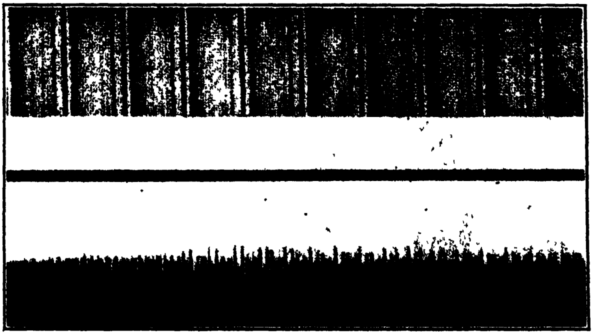

FIG. 9. Variable-density and variable-area sound records on motion-picture film.

All four methods which have just been described give records of the wave form of sound. In general, the acoustical engineer is interested not in the form of the wave itself but in the frequency components which make up the wave form, for it is these component vibrations which must be faithfully preserved in order that the quality of sound be unimpaired. These components are determined by analyzing the wave form for any particular sound into its simple harmonic elements. Instruments for making such analyses are called harmonic analyzers. There are two principal types of analyzers: the electrical, and the mechanical. In the electrical analyzer, the sound, which must be sustained during the analysis, is picked up in the usual manner with the condenser microphone and amplifier, and is then impressed upon a resonant electrical circuit and galvanometer. By adjusting the inductance and capacitance in the electrical circuit so that it is successively resonant to all the frequency components which are likely to occur in the sound, a so-called spectrum of the sound is obtained by plotting or recording the deflection of the galvanometer as a function of frequency. A typical record of the sound of a 160-cycle buzzer, analyzed by this method, is shown in Fig. 10. The inset in the upper right corner is a record of the wave form. It will be noted that peaks occur in the record at frequencies corresponding to the harmonics of the fundamental frequency, that is, at 160, 320, 480, 640, . . . up to 4800 cycles. The sound of a buzzer therefore is very rich in harmonics, and, because of the abundance of the harmonics, the buzzer is a useful source of sound for measuring hearing acuity, or for measuring the masking effects of noise.

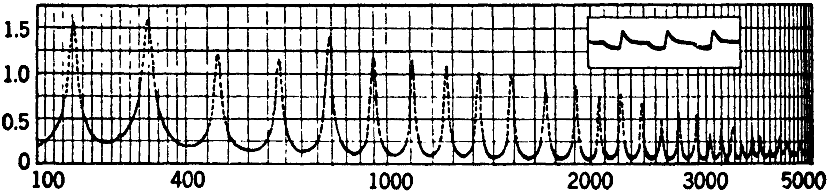

FIG. 10. Record of vibration of 160-cycle buzzer, analyzed with electrical analyzer. (*Wegel and Moore.*)

Mr. L. P. Delsasso[5] has developed an electromechanical analyzer which is very useful for determining frequency components in sustained sounds. The sound is picked up by a microphone, amplified, and impressed upon a sharply resonant vibration electrometer. The resonant system consists of a small aluminum needle supported between the plates of an electrometer by three fine tungsten wires a_1, a_2, and a_3 (see Fig. 11).

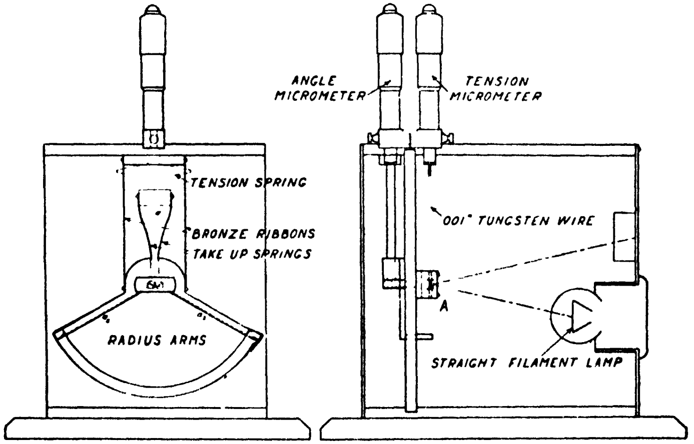

FIG. 11. Electro-mechanical analyzer. (*Delsasso.*)

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[5] L. P. Delsasso, "A New Acoustic Analyzer," Jour. Acous. Soc., **3**, 167 (July, 1931).

The restoring torque on the needle is made continuously variable, in part by the twisting of the suspensions (which are under a controllable tension), but largely by the bifilar action of the two lower fibres a_2 and a_3; and in this manner the natural frequency of the needle system can be sharply tuned to any of the component frequencies in the vibration which is impressed upon the analyzer. An analysis of a complex source of sound is made by varying the tuning of the needle system throughout a wide range of frequencies and observing optically the amplitude of vibration of the needle for frequencies corresponding to maximal deflections. Fig. 12 shows the sound spectrum of the noise produced by two

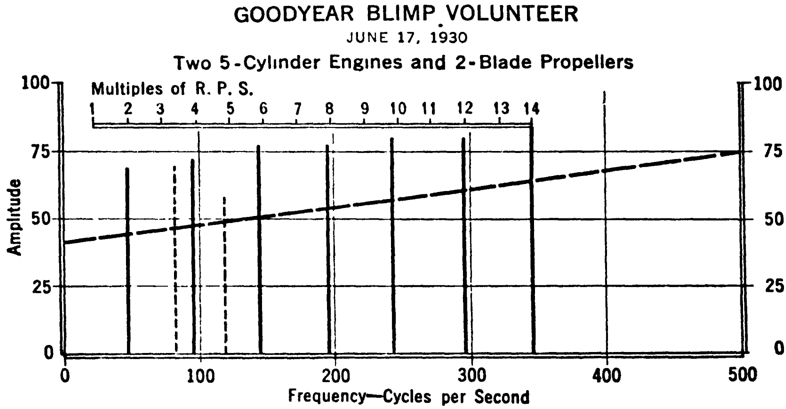

FIG. 12. Sound spectrum of noise in the cabin of a Goodyear blimp. (*Delsasso.*)

five-cylinder engines and two-blade propellers in the cabin of the Goodyear Blimp, *Volunteer*. Other noises, such as those which are in or near buildings, can be analyzed by the same method.

16. Analytical Expressions for a Sound Wave. The vibrations of a tuning fork (or of any other sound source that vibrates with simple harmonic motion) can be described by a simple trigonometric relation, namely,

$$a = a_0 \sin (2\pi nt + \theta), \tag{2}$$

where a represents the displacement at the time t of the vibrating body from its equilibrium position; a_0 the amplitude of vibration; n the frequency of vibration; and θ the phase angle which gives the location of the vibrating body at time $t = 0$. The wave motion which is propagated from such a vibrating source can be described in terms of two variables, the time t and the distance x from the source. Thus, y, the instantaneous displacement, or pressure, or velocity of the vibrating particles of the medium (usually air) at a time t and at a distance x

from the source, can be described by the relation

$$y = f(x)y_0 \sin 2\pi(nt - mx - \phi), \tag{3}$$

where y_0 is the maximal displacement at the origin, that is, at $x = 0$; $f(x)$ describes how the amplitude of vibration diminishes with the distance from the origin; m is a constant equal to the frequency of vibration divided by the velocity of propagation, that is, m is the reciprocal of the wave length; and ϕ is a phase constant. For a plane wave, that is, one which travels as a parallel beam, $f(x)$ is equal to unity,[6] in which case the analytical expression for a plane sound wave is

$$y = y_0 \sin 2\pi(nt - mx - \phi). \tag{4}$$

This implies that the wave motion does not diminish in intensity as it advances in the direction of x, so long as it continues in the same medium. This condition is closely approximated in the propagation of plane sound waves which have a frequency of less than 1000 cycles, that is, there is no appreciable dissipation of sound energy for low-frequency sound waves. (It is necessary to apply a correction for high-frequency waves. See Sec. 54.) But when the sound waves encounter another medium, as the solid walls of a room, a certain amount of the sound energy is dissipated into heat. The behavior of a sound wave when it encounters the boundaries of an enclosure is a matter of pre-eminent importance in determining the acoustical properties of a room. For example, such pertinent problems as absorption, transmission, and reflection are determined by the nature of the boundary materials of the room. These three phenomena will be the subject of a large portion of this book, and it is necessary now that they be clearly comprehended.

17. Reflection, Transmission, and Absorption of Sound. When a sound wave strikes the boundary walls of a room, a portion of the incident sound is refracted and transmitted through the wall, a portion is absorbed by the wall, and the remainder is reflected back into the room. This is illustrated in Fig. 13, which shows the incident, transmitted, and reflected components of a plane wave which has encountered a porous material, like hair felt or mineral wool — a material which is free from diaphragm action. The sound wave, since it is plane, is of a constant amplitude until it strikes the boundary. (If the wave be spherical, as is customary in free space, or even in auditoriums, the amplitude would vary inversely as the distance from the source.) One portion of the plane wave is transmitted through the flexible material, suffering a slight refraction, or bending, and a considerable attenuation, and then emerges with a constant but reduced amplitude. The other portion of the plane

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[6] Provided of course that the attenuation in the air be neglected.

wave is reflected with a diminished but a constant amplitude. The relative magnitudes of the absorbed, transmitted, and reflected components are dependent primarily upon the nature of the boundary material, but the magnitudes may vary for sound waves of different frequencies. This matter will be considered later.

In general, there are changes of phase at the boundary. Thus, the rigid walls of a room introduce a change of phase of approximately 180° for the reflected component, but no change of phase for the refracted ray. For flexible, porous materials the phase changes depend upon the rigidity and density of the boundary material.

The relations exhibited in Fig. 13 are realized only when the wall material is a flexible, porous material which does not vibrate as a whole. The usual wood, plaster, or masonry walls of a room are set into vibration by the impinging sound waves, so that the wall vibrates like a diaphragm. In fact, most of the sound which is communicated from one room to an adjacent one is transmitted by means of the diaphragm action of the walls. Rigid, heavy walls should therefore be better insulators of sound than flexible, light ones; and experience gives abundant evidence that this is indeed the case.

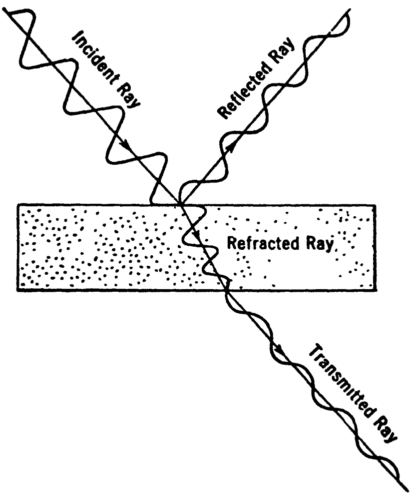

Fig. 13. Schematic representation of a sound wave encountering a new medium, showing reflection, transmission, and absorption of sound.

In most building materials, such as stone, concrete, or wood, the refracted ray is not attenuated so much as it is in porous materials, similar to that shown in Fig. 13. Everyone who has put his ear against the iron rail of a railway track to ascertain whether a train is approaching knows that steel, for example, is a very good conductor of sound. When a sound wave is once established in such materials as stone, concrete, masonry, or even water, it is propagated with but very little attenuation.

It is customary in architectural acoustics to identify the transmitted ray with the ray that emerges on the opposite side of the wall, or boundary. In accord with this view, the incident wave splits up into two components, the reflected one and the transmitted one. Then, for an observer in the room in which the sound originates, the absorbed component is simply that portion of the wave which is not reflected, that is, it represents that portion of the incident wave which is given up at the boundary, either by absorption in the boundary material or by transmission to the medium beyond the boundary. In the following discussion it is assumed that the wall is so massive and rigid that it cannot vibrate as a diaphragm, and that the internal resistance of the wall is so small that there is no attenuation of the refracted ray in the solid medium. Therefore all of the incident wave is either reflected or transmitted.[7] If I_i represent the intensity of the incident ray, I_r that of the reflected ray, and I_t that of the transmitted ray, then I_r/I_t is called the **coefficient of sound reflection**, or the **reflectivity**. It will be designated by β. Also, I_t/I_i is called the **coefficient of sound transmission**, or **transmittivity**. It will be designated by τ. In considering the acoustical properties within a room, as was stated above, all sound which is not reflected is considered to be absorbed. The **coefficient of sound-absorption**, or **absorptivity**, which will be designated by α, is, in the special case of the massive, rigid wall, approximately $1 - \beta$. That is, it is usually very small, and approximates the transmission coefficient τ. It should be emphasized that this applies only to the assumed ideal rigid wall, which does not vibrate and in which there is no internal damping. In case the wall does absorb some sound energy, as it always does, α will of course be greater than τ. In fact, in many porous materials, α may be many times greater than τ. But for rigid, dense materials α is not much larger than τ, and consequently the determination of τ is of interest not only because it indicates the amount of transmitted sound but also because it gives the lower limit to the coefficient of sound-absorption.

It is possible to calculate the approximate values of τ and β for rigid, non-dissipative walls from theoretical considerations of sound waves.[8] The theory is almost identical with the well-known optical theory of plane waves which leads to the Fresnel Equations for normal reflection. By introducing in Eq. (4) the boundary conditions, namely that both *particle velocity* and *pressure variation* be continuous across the boundary, it can be shown that

$$\beta = \left(\frac{R' - R}{R' + R}\right)^2, \qquad (5)$$

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[7] In problems or measurements which arise in sound-insulation, the transmitted wave includes both the emergent refracted ray and the ray produced by the forced vibration of the wall. The *transmitted wave* as defined in this section refers only to the wave which is transmitted *into* the reflective medium.

[8] See Crandall, "Theory of Vibrating Systems and Sound," 93–95 (Van Nostrand, 1926).

and that
$$\tau = \left(\frac{2R}{R' + R}\right)^2 \frac{R'}{R} = \frac{4RR'}{(R' + R)^2}. \tag{6}$$

Whence
$$\beta + \tau = 1. \tag{7}$$

R stands for the radiation resistance of the air and R' for the radiation resistance of the reflecting material. The radiation resistance of a material is an important acoustical constant which is similar to ohmic resistance in electrical problems and to the index of refraction in optical problems. The **radiation resistance** of a material is given by the product of density of the material and the velocity of sound in the material[9]; or, since the velocity of sound is equal to $\sqrt{k/\rho}$, where k is the compressibility modulus and ρ the density of the material, the radiation resistance is also equal to $\sqrt{\rho k}$. The values of ρ and k, or ρ and the velocity, for most standard building materials, can be obtained from dependable physical tables. It is therefore possible to determine, with the use of (5) and (6), the reflection and transmission coefficients for many materials. The radiation resistance for air, R, is $\sqrt{\rho k} = \rho c = 0.0012 \times 34{,}400 = 41$. This quantity nearly always enters into the calculation of reflection or transmission coefficients because we are dealing with problems in which the sound originates in the air medium. The values of ρ, c, R', β and τ for a number of common materials used in building construction are given in Table I.

The numerical calculations of reflection and transmission coefficients for a number of typical building materials indicate that very little sound energy in a room penetrates into the solid boundary of the room. For example, when a sound wave traveling in air encounters a solid brick wall only 0.026 per cent of the sound energy actually penetrates the brick wall, whereas 99.974 per cent of it is reflected. When the *transmitted* wave emerges from brick to air, again only 0.026 per cent of the wave will be transmitted to the air. Measurements of the sound-insulation supplied by rigid walls, such as brick or masonry, indicate that more energy is transmitted to the opposite side of the partition than is predicted by the calculations given in the preceding paragraph. As has been suggested, the sound energy is transmitted from one room to another principally by the diaphragm action of the walls, and only a small percentage of the sound which is transmitted from one room to another travels as a sound wave through the rigid walls and partitions. The calculated amounts of reflected sound, on the basis of the foregoing theory, are in fairly good agreement with measured results. Many dense, rigid materials, like concrete, stone, or steel, actually reflect as much as 99 per cent of the sound energy which strikes their surfaces.

[9] This is the product which occurred in the denominator of the right-hand member of Eq. (1).

TABLE I

Material	ρ in Grams per Cubic Centimeter	c in Meters per Second	R'	β $\left(\frac{R'-R}{R'+R}\right)^2$	τ* $(1-\beta)$
Steel	7.8	5000	3,900,000	0.99996	0.00004
Granite.	2.7	3950	1,067,500	.99984	0 00016
Masonry.	2.2	3480	761,000	.99978	0.00022
Brick.	1.8	3600	647,500	.99974	0.00026
Water	1.0	1450	145,000	.99886	0.00114
Ash (along fibre). . . .	0.75	4670	350,000	.99954	0 00046
Ash (across fibre). . .	0.75	1390	104,200	.99842	0 00158
Oak (along fibre). . .	0.75	3850	277,300	.99940	0 00060
Pine (along fibre). . .	0.84	3320	281,000	.99940+	0 00060−
Cork.	0.24	500	12,000	.98643	0.01357
Rubber	0.92	54	4,975	.96757	0.03243
Air.	0.0012	344	41	.00000	1.00000

* These values of τ should not be confused with the coefficients of transmission for walls of finite thickness. The values of τ in the table give only the fractional amount of wave energy transmitted *into* the medium.

An inspection of Eq. (5) shows that for a large reflection coefficient R' should be large in comparison with R. That is, the reflecting material should be very dense and incompressible. On the other hand, if R' become more nearly equal to R, the reflection coefficient becomes smaller and smaller. If R' be equal to R, no sound whatever would be reflected. An open window will fulfill these conditions, and hence according to this simple theory no sound is reflected from an open window. Hence, the transmission coefficient and also the absorption coefficient of an open window are each equal to unity, as is shown by Eq. (6), and as is generally known from experience. A highly absorbent material should therefore possess density and compressibility properties as nearly like the air as possible. In other words, the material should be as light as possible and it should also be readily compressible, if it is to possess a high coefficient of sound-absorption.[10]

These fundamental properties of reflection, transmission and absorption of sound will be helpful in the study and selection of materials for controlling the acoustical properties of architectural interiors. For example, orchestra shells for concert halls, dance halls, and open-air

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[10] Other properties may be utilized to secure high absorptivity in materials, as porosity, flexural vibration, etc. These properties will be considered in Chap. VI.

theatres should be lined with dense, rigid materials,[11] so that they will be efficient reflectors of sound. On the other hand, living and work rooms should be lined with porous or compressible materials so that they will reflect little and absorb much of the sound.

18. Echoes. The reflection of sound has certain virtues in acoustics, such as the enhancement of loudness and the enrichment of tonal quality, but if not properly controlled it can be responsible for two of the most outstanding defects of good acoustics — echoes and reverberation. These two companion offenders are arch enemies of the architect, and, although the architect often strives and prays for deliverance from them during the design and construction of an auditorium, he is too often the victim of these evildoers.

An echo is produced when a direct and a reflected sound wave, coming from the same source, arrive at the ear with a time interval in excess of about one seventeenth of a second. Since the speed of sound is about 1125 feet per second, it will travel about 66 feet in one seventeenth of a second. Consequently, if the shortest distance from a source of sound to a listener be shorter by 66 feet or more than the path taken by the reflected sound from source to listener, the reflected sound will be heard as an echo.

There are many interesting types of echoes, some of which occur in buildings and others out-of-doors. Some of these echoes intrigue the imagination; and often very bizarre superstitions have been associated with them. For example, thunder was formerly regarded as the angered voice of the gods, but every schoolboy now knows that it is a succession of echoes or reverberations between neighboring clouds or between clouds and earth, all originating from the initial " clap " which accompanied the flash of lightning. Reflected sounds from great distances, especially in quiet, mountainous regions, are often attended by peculiarities, sometimes musical and often mysterious. Tyndall records some remarkable instances of echoes, from which the following is quoted:

" Visitors to Killarney will remember the fine echo in the Gap of Dunloe. When a trumpet is sounded in the proper place in the Gap, the sonorous waves reach the ear in succession after one, two, three, or more reflections from the adjacent cliffs, and thus die away in the sweetest cadences. There is a deep *cul-de-sac,* called the Ochsenthal, formed by the great cliffs of the Engelhörner, near Rosenlaui, in Switzerland, where the echoes warble in a wonderful manner. The sound of the Alpine horn, echoed from the rocks of the Wetterhorn or the Jungfrau,

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[11] The resonant properties of materials must also be considered in choosing materials for orchestra shells. Such materials as thin wood paneling and plaster on lath are sufficiently dense and rigid, and at the same time have desirable resonant properties.

is in the first instance heard roughly. But by successive reflections the notes are rendered more soft and flute-like, the gradual diminution of intensity giving the impression that the source of sound is retreating farther and farther into the solitudes of ice and snow."

There are a number of musical echoes which can be observed in coliseums and open-air theatres. In a coliseum with concrete seats or benches in successive steps surrounding the entire athletic field, as the Coliseum at Exposition Park in Los Angeles, sound originating on one side of the empty Coliseum is reflected from the other side with a characteristic musical tone of low pitch. The pitch is determined by the horizontal distance between the successive vertical risers of the concrete seats. The distance between the two sides of the Coliseum is of the order of 600 or 700 feet, so that the reflected sound is delayed more than a second. Further, the echo is sustained for nearly a second because the reflecting surfaces become further and further away as the direct wave approaches the more remote and upper seats. Similar reflections occur in the Greek Theatre at the University of California, Berkeley, and in the Hollywood Bowl, Los Angeles. These echoes disappear when the seats are occupied with an audience because the reflecting surfaces are then covered with a highly absorptive surface. Reflections from picket fences, the steps of stairways, or even from the trees of the forest, will often be of this musical character, owing to the regularity in the spacing of the reflective surfaces. The phenomena are explained by a combination of the effects of reflection, diffraction, and interference. Interference and diffraction effects will be considered at some length in Secs. 21 and 23.

In large rooms with unbroken wall and ceiling surfaces, echoes are of common occurrence. If one stands between the parallel walls of any large room a whole series of echoes will follow the production of any impulsive sound, as that produced by clapping the hands. The sound is successively reflected back and forth between the parallel walls, producing a flutter which gradually diminishes with successive reflections. Curved surfaces, which are capable of converging sound to a focus, often produce very distinct and troublesome echoes. A spherical dome, with a radius of curvature greater than about 35 feet and with its centre of curvature near the floor level, provides an outstanding type of structure for producing an echo. Any sound originating at the centre of curvature of the domed ceiling is reflected back to this same point, or sounds originating in many parts of the building are reflected to conjugate foci,[12] and in each case the reflected sound is delayed long enough to be

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[12] In order that the sound be brought to a sharp focus, it is necessary that the wave length be small in comparison with the radius of curvature of the concave surface. In general, the wave lengths of ordinary sound are not short enough to produce sound

distinctly separated from the direct sound. Further, because of the converging effect which the dome imposes upon the reflected sound, the echo may be as loud as or even louder than the original sound. Examples of this type of domed structure, which became so popular in the nineteenth century, abound in almost every community; and nearly everyone has experienced the peculiar effect of having his own voice, aped with insolent mimicry, thrown back at him from domed or cylindrical surfaces in large monumental buildings. Obviously, structures which inherently possess such reflecting surfaces should be avoided, or the surfaces should be treated in such a manner as will eliminate these disturbing reflections.

19. Whispering Galleries. A phenomenon closely associated with the reflections from curved surfaces is the tendency for sound, especially high-pitched sound, to travel or " creep " around a large concave surface. This phenomenon has become famous in connection with St. Paul's Cathedral in London, and can be observed in many other concave structures. A whisper directed along such a concave surface may be heard distinctly at least 200 feet away. The new shell for the Hollywood Bowl (see Fig. 229), which is made up of one half of a truncated right circular cone, has a series of large triangular grooves which extend along the entire semicircular span of the shell. Two persons standing at the opposite ends of one of these grooves, although 90 feet apart (measured across the stage), can carry on a whispered conversation even when there is loud conversation on other parts of the stage. Rayleigh[13], referring to St. Paul's whispering gallery, states that the " whisper seems to creep around the gallery horizontally, not necessarily along the shorter arc, but rather along that arc toward which the whisperer faces." He ascribes this to the " very unequal audibility of a whisper in front of and behind the speaker," a phenomenon which is well known and which results from the marked directional effect of the high-frequency vibrations which comprise whispered speech. Rayleigh's explanation of this phenomenon predicts, and Raman and Sutherland's[14] experiments in St. Paul's show, that the whispered sound, for the most part, is concentrated in a narrow band skirting the circular base of the dome, and that the thickness of this band decreases with diminishing wave length. Impulsive sounds, such as hand clapping,

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images in the optical sense — the image usually consists of the central "bright" spot surrounded by the characteristic diffraction rings. Nevertheless, large concave surfaces are very potent in converging reflected sound, and the application of the laws of geometrical optics to reflections of sound is very helpful in describing the action of sound in closed spaces.

[13] "Theory of Sound," **2**, 127 (The Macmillan Company, London, 1926).

[14] C. V. Raman and G. A. Sutherland, Nature, **108**, 42 (September 8, 1921).

will travel around the gallery several times, and the succession of the impulsive sounds will be separated by time intervals equal to the time required for sound to travel around the circumference of the gallery.

Similar effects can be observed in nearly every circular or elliptical structure where the curved surfaces are continuous for long distances, and although the phenomenon is often quite harmless from the standpoint of good acoustics it may under certain circumstances become a real trouble maker. It is good practice to avoid shapes which are likely to become whispering galleries, especially in music rooms and in rooms where speech may originate from vulnerable positions.

20. Reverberation. Any sound which originates in, or enters, a closed space is successively reflected back and forth, to and fro, and up and down by the boundaries of the enclosed space. These multitudinous reflections produce a definite persistence of every sound within the closed space even after the source of sound has been stopped. If the enclosed space be a large and empty room constructed of dense, rigid boundaries, the multiple reflections may prolong the audibility of the sound several seconds after the source of sound is stopped. Such a prolongation of reflected sound in a room is called **reverberation.** Although a limited amount of reverberation is desirable in most rooms, it is safe to say that excessive reverberation is responsible for at least 90 per cent of the acoustical defects which have marred otherwise faultless buildings. For example, scores of famous cathedrals in Europe, such as St. Peter's (Rome), St. Paul's (London), Milan and Cologne, are so very reverberant that a chord sounded by the organ may remain audible 10 to 15 seconds after the organ is stopped. Nor is it necessary to seek far from one's home town to find similar examples, even in recently erected buildings. One of the most extreme examples was exhibited in a recently completed reading room in Los Angeles; a loud shout remained audible in this room, when empty and unfurnished, for 25 seconds — and this result could have been predicted by a ten-minute calculation in advance of construction! It is of course impossible to carry on a conversation in such a room, and every noise generated in or near the room seems to be magnified at least tenfold. The successive components of speech in such a room are confused into an utterly unintelligible hodge-podge. And in such a room music becomes a confused and discordant conglomeration of sound. In a recently completed church auditorium of modern design the reverberation was so excessive even during construction that the plasterer on the scaffolding could not make himself understood by the hod carrier below. Here indeed was a modern Tower of Babel. These examples, together with the many others every reader must have observed, will suffice to demonstrate that excessive reverberation is one of the most damaging and annoying defects which may be inflicted upon an auditorium.

The imperative necessity for the proper control of reverberation in acoustical design has established a standard of measure which has become almost universally accepted. This standard is called the **time of reverberation.** The time of reverberation in a room is the time required for a specified sound to die away to one millionth of its initial intensity. The specified sound is usually a pure tone of 512 cycles, and has an intensity equal to one million times the intensity of a tone of that frequency which is just barely audible. A decay in intensity of sound of one million fold may seem like an enormous decay, but it will be shown in the following chapter that the ordinary sounds of speech and music in a small room are of an intensity of about one million times the intensity which is just barely audible, so that the time of reverberation is approximately a measure of the duration of audibility of average sounds in a quiet room. It is possible therefore to make a rough measure of the time of reverberation in a quiet room by singing a fairly loud note and measuring the time that the note remains audible. If any noise be present in the room, a suitable correction must be made.

The subject of reverberation is so pertinent to good acoustics that an entire subsequent chapter will be devoted to the nature, control, and measurement of reverberation.

21. Combination of Sound Waves. The waves of sound, like the waves of water and light, combine to produce a variety of phenomena. Reenforcement, interference, resonance, beats, and tonal quality are a few of the more important phenomena resulting from the combination of sound waves. These phenomena are basic in understanding and controlling the acoustical problems in buildings.

When two or more wave motions of the same frequency combine, they produce a wave motion of the same frequency as those of the component waves, but the amplitude may vary from zero to the sum of the amplitudes of all the component waves. The resulting amplitude depends not only upon the component amplitudes but also upon the phase relations of the component waves. If all waves unite in the same phase, that is, if condensations unite with condensations and rarefactions unite with rarefactions, the separate wave motions conspire to produce a wave motion having an amplitude equal to the sum of the amplitudes of the component motions. This is illustrated diagrammatically in Fig. 14, which shows three component wave motions a, b and c, all in phase, and the resultant wave motion R. On the other hand, if two wave motions unite with opposite phase, that is, if condensations unite with rarefactions, the separate wave motions oppose each other in

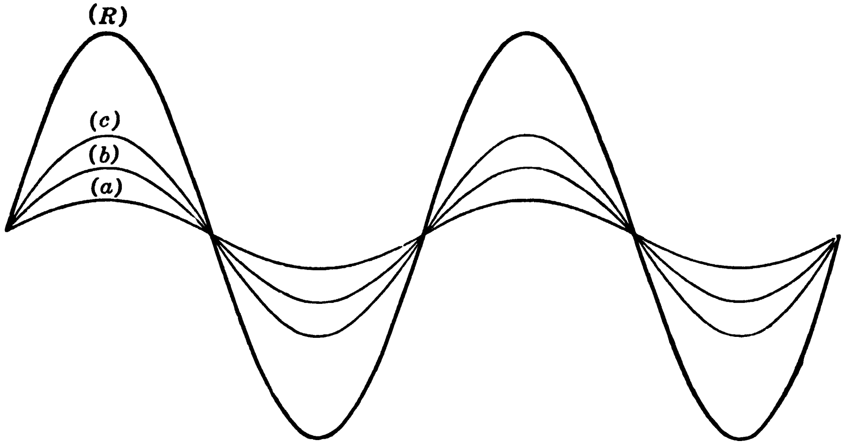

Fig. 14. Composition of three S.H.M.'s of the same frequency and phase.

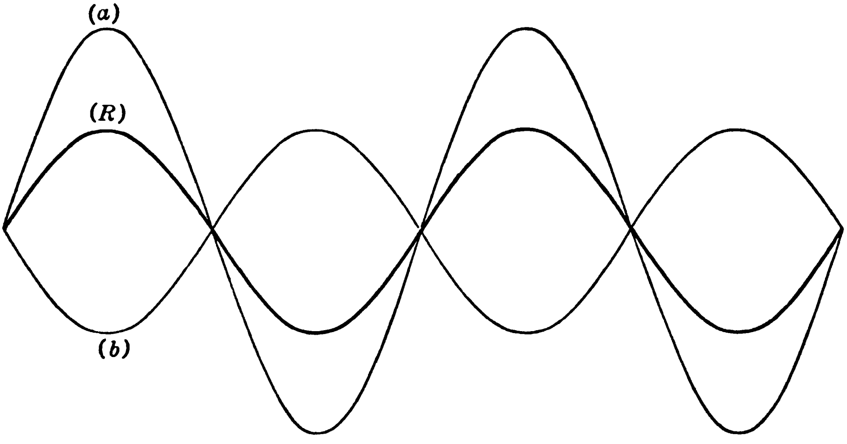

Fig. 15. Composition of two S.H.M.'s of the same frequency but opposite phase.

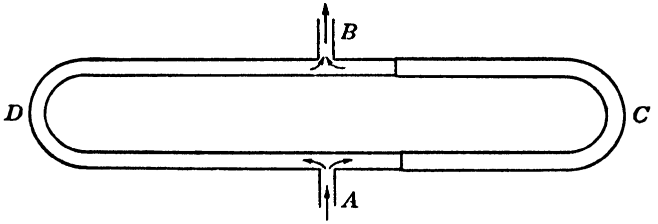

Fig. 16. Trombone arrangement for exhibiting interference and reenforcement of sound waves.

such a manner that the amplitude of the resulting wave motion is the difference of the two component wave motions. This is illustrated in Fig. 15, which shows two component wave motions *a* and *b* in opposite phase, and the resultant *R*. An interesting demonstration of the manner in which two sound waves may unite can be given by means of the apparatus shown schematically in Fig. 16. A sound wave entering the trombone arrangement at *A* bifurcates, one component going around by tube *D* which is of fixed length, and the other component going around the tube *C* which is of adjustable length. The two components unite and emerge at *B*. If the lengths of the paths by way of *C* and *D* are equal, the two components meet in phase, producing a reenforcement or augmentation of the sound. But if the length of path *C* exceeds that of path *D* by a half wave length, or any odd multiple of half wave lengths, the two components meet out of phase, producing an interference or marked diminution of loudness. In order to make a good demonstration, the sound entering at *A* should be a pure tone, and it should be wholly confined to the tube, so that no sound reaches the ears except that which has traveled through the tubes. A telephone receiver, or dynamic speaker, sealed to *A*, and actuated by a pure sine wave current, from a vacuum-tube oscillator, is a very good source of sound. In the absence of an oscillator, a tuning fork with a megaphone will serve satisfactorily. A horn of a loud speaker attached at *B* will greatly increase the loudness of the emergent tone.

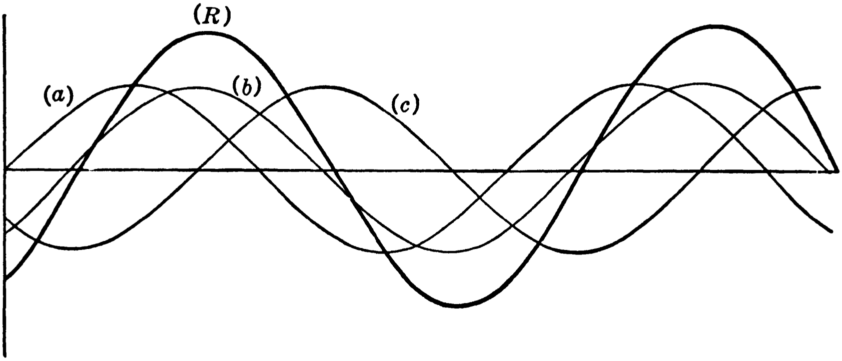

FIG. 17. Composition of three S.H.M.'s of the same frequency and amplitude but random phase.

If a number of wave motions of the same frequency meet with random phase relations, the resulting motion will be similar to that shown in Fig. 17, which shows three component vibrations and the resultant. This case is similar to, but simpler than, the actual combinations of reflected sound waves which occur in rooms. At one position in the room the waves may meet as is illustrated in Fig. 17, except that there may be fifty or more instead of three components. In another position they may meet with different phases and amplitudes, and consequently the resultant will be different. As a result, the amplitude of the composed sound waves will differ greatly in different positions in the room, varying from nearly zero to the sum of the amplitudes of all uniting components. (See Fig. 6.) This can be demonstrated very impressively by moving about in a reverberant, rectangular room in which a sustained tone is sounding. In certain positions in the room the tone will sound almost painfully loud, whereas in other positions the same tone will be almost inaudible. If one walks about in the room, a succession of prominent maxima and minima will be recognized, and they will be found to be spaced at regular intervals, depending upon the frequency or wave length of the tone. Measurements of the intensity of a pure tone in a reverberant room show that the intensity may vary from point to point as much as one hundred fold.[15] Obviously, this dependence of intensity upon position in a room has an important bearing upon the quality of speech or music in that room. At any one position in the room, certain frequency components are over-emphasized while others are greatly suppressed, depending upon the amplitude and phase relations of the various reflected components which reach the ear. It might appear that the effect would be utterly ruinous to the quality of sound in a room, but the nature of hearing is such that rather large and serious physical distortions of sound can be tolerated without appreciable impairment of quality. However, for perfect reproduction of speech or music, it is necessary that the room be relatively free from all distorting factors, including the distortion which results from interference.

The combination of sound waves having the same frequency is the type of combination which most concerns the problem of acoustics in buildings, but there are two other types of combination which should be considered briefly: the combination of two sound waves of nearly the same frequency; and the combination of a number of sound waves having frequencies which are integral multiples of a single frequency called the fundamental. The first type is of general interest because it gives rise to the familiar phenomenon of beats; and it is of special interest in architectural acoustics because it illustrates how the phase relations of combining sound waves affect the resultant sound wave, and also because the principle of beats is utilized in beat frequency oscillators which are being used more and more in acoustical measurements.

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[15] For a theoretical consideration of the uniting of isoperiodic waves of random phase relations see Rayleigh, "Theory of Sound," 1, 35–42.

A graphical representation of the combination of two sound waves of nearly the same frequency is shown in Fig. 18. The resulting sound wave has a frequency intermediate between the two component frequencies and an amplitude which varies periodically from the difference to the sum of the amplitudes of the two component frequencies. When the two components are in phase the amplitude is a maximum, equal to the sum of the two component amplitudes; and when the two components are out of phase the resultant amplitude is a minimum, equal to the difference between the amplitudes of the two component frequencies. The number of maxima or minima which occur per second is called the beat or heterodyne frequency, and is equal to the difference between the frequencies of the two combining sound waves. The two component waves in Fig. 18 unite with all possible phase differences, between complete agreement and complete disagreement, and the resultant shows clearly the important role of phase in the combination of sound waves of the same or nearly the same frequency.

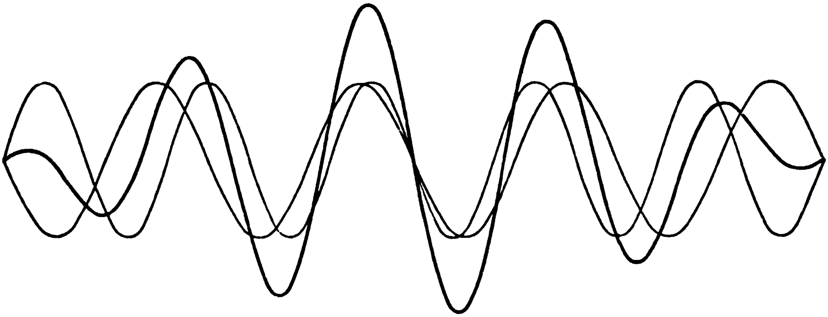

FIG. 18. Composition of two S.H.M.'s of nearly the same frequency. Beats.

A graphical representation of the combination of three harmonic sound waves is shown in Fig. 19.[16] This illustrates an analysis of a violin tone, shown at the top of the figure, into its three harmonic components. The frequencies of the three components are in the ratio of

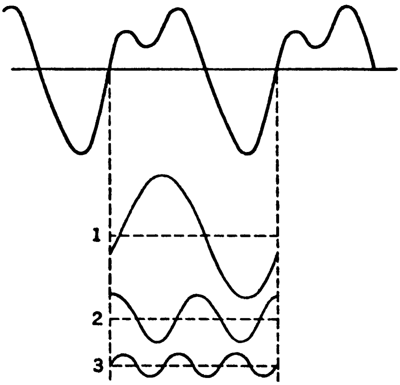

FIG. 19. Combination of three S.H.M.'s having commensurate frequencies. (*D. C. Miller.*)

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[16] Taken from D. C. Miller's "The Science of Musical Sounds," 103 (The Macmillan Company, 1916).

1 : 2 : 3, and the amplitudes and phases of the three components are shown in the figure. If the corresponding ordinates of the three components be added, the sums will give the ordinates of the original wave at the top of the figure. The original wave, which is periodic, has the same frequency as that of the gravest or fundamental component. Other periodic wave forms can be analyzed into their harmonic components; or conversely, other combinations of harmonic components can be composed into an infinite variety of wave forms. In general, the wave form resulting from any combination of harmonic components is determined by the number, prominence, and phase relations of the combining components. Thus, if only the phase relations among the three components shown in Fig. 19 were altered, the resultant wave form also would be altered.

The analysis of periodic waves into their harmonic components can be accomplished by methods and devices based upon Fourier series, or, in the case of sustained electrical or acoustical vibrations, by harmonic analyzers of the type described in Sec. 15. The syntheses of harmonic sound waves into complex waves, and the analyses of complex waves into their simple harmonic components, comprise the physical basis for the important subject of the quality of sound, which will be more fully discussed in the following two chapters.

22. Simple Laws of Reflection and Refraction of Sound. The reflection and refraction of sound conform to the familiar laws of reflection and refraction of light. In the case of sound and light, provided the reflecting or refracting surfaces be large compared with the wave length, (1) the reflected ray lies in the plane of incidence, and the angle of reflection equals the angle of incidence; and (2) the refracted ray lies in the plane of incidence, and the ratio between the sine of the angle of incidence and the sine of the angle of refraction is a constant. This constant is called the index of refraction, and is equal to the ratio of the velocities of propagation in the incident and refractive media. By referring to Fig. 20, these two laws may be formulated:

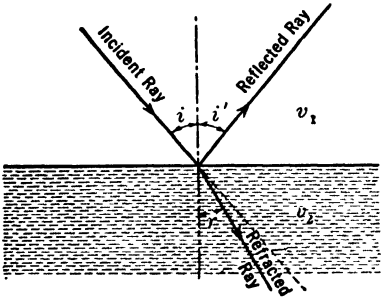

FIG. 20. Reflection and refraction of sound showing angles of reflection and refraction.

$$\text{Law of reflection, } \angle i = \angle i', \tag{8}$$

$$\text{Law of refraction, } \frac{\sin \angle i}{\sin \angle r} = \mu = \frac{v_1}{v_2}, \tag{9}$$

where v_1 and v_2 are the velocities of propagation in the incident and refractive media, respectively, and μ is the index of refraction from the upper to the lower medium. Frequent use of the law of reflection is made in investigating shapes of proposed auditoriums, and occasional use of the law of refraction is made in studying the propagation of sound in the atmosphere where changes of temperature, density, and humidity affect the paths of sound rays. It should be remembered that many surfaces in rooms are *not* large in comparison with the wave lengths of sound, especially low-pitched sound, and therefore caution must be exercised in applying the simple law of reflection to the problem of determining the reflected rays of sound in an enclosed space. Large, smooth wall or ceiling surfaces will reflect sound such that the angle of the reflected ray equals the angle of the incident ray, but windows, doors, pilasters, beams, coffers, or any form of relief ornamentation in rooms will introduce diffraction phenomena that will greatly alter the nature of the reflected sound. The nature of these diffraction phenomena will be considered in the following section.

Reflections of sound from a plane, a concave, and a convex surface are shown in Fig. 21. Positions of the direct and reflected wave fronts are shown after the direct wave has advanced from its origin P a distance PC.

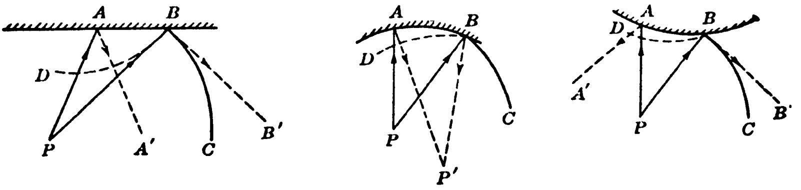

FIG. 21. Reflections from a plane, a concave, and a convex surface. The dotted lines show the paths and wave fronts of the reflected sound.

23. Diffraction of Sound. In the preceding sections there have been discussed many of the basic principles of sound, such as reflection, transmission, absorption, and the combination of waves, all of which have analogies in the subject of light. The rectilinear propagation of light gives rise to that branch of optics called geometrical optics, and rectilinear propagation accounts for the sharp shadows and images which can be formed by light. For example, light coming through a small opening in a door is confined to a narrow beam of about the same shape as the opening. If sound comes through the same opening, it spreads out almost uniformly throughout the entire room. This bending of sound as it passes through an opening, or by an obstacle, is called

diffraction. It would appear that, in respect to diffraction, light and sound behave very differently. Indeed, because of the pronounced diffraction of sound, it may seem on first thought that it would be of little value to the study of architectural acoustics to develop a branch of geometrical acoustics along the lines of geometrical optics — that is, to proceed with the assumption that sound rays always travel along straight lines, and obey the simple law of reflection stated in the preceding section. On the contrary, these simple laws of reflection are of prime importance in investigating acoustical problems provided one recognizes the limitations imposed by diffraction. Both theory and experiment show that sound and light behave very much alike provided the openings and obstacles in the sound field are in the same proportions to the wave length of sound as the openings and obstacles in the light field are to the wave lengths of light. Light waves have wave lengths of the order of 0.000015 to 0.000030 inch, whereas sound waves have wave lengths of the order of 0.06 to 60 feet. It is principally because of this great disparity in the wave lengths of sound and light that we usually observe that light travels in straight lines through openings and past obstacles, whereas sound spreads out very considerably under the same circumstances. If the openings and obstacles in either a sound field or a light field are large in comparison with the wave length, the same laws apply to either acoustics or optics. That is, the laws of geometrical acoustics will be the same as the laws of geometrical optics. Thus, high-frequency sound will produce sharp shadows or images, or will travel through an opening, as an open door or window, in the same manner that light does. It is possible to reflect high-frequency sound, by means of a parabolic reflector, in a concentrated beam which diverges but very little.[17] On the other hand, low-frequency sound, that is, sound having a long wave length, in coming through a door or out of the horn of a loud speaker would spread out in all directions, or in being reflected from a parabolic reflector of ordinary size would spread out or diverge in all directions. Diffraction of sound occurs whenever sound passes through openings or is reflected by surfaces which are not large in comparison with the wave length of the sound. It is important that the student of architectural acoustics be familiar with this phenomenon, and consequently it will be discussed in some detail. Many mistakes are made in the acoustical design of buildings because it is assumed that sound will be reflected in the same manner as light. If the reflecting surfaces are very large, say 10 to 100 feet in extent, sound will be reflected regularly, like light; but if the reflecting surfaces are only a few

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[17] The divergence is proportional to sin 0.61 l/r, where l is the wave length of the sound and r is the radius of the reflector.

feet in extent the reflections will be very much modified by sound diffraction.

Three cases of the diffraction of sound will be considered: (1) the transmission of a parallel beam of sound through a small opening; (2) the transmission of a parallel beam through a large opening; and (3) the transmission of a parrallel beam through an opening comparable in size with the wave length of sound. The first case is illustrated in Fig. 22. A parallel beam of sound falls upon a very large surface in which there is an opening *o*, small in comparison with the wave length of the sound. According to the Huyghens' principle, which states that the wave front at any instant may be regarded as a source for secondary waves, the opening *o* may be regarded as a new point source for sound, from which the sound spreads out as a spherical wave. Whereas the sound wave was a parallel, non-diverging wave before it reached the small opening, the emergent sound beyond the opening diverges approximately as a spherical wave. If the opening be very small in comparison with the wave length of the sound, the spreading out is uniform in all directions, that is, the intensity of sound in the emergent beam is the same in all directions. Many of the openings which are found in buildings, such as cracks around doors, or the openings from ventilating ducts, or open passageways, are so small that the diffraction of sound — at least of low frequency — coming through these openings is similar to the case illustrated in Fig. 22.

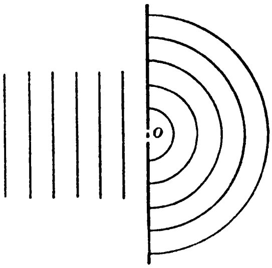

FIG. 22. Diffraction of sound passing through a small opening.

On the other hand, a large opening, such as the proscenium opening between the stage and the main part of an auditorium, allows considerable rectilinear propagation of sound through the opening, and there is only a relatively small amount of diffraction around the edges of the opening. This is illustrated in Fig. 23, which shows how a parallel beam of sound is propagated through an opening which is large in comparison with the wave length of the sound. In this case a large portion of the beam of sound continues in its parallel motion through the opening but there is a slight bending toward the edges, as is illustrated by the lines at the right of the

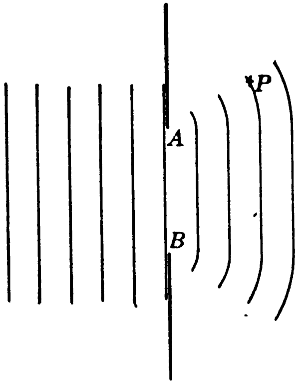

FIG. 23. Diffraction of sound passing through a large opening.

opening, which represent the wave front of the emergent sound. The extent of the bending is determined by the relation of the wave length to the size of the opening. If the opening be many times larger than the wave length, the propagation is essentially rectilinear, that is, there is very little bending around the edges.

The diffracted sound shown in Fig. 23 falls off in intensity with the extent of its divergence from the parallel beam, but it does not fall off uniformly. Instead, the diffracted sound surrounding the rectilinear beam consists of the characteristic succession of alternate maxima and minima, which gradually merge and fade to an insignificant intensity at a considerable divergence from the rectilinear beam. The distribution of the diffracted sound in successive maxima and minima can be explained by considering the sound which reaches the point *P* from all points of the wave front along the opening *AB*. If, in accordance with the Huyghens' principle, the separate wavelets coming from *AB* to the point *P* meet in such phase relations as to conspire, there will be a maximal intensity at *P*; if they meet in such phase relations as to interfere, there will be a minimal intensity. If the opening *AB* be small in comparison with the wave length of the sound, the intensity at any point outside of the rectilinear beam, such as *P*, cannot be zero, since all the wavelets coming from *AB* travel nearly the same distance in reaching *P* and therefore they unite in nearly the same phase. There will be a slight falling off in the intensity of the diffracted sound as it diverges from the rectilinear portion, but if the opening be very narrow the distribution approaches uniformity; and in the limit of an infinitesimally small opening, as is assumed in Fig. 22, the distribution is uniform. On the other hand, as the opening becomes very large in comparison with the wave length of the sound, the entire plane wave is propagated through the opening as a rectilinear beam, and the diffraction effect becomes more and more negligible.

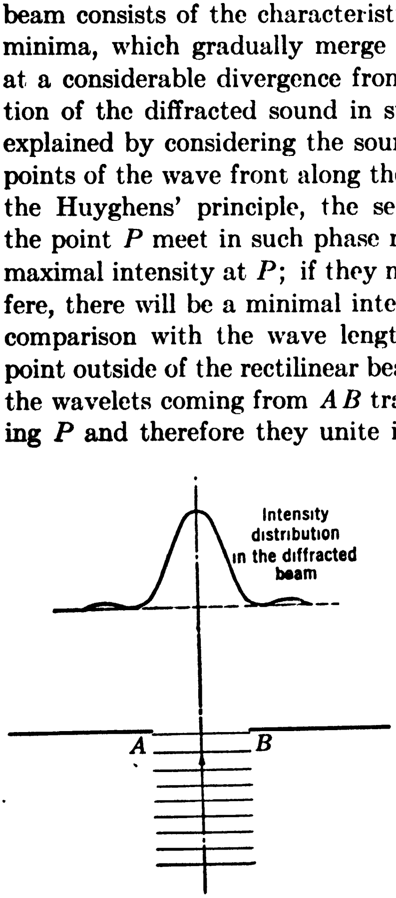

FIG. 24. Diffraction of a pure tone of 512 cycles passing through an opening 4 feet wide. The curve shows the intensity distribution of the transmitted and diffracted beam of sound.

Finally, let us consider the propagation of a plane wave of sound through an aperture which has a width equal to, say, twice the wave length of the sound. Such a case is represented in Fig. 24. For a pure tone of 512 cycles, the opening would be about 4 feet wide. The intensity distribution of the diffracted sound at a distance of about 5 feet behind the opening is indicated in the upper part of the figure. Only the first secondary maxima are shown on either side of the primary beam. It will be seen that the intensity distribution in the beam has been markedly altered by the diffraction of the opening *AB*, which in this case is twice as wide as the wave length of the sound. In all cases of the diffraction of sound in passing through openings the intensity distribution will be somewhat similar to that shown in Fig. 24 — the exact distribution depending upon the wave length of the sound, the size and shape of the opening, and the distance from the opening.

Since the wave lengths of sound vary from 0.06 to 60 feet, that is, a thousand fold, the diffraction of sound is very much dependent upon the frequency or wave length of the sound, and diffraction may be marked for some frequencies and negligible for others. An opening which is small for the lowest frequencies of sound, which may have wave lengths as long as 60 feet, may be large for the highest frequencies, which may have wave lengths as small as 0.06 foot. For example, a 3-foot door opening would be small compared with a 60-foot sound wave, and therefore such low-frequency sound would be very much diffracted in going through the door, the emergent sound spreading out almost uniformly in all directions; whereas this same door opening would be very large compared with a 0.06-foot sound wave, and therefore such high-frequency sound would be transmitted through the door almost rectilinearly, with but very little diffraction. Obviously, complex sounds, such as are used in speech and music, which are made up of a wide range of frequencies, are peculiarly diffracted because the low-frequency components will diverge widely, and the high-frequency components will continue in their rectilinear beam. This is strikingly demonstrated in the radiation of sound from the horn of a loud speaker, such as is used for reproducing sound in the motion-picture theatre. If a listener sits near the axis of the projecting horn, he will hear plainly both the high- and low-frequency components, and the reproduction ordinarily will sound very good; but if he sits far away from the axis of the horn, he will observe a noticeable diminution of the high-frequency components, and the quality will therefore be considerably impaired. The dimensions of the horn are small compared with the wave lengths of the low-frequency components of speech or music, and consequently these components spread out almost as spherical waves. On the other hand, the horn is large compared with the wave lengths of the high-frequency components; and consequently these components are only slightly diffracted, and are concentrated along the axis of the horn. Obviously, such diffraction effects have an important bearing upon the quality of both speech and music.

We have discussed the phenomena of diffraction primarily with reference to the transmission of sound through openings. Equally important, or perhaps of even greater importance, in architectural acoustics, are the diffraction effects which accompany the reflection of sound. The architectural and decorative treatment of rooms, such as beams, trusses, pilasters, and ornamental plaster, results in regular or irregular breaks or discontinuities in the boundaries of the room, and consequently the interiors of most rooms are of such a nature as to introduce complicated diffraction phenomena. As an instance of how sound is reflected and refracted from a broken surface, such as the coffers in a ceiling, a spark photograph obtained from a model of an auditorium is shown in Fig. 25. An inspection of this photograph will show that the many wavelets originating at the ribs of the coffers cannot be explained on the basis of the simple laws of reflection, but that they are readily accounted for by diffraction. The diffraction from the projecting ribs is similar to the diffraction through small openings: the edges of the ribs of the coffers are small in comparison with the wave length of the sound, and therefore these edges become secondary sources, and diffract or diffuse the sound in the same manner as though the sound originated at these edges.

FIG. 25. Spark photograph showing reflection and diffraction from a coffered ceiling. Royce auditorium, University of California at Los Angeles.

Sufficient has been said concerning the phenomena of diffraction to demonstrate that the simple laws of reflection are wholly inadequate to predict the behavior of sound in architectural interiors. If the surfaces are smooth and plane, the laws of reflection will give a fair approximation to the actual behavior, but the usual architectural treatment of the room introduces broken surfaces which greatly affect the distribution of reflected sound in a room. The most satisfactory method of investigating these diffraction effects consists of obtaining spark photographs of sound waves traveling through model sections of the auditorium. This method will be considered in greater detail in Sec. 29. It is often possible, however, to determine the principal effects of reflection and diffraction from a study of the plans and sections, based upon the simple laws of reflection or the theory of acoustical images.

24. Acoustical Images. Although acoustical images are in general not so sharply defined as optical images, nevertheless the use of acoustical images is of considerable help in investigating the action of sound in interiors. If a point source of sound be located in front of an extended plane reflecting surface, as the wall of a room, it may be regarded as having a point image behind the wall, on the projection of the perpendicular drawn from the point source to the wall and at a distance behind the wall equal to the distance from the wall to the point source. Further, if the wall have a high coefficient of reflection (hard plaster, concrete, and masonry reflect 97 to 99 per cent of the incident sound energy), the image will have a "strength" almost equal to the source, and in the case of all rigid reflectors such as are encountered in buildings the phase of the waves from the image will agree with the phase of the waves from the source, so that the resultant effect in the room will be the sum of the effects owing to both the source and its image.

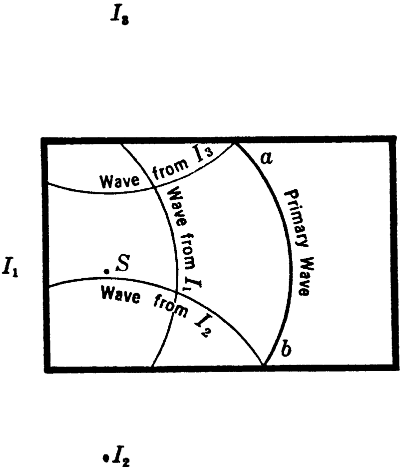

FIG. 26. The three nearest images of a source of sound S near the three walls of a rectangular room, and the reflections resulting from these three images.

In Fig. 26 are shown the three images from three near-by walls for a point source of sound in a rectangular room. The primary and reflected waves are shown as they would be, neglecting diffraction, at the instant the primary wave has advanced to the position *ab*. There will be other similar images from the other end wall, the floor, and the ceiling; these images will then have second, third, and higher order images, all of which will contribute to the sound energy in the room. Usually, however, in architectural acoustics, the first order images are the ones of prime importance, and it is rarely necessary to consider higher orders than the second in determining the most favorable reflecting surfaces for architectural interiors. If the reflected wave from I_1 be sufficiently close behind the primary wave *ab* — closer than about 55 feet — it will provide a beneficial reenforcement of sound; but if it be delayed more than about 55 feet it will produce an interfering effect, and if it be delayed as much as 66 feet it will be heard as an echo. The same applies to all other reflected waves. Thus, the reflected waves from I_2 and I_3 will be beneficial for auditors seated near the side walls, but in very large auditoriums they may constitute an interference in the central part of the auditorium. For this reason the central seats on the main floor of an auditorium may be very poor seats for hearing.

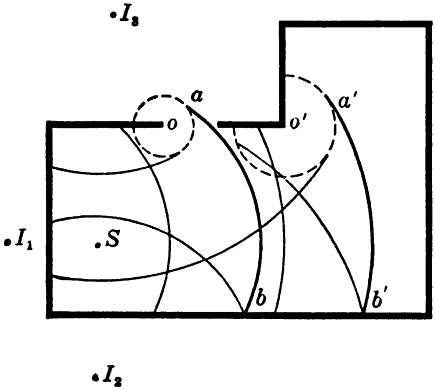

FIG. 27. Geometrical representation of reflected and diffracted sound waves.

In Fig. 27 the primary wave is shown at two successive positions, namely at *ab* and at *a′b′*, represented by heavy lines. The reflected waves are represented by lighter lines, and typical effects of diffraction from the edge of the opening *o* and from the projecting corner *o′* are represented by dotted lines. The points *o* and *o′* are thus seen to become secondary sources for the diffracted sound. There are of course many other reflected and diffracted waves, but the ones which have been drawn in Fig. 27 are sufficient to indicate the use of images in studying the action of sound in rooms.

25. Resonance. There has been a tendency, especially among those who are not acquainted with the fundamentals of physics, to confuse resonance with reverberation. Many persons, including some musicians, speak of a room as having too much resonance, whereas the complaint of which they speak is excessive reverberation. Reverberation has been defined as the persistence of sound in a room after the source is stopped. Reverberation results from the multitudinous reflections of sound from the boundaries of the room, and may exist independently of the vibratory properties of the walls or objects within the room. **Resonance,** as defined and used in physics, is a phenomenon which results from the coincidence or synchronization of the free vibrations of a body and vibrations which are forced or impressed upon that body. The free or natural vibrations are excited by external forces, but principally by periodic vibrations of the same frequency as the free or natural vibrations of the resonating body. When these external vibrations are of the same frequency as the frequency of one of the free or natural vibrations of the body, the response of the vibrating body is very pronounced; that is, the body is said to **resonate** at this particular frequency. The most familiar example of resonance is very well demonstrated by two tuning forks mounted on separate boxes, both forks being carefully tuned to the same frequency. If the two forks be separated by a distance of about 10 feet or less, it is possible to excite " sympathetic " vibrations in one fork by the vibrations of the other. Thus, if one of the forks be set into vigorous vibration and then stopped, it will be observed that the other fork will have been excited into sympathetic or resonant vibration. If the tuning of either fork be slightly altered, so that the forks differ ever so slightly in frequency, the resonant phenomenon is greatly diminished, and it disappears almost completely when the two forks differ in pitch as much as a semitone. This same phenomenon of resonance is demonstrated every time one tunes in a radio station on a radio receiver set. In this case, the free or natural frequency of the receiving apparatus is adjusted to coincide with the radio or carrier frequency of any particular station.

Many objects in a room respond on this basis of physical resonance. A wood panel, a window pane, a large vase, an entire wall, niches or alcoves, various pieces of equipment or ornamentation, or even the entire volume of air in a room, may resonate to the vibrations produced in the room. For example, a glass pane in a door of a radio broadcasting studio was found to be a troublesome source of disturbance, because it always resonated to a particular musical note, about an octave below middle C. Everyone has witnessed the resonance in a small room with hard reflecting walls, such as a bathroom. And every preacher finds it to his advantage to ascertain, and to adapt his voice to, the natural resonance of the room in which he speaks. Nearly every room seems to resonate or respond to a characteristic tone, and in most cases this tone seems to be near the tenor A.[18] A similar resonance may be observed in small

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[18] See Bagenal and Wood, "Planning for Good Acoustics," 216–218 (Methuen, 1931). Theoretically, there should be a *large number of resonant frequencies or tones* in a room, and there seems little warrant for a *single characteristic tone.*

alcoves or recesses, or in various vessels or vases. Thus the Greeks and Romans deliberately placed large vases in their theatres for the purpose of augmenting certain frequency components of speech and music by means of resonance. The resonators were adjusted to those frequencies which were thought to be most desirable for the proper rendition of speech and music. Recently, an acoustical tile has been placed upon the market which is supposed to produce a similar resonance, thereby augmenting the loudness of certain components of speech and music. Such resonance may be helpful to the acoustics of rooms, but it should not be regarded as a correction for excessive reverberation. In fact, as the resonance of the room is increased, the reverberation should be decreased, since both resonance and reverberation tend to sustain or even augment sound. Although a number of extravagant claims have been made for a patented cement tile which is supposed to vibrate nearly as freely as the sounding board of a piano, such a product must not be regarded as a panacea for poor acoustics.

In general, resonators of the type found in rooms have discrete series of frequencies (partial tones) to which they will resonate, and these series do not comprise, as a rule, all the frequencies required for speech and music. Since speech and music are made up of a wide band of frequencies, embracing at least eight octaves, about all that can be expected from resonators is an emphasis of only a few of the component frequencies of speech and music. Such an emphasis of selected frequencies introduces a distortion, which in general would be expected to be harmful rather than helpful to the quality of speech or music. However, it should be mentioned that the resonance set up in such materials as wood paneling or wood flooring may be of appreciable value in both speech and music rooms, since these wood structures are not sharply resonant to one or a few frequencies but respond throughout a wide range of frequencies. In such structures it is the forced vibrations as well as the free or resonant vibrations which are of interest.[19]

26. Forced Vibrations. The diaphragm or moving element in any device which is used for converting electrical vibrations into acoustical vibrations is forced to vibrate with the same frequencies as are impressed upon it. In a similar manner, all structures or objects in a room which are free to vibrate are forced into vibration by the sound waves in the room. This can be readily sensed by placing the finger tips against panels of wood or glass, or even plaster on wood or metal lath, when

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[19] The subject of resonance as applied to architectural interiors deserves more attention than it has been accorded by physicists and acoustical engineers. The subject is at present chaotic and mostly empirical, and yet it must be admitted that resonance is an important factor in the acoustics of music rooms.

loud, sonorous tones are produced in a room. Such forced vibrations of panels or walls are of course most vigorous when the frequencies of the tones in the room (the exciting or driving frequencies) are in agreement with fundamental or partial frequencies of the panel or wall (these are the free or resonant vibrations considered in Sec. 25); but owing to the large number and closeness of these partial frequencies, and to the high internal damping within the vibrating panel or wall, the forced vibration is nearly uniform for the entire useful range of frequencies used in speech and music. Consequently, such vibrations of the boundaries of a room will not over-emphasize certain components or introduce any harmful distortions, and may contribute to the acoustical merit of the room by providing a more diffuse reflection of sound, and by imparting a sustenance to the desirable characteristics of music. In the case of such musical instruments as make direct contact with the floor, as the cello, bass viol, and piano, the use of wood flooring, and of wood paneling directly joined to the wood floor, can serve the same purpose as does the sounding board in a piano. The value of forced vibrations and resonance in the materials which form the boundaries of rooms will be considered at greater length in subsequent chapters.

27. Frequency Standards. Nearly all measurements and calculations in architectural acoustics are made with pure tones of the following frequencies: 64, 128, 256, 512, 1024, 2048, and 4096 cycles. These are representative of the more important range of frequencies used in speech and music, although speech and music contain frequencies about two octaves lower than 64 cycles and also two octaves higher than 4096 cycles. Many fundamental calculations, such as the determination of the time of reverberation in a room, are usually limited to a single tone of 512 cycles, and in the practical applications of acoustics to building design this one tone is of such preeminent importance that it may rightly be regarded as the standard tone in architectural acoustics. However, caution must be exercised in the use of a single frequency standard. It should be used alone only when the architect or engineer knows that the characteristics of the room will be satisfactory for all other frequencies. In theatres, churches, music rooms, and lecture halls it is advisable to make calculations of reverberation at three frequencies, namely, 128, 512, and 2048 cycles.

Any set of good tuning forks having rated frequencies of 64, 128, 256, 512, 1024, 2048, and 4096 cycles will suffice for the frequency standards required for calibrating such apparatus as is used in testing the absorptive and insulative properties of rooms and materials. Recently, a new type of tuning fork has been developed, using a special alloy instead of steel for the fork material. These new forks are called " duratone "

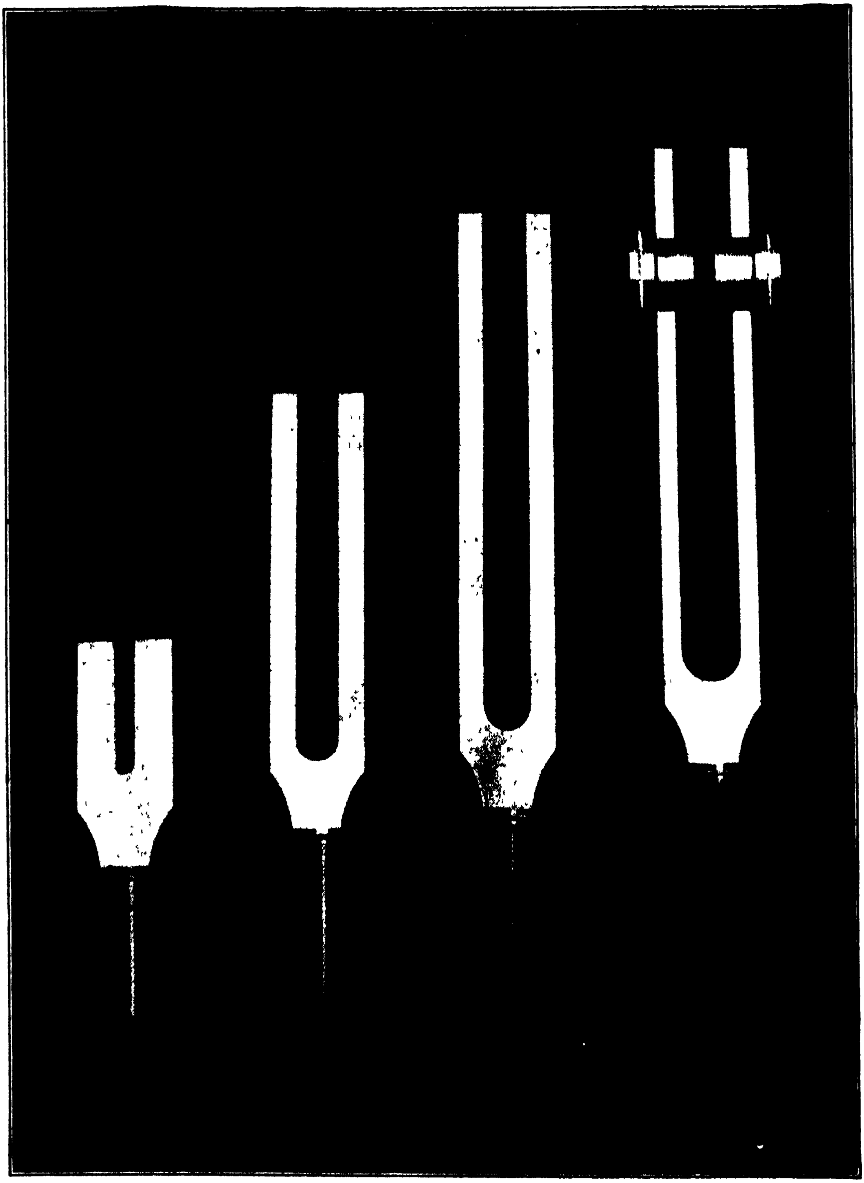

FIG. 28. Duratone tuning forks for frequency standards and for the measurement of noise.

tuning forks. They maintain their tones much longer than do the older steel forks — some of them remain audible for three or four minutes. In addition, they retain their pitch accuracy better than steel forks do, and they have an extremely small change of frequency with temperature changes. The forks of low frequency (below 256 cycles) should be struck on very soft objects, as the palm of the hand; those of intermediate frequency (256 to 1000 cycles) with a soft rubber or felt hammer; and those of high frequency with a hard rubber hammer.

Tuning forks are not only useful for the frequency calibration of acoustical measuring instruments, but when their rate of damping is known they may be used for determining the intensity and frequency distribution of noises. (See Sec. 87.)

28. Sources of Sound for Acoustical Studies and Measurements. Several sources of sound have been mentioned in the preceding sections of this chapter, and some of these may be used for investigations in acoustics. The use of the tuning fork, which always has been a venerable standard in acoustical measurements, was mentioned in Sec. 27. It is inexpensive, simple to operate, and gives a very pure tone of constant pitch. However, it is quite limited as a useful source for acoustical investigations. It does not radiate a sufficient amount of sound energy for most types of measurements employed in architectural acoustics. Further, it is difficult to operate the fork at a constant amplitude, and therefore at a constant loudness level.

The organ pipe, blown at a proper and constant pressure, overcomes many of these difficulties, and therefore it has served as a dependable source of sound for investigating the acoustics of interiors. It was the standard source of sound used by the American pioneer in architectural acoustics, W. C. Sabine, and has been used largely by subsequent investigators. However, the organ pipe does not emit a physically pure tone. In addition, a series of organ pipes with associated wind chest, such as would be required for acoustical measurements, is lacking in portability.

Since the advent of the thermionic vacuum tube, used so extensively in radio, sound pictures, and telephony, the tube oscillator with an associated loud speaker has come to be one of the most useful sources of sound for acoustical measurements. It is a dependable generator of tones of any desired pitch and loudness; the control for either pitch or loudness is flexible and convenient; and the pitch and loudness of the tones can be readily determined. Further, with the use of appropriate electric filters, the generated tones are of a pure quality; that is, they are free from overtones or harmonics. Fig. 29 is a photograph of a typical audio-frequency oscillator. Oscillators similar to this one are very useful for investigating the acoustical problems of architectural interiors, and many of the problems which will be considered in this book have been investigated with the aid of such tone generators. For this reason, a simple oscillator circuit is shown diagrammatically in Fig. 30. Anyone familiar with even the most simple radio circuits will understand the general features of this circuit for generating alternating currents. *L* is an inductance coil with a tap brought out from about the middle of the winding and connected to the filament of the oscillating tube. The two ends of this coil are connected, indirectly, to the grid and the plate of the first vacuum tube, and thus the coil inductively couples the output and the input of the oscillator tube. *C* is a variable mica condenser connected across the inductance coil. The combination of *L* and *C* is called the tuning circuit because it determines the frequency of oscillation of the generated alternating current. Thus, if *L* be 1.0 henry and *C* be 0.096 microfarad the frequency of oscillation will be approximately 512 cycles. When an electric current of this frequency is im-

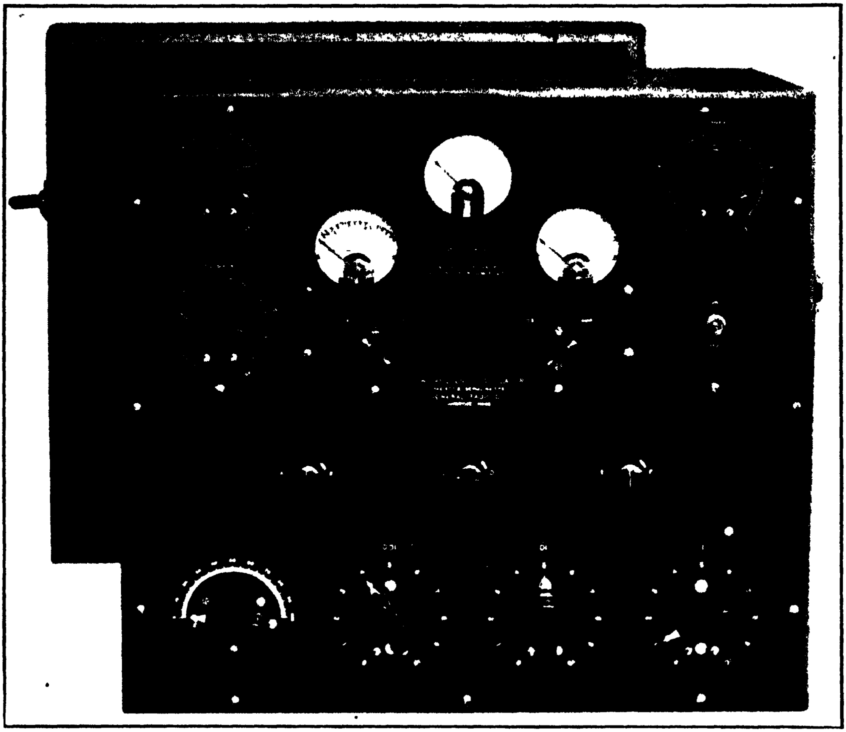

FIG. 29. General Radio Company's audio-frequency oscillator.

pressed upon a loud speaker, a tone having the pitch of approximately one octave above middle C is produced. (The electrodynamic type of loud speaker is generally used, principally because its acoustical output is directly proportional to the electrical power which actuates the speaker.[20]) Other tones of any desired pitch can be obtained simply by changing L or C. In fact, the frequency f of the generated tone is given approximately by $f = 1/2\pi\sqrt{LC}$. The loudness of the tone is governed by the strength of the electric current flowing through the loud speaker, which can be controlled and measured by a simple resistance attenuator and a thermocouple. It is thus possible to provide tones of any required pitch and loudness by the appropriate setting of the dials which control the inductance L, the capacitance C, and the resistance attenuator connected between the oscillator and the loud speaker. The low-pass filter shown in the figure eliminates all harmonics above the fundamental, and thus a pure sine wave alternating current is generated.

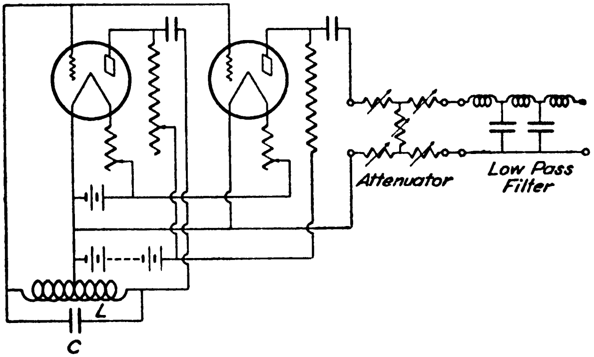

FIG. 30. Circuit diagram of a vacuum-tube oscillator and a low-pass filter.

For many acoustical measurements "warble" tones are better than single-frequency tones such as are produced by an audio-frequency oscillator. A "warble" tone is produced by varying the frequency continuously between the two frequency limits. Thus, 512 ± 100 cycles is made up of a frequency band 200 cycles wide, the frequency varying periodically from 412 to 612 and back again to 412. For most purposes, this periodic variation of frequency should occur about five to seven times per second. Such warble tones help very much to overcome the difficulties of the interference pattern in a room which results when pure tones are used; and they also help to maintain a uniform "loading" on the loud speaker. A warble frequency is easily produced by rotating

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[20] This will be the case only when the "loading" on the loud speaker remains constant.

a small auxiliary air condenser connected to the condenser in the tuning circuit of one unit of a beat frequency oscillator. Fig. 31 shows a circuit diagram of a beat frequency oscillator used in the Acoustical Laboratory at the Bureau of Standards.[21] This circuit is remarkably free from frequency drift, and in all respects is highly satisfactory for laboratory measurements in architectural acoustics.

A high-quality phonograph with electrically cut records of pure or warble tones often may be employed as a source of sound for measurements in architectural acoustics. It is simple, convenient, and reliable in operation.

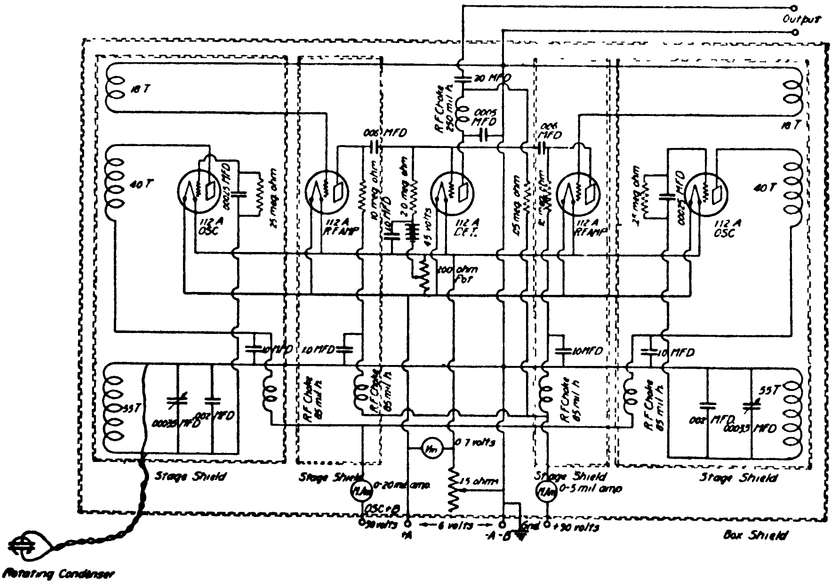

FIG. 31. Circuit diagram of beat frequency oscillator used at Bureau of Standards. (*Chrisler and Snyder.*)

29. The Use of Water Waves and Sound-Pulse Waves in Architectural Acoustics—The Ripple Tank and Sound-Pulse Photography. The acoustical design of an auditorium is dependent upon the paths of all possible sound rays from the source to the listener. Because of the complexities of reflection and diffraction, which have been considered in this chapter, it is not always an easy matter to ascertain what these paths will be from a purely geometrical consideration of the plans and sections for the auditorium. Accordingly, methods have been developed

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[21] Chrisler and Snyder, Bureau of Standards Research Paper No. 242, 5 (October, 1930). See also G. F. Lampkin, Radio Broadcast, 13, 157 (July, 1928); Cohen, Aldridge and West, Jour. Inst. Radio Engineers (London), 64, 1023 (1926).

for studying the progress of sound waves in small two- or three-dimensional models of the proposed auditorium. These studies often reveal defects of shape which would not be suspected from a geometrical study of the plans. In the use of such models it is necessary that the model be of such size that the ratio of its linear dimensions to the wave lengths of the waves used in the investigation be approximately the same as the ratio of the linear dimensions of the auditorium to the wave lengths of the speech or music which will be used in the room. The diffraction effects observed in the model will then be comparable with those which will result in the auditorium. Since, from the standpoint of cost, it is desirable to work with small models, it is necessary that means be provided for producing experimental waves of correspondingly small wave length. Two principal means have been utilized for producing these small waves: the ripples on a shallow tank of water; and intense sound pulses of very short wave length, such as may be produced by a sudden discharge of a highly charged electrical condenser. Methods which utilize these two types of waves are limited to a two-dimensional study of wave propagation, so that it is necessary to make models representing the plan, the longitudinal section, and the transverse section, of the auditorium which is to be investigated. It is usually possible to ascertain the nature of the propagation of sound in the three-dimensional audito-

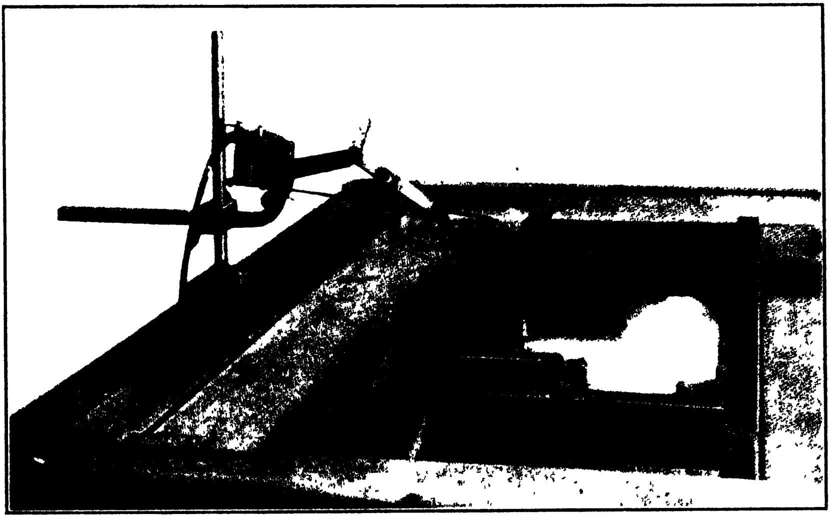

FIG. 32. Photograph of the ripple tank used at the National Physical Laboratory. (*Davis and Kaye.*)

rium from a composite study of the propagation of waves in the two-dimensional models.

One of the oldest and most commonly used methods for investigating the paths of sound waves in an auditorium makes use of water ripples. Davis[22] has given a description of the historical development, and the advantages as well as the limitations, of the use of water ripples in the study of the shape of auditoriums. If simple harmonic ripples be maintained on a tray of water, the depth of which is greater than one half the wave length of the ripples, the analogy between these water ripples and sound waves is good enough to reveal the behavior of sound waves in an auditorium. Fig. 32 is a photograph of the ripple tank used at the National Physical Laboratory, with a two-dimensional model in position for study. The model, made of wood, to a scale of ¼ inch to 1 foot, is a longitudinal section of an auditorium. The model is lying upon the glass plate of the ripple tank, and the tank is filled to a depth of slightly less than 1 inch. A plunger, operated with an electromagnet, starts the ripples at a point which would be occupied normally by a speaker. The wave length of the ripples is of the order of ½ inch, so that they are comparable with sound waves having a wave length of about 2 feet in the auditorium. Light from a powerful arc lamp passes vertically upward through the glass bottom of the tank, and by means of a plane mirror above the tank, inclined at an angle of 45°, the shadow of the ripples is thrown upon a vertical screen. The projected image on the screen furnishes a very satisfactory means for studying the progress of the ripples, since they can be followed visually from the source across the model and also after they have suffered reflection or diffraction. Or, by means of a

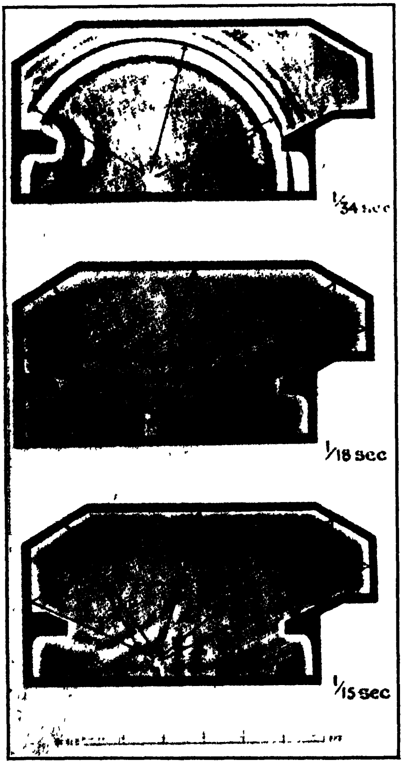

FIG. 33. Three photographic views of ripples in a model obtained at the National Physical Laboratory. (*Davis and Kaye.*)

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[22] Phys. Soc. Proc., 38, 234 (1926).

camera placed above the tank, it is possible to obtain instantaneous photographs of the position of the ripples at any desired time. Fig. 33 gives three photographic views of an advancing ripple in a model obtained at the National Physical Laboratory. These three views correspond to the positions of the sound waves $\frac{1}{84}$, $\frac{1}{18}$, and $\frac{1}{15}$ second after the train of waves left the origin. The waves reflected from the various portions of the boundaries of the model are clearly shown in the three photographs.

It will be noted in the third photograph of Fig. 33 that the ripples have become very diffuse and vague after an interval of about $\frac{1}{15}$ second, that is, before the second reflection has taken place. This rapid damping of the ripples limits the usefulness of this method, since the little waves disappear very soon after the first reflection, whereas at least the first two or three reflections should be investigated in making a study of auditorium design. However, since the first reflection is usually the one which will produce an echo or a pronounced interference in an auditorium, the ripple tank often affords a means of determining the relative merits of different shapes for a proposed auditorium.

It is possible to obtain more satisfactory photographs of sound waves by means of sound-pulse photography. In this method the model is usually made of plaster of Paris, or wood, and is made to a scale of about $\frac{1}{16}$ inch to the foot. The model is therefore considerably smaller than the one which would be used with the ripple tank. In the sound-pulse method, the waves are produced by the sudden and violent discharge of an electrical condenser. The noise produced by such a discharge is similar to the report of a pistol, but is of a higher frequency. It produces a very intense sound pulse which consists principally of a single condensation followed by a rarefaction which spreads out from the source with the velocity of sound. The pronounced condensation in the advancing wave front is very much denser than the surrounding air, so that this condensed air has the same effect as though a refractive medium, such as glass, had been introduced into the air medium. When light passes through such a region of marked condensation it is refracted in accordance with familiar laws of geometrical optics. In fact, the light which passes through the condensed air is sufficiently refracted to produce an image of the sound pulse, which can be viewed on a ground-glass screen, or photographed on a sensitive film. The illumination, either for viewing or photographing, is accomplished by means of a second spark discharge which is timed to follow the sound pulse by only a few hundred thousandths of a second. This delay of the light spark can be controlled by means of condensers and a resistance so that the light spark can be adjusted to illuminate the sound spark at any desired position or time interval after the pulse leaves the source. In this way, it is possible to study, either visually or photographically, as many as two or three successive reflections by the boundaries of the model. Various types of equipment utilizing this principle (first developed by Foley) have been devised by different investigators.[23] The apparatus which has been developed at the University of California at Los Angeles, largely through the efforts of Mr. Leo P. Delsasso, is shown in the photograph in Fig. 34. A number of interesting and instructive sound-pulse photographs, obtained by Foley, are shown in Figs. 35 to 38. The photographs, which illustrate several of the fundamental principles of physical acoustics, are described in the legends accompanying the figures.

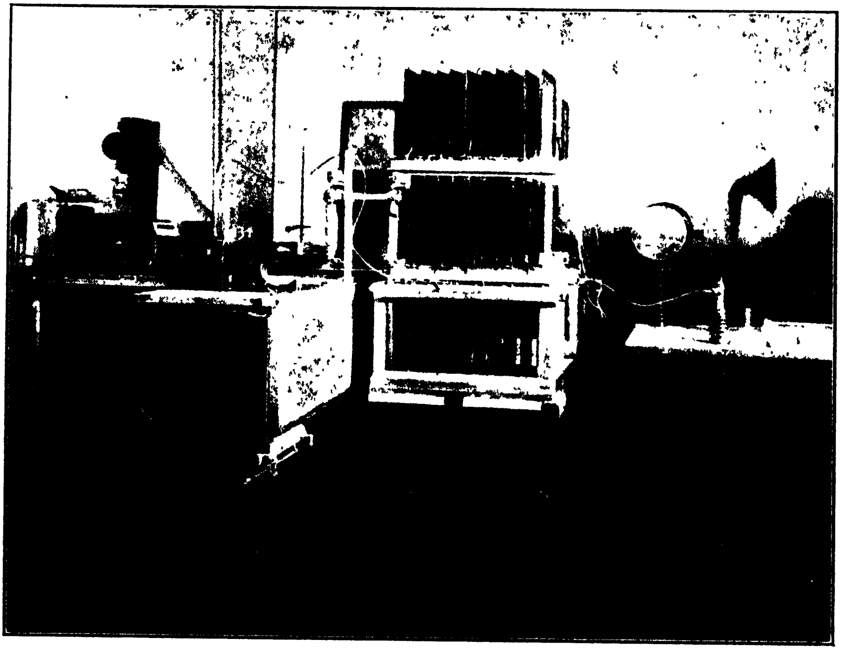

Fig. 34. Photograph of the sound-pulse apparatus at the University of California at Los Angeles.

30. Optical Methods for Investigating the Paths of Sound in Models of Auditoriums. Several optical methods have been devised for studying the effects of form upon the reflected beams of sound in model sec-

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[23] Foley, Am. Arch. and Arch. Rev. (November 8, 1922); Foley and Souder, Phys. Rev., **35**, 373 (1912); W. C. Sabine, "Collected Papers on Acoustics," 180 (Harvard University Press, 1922); Davis and Fleming, Jour. Sci. Insts., **3**, 393 (1926).

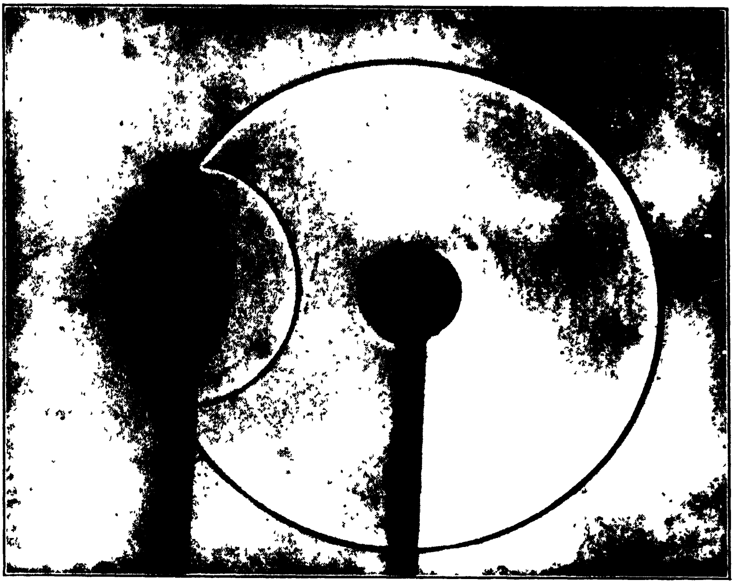

FIG. 35. Sound pulse propagated as a spherical wave from a point source and reflected from a convex surface. The reflected wave is divergent. (*Foley.*)

FIG. 36. Sound pulse reflected from a concave surface. The reflected wave is convergent. Note the diffracted sound wave from the lower edge of the concave reflector. (*Foley.*)

FIG. 37. Refraction of sound pulse passing through sulphur dioxide gas. The refracted wave is just emerging from the "lens," and has been rendered convergent in passing through the lens. (*Foley.*)

FIG. 38. Diffraction of sound pulse by plane grating with four apertures. Note that spherical waves originate from the openings for both the transmitted and reflected waves. (*Foley.*)

tions of an auditorium.[24] The apparatus devised by Satow at Waseda University, Tokyo, provides a simple and convenient method for observing the paths of reflected light in model sections made of highly polished metal. Models are made of the principal sections of a proposed room (such as the floor plan, longitudinal section, and cross section) and placed in a glass box filled with smoke. A source of light is located at the position corresponding to the normal position of the sound source in the room, and is enclosed by a cylindrical screen containing narrow parallel slits which limits the emergent light to a large number of radial beams. These beams are reflected by the mirror boundaries of the model and are made clearly visible by the diffuse scattering of light from the smoke particles. Fig. 39 shows the arrangement of the apparatus and model; Fig. 40 shows a photograph of the beams of light in models which were made by Satow in connection with the acoustical design of Okuma Memorial Auditorium.

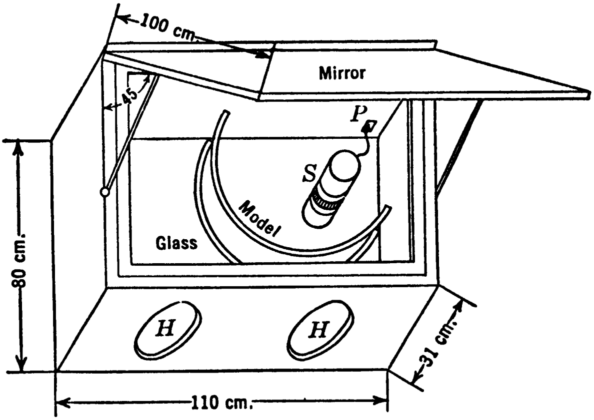

FIG. 39. Smoke box apparatus for investigating rays of reflected light in sectional models of an auditorium. (*Satow.*)

This method of investigating the *acoustical form* of auditoriums has the following advantages: (1) The models are of simple construction and can be easily modified so that the effects of changing the form of an auditorium can be determined readily during the early stages of design; (2) the apparatus is simple and inexpensive, and does not require any

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[24] R. F. Norris, "A Practical Method of Detecting Distorting or Echo-Producing Surfaces in Auditoriums by a Photographic Analysis of the Plans," Bulletin No. 2, C. F. Burgess Laboratories, Inc.; Takeo Satow, "Acoustics of Auditorium Ascertained by Optical Treatment in Models," World Engineering Congress, Paper No. 118 (1929).

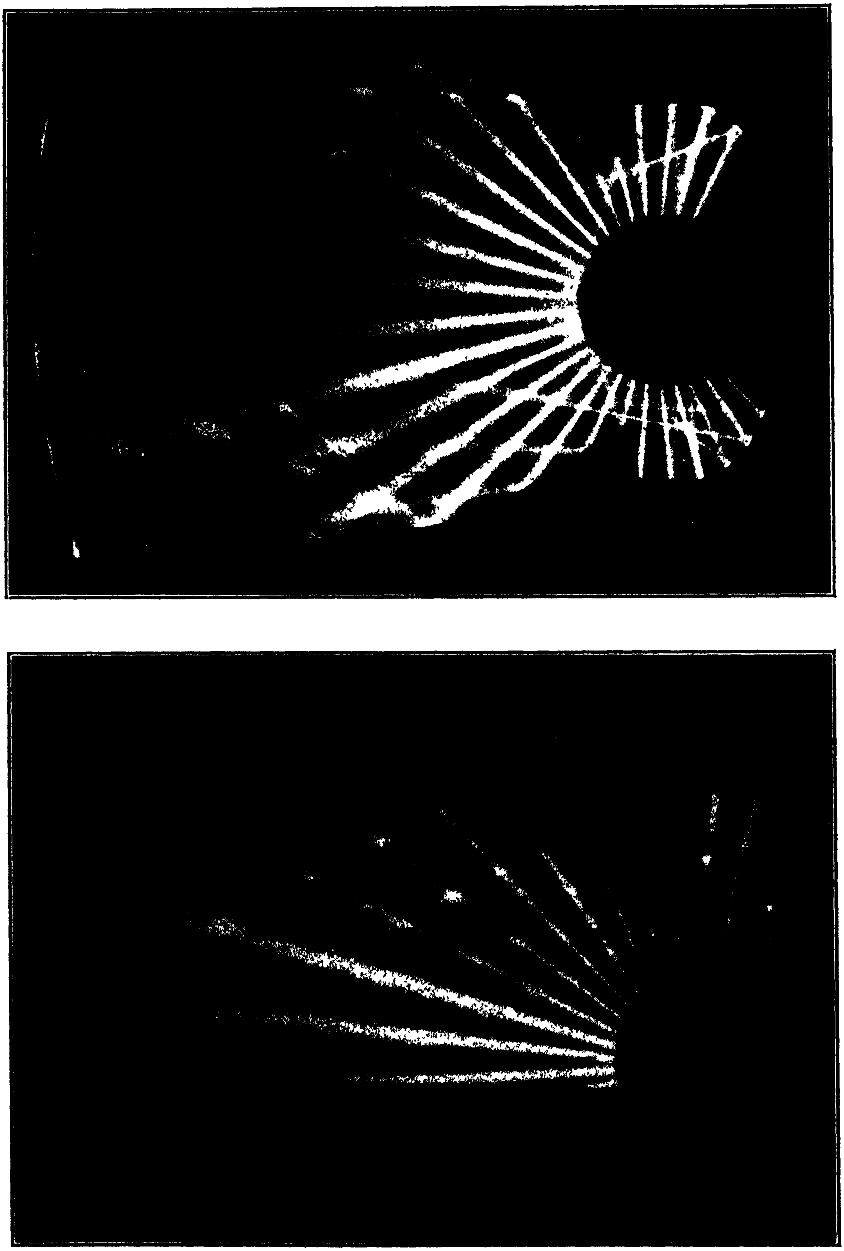

Fig. 40. Photographs of rays of light in plan and sectional models of Okuma Memorial Auditorium. (*Satow.*)

special skill or training on the part of the operator; and (3) it provides an effective means of demonstrating to building committees or prospective building owners the defects and merits of different designs.

The method has two limitations which should be recognized in the interpretation of results: (1) the effects of diffraction of sound are not shown since the wave lengths of light are so short that all beams in the model are reflected rectilinearly; and (2) the model sections limit the study of reflection to a single plane for each model; that is, the study is a *two-dimensional* rather than a *three-dimensional* study.

The construction of a three-dimensional model, and a spherical screen (with circular holes in its surface) instead of a cylindrical screen surrounding the light source, provides a means of studying the paths of reflected light in three dimensions. It also is possible to construct three-dimensional models from non-reflective materials, as wood or plaster, to use a small flash light for the source of light, and to attach a number of small plane mirrors to different portions of the interior boundaries of the room. In this manner the reflections from any or all parts of the boundary can be studied.[25] In the use of such models it is necessary, in order to make observations of the paths of light, to leave one side (or a part of one side) open. Usually the stage end of the model is left open, since reflections from this part of the room are of a well-known type or they can be readily determined from a simple geometrical study of the plans and sections.

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[25] The National Physical Laboratory has on exhibit a model of this type of Albert Hall, London, which shows very clearly the nature of the acoustical defects in this hall. (See Sec. 186.)

CHAPTER III

THE NATURE OF HEARING[1]

31. Introductory. In order to gain a clear comprehension of the acoustical requirements for good hearing in an auditorium it is necessary to become acquainted with the pertinent facts which are known concerning *how we hear*. It is true that the problem of hearing still remains an unfinished and a bewildering subject. However, during the past ten years much work has been done by physicists, engineers, physiologists, and psychologists, particularly by the application of modern telephone and radio equipment to the auditory problem. Although many of the facts of audition are as old as or older than Helmholtz yet many recent discoveries and quantitative measurements of hearing have helped very considerably to clarify the acoustical problems in auditoriums.

Among the more important of recent findings are the determination of (1) the absolute sensitivity of the ear for tones of different frequencies, (2) the relative values of the different frequency components in attaining a faithful reproduction of speech and music, and (3) the interfering effects of noise upon the hearing of speech and music. All these characteristics of hearing, and many others, have a pertinent relation to the problem of hearing in architectural interiors, and therefore they will now be described.

In an attempt to understand auditory function, the most useful information may be obtained by regarding the ear as a physical instrument. It is possible to determine the acoustical characteristics of the ear in a manner analogous to the methods ordinarily employed for determining the electrical characteristics of a galvanometer. In the case of either the ear or the galvanometer, quantitative data are obtained which give the relation of the response of the instrument to definite stimuli.

Thus, in order to determine the characteristics of a sensitive galvanometer, one determines, first, how small an electric current it will detect; second, how small a difference in the strength of the current it will detect; and third, how large a current it will accommodate. The

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[1] A large amount of the material in this and the following chapter has been taken from "Speech and Hearing" by Harvey Fletcher (Van Nostrand, New York, 1929). The interested reader should consult this valuable book. See also V. O. Knudsen and I. H. Jones, Annals of Otology, Dec., 1925, and Mar., 1926.

minimal current it can detect is a measure of its **sensitivity**; the minimal difference of current it can detect is a measure of its **sensibility**, or **differential sensitivity**; and the minimal and maximal currents which it will accommodate are a measure of its range of response. In an analogous manner, the minimal intensity of sound of a given frequency that the ear can detect is a measure of its sensitivity at that frequency; the minimal difference of intensity which the ear can detect is a measure of its **intensity sensibility**; the minimal difference of frequency which the ear can detect is a measure of its **frequency sensibility**; and the minimal and maximal frequencies and intensities of sound which it will accommodate are a measure of its range of response. These basic characteristics of the hearing apparatus will be more fully described in Secs. 34 and 35 of this chapter. Before continuing this subject, however, it will be helpful to describe briefly the organ of hearing and to define different types of sound.

32. The Human Ear. The human ear has two distinct functions: (1) the sensing of motion, which is accomplished by the vestibular portion of the ear — made up principally of the three semicircular canals and the otoliths; and (2) the sensing of vibration, which is accomplished by the cochlea and its associated apparatus. Only this second function of the ear is concerned with hearing. Therefore, the cochlea with its associated apparatus will be referred to as the hearing mechanism. The hearing mechanism may be divided into three portions: the external ear, the middle ear, and the inner ear. These are shown in Fig. 41, as

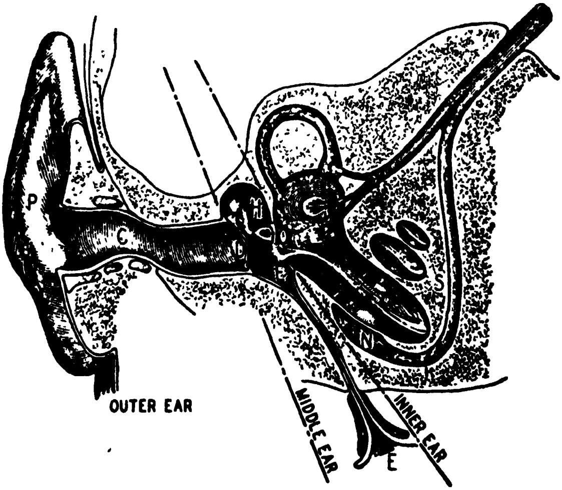

Fig. 41. Section of the human ear.

are also the principal anatomical portions of the hearing mechanism. The external ear is a sound collector in the form of a trumpet. The tube of the trumpet is about 1¼ inches long and is closed at one end by the drum membrane. The middle ear contains three tiny bones or ossicles which connect the drum membrane with the inner ear. The inner ear contains the cochlea in which terminate the auditory nerves. The external ear collects and intensifies the vibrations which impinge upon the drum membrane. The three tiny ossicles in the middle ear — the hammer, anvil, and stirrup — constitute a lever mechanism which intensifies the vibrations communicated to the oval window, which is the entrance to the internal ear or cochlea. Since the foot plate of the stirrup is only about one twentieth as large as the drum membrane, the force of the vibrations communicated to the oval window is further intensified about twenty fold. The action of the middle ear therefore is that of a transformer — an efficient coupling for communicating the vibrations in the air (which has a low impedance) to the liquid in the internal ear (which has a high impedance).

Thus far the action of the ear is purely mechanical, and all authorities agree upon its manner of operation. What actually takes place in the cochlea, or between the oval window and the cerebral cortex, however, is somewhat more speculative, although most of the accumulating evidence seems to indicate that both *physical resonance of the structure within the cochlea* and the *frequency of impulses along the nerve fibres* account for the attributes of auditory sensations.[2] Thus, there are fibrous membranes in the cochlea — the basilar and tectorial membranes — which may be compared, although the resemblance is not very close, to the stretched strings of a harp. The natural frequencies of vibration of these fibres will be determined by their effective length, tension, and mass — but the mass is largely influenced by the amount of cochlear fluid set into vibration with the fibres. Some of the fibres are short and tightly stretched, and others are relatively long and loosely stretched. The long ones at the apical end of the cochlea respond to low-frequency vibrations, whereas the short ones at the basal end of the cochlea respond to high-frequency vibrations. When these fibres are set into vibration they stimulate the nerve fibres which are in close proximity to them, and these stimulated nerve fibres elicit the sensation of sound. According to the resonance theory, it is in the cochlea — with its complicated structure and *modus operandi* — that the physical vibrations of sound are converted into nervous impulses. The physical

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[2] L. T. Troland, "Psychophysiological Considerations Relating to the Theory of Hearing," Jour. Acous. Soc., 1, 301 (1930); H. Fletcher, "A Space-Time Pattern Theory of Hearing," Jour. Acous. Soc., 1, 311 (1930).

characteristics of the cochlea, with its associated apparatus, provide explanations for the sensitivity and sensibility properties of the ear, for tonal analysis, subjective tones, and auditory masking. In general, it may be said that loudness at any one pitch is determined by the rate at which nervous energy is communicated to the brain, that is, by the number and activity of the fibres which are set into vibration. Pitch, as stated above, is determined principally by the location of the fibres which respond sympathetically to the physical vibrations, although the nerve impulse frequency is coming to be more and more recognized as a contributing factor. Tonal quality is determined largely by the number, location, and extent of vibration of cochlear fibres which are set into resonant vibration. This will be considered at greater length in Sec. 39.

33. Classification of Sounds — Definitions. All the sounds we hear may be classified as musical or non-musical, although some sounds, such as many of the vowel sounds in speech, possess both musical and non-musical characteristics. In general, musical sounds are made up of regular, periodic vibrations, and non-musical sounds are made up of irregular, non-periodic vibrations. Noise is perhaps the most common of non-musical sounds — street and building noises, for example, are very complex conglomerates of all sorts of vibrations, full of transients and inharmonic components. The following musical sounds, and the definitions given, are of interest in architectural acoustics: (*a*) A **pure tone** consists of a pure simple harmonic vibration. (See Fig. 3 for the form of vibration of a pure tone.) (*b*) A **tone** consists of a series of pure tones — made up of a fundamental tone with a characteristic series of overtones. The word **note** is often used to convey the meaning that is here given to the word *tone*, but *note*[3] is sometimes used to represent the symbol on the musical staff which gives the pitch and duration of a tone. A tuning fork emits (approximately) a pure tone, and such instruments as the piano, clarinet, or organ emit tones. Groups of singers or players, and such instruments as the organ or piano, often generate many tones simultaneously, and these combine into artistic, and sometimes elaborate, compositions. The elemental tones of musical compositions have three fundamental characteristics, and two other secondary properties, which will be considered in Secs. 36 and 40.

34. Sensitivity of the Ear. A sound vibration must be restricted between certain frequency and intensity limits in order to be sensed as a sound. Roughly, the frequency must be greater than 20 and less than 20,000 cycles. In addition, the intensity must attain a certain value;

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[3] See definition proposed by the Acoustical Society's committee on standardization of acoustical terms, Appendix I.

that is, the amplitude of vibration which reaches the ear must exceed what is called the minimal threshold amplitude. This minimal threshold, or the requisite intensity in order that a tone may be just barely audible, varies greatly for tones of different pitch. The lower curve in Fig. 42 shows the minimal threshold, for tones of different pitch, for the average person with normal hearing. The frequency of the tone is indicated along the horizontal axis; and the pressure variation against the eardrum, in root mean square dynes per square centimeter, is indicated along the vertical axis. (The actual amplitude of vibration of the drum membrane is proportional to the root mean square pressure, and the intensity of the tone is proportional to the square of the root mean square pressure.) It will be noted that the sensitivity of

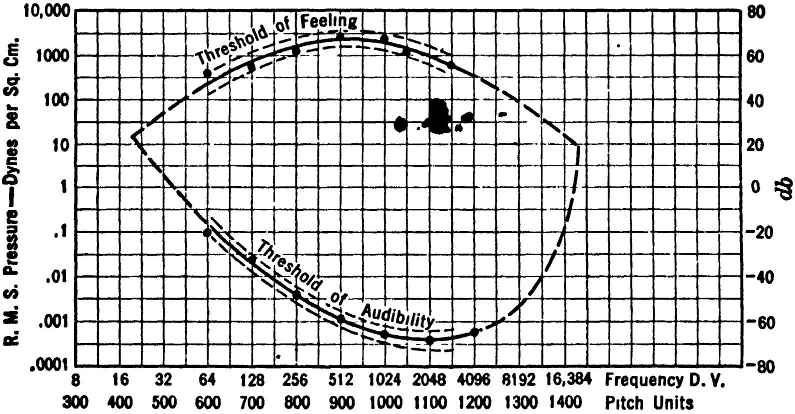

FIG. 42. Frequency-sensitivity curves for hearing. (*Fletcher-Wegel.*)

hearing varies enormously for tones of different pitch: between 500 and 7000 cycles a pressure variation as small as 0.001 dyne per square centimeter is capable of eliciting a sensation of hearing, whereas at 20 cycles and 20,000 cycles the pressure variation must be as great as 10 dynes per square centimeter, which is ten thousand times the pressure variation required in the region of maximal sensitivity. It happens that the range of maximal sensitivity, namely 500 to 7000 cycles, is the frequency range which is of greatest importance for the preservation of intelligibility in the sounds of speech. This range is also very important in the formation of musical sounds. It appears that man is equipped with a hearing organ which has its sensitivity adapted in the best possible way for the hearing of speech and music; or to state the case more accurately, since in the evolution of man speech and music were later developments than the sense of hearing, speech and music have evolved in such a manner as to be well adapted to the sensitivity characteristics of the ear.

The loudness sensation of a pure tone depends upon the magnitude of the pressure variation against the drum membrane, the frequency, and the acuity of the listener's ears. In general, individuals who have no impairments of hearing have approximately the same hearing sensitivity, and the same physical sounds will be heard about equally loud by all who have normal hearing. Persons with impaired hearing, on the other hand, will have a much lower sensitivity than that indicated by the minimal threshold curve for the normal shown in Fig. 42, and consequently they will hear sounds in a relatively diminished loudness, as compared with the loudness of the same sounds as heard by individuals with normal hearing.

As the amplitude of vibration of a pure tone is increased, the resulting tone becomes louder and louder until it attains the upper threshold of loudness. This upper threshold is defined as the limit at which the sound can be felt — as a sort of tingling sensation — as well as heard. At this threshold, the tone often becomes painfully loud. If the intensity of the vibration be carried beyond this upper threshold, there is a mingled sensation of sound, feeling, and pain. The upper curve in Fig. 42 gives this upper threshold of hearing, that is, the threshold of feeling for the average person. It will be seen that this curve also varies for tones of different pitch and that it intersects the lower curve at two points. These two points of intersection determine the lower and upper frequency limits of audition; namely, about 20 cycles for the lower limit and about 20,000 cycles for the upper limit. Again, it will be noted that the range from the minimal threshold to the upper or maximal threshold is greatest for frequencies from 500 to 7000 cycles, that is, for the range of frequencies which is most important in speech and music.

The characteristics of hearing exhibited by Fig. 42 are of prime interest in considering many basic problems in architectural acoustics. For example, in order to insulate against painfully loud sounds it is necessary that the pressure or amplitude be reduced as much as a million fold. This emphasizes the difficulty which is so commonly encountered in soundproofing. Again, the two curves for the minimal and maximal thresholds taken together have a bearing upon the reverberatory properties of rooms. A discussion of this subject will be reserved for a later chapter.

35. Sensibility of the Ear. The **intensity sensibility** of the ear for pure tones — that is, the analytical function of the ear to resolve differences of intensity in a pure tone — is measured by the ratio $\Delta E/E$, where ΔE represents the smallest change of intensity in the tone which the ear can recognize, and E represents the intensity of the tone. Similarly, the **frequency sensibility** is measured by $\Delta N/N$, where ΔN is the smallest change in frequency which the ear can recognize, and N is the frequency of the tone. According to the well-known, but much disputed, Weber-Fechner Law, which states that for all sensations there is a constant ratio between the smallest perceptible increase of a stimulus and the total stimulus, the intensity sensibility defined by $\Delta E/E$ should be a constant. Careful experiments indicate that this is approximately but not rigorously true. For tones not too near the minimal threshold of intensity, and within the frequency range of about 100 to 4000 cycles, $\Delta E/E$ is approximately 0.10; that is, the smallest perceptible change in energy which the ear can detect is approximately 10 per cent of the total energy. For tones near the minimal threshold, and for frequencies below 100 cycles and above 4000 cycles, the ratio of $\Delta E/E$ increases; that is, the ear becomes less sensible to changes of intensity at very feeble intensities, and also at very low and very high frequencies.

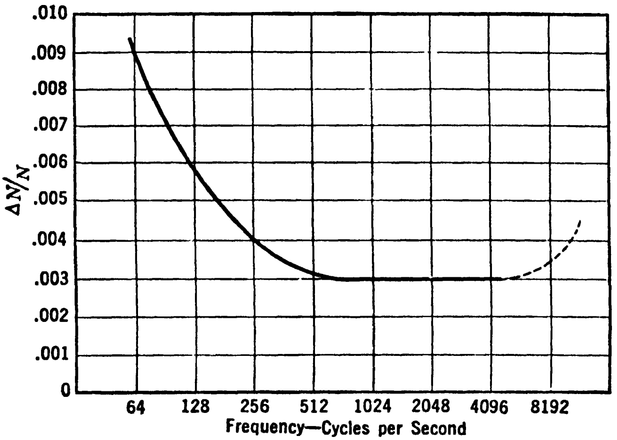

FIG. 43. Curve showing the frequency sensibility of the ear. The smallest fractional change of frequency which can just be detected, $\Delta N/N$, is plotted as a function of the frequency.

The frequency sensibility of the ear is shown in Fig. 43. It will be noted that for frequencies above 512 and below 4096 cycles the smallest perceptible change in frequency which the normal ear can detect is approximately 0.3 per cent. That is, the differences between 500 and 501.5 cycles, between 1000 and 1003 cycles, or the difference between 2000 and 2006 cycles, represent the smallest perceptible changes in frequency which the ear can detect. At frequencies below 512 and above

4096 cycles the ear becomes less sensible to changes of frequency, that is, a larger percentage change is required in order to be barely perceptible.

The analytical function of the ear to differentiate small changes of intensity or frequency is of importance in the hearing of speech and music. Anything that interferes with this analytical function of the ear renders the hearing of speech or music more difficult. The reverberation of sound in rooms introduces such an interference, owing to the overlapping and fusing of the tonal components in articulated speech or music. It is necessary therefore, for this reason as well as for other reasons, to control the reverberation in rooms.

36. Loudness, Pitch, and Quality — General Considerations. When we listen to a musical tone, we are conscious of three properties; namely, loudness, pitch, and quality. In the preceding chapter it was shown that a sound wave is characterized by the three physical properties of amplitude, frequency, and wave form. Everyone is familiar with experiments which demonstrate that the amplitude of the sound wave determines the loudness of the sound sensation, and that the frequency of the sound wave determines the pitch of the sound sensation. In fact, there is an ordinal relation between amplitude of vibration and loudness, and also between frequency of vibration and pitch: the greater the amplitude the louder the sound, and the higher the frequency the higher the musical pitch. On the other hand, there is no simple ordinal relation between wave form and quality. In general, the more complex the form of the wave, provided it be periodic, the richer will be the quality of the musical tone. The subject of quality is so important that it will be considered further in Sec. 39 of this chapter and again in Chap. IV. But it will be helpful first to consider certain aspects of loudness and musical intervals.

37. Intensity, Sound Level, and Loudness. Although, as was stated in the preceding section, the relation between loudness and the intensity of the external vibration is an ordinal one, it is not one of a direct or simple proportion; that is, a doubling of the intensity does not produce a doubling of the loudness. In general, the loudness of a sound depends upon the frequency as well as the intensity of vibration, and its quantitative definition will be given later in this section. For the present, consideration will be given to a very important logarithmic property of the intensity of sound. This relation is suggested by the data on the intensity sensibility of the ear. If the sensibility of the ear, as measured by $\Delta E/E$, is constant, which is approximately true for tones between 100 and 4000 cycles (not too near the minimal threshold), it follows from a simple integration that the intensity of the sensation should be proportional to the logarithm of the intensity of the tone. This is only approximately borne out by experiment. The logarithmic relation between stimulus and auditory response is characteristic of other senses, and is a common form of stating the Weber-Fechner Law. According to this law, the intensity of nearly all sensations is proportional to the logarithm of the intensity of the external stimulus. On this basis, a tone having an intensity of one million times the intensity of a barely audible tone of the same pitch would be regarded as producing only double the amount of sensation of that which would be produced by a tone having an intensity of one thousand times the intensity of a barely audible tone of the same pitch. That is, although the one tone contains one thousand times more energy than the other, in this case the more intense tone is regarded as producing only double the amount of sensation which would be produced by the weaker tone, since the logarithms of 1,000,000 and 1000 are to each other as 2 is to 1.[4]

This logarithmic method of expressing sound intensities, even though it does not give an accurate measure of loudness, has come into common use in all branches of acoustics, including architectural acoustics, and since it will be used frequently throughout this book, it is necessary that the student gain a fair notion of its significance and usefulness. The use of a logarithmic unit for describing and measuring sound intensities is justified by its convenience rather than by its veracity in expressing the exact relation between the intensity of sound and the resulting sensation. Thus, the intensity of a sound is often referred to some other intensity of sound, as in problems of sound-insulation in which the intensity of the noise inside the room is compared with the intensity of the noise outside the room.

A logarithmic unit, called the **bel,** has recently been adopted for use in telephone work, and this same unit is finding wide acceptance in architectural acoustics. If I represent the intensity of a sound in joules per cubic centimeter, then the **intensity level** of I, in *bels,* is defined as $\log_{10} I$. For most practical purposes a unit which is one tenth of the bel is more convenient than the bel. This smaller unit is called the **decibel,** and is designated by **db.** The difference in decibels between

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[4] Recent experiments by Parkinson and Ham, Marvin, Laird, and others indicate that two tones which have intensities proportional to say 1000 and 1,000,000, as used in the example just cited, would be regarded by the average person as differing in *loudness* by more than a ratio of 1 to 2. In fact, Parkinson and Ham found that when the intensities were proportional to about 100,000 and 1,000,000 the loudness was judged to be in the ratio of about 1 to 2. This result is significant and will be referred to later in connection with the reduction of noise in rooms, but the logarithmic property of sound just referred to has become basic in the entire system of acoustical measurements.

two sounds having intensities of I_1 and I_2 would then be given by 10 $\log_{10} I_1/I_2$.

Since the intensities of so many sounds are evaluated in terms of the minimal threshold intensity, it is convenient to adopt a name which will designate how many decibels a certain sound is above the threshold of audibility for the average person with normal hearing acuity. Throughout this book the term **sound level**[5] will be used for this purpose. In dealing with specific types of sound, as speech or noise or musical tones, the terms **speech level, noise level,** and **tone level** will be used instead of the more general term *sound level.* Thus, if I represents the intensity of a certain sound, and I_0 represents the intensity of the same sound when it has been reduced to the minimal threshold of audibility, then the *sound level* of that sound will be given by the following equation:

$$\textit{Sound Level} \text{ (in db)} = 10 \log_{10} \frac{I}{I_0}\cdot \qquad (10)$$

To give a specific example of the use of this relation, the standard tone which is commonly used in architectural acoustics has an intensity which is one million times the intensity of a tone of the same pitch which is just barely audible. Since the logarithm of 1,000,000 is 6, the *tone level* of such a tone is 60 db, that is, it is 60 db above the threshold of minimal audibility. Similarly, a tone which has a tone level of 70 db has an energy content equal to ten million times the energy content of a tone of the same pitch which would be just barely audible.

The data on the sensitivity of the ear (see Sec. 34) show that the ear is very much more sensitive to frequencies between 500 and 4000 cycles than it is to very low or very high frequencies. For this reason, it is obvious that *sound level* will not serve as a measure of the loudness of a sound. It might seem reasonable that the sound level would furnish an accurate measure of the comparative loudness of tones of different pitch, but it is found for example that a pure tone of 100 cycles and a pure tone of 700 cycles, both having the same sound or tone levels, differ very appreciably in loudness as judged by the ear. Thus, if each of these tones have a tone level of 30 db it will be found that the tone of 100 cycles seems very much louder than the tone of 700 cycles. For frequencies between 700 cycles and 4000 cycles, the sound level gives a satisfactory comparative measure of the loudness level; that is, two tones within this range having the same sound level will be judged as

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[5] The term *sensation level* is used by many writers to denote the same meaning that is here denoted by the term *sound level.* (See Appendix I, 3008.) But the term *sensation level* is likely to be confused with the ordinary concept of loudness, and therefore the term *sound level* seems preferable.

equally loud. The relation between sound level and loudness has been investigated by Kingsbury.[6] The most important data of Kingsbury, for the purpose of this book, are shown in Fig. 44. The data for these curves were based upon the use of a 700-cycle tone as a standard of comparison. That is, tones of the frequencies designated by the numerals adjacent to the curves were adjusted until they were judged to be of the same loudness as an arbitrarily chosen level at 700 cycles. The loudness then is measured in terms of the equivalent loudness of a pure tone of 700 cycles, and the unit of loudness is *equivalent decibels*. It will

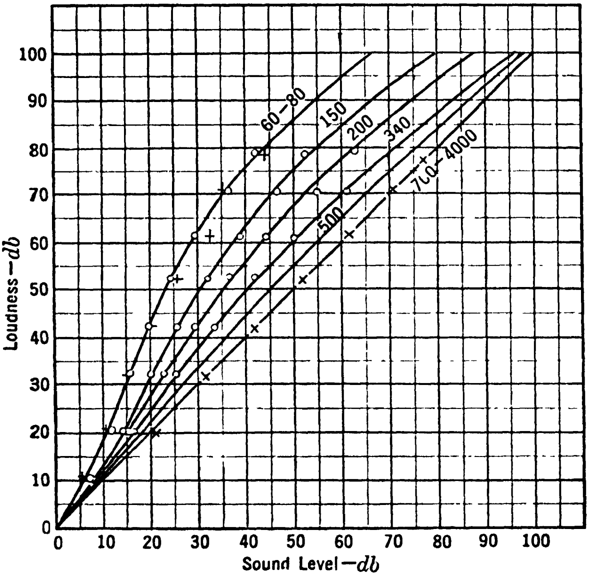

FIG. 44. Loudness of pure tones as functions of frequency and sound level.

be noted that for frequencies between 700 and 4000 cycles, as already stated, the sound and loudness levels increase alike; that is, all pure tones in this range having the same sound level will be judged to be of the same loudness. For frequencies below 700 cycles, however, the loudness increases more rapidly than does the sound level. For example, a tone of 150 cycles, having a sound level of 30 db, will have a loudness of 50 db; that is, it will be judged as loud as a tone of 700 cycles which has a sound level of 50 db. This relation between sound level and loudness for tones of different pitch is not only of interest in connection with the physiology of the cochlea, but it is of practical importance in many problems in architectural acoustics. Thus, it has a direct

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[6] H. Fletcher, "Speech and Hearing," 229–231.

bearing upon the type of absorptive material which will give the best acoustical effect in a room; it has a significant bearing upon the faithfulness of reproduction of amplified sound; and it affects all judgments of loudness of complex sounds.

38. Musical Intervals. There is a logarithmic relation between the frequency of a sound wave and the pitch sensation — similar to the logarithmic relation discussed in the preceding section, although the base of the logarithm is 2 instead of 10. This relation is well known in the following equivalent form: There is the same interval of pitch between 32 and 64 cycles as there is between 2048 and 4096 cycles. This interval of pitch is known as the octave. Generalizing, a constant frequency ratio corresponds to a constant musical interval. The octave, for example, is the interval between two tones which have a frequency ratio of 2 to 1. This frequency ratio of 2 to 1 for the octave is the basis for the logarithmic relation between pitch and frequency. Thus, the pitch difference, in octaves, between two tones having frequencies N_2 and N_1, is proportional to $\log_2 N_2/N_1$; and the pitch difference in centi-octaves is $100 \log_2 N_2/N_1$. This small unit is often used in acoustical problems.

There are many other musical intervals besides the octave, and in all cases equal ratios of frequencies correspond to equal intervals of pitch. The most common intervals of pitch, and their frequency ratios, are given in the following table:

Octave	2 : 1
Fifth	3 : 2
Fourth	4 : 3
Major third	5 : 4
Minor sixth	8 : 5
Minor third	6 : 5
Major sixth	5 : 3

These are the generally recognized consonant intervals within the range of a single octave. It will be noted that all the ratios are expressed by small integers, and that the more consonant intervals, such as the octave, the fifth, and the fourth, are comprised of the smallest integers. In general, the simpler the frequency ratio, that is, the smaller the integers which make the ratio, the more consonant will be the two tones when sounded together. Two other intervals which are useful in problems of architectural acoustics are the major second (9 : 8) and the semitone (25 : 24).

39. Quality of Musical Sounds. The characteristics of loudness and pitch have been considered in the preceding sections. The third characteristic of a musical tone which will now be considered is quality or timbre. This property of a musical tone is determined largely by the shape of the wave form, although this statement must be made with reservation. More strictly, it is the number and prominence of the component overtones[7] which determine quality. In general, a series of overtones will produce a characteristic wave form, but the wave form is not unique for this particular series, since a change of phase only, without a change of the number and prominence of the overtone components, will produce a change in the resulting wave form. In other words, the phase relations of the different components of a complex tone do not seem to affect the quality. This is consistent with the resonance theory of hearing, which postulates that the cochlea, like a harp, responds in conformity with the laws of physical resonance. In other words, a complex tone, which is made up of a fundamental frequency and several overtones, stimulates various portions of the cochlea — the low-frequency components excite those cochlear fibres which are relatively long and loosely stretched, whereas the high-frequency components excite those cochlear fibres which are relatively short and tightly stretched. This process of the reception of sound by the cochlea, on the basis of physical resonance, can be strikingly illustrated by removing the dampers from the strings of a piano so that all strings are free to resonate to their own natural frequencies. If one sings a tone near these undamped piano strings, those frequency components which are in the sung tone will set into vibration those strings which have the same frequencies as the components of the sung tone, and the result is that the piano sounds back a fairly good reproduction of the singer's voice. Similarly, if one shouts at these strings, the shout is returned with remarkably good mimicry. In the case of hearing, the cochlea acts in much the same way. It sends to the brain a pattern or a " mosaic " of those frequency components which were in the original sound outside of the ear. Whenever quality or timbre is identified with wave form it should be borne in mind that it is the number and prominence of the overtone components which determine the quality of the sound, and that different wave forms, which differ only in the phase relations among the overtones, will have, at least very approximately, the same quality.

The tone produced by a tuning fork is a close approximation to a pure

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[7] There is sometimes an ambiguity in the use of the terms *overtone* and *harmonic*. Overtones are component frequencies of a tone which have a higher frequency than the fundamental or gravest component — they may be harmonic, that is, integral multiples of the fundamental, or inharmonic, that is, non-integral multiples of the fundamental. The overtones of stringed and pipe instruments are all harmonic, whereas the overtones of rods, diaphragms, and bells are for the most part inharmonic.

tone, and consequently the wave form will be sinusoidal. This is shown in the upper curve in Fig. 45. The middle curve in Fig. 45 represents the wave motion of a violin tone having the same pitch and amplitude as that produced by the tuning fork. The curve at the bottom, in like manner, represents the wave form of a tone produced by the oboe, having the same amplitude and frequency as the tones produced by the tuning fork or violin. It will be noted at once that the wave form of the tone of the oboe is very much more complicated than the tone of the tuning fork or even the tone of the violin; that is, it is very rich in harmonics. The three curves shown in Fig. 45 represent tones of the same pitch and loudness, but differing in quality. There are many musical tones which agree in pitch and loudness but which contain large numbers of characteristic overtones. It is evident, therefore, that the acoustical properties of a room may alter very appreciably the quality of such tones by reason of selective interference or absorption of certain of the overtone components. It is necessary therefore that the acoustics of a room be adjusted to preserve as nearly as possible all the frequency components which are used in speech and music, otherwise the ear will receive a distorted image of the original sound.

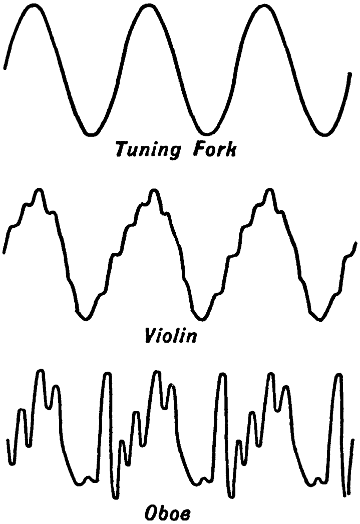

FIG. 45. Wave forms of tones produced by the tuning fork, the violin, and the oboe. All three tones are of the same pitch and (approximately) the same loudness.

40. Volume and Brightness. There are two other characteristic properties of tone which are often associated with quality, but which should be considered separately since they result from different physical effects. **Volume** of tone, apart from intensity or loudness, designates a certain extensity or *spreading out* of tone; it is regarded as large for low-pitched sounds, and diminishing with rise in pitch. It also seems to increase with increasing loudness of tone. It is probably related to the length or extent of the cochlear membrane which is activated by a particular tone. Thus a pure tone of large volume is one which is associated with a relatively broad band of activated cochlear fibres, and a pure tone of small volume is one which is associated with a narrow band of activated fibres. According to present theories of hearing, both low and loud tones would excite broad areas of cochlear fibres, and we therefore should expect such tones to have a large volume according to this view.

Brightness, on the other hand, is associated with the sharpness of curvature of the resonant area of the cochlear membrane — if a tone is judged as being very *bright* it is supposed that the activated cochlear fibres are deformed into a relatively pointed area, whereas if a tone is judged as lacking brightness it is supposed that the resonant area is relatively flat. These properties of volume and brightness are important in determining the musical value of tone, and must not be disregarded in the design of music rooms. Thus, it is very probable, on the basis of these concepts, that the resonant properties of thin wood paneling, for example, will alter both the volume and the brightness of tone quality.

41. Auditory Masking. It is a common observation that noise interferes with the hearing of speech or music. Thus, in a noisy subway car, it is necessary to shout almost at the top of one's voice to be heard by a near-by companion; whereas in a thoroughly insulated sound studio or acoustical laboratory the faintest whispers can be heard at considerable distances from the speaker. In absolutely quiet rooms one can even hear one's heart beat or the surge of blood through the arteries of the head. It is possible therefore to find rooms so quiet as to be unpleasantly quiet, although such rooms are exceedingly rare.

It is impossible completely to ignore a loud noise and listen only to another sound, such as speech or music. Unless the loudness of the speech or music be sufficiently above the level of the noise, the speech or music cannot be fully recognized or appreciated because of the masking effect of the noise. This subject of the interfering effect of noise is so pertinent to the hearing of speech or music in auditoriums that considerable space will be devoted to it in a subsequent chapter. Only a few of the fundamental properties of auditory masking will be mentioned in this section.

If two tuning forks — one of say 400 cycles and the other of 1200 cycles — be sounded simultaneously, both tones will be recognized for several seconds, after which the one of higher pitch will fade away until only the tone of lower pitch can be recognized. If now the fork of lower pitch be stopped, one is surprised to hear the other fork sounding at an appreciable loudness. The low-pitched tone had completely masked the one of higher pitch. If, on the other hand, one sounds both forks again and, after several seconds, stops the high-pitched fork, it is observed that the higher tone had relatively little masking effect upon the lower tone. It appears from this experiment that low-pitched tones — especially if they are of considerable intensity — produce a rather marked masking effect upon high-pitched tones, whereas high-pitched tones produce only a feeble masking effect upon low-pitched tones.

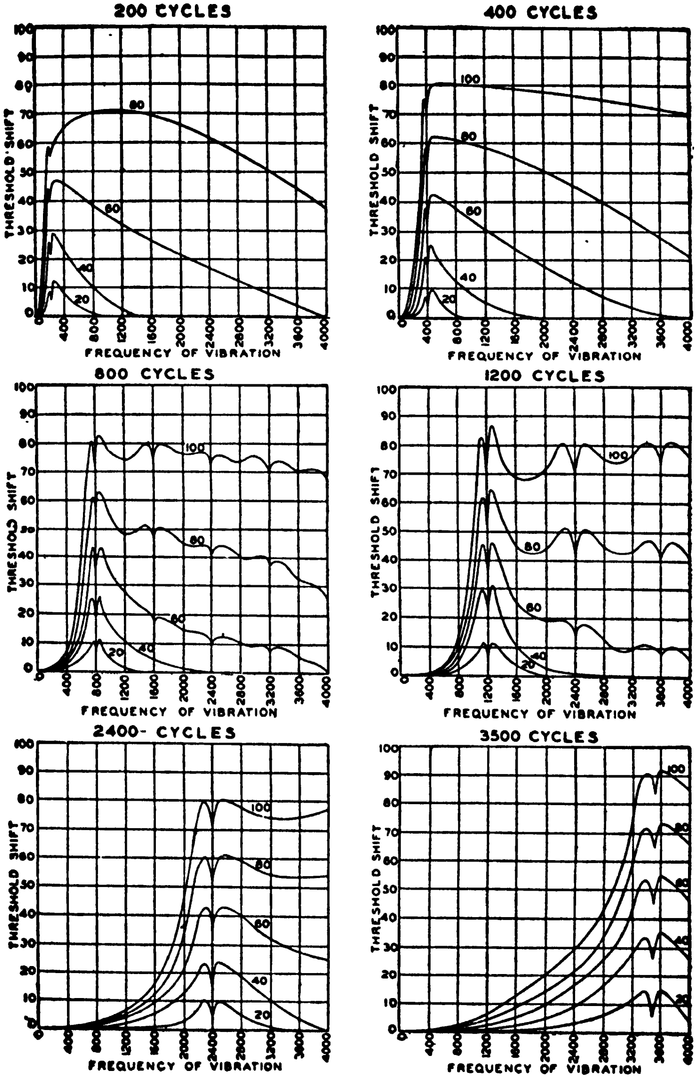

Fig. 46. Auditory masking of one tone by another. (*Wegel and Lane.*)

More precise measurements of the auditory masking of one tone upon another indicate that the greatest masking occurs when the pitch of the masking tone is almost identical with the masked tone. A thorough investigation of the auditory masking of one tone upon another has been made at Bell Telephone Laboratories.[8] The most important data obtained in this investigation are represented by the curves in Fig. 46. The frequency of the masking tone is indicated by the number above each chart; and the sound level of the masking tone, in decibels above the threshold, is indicated by the number at the top of each curve. The frequency of the masked tone is represented on the horizontal axis; and the number of decibels the masked tone must be elevated above its minimal threshold in order to be just barely recognized in the presence of the masking tone is represented on the vertical axis. For example, the chart in the lower left-hand corner of Fig. 46 shows the masking effect of a tone of 2400 cycles, at sound levels of 20, 40, 60, 80, and 100 db above the threshold. It will be noted that the greatest masking occurs for tones near or above the frequency of the masking tone. Thus, in order to hear a tone of 3200 cycles in the presence of another tone having a frequency of 2400 cycles and a sound level of 80 db, it must be elevated about 54 db above the level at which it would be heard in a perfectly quiet place. In general, all tones, especially if they are loud, are shown to offer considerable masking for all tones of higher frequency than the masking tone. Therefore, low-frequency hums or noises usually offer especially troublesome sources of interference for the hearing of speech or music since they mask nearly the entire range of frequencies which make up speech and music.

42. Impaired Hearing. The person with normal hearing ordinarily experiences some difficulty in hearing speech in large auditoriums, even if the acoustics of the room is as nearly ideal as possible. The reason for this is that the energy of speech of the average speaker in a large auditorium is inadequate for perfect hearing. If a person therefore has even a slight impairment of hearing he may be placed at a marked disadvantage because the intensity of average speech in large rooms is just barely adequate for the person with normal hearing. For this reason, many complaints concerning the poor acoustics of auditoriums come from persons who, unknowingly, have slightly impaired hearing. Impaired hearing is much more prevalent than is generally recognized. Thus, recent surveys of the hearing of school children indicate that there are probably 3,000,000 school children in the United States with impaired hearing. Most cases of impaired hearing are so slight that they are not detected either by the person with the impaired hearing or by his associates.

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[8] R. L. Wegel and C. E. Lane, "Auditory Masking and Dynamics of the Inner Ear," Phys. Rev., **23**, 266 (February, 1924). See also Fletcher's "Speech and Hearing," 167.

Impairments of hearing are of two general types, and the physical characteristics of these two types are strikingly different. In the one type of impairment — called nerve deafness — the greatest loss of acuity is for tones of high frequency. In some cases of nerve deafness the acuity may be nearly normal for low-frequency tones, in which case the individual hears nearly all the low-frequency components of speech and music; but the high-frequency components are missing. Consequently, he does not hear the consonants in speech, which are comprised of high frequencies, and the higher harmonics of music are lost to his hearing. In the other type of impairment — called conductive deafness — the greatest loss of acuity is for tones of low frequency, and the acuity may be nearly normal for tones of high frequency. In general, this type of deafness does not handicap an individual so much as does the nerve or perceptive type, since the low-frequency components of speech and music are not so important as are the high-frequency components.

Ordinary conversation in small rooms is sufficiently loud to enable persons with 80 per cent or more of normal hearing to understand average speech or conversation without noticeable difficulty. In a small room the average level of speech is about 60 or 65 db for a person with normal hearing, and for a person with only 80 per cent of normal hearing this same speech would have an apparent level of about 40 to 45 db, which is sufficient for satisfactory hearing. On the other hand, the average level of speech in a large auditorium is not more than 50 db for a person with normal hearing, and this is reduced to about 30 db for a person with 80 per cent of normal hearing, which is insufficient for satisfactory hearing. These statements are not only justified by experiments which show the percentage articulation for speech at different sound levels,[9] but they are also borne out by the statements from individuals with impaired hearing (those having about 80 per cent of normal hearing) who state that they experience no difficulty when listening to conversation in a small room, but that they do not hear in a large auditorium unless they sit in the first three or four rows. When the sounds of speech and music are diluted by spreading throughout a large auditorium, those who have impairments of hearing will suffer a relatively great handicap, especially when the auditorium is very quiet. If there is an appreciable amount of noise in an auditorium — and there is rarely less than 15 or 20 db — persons who have as much as 85 per cent of normal hearing will not suffer any appreciable handicap, since the masking effect of the noise produces a slight *deafening* effect upon the individuals with normal hearing, and the individuals with impairments of hearing are not bothered by the noise since they do not hear it. It

[9] H. Fletcher, "Speech and Hearing," 272.

often happens therefore that an individual with as much as 85 per cent of normal hearing will hear as well as a person with normal hearing.

A properly designed public address system in an auditorium is of special benefit to the 3 per cent or more who have impairments of hearing. Such a public address system, or the sound-reproducing equipment in the modern motion-picture theatre, increases the intensity of speech to a level of at least 70 db for persons with normal hearing. This provides a sound level of at least 50 db for all those who have as much as 80 per cent of normal hearing. For this reason many persons with impaired hearing may not hear satisfactorily in the legitimate theatre but may hear with entire satisfaction the amplified speech from a public address system or from the loud speaker associated with motion-picture apparatus.

Impaired hearing is particularly prevalent among those who are advanced in age. Such persons should always be seated near the speaker. In many churches, and in theatres where sound-reproducing equipment is installed, it is advisable to equip a section of seats with special telephone receivers which are connected either with the microphone at the pulpit, or with an appropriate part of the electrical circuit in the sound-reproducing equipment. The installation of equipment of this type, for amplifying sound for those having impairments of hearing, is an acoustical factor in the design of auditoriums which should not be overlooked. Such an expedient may be a real accommodation to as many as 3 to 10 per cent of the auditors in a room. Already a number of churches and theatres have installed equipment of this type, and the results are highly satisfactory.

43. Summary. The hearing mechanism is a most remarkable instrument, responding to a range of frequencies 10 octaves in extent, sensitive to pressure variations against the eardrum as small as 0.001 dyne per square centimeter (corresponding to amplitudes of the drum membrane as small as 0.000000001 inch) and as large as 1000 dynes per square centimeter, and sensible to intensity changes of about 10 per cent, and to frequency changes of the order of 0.3 per cent. Besides, it has the capacity to analyze complex vibrations into their simple harmonic components. Few, if any, instruments can compare in range of response, sensitivity, and analytical power with the hearing mechanism. But in spite of these extraordinary properties it has limitations which must be clearly recognized if one is to understand the problems of hearing in auditoriums. Thus, all the components of speech and music in an auditorium must possess intensities of sufficient strength to excite appropriate sensations in the normal hearing mechanism; all noise and the prolongation of legitimate sounds, which produce a masking effect upon hearing, must be suppressed adequately; and special provisions should be made in lecture and other large rooms which will enable many hard-of-hearing individuals to hear satisfactorily.

The ear is the ultimate appraiser of the acoustical outcome of every auditorium, and therefore the architect or acoustical engineer will do well to gain as complete an understanding of the nature of hearing as is possible.

CHAPTER IV

THE NATURE OF SPEECH AND MUSIC

44. Introductory. In Chap. II some of the more important physical characteristics of sound were described. In the present chapter attention will be confined to the physical characteristics of speech and music — the two principal forms of sound energy which concern the problem of architectural acoustics. The distinguishable as well as the esthetic characteristics of speech or music must be carefully preserved during its transmission from the source to the listener.

In the preceding chapter, sounds were classified into two principal types: musical and non-musical. This classification may be altered slightly, for the present purpose, so as to include three groups of sounds: music, speech, and noise. Music is made up of combinations of periodic vibrations. The vibrations are regularly repeated, and they usually have frequency ratios which can be expressed by simple whole numbers, as 2, 3, 4, 5, 6, and often larger numbers. Speech is made up of vibrations, both regular and irregular, produced by the forced flow of air through the vocal cords and oral cavities, and modified by the action of the tongue, lips, and teeth. Speech, therefore, is both musical and non-musical. Noise, on the other hand, is made up of a highly irregular combination of vibrations. In fact, if the *spectrum* be determined for many complex noises, such as street noises, it will be found that practically all audible frequencies from the lowest to the highest are present. The periodic and harmonic qualities of music or even speech are lacking; instead, the component frequencies are transient and usually dissonant. Although, according to this definition, noise is different from speech and

FIG. 47. Photographic record of the vibration produced by a horn. (*D. C. Miller.*)

music, it often happens that extraneous speech or music coming from an adjacent room may constitute a noise. From this standpoint, any sound which interferes with the hearing of speech or music, that is, all extraneous sound, may be regarded as noise.

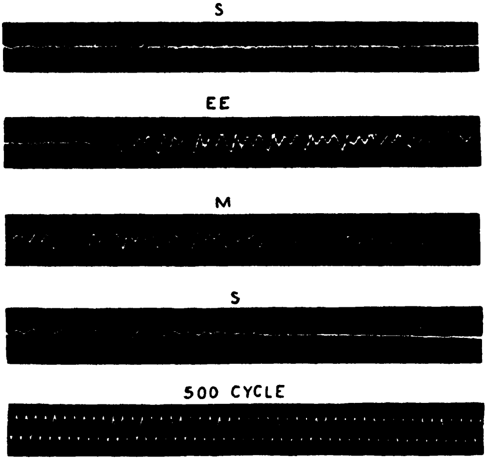

Fig. 48. Oscillogram of the word *seems*. (*Fletcher*.)

The physical characteristics of music, speech, and noise are illustrated in Figs. 47, 48, and 49. Fig. 47 is a photographic record of the form of vibration produced by a horn. It will be noted that the vibrations follow in a regular or periodic fashion, and in addition there is a slower periodicity of changing amplitude. This is one of the simplest of musical tones. Others, such as the struck string of the piano, are more complicated. When an entire symphony orchestra is playing, the resulting vibrations, although principally harmonic, are amazingly complicated.

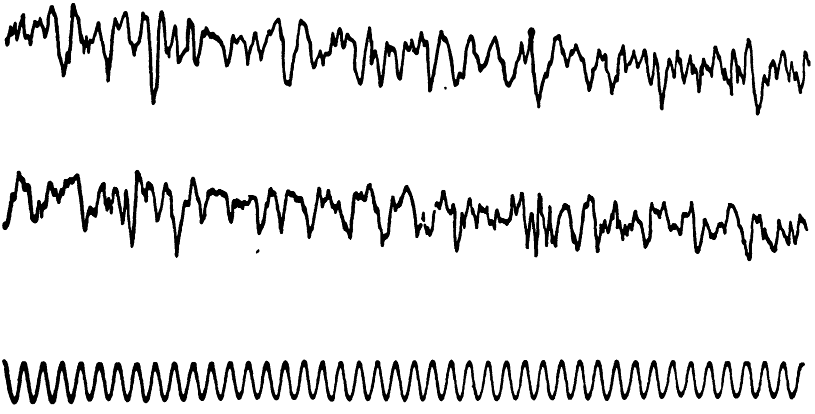

Fig. 49. Oscillogram of street noise. (*Fletcher*.)

Fig. 48 shows an oscillographic record of the spoken word *seems*. The various forms of vibration corresponding to the different parts of the word are clearly shown on the oscillogram. For comparison, a pure tone of 500 cycles is shown at the bottom of the record.

In Fig. 49 is shown an oscillographic record of street noise. The highly irregular character of the vibrations which comprise this noise is clearly shown. It is a complicated mixture of all sorts of ever-changing vibrations, made up from the endless variety of honking horns, grinding gears, accelerating motors, squeaking brakes, and a thousand other manifestations of the " machine age."

45. Classification of Speech Sounds. Many schemes have been developed and adopted for classifying the different sounds of speech into vowels, consonants, etc. The scheme which is best suited for the study of speech in auditoriums is the one used by telephone engineers for studying the nature of speech as it is reproduced over telephone equipment. Using essentially this scheme,[1] the principal sounds of spoken English, which can be distinguished by the average person, are made up of the 40 following speech sounds:

Six long vowels
ū (*school*) *ō* (*dome*) *ä* (*talk*) *â* (*far*) *a* (*late*) *ē* (*see*)

Five short vowels
u (*book*) *o* (*some*) *ă* (*hat*) *ĕ* (*men*) *ĭ* (*tin*)

Four diphthongs
ī (*light*) *ou* (*ounce*) *oi* (*oil*) *ew* (*new*)

Four transitionals
w (*water*) *wh* (*when*) *y* (*young*) *h* (*hot*)

Five semi-vowels
l *r* *m* *n* *ng*

Four voiced fricative consonants
v (*very*) *z* (*zone*) *z* (*azure*) *th* (*this*)

Four unvoiced fricative consonants
f (*fine*) *s* (*sing*) *th* (*thick*) *sh* (*sheet*)

Four voiced stop consonants
b *d* *j* (*jump*) *g* (*good*)

Four unvoiced stop consonants
p *t* *ch* (*church*) *k* (*kite*)

There are other speech sounds, some of which are intermediate between those listed, as the *a* in *dance*, the *o* in *not*, and many others. And there

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[1] H. Fletcher, "Speech and Hearing."

are the many other sounds which are peculiar to foreign languages, as the umlauted *o* and *u* in German, and the nasal vowels in French. However, the ones listed above will be adequate for the conducting of English speech tests in auditoriums, and for formulating the requirements for the hearing of speech in interiors.

46. Energy Content of Speech. Most generators of sound are very inefficient; that is, the acoustical energy developed is only a small portion of the total energy expended in producing the sound. The organ of speech is one of the more efficient of instruments which generate sound, although even in the production of speech only a small amount of the energy expended is converted into sound energy. (The efficiency of some of the best electrodynamic loud speakers is as high as 25 per cent, but the efficiencies of most musical instruments and also the human voice are very much lower than this.)

Measurements made by telephone engineers indicate that the average American in ordinary conversation generates approximately 10 microwatts of speech energy (average value, including peaks and silent intervals). The deviations from this average are very great; many speakers generate as much as 500 microwatts, whereas others generate less than 1 microwatt. Again, the same speaker is subject to very wide fluctuations in speech power, varying from less than 0.1 microwatt to several thousand microwatts.

It is well known that a speaker attempts to raise the power output of his voice when he is speaking in an auditorium, and the larger the auditorium the more he exerts himself. It is to be expected therefore that the average power of speech increases with the size of the auditorium. Tests conducted in a small auditorium, 27,000 cubic feet, indicate that the average speech power of the average speaker in such an auditorium is about 27 microwatts. Similar tests conducted in a larger auditorium, 240,000 cubic feet, indicate that the average speech power in an auditorium of this size is approximately 50 microwatts. The results of these tests confirm a reasonable expectation based upon everyday observations, namely that a speaker increases the power of his voice in his attempt to discount the effect of the size of the auditorium in which he is speaking. He attempts to speak so that he will be heard by all auditors in the room. That he falls short of the requirements for good hearing in large auditoriums will be made manifest in a subsequent chapter.

The average person is surprised at the exceedingly minute amount of energy contained in speech. Thus, as was mentioned in Chap. II, 15,000,000 lecturers speaking at the same time generate only one horse power of acoustical energy. When the speech power of a single speaker is diffused in a large auditorium the density of sound energy throughout the room is reduced to a very small amount. Under such circumstances, it is easy to realize why it is difficult to hear well in a large auditorium, and why very feeble sources of extraneous noise or vibration may produce a serious disturbance. For example, the vibrations of a distant ventilating fan or motor, or the shuffling of feet on the floor, or the jarring of a near-by door may be sufficient to mask many of the speech sounds which reach an auditor in a large auditorium.

Most of the energy in speech is made up of frequencies below 500 cycles. The fundamental pitch of a man's voice is in the neighborhood of 100 to 125 cycles, whereas the fundamental pitch of a woman's voice is between 200 and 250 cycles, that is, about one octave above a man's voice. In Fig. 50 is shown a curve which represents the average frequency distribution of sound energy in the speech of six speakers — four men and two women. The energy distribution shown in this curve was affected by the frequency of occurrence, as well as by the intensities, of the frequency components. Thus, the peak in Fig. 50 may be attributed either to the frequent occurrence of components having fre-

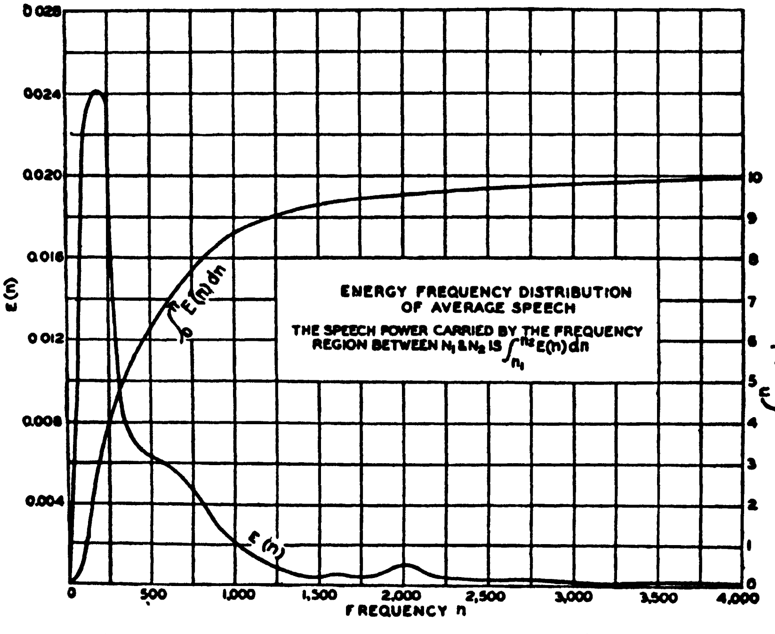

FIG. 50. Curve [marked $E(n)$] showing the frequency distribution of sound energy in speech. (*Crandall.*)

quencies around 200 cycles, or to higher intensities of these components.

It will be noted that there is relatively little energy in frequencies above 1000, and that the peak of this energy distribution curve is in the neighborhood of 200 cycles. Although this curve represents the frequency distribution of the energy of speech, it does not mean that what the ear hears are predominantly frequencies below 1000 cycles. The sensitivity of the ear is much greater for high-frequency components than it is for low-frequency components, the maximal sensitivity occurring for frequencies between 2000 and 4000 cycles. Hence, if the curve shown in Fig. 50 were corrected for the sensitivity of the ear so that it represented the sound level or the loudness of the various frequency components as heard by the ear instead of the intensity, the maximum would occur between 500 and 1000 cycles, and the curve would slope down rather gently for lower and higher frequencies. This will be better appreciated if the reader will recall the nature of the hearing sensitivity curve (see Fig. 42).

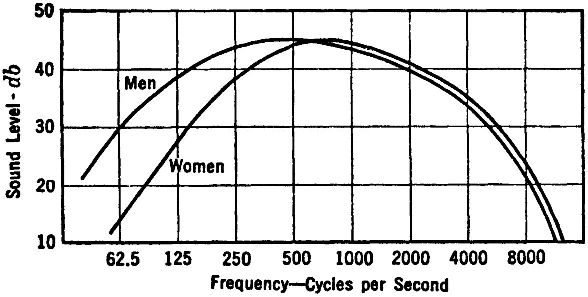

FIG. 51. Curves showing the approximate frequency distribution of the average sound level in speech for men and for women. (*Fletcher.*)

The curves in Fig. 51, due to Fletcher,[2] give relative values of the average sound level per octave, throughout the audible range, for both men and women. The ordinates correspond quite closely to the average level of speech in a fairly large auditorium (250,000 cubic feet). The curves indicate that the sound level for men's voices has a maximum at about 400 cycles, and that the sound level for women's voices has a maximum at about 800 cycles. The maximum for both men's and women's voices would be at about 600 cycles. (Use will be made of these curves in Sec. 132.)

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[2] H. Fletcher, "Physical Characteristics of Speech and Music," Bell System Tech. Jour., **10**, 349 (July, 1931).

47. Vowel Sounds. The outstanding property of vowel sounds is a prolonged continuance of the same sound. The vocal mechanism involved in the production of vowels is yet a controversial subject, but the conclusions reached by Russell,[3] who has made a careful and extensive study of the voice by means of X-ray photography and with his own laryngo-periskop, indicate that vocal quality in both speaking and singing is determined largely by the following:

1. The mode of vibration of the vocal cords, modified by the surrounding and overhanging tissues which control such factors as tension, damping, width of aperture, and the effective length of the cords.
2. Amplification or intensification of sound by the "sounding board" function of the hard palate and the "megaphone" function of the mouth.
3. Frictional noises produced by the motion of air through constricted parts of the oral cavities.
4. The emphasis or accentuation of one or more bands of frequencies produced by the resonant action of the oral cavities, and especially the large cavity between the lips and the throat.

Physicists and acoustical engineers have been prone to regard the resonant action of the oral cavities as the all-important factor in determining vocal quality. It is true that this resonant action plays an important role in the production of vowels. Thus, the tongue divides the large cavity between the lips and the throat into two cavities, which form a *double resonator.* The sizes of these two cavities, one fore and the other aft, and the size of the opening between them which is controlled by the position of the tongue with respect to the palate, impart significant resonant qualities to the sounds generated by the larynx. Each of the two resonators has its natural or resonant frequency; and both are altered by the nature of the coupling, or opening, between the two cavities. The resonant frequencies of these cavities, together with the damping effects which the surrounding tissues have upon the emergent sound, largely determine the characteristic quality of vowels. In fact, if models be carefully built to full scale, possessing the same volumes and shapes and the same opening between the two cavities as exist in the mouth during the production of vowels, it is possible to produce artificially the principal vowel sounds. With such models, Sir Richard Paget has been able to reproduce artificially a number of characteristic vowels, and even some consonants. It is necessary, of course, to have a source of sound similar to that produced by the vocal cords. A large bellows blowing a suitable reed, or an elastic band stretched over a small

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[3] G. Oscar Russell, "Speech and Voice," 146 (Macmillan, 1931).

orifice, will provide a sound quite similar to that produced by the vocal cords. If such a sound, which is complex and therefore rich in overtones, passes through the two coupled cavities or resonators, it is altered by the resonance and damping characteristics of the two resonators in a way similar to that accomplished by the oral cavities in speech.

In sounding the vowel *ū*, the lips are rounded and the tongue is elevated near the throat, thus forming a large resonating cavity in the front portion of the mouth, and a small and less important cavity in the rear portion of the mouth. In sounding the vowel *ā* the tongue divides the cavity into two more nearly equal cavities; and in sounding the vowel *ē* the front cavity is made rather small and the rear one relatively large, and in this case both cavities produce marked resonance effects. Other vowel sounds are characterized by one or more regions of resonance, and it is the presence of these resonant *regions* which leads physicists to attach so much importance to the resonant properties of the oral cavities.

These regions of resonance in the principal vowel sounds are shown in Fig. 52. These curves also show the relative prominence of all the different frequency components which comprise the principal vowel sounds — taking into account the sensitivity of the ear so that the ordinates represent the sound level rather than intensity. Note that there are rather marked physical differences among the different vowels, and that the detailed structure of each sound is very complicated. It is rather surprising that the sounds produced by a man's voice differ so much, not only in the fundamental resonant frequencies but also in fine structure, from the same sounds produced by a woman's voice. In most of the curves there are two outstanding regions of resonance corresponding to the resonant frequencies of the front and rear oral cavities of the mouth, and it is these characteristic regions of resonance which identify the different vowel sounds.

The curves given in Fig. 52 are of interest in the study of architectural acoustics, because they show the range of frequency and the form of vibration of the principal sounds of speech. For example, the *ū* as in *pool* includes principally the range between 128 and 2048 cycles, whereas the *ē* as in *team* has a very important band of frequencies well above 2048 cycles. In general, these curves indicate that for the hearing of speech in auditoriums it is necessary to consider the characteristics of the room for the frequency band between at least 100 and 5000 cycles. Again, considering the differences between the same vowels as spoken by a man or a woman, or even by different men or women, it is obvious that considerable distortion can be tolerated without sacrificing those characteristics which are essential for the correct auditory recognition of the sounds of speech. This is most fortunate for the hearing of speech in auditoriums, since there are many unavoidable distortions owing to interference, selective absorption, resonance, and reverberation.

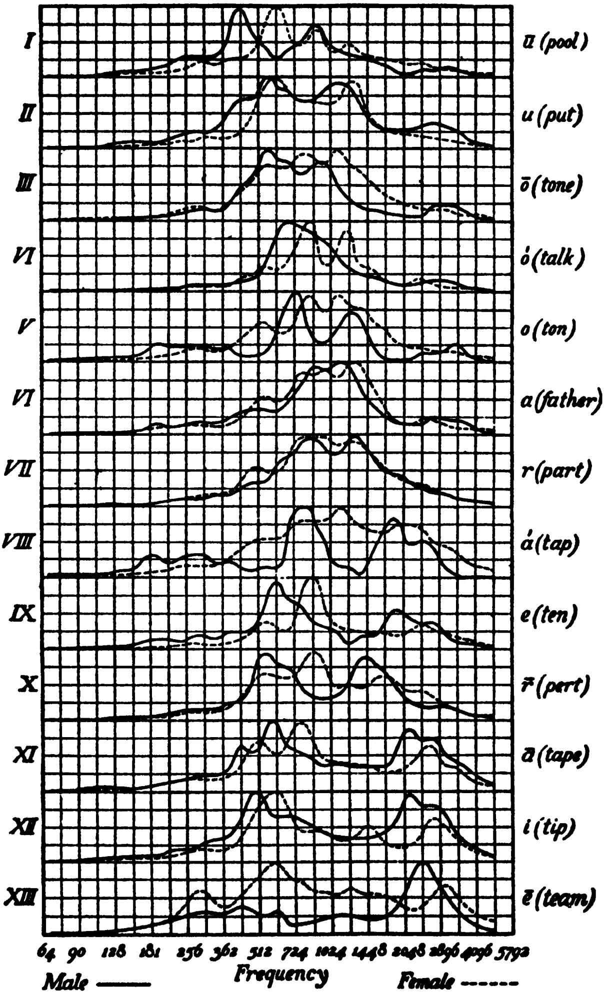

FIG. 52. The energy distribution of speech for a number of typical speech sounds, corrected for the sensitivity of the ear. (*Crandall.*)

The whole problem of vowel formation is still a battle ground for phoneticians and others, and some authorities insist that the form of vibration of the vocal cords is the principal factor in determining the composition of vowel sounds.[4] We are sure of one thing, and that is the physical constitution of the vowels after they are formed; namely, the frequency components, the amplitudes of the various components, and the general form of the vibration, including the initial and terminal endings. The types of vibration can be faithfully recorded by distortionless oscillographs, and these can be carefully analyzed by mechanical or electrical analyzers. The oscillographic records obtained by Dr. I. B. Crandall, and shown in this chapter, are among the very best which have been obtained to date. Such a record of the vowel ū as in *pool* is shown in Fig. 53. The time, in hundredths of a second, is stamped above the record. It will be noted that the sound builds up to

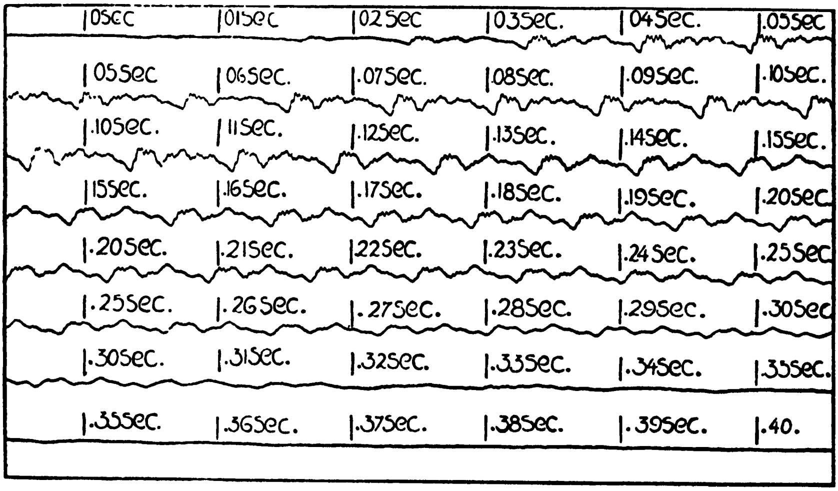

FIG. 53. Oscillogram of the vowel ū, as in *pool*. (*Crandall and Sacia.*)

a fairly steady state in 0.04 or 0.05 second, continues in this steady state for about 0 2 second, and then dies away for about 0.1 second. Segments taken from similar records of all the long vowels are shown in Fig. 54. It will be noted that there is a marked difference among all of these, and especially between the ū in *pool* and the ē in *team*. One would expect that these latter two sounds would never be confused, and such is found to be the case. On the other hand, the wave forms for the ä as in *talk* and the â as in *part* are more nearly alike, and it is found that these sounds are more frequently mistaken, especially in auditoriums

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[4] See for example the X-ray photographs of Russell (Figs. 123 and 124) in his book on "Speech and Voice," which show two greatly different shapes of the oral cavity in the same speaker while sounding a perfectly normal "ah." See also Figs. 13 to 18 in Russell's book.

where there is appreciable distortion from interference and reverberation. However, in spite of these close similarities in certain vowels and the distortion introduced by reflections of sound in auditoriums, the vowels are nearly always heard correctly in auditoriums. The vowels enjoy the distinction of comprising most of the energy of speech — a most potent advantage in large auditoriums, and they differ sufficiently in their physical characteristics to make their identification quite certain, even in rather faulty auditoriums. Nearly all the difficulties which arise in the hearing of speech in auditoriums are attributable to errors in the recognition of the consonant sounds.

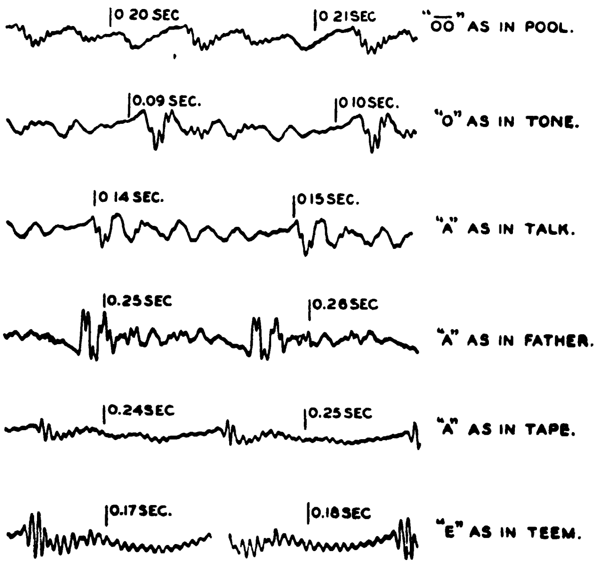

FIG. 54. Portions of typical oscillograms of the long vowels. (*Fletcher.*)

48. Consonant Sounds. Many of the consonant sounds are characterized by a prolonged continuance of the same sound, as *z* in *zone* and *g* in *good.* In such consonants, that is, the voiced consonants, the vocal cords produce the sound in much the same way that they do for the vowels. However, there are many consonants such as *p*, *k*, *t*, *f*, and *s*, which do not utilize the vocal cords, but which are produced largely by frictional vibrations set up between the lips, between the tongue and teeth, or between the tongue and palate. In general, these unvoiced consonants are made up of relatively high frequencies, and their energy content is very small compared with that of the vowel sounds. Some of these unvoiced consonants contain frequencies as high as 15,000 cycles, and contain an amount of energy which is only about one ten-thousandth of the energy of vowels.

A number of interesting characteristics of both vowels and consonants are shown in Fig. 55. This chart contains the curves for the minimal threshold of audibility and also the threshold of feeling. These were discussed in the preceding chapter. In addition, this figure shows the more important regions of frequencies and intensities involved in the production of either vowels or consonants. Thus, the vowels and voiced consonants are made up principally of frequencies between 500 and 3000 cycles, and in normal conversation these sounds produce a pressure against the drum membrane of about 1 dyne; that is, the sound level is about 60 db. On the other hand, the unvoiced consonants are made up principally of frequencies between 2500 and 10,000 cycles, and the pressure against the drum is of the order of 0.05 dyne, or the average sound level is about 25 db. The chart also shows the difference in the fundamental pitch of a man's voice and a woman's voice. Since the fundamental of a woman's voice is about one octave higher than the fundamental of a man's voice, all the speech sounds produced by a woman contain frequency components which are considerably higher than those produced by a man's voice. A woman's voice therefore contains a relatively greater proportion of frequency components above, say, 4000 cycles and a smaller proportion below 4000 cycles than does a man's voice, and for this reason, if for no others, the speech of women is more difficult to understand than the speech of men. Tests of telephone engineers indicate that women's voices are not heard so well over the

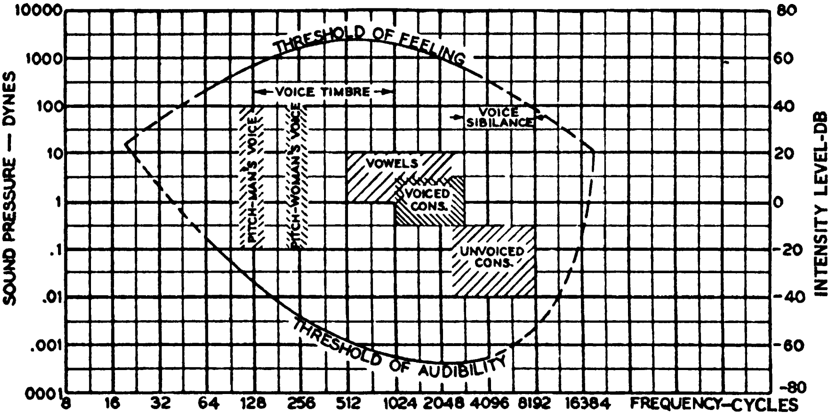

FIG. 55. Frequency-sensitivity curves showing approximate frequency and intensity ranges for vowels and consonants. (*Steinberg.*)

telephone as are men's voices. Experience also bears out this same conclusion in regard to the hearing of women in auditoriums. In the design of auditoriums, it is well to bear in mind these fundamental differences in the speech of men and women. It means that the auditorium which is designed exclusively for women imposes a slightly more difficult problem than does the auditorium which is designed exclusively for men. In practice, little if any attention is given to this difference, but in special cases it is a factor which should not be overlooked.

49. Articulated Speech. In the preceding sections the physical characteristics of vowels and consonants have been considered separately. Articulate speech consists of a flow of various combinations of consonants and vowels. The nature of the articulation of the separate syllables and words in speech, and the rapidity with which the separate syllables follow one another, have a potent bearing upon how well the speech will be heard in an auditorium. If the separate syllables are clear cut and accurately pronounced, and if they follow each other deliberately, and at a sufficiently slow speed, the speech will be readily understood. On the other hand, if the separate syllables are inaccurately formed, and if they follow each other in rapid succession, they will not be heard distinctly. The rate at which the separate syllables are spoken has a most significant bearing upon how well speech is heard in most rooms. In a room which is free from reverberation, the separate syllables may follow each other in rapid succession and yet be clearly understood, because each sound dies away quickly and does not interfere with the succeeding ones. On the other hand, rapidly flowing speech in a reverberant room is heard very poorly because the separate sounds of speech persist so long that they all confuse.

The normal rate of flow of speech is about four to five syllables per second. Each sound does not have more than about one fifth of a second in which to make its impression upon the auditory mechanism. Since the time of reverberation in a room is nearly always in excess of one second, the three or more syllables preceding the one upon which attention is focused will yet remain audible and will produce a masking effect dependent upon their intensities and their frequency composition. A detailed discussion of this effect will be given in a subsequent chapter.

50. Physical Characteristics of Musical Sounds. Music, like speech, is a composition of vibrations, often complicated, but the frequencies are usually related to series of simple numbers. The range of frequencies employed is even a little wider than that used in speech, extending from about 20 or 25 cycles to 17,000 cycles. In addition, the acoustical power generated by musical instruments, including the singing voice, is in general considerably greater than that which is generated in speaking. Thus, whereas the average speaker generates an average power of about 50 microwatts in a fairly large auditorium, a vocalist or a musical instrument generates an average power of about 100 microwatts and will often generate 500 to 5000 microwatts in the same auditorium; that is, the intensity of music in a room is usually several decibels higher than the average intensity of speech. For this reason, less difficulty is encountered in hearing music in auditoriums than is encountered in hearing speech. The acoustical power generated in singing, or in the playing of musical instruments, is therefore adequate for satisfactory hearing, even in auditoriums considerably larger than those in which it is possible to hear speech.

Again, musical sounds are not so transient in character as speech sounds. The separate tones of music often are sustained for an appreciable fraction of a second or longer, and the change in pitch is nearly always ordered in conformity with the simple number relations among the frequencies which make up the musical scale. Thus, three tones which are basic in musical composition have the frequency ratio of 3 : 4 : 5. This combination constitutes what is known as a major triad, an example of which is the familiar *do*, *mi*, *sol*. (The frequency ratios of the most common musical intervals were given in Sec. 38.) Other simple ratios are characteristic of the frequencies which make up the notes in the commonly used diatonic scale. In fact, the basis of harmony in music is the simplicity in the ratios of the frequencies which make up a musical chord for a musical composition. If a number of tones have frequencies which are proportional to small integral numbers, the tones when sounded together will be harmonious, or consonant. On the other hand, if a number of tones have frequencies which are represented by fractional numbers, these tones when sounded together will in general be discordant, or dissonant.

A certain amount of reverberation in auditoriums can be tolerated, and in fact is often a desirable property, for musical tones which follow each other in a harmonious sequence, since the persistence of the separate tones, owing to reverberation, blend or harmonize with the successive tones. On the other hand, a sequence of tones which would constitute a dissonant series may suffer more from reverberation since the persistence of the separate tones would not combine in a harmonious manner. It is apparent therefore that reverberation may contribute to the acoustical quality of a room intended for music, since the separate tones are rounded out and blended into an artistically integrated whole; and at the same time the same amount of reverberation might prove a real hindrance to the hearing of speech.

The separate tones which comprise music are in general made up not of a single simple harmonic vibration, but of long and complex harmonic series. In some instances the higher harmonic components may be much more prominent than the fundamental. As was shown in the preceding chapter, it is the number and prominence of these harmonic components which determine the quality or timbre of musical tones. If there is an abundance of harmonics, the tone is said to be rich, or full, or round. On the other hand, if there are relatively few harmonics, the tone is said to be thin, or poor.

The wave form and the harmonic components of musical sounds have been analyzed by Professor D. C. Miller, using the phonodeik and mechanical harmonic analyzers; by Bell Telephone Laboratories, using a high-quality oscillograph and an electrical harmonic analyzer; and by others. In Figs. 56, 57, 58, and 59 are shown the oscillograms and the resulting acoustical spectra of some musical sounds produced by the human voice, the piano, violin, clarinet, and organ pipes. The ordinates in these acoustical spectra represent the amplitude of vibration of the various components and not the sound level in decibels. An inspection of Fig. 56 shows that the voice is characterized by a rather prominent fundamental tone with the harmonics diminishing as they become of higher order. This is also generally true of the piano and the violin, as will be seen in Figs. 57 and 58. On the other hand, it will be noted in Fig. 58 that the clarinet is particularly rich in high harmonics, especially the eighth, ninth, and tenth harmonics. In the case of the cello organ pipe (Fig. 59), it will be noted that the third harmonic is about five times greater than the fundamental. It should be mentioned that in general there are frequency components higher than those shown in the spectra — extending perhaps as high as 15,000 or 17,000 cycles. They are not indicated in the reproduced spectra because of the limitations of the analyzing equipment.

Recently, the Bell Telephone Laboratories have developed an elaborate and time-saving analyzer which is very useful for determining both the average and peak values of the sound energy in different frequency bands of music, speech or noise.[5] In Figs. 60 to 69 are shown the average relative sound pressures for different frequency bands produced by certain musical instruments and by a 75-piece orchestra. The ordinate is the ratio of the average alternating pressure for the frequency band considered to the average pressure for the entire range of

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[5] See H. K. Dunn, "A New Analyzer of Speech and Music," Bell Laboratories Record, **9**, 118 (November, 1930); L. J. Sivian, "Speech Power and Its Measurement," Jour. Acous. Soc. (Supplement to January, 1930); Sivian, Dunn, and White, "Absolute Amplitudes and Spectra of Certain Musical Instruments and Orchestras," Jour. Acous. Soc., **2**, 330 (1931).

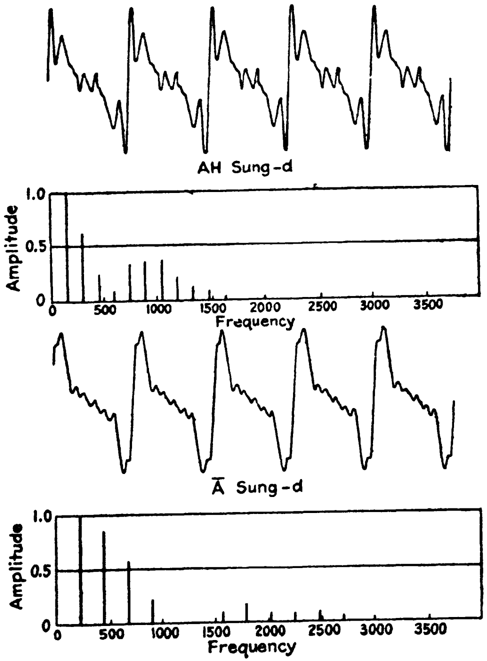

FIG. 56. Wave forms and sound spectra of sung vowels. (*Fletcher.*)

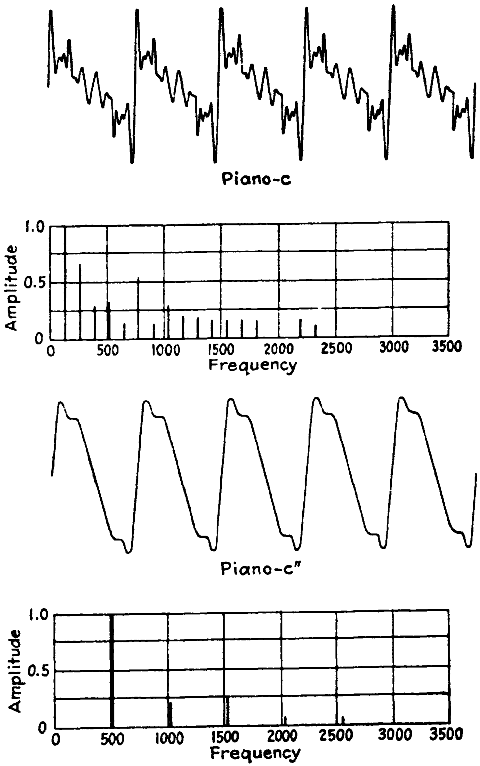

FIG. 57. Wave forms and sound spectra of piano tones. Note the abundance of overtones in the tone of lower pitch shown at the top. (*Fletcher.*)

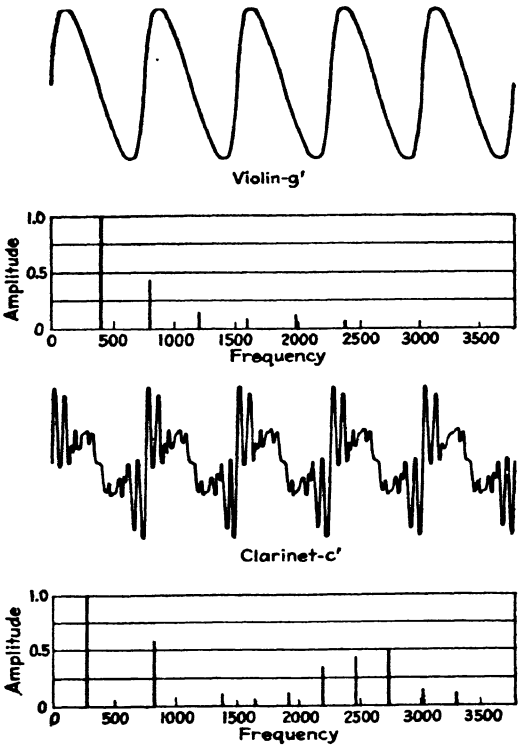

FIG. 58. Wave forms and sound spectra of a violin tone (at top) and a clarinet tone. Note the prominence of the eighth, ninth, and tenth harmonics for the clarinet tone. (*Fletcher.*)

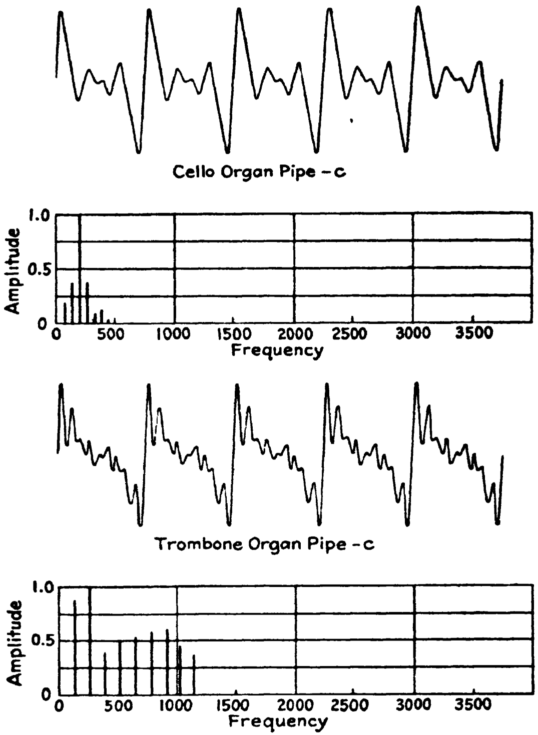

FIG. 59. Wave forms and sound spectra of a cello organ pipe (at top) and trombone organ pipe. Note that the third harmonic for the cello organ pipe is much more prominent than the fundamental. (*Fletcher.*)

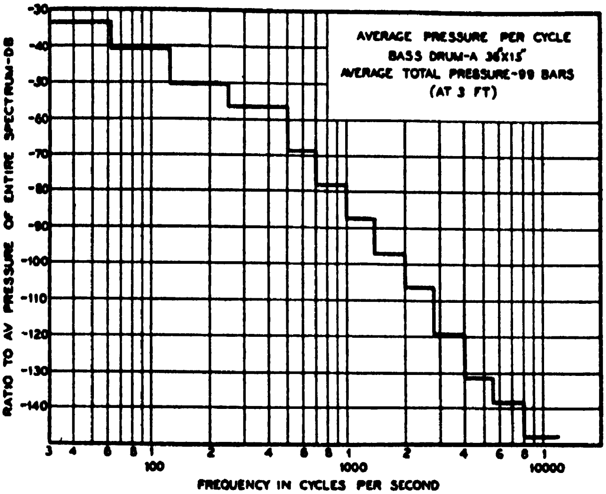

FIG. 60. Curve showing the average pressure per cycle of various frequency bands for a bass drum. (*Sivian, Dunn, and White.*)

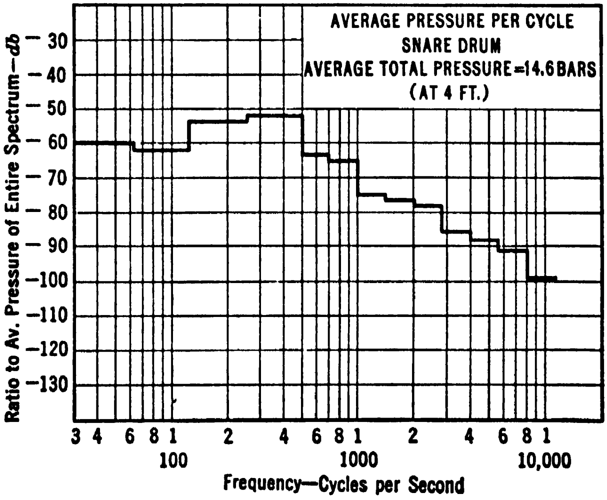

FIG. 61. Curve showing the average pressure per cycle of various frequency bands for a snare drum. (*Sivian, Dunn, and White.*)

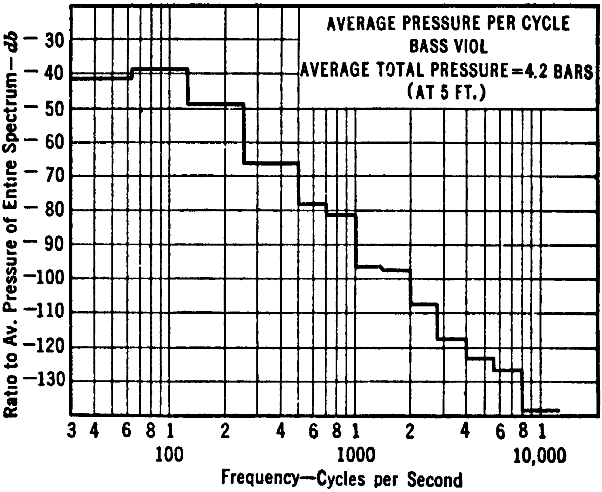

FIG. 62. Curve showing the average pressure per cycle of various frequency bands for a bass viol. (*Sivian, Dunn, and White.*)

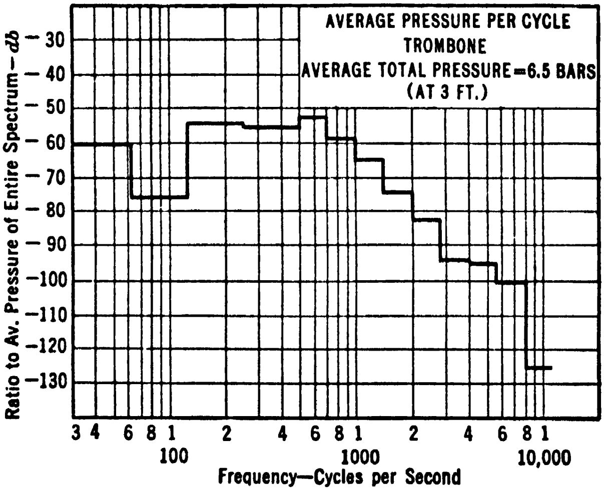

FIG. 63. Curve showing the average pressure per cycle of various frequency bands for a trombone. (*Sivian, Dunn, and White.*)

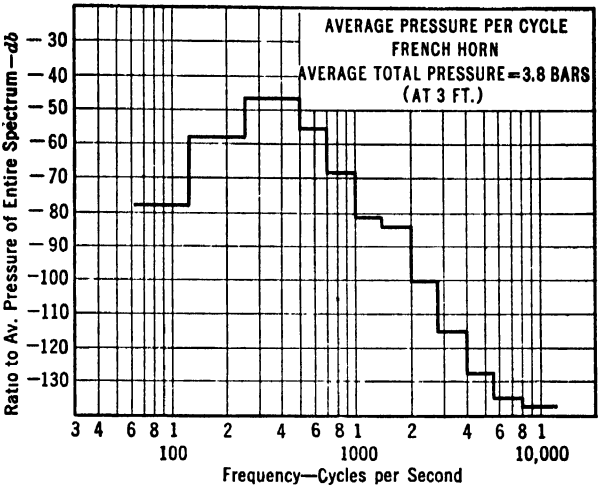

FIG. 64. Curve showing the average pressure per cycle of various frequency bands for a French horn. (*Sivian, Dunn, and White.*)

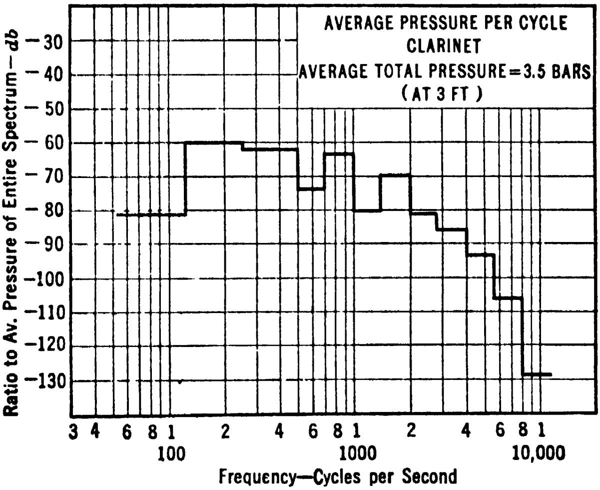

FIG. 65. Curve showing the average pressure per cycle of various frequency bands for a clarinet. (*Sivian, Dunn, and White.*)

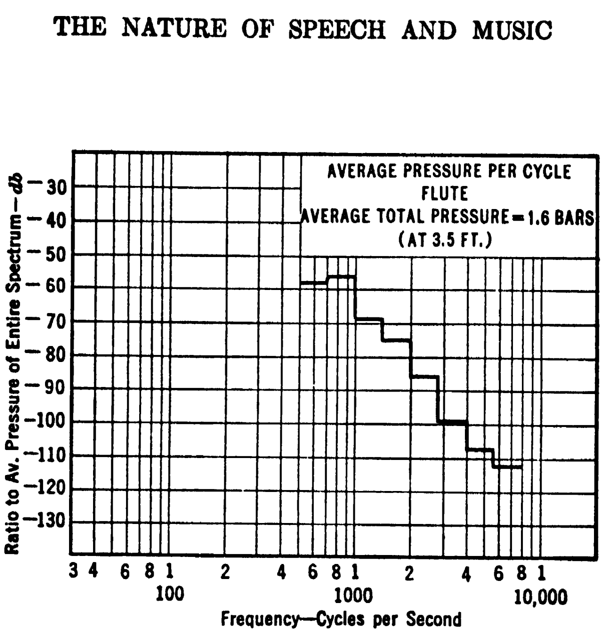

Fig. 66. Curve showing the average pressure per cycle of various frequency bands for a flute. (*Sivian, Dunn, and White.*)

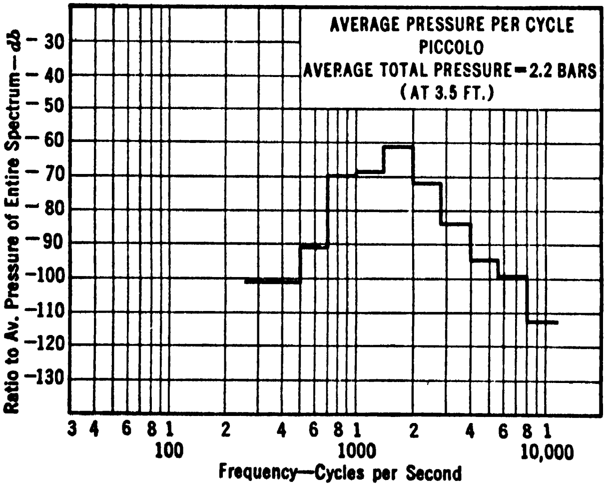

Fig. 67. Curve showing the average pressure per cycle of various frequency bands for a piccolo. (*Sivian, Dunn, and White.*)

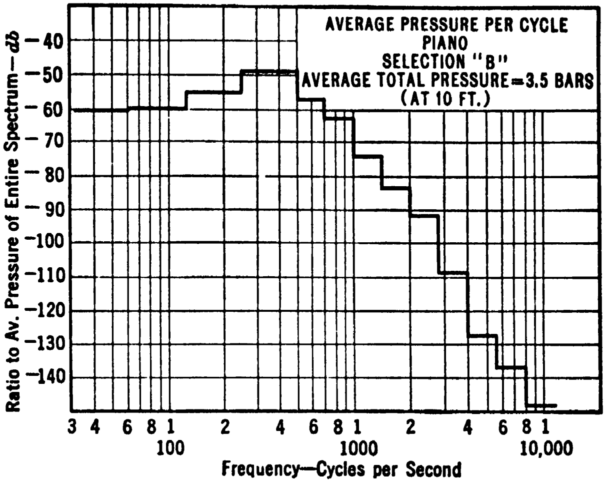

FIG. 68. Curve showing the average pressure per cycle of various frequency bands for a piano. (*Sivian, Dunn, and White.*)

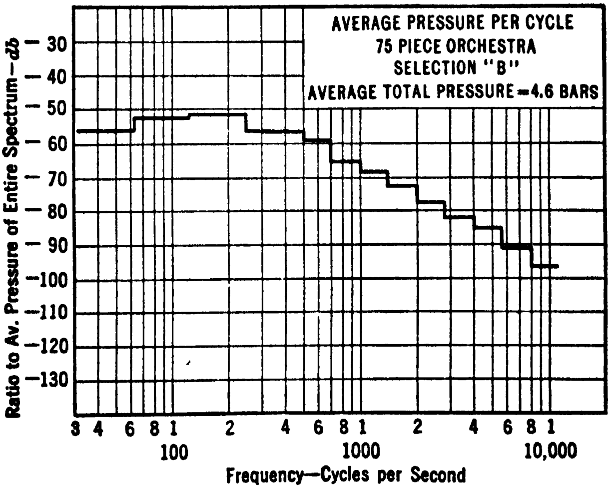

FIG. 69. Curve showing the average pressure per cycle of various frequency bands for a 75-piece orchestra. (*Sivian, Dunn, and White.*)

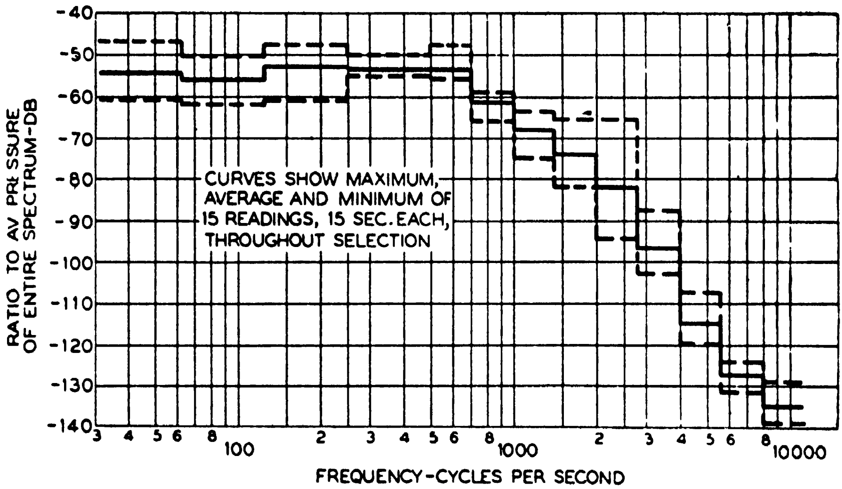

FIG. 70. Curves showing the average pressure per cycle of various frequency bands for Liszt's Hungarian Rhapsody No. 2, played on the piano. (*Sivian.*)

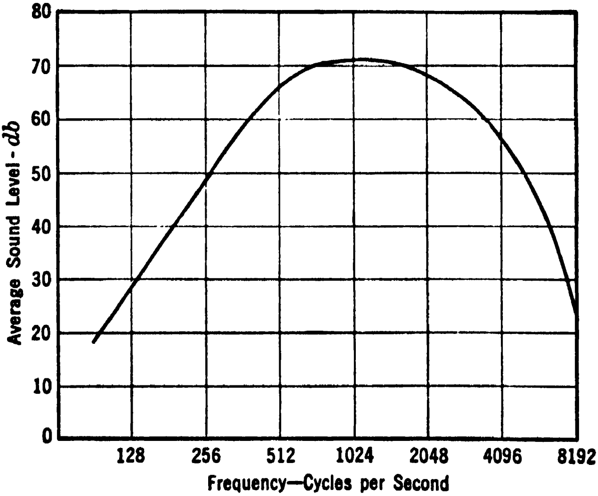

FIG. 71. Approximate frequency distribution of the sound level of the average musical composition as played by piano or orchestra.

frequencies divided by the width of the band in cycles per second. In Fig. 70 are shown the average pressures produced by a rendition on the piano of Liszt's Hungarian Rhapsody No. 2. If the data given by Figs. 69 and 70, that is, the data for the orchestra and for the piano, be converted into average sound levels, in decibels above the minimal threshold, the average distribution will be approximately as given in Fig. 71.

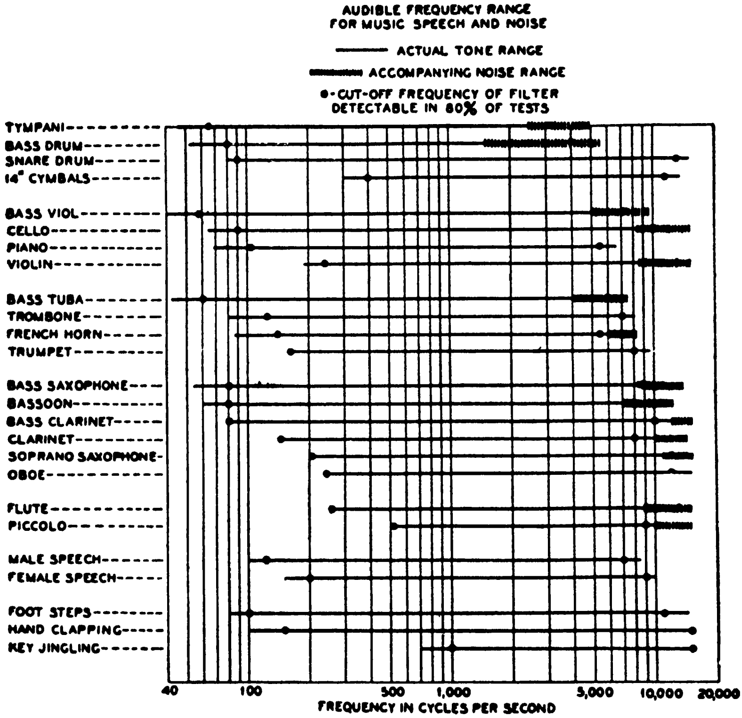

FIG. 71*a*. Chart showing the range of frequency for different musical instruments. The actual tone range, the range which is accompanied by noise, and the range required to give distortionless reproduction for each instrument are indicated on the chart. According to this chart, the frequency range required for distortionless transmission or reproduction of music is about 60 to 16,000 cycles per second. (*Snow.*)

This distribution may be regarded as fairly representative of the average musical rendition in music rooms, and therefore is of considerable importance in connection with the acoustics of music rooms. (See Chap. XVIII.)

It should be mentioned that these average values of sound levels are based not only upon the intensity distribution in any one chord, but also upon the frequency of occurrence of the different frequency components throughout the entire composition. They reveal, however, the general trend of the distribution of sound energy for different musical instruments and for typical compositions of music.

It is obvious that in order to preserve the characteristic quality of musical tone it is necessary that all harmonic components be unaltered as they are transmitted from their source to the listeners in an auditorium. This is strictly impossible in an auditorium where there are reflecting surfaces which cause certain frequency components to unite in phase and other frequency components to unite out of phase. Further, the rate of absorption of sound by the boundaries and contents of the room may be greater for certain frequency components than for others. Thus, many acoustical materials are of such a nature that the high-frequency components will be absorbed more rapidly than the low-frequency components. This may detract from the richness of musical quality, by suppressing the higher overtones. These sources of distortion are not encountered in the open, and therefore music in the open retains its original quality with greater fidelity than it possibly can in a room, although music in the open will lack the beneficial effects of reverberation and resonance which are supplied by properly designed architectural interiors.

It should be the aim of all acoustical designing to treat a room in such a manner that all the harmonic components will be preserved as nearly as possible in their true proportions. It is particularly advisable in this connection to avoid materials which are highly absorptive for the high-frequency components and very poorly absorptive for the low-frequency components. This matter will be discussed more fully in a subsequent chapter.

PART II

FUNDAMENTAL PRINCIPLES AND DATA

CHAPTER V

THE REVERBERATION OF SOUND IN ROOMS

51. Introductory. The simple action of reverberation and its importance in determining the acoustical properties of a room have been discussed in preceding chapters. Consideration will be given in the present chapter to the theoretical aspects of reverberation; that is, to the formulation of quantitative principles or laws which will clarify the phenomenon of reverberation and which will make it possible to calculate the reverberatory properties of enclosed or partially enclosed spaces, and to determine the absorptive properties of building materials.

When a sound is generated in a room it is propagated in all directions from the source with a speed of more than 1100 feet per second. The spreading sound waves soon encounter the boundaries of the room and are reflected or diffracted in accordance with the laws which were set forth in Chap. II. The reflected components soon strike other portions of the boundaries and are successively reflected and absorbed until the vibratory motion is completely absorbed by the air or the boundaries of the room. Most of the absorption takes place at the boundaries, although high-frequency sounds are absorbed appreciably as they are transmitted through the air.[1] If the source continues to generate sound at a constant rate, a condition of equilibrium will be reached in which the rate of supply of sound energy to the room is just equal to the rate of absorption by the air and the boundaries. When the source is first started in the room, the average intensity of sound builds up until this steady state condition is reached. If now the source be stopped, the sound in the room will die away at a rate equal to the rate of absorption, which is determined principally by the size, the shape, and the boundaries of the room. The time required for the intensity of the sound to be reduced a specified amount will depend upon (1) the number of reflections which occur per second, and (2) the amount of sound energy which is absorbed at each reflection. If the room be a large one there will be only a few reflections per second; and in addition, if but a little sound energy be absorbed at each reflection, it will require a relatively long time for the intensity of ordinary sounds to be reduced to the threshold of audibility. Such a room will be excessively reverberant. On the

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[1] V. O. Knudsen, "The Absorption of Sound in the Air," Jour. Acous. Soc., **3**, 126 (July, 1931).

other hand, if the room be small and the boundaries highly absorptive, the room will be free from reverberation.

Since the average intensity of speech or music in a room is of the order of one million times the intensity which is just barely audible, and since the hard, rigid boundaries may reflect as much as 95 per cent of the incident sound energy, it is apparent that an appreciable time, amounting to several seconds in many instances, is necessary for the sounds of speech or music to be reduced to inaudibility. For example, consider a room in which reflections occur, on the average, at intervals equal to the time required for a sound wave to advance 51 feet. That is, the average distance which a sound wave travels through the air between successive encounters against the boundaries of the room is 51 feet. This distance is called the **mean free path.** Since the velocity of sound is approximately 1122 feet per second, there will be in this room just 22 reflections each second. Thus, if the initial sound in the room has an intensity of 1,000,000 threshold units, and if 98 per cent of the incident sound energy is reflected at each reflection, it will be possible to arrive at an approximate notion of the nature of the reverberation or the duration of audibility in the room in the following simple manner. After the first reflection 1×0.98, or 0.98 of the sound energy, remains in the room; after the second reflection 0.98×0.98, or 0.96 of the initial sound energy remains in the room, and so on. If by this process the energy is to be reduced to one millionth of its initial amount, it would require n successive reflections, where n is given by the equation $0.98^n = 0.000001$; that is, 0.98 to the nth power will be equal to one millionth. If this equation be solved for n, it will be found that n is equal to 684; that is, it requires 684 successive reflections in this particular room for the sound to die away to inaudibility. Since 22 reflections occur each second in this room, the time required for the sound to die away to inaudibility would be $684 \div 22$, or 31.1 seconds; that is, the time of reverberation in this room would be approximately 31.1 seconds.

By a similar consideration it can be shown that if this same room were completely lined with a material which reflects only 50 per cent of the incident sound energy, the total number of reflections would be reduced to about 19.9, and the time of reverberation would be of the order of 0.9 second. The absorptive properties of the boundaries of a room are thus seen to have a profound influence upon the reverberation time for that room.

52. Theoretical Considerations of Reverberation in a Room — Approximate Theory. The problem of the reverberation of sound in a room was solved in an approximate manner by W. C. Sabine, who attacked the problem by an ingenious combination of experiments and inductive reasoning. Sabine determined the most fundamental properties of reverberation, and derived a formula which has been extremely useful for calculating the time of reverberation in rooms. Until recently, the Sabine formula for reverberation has been used very widely by engineers and architects throughout the world.

In 1911, Jaeger[2] attacked the problem by a statistical method similar to the classical methods which had been so successful in the development of the kinetic theory of gases. He deduced essentially the same reverberation formula as had been obtained by Sabine, and his theoretical equation constituted a rather remarkable confirmation of the Sabine equation. The fundamental assumptions upon which both the Sabine and Jaeger formulas are based require (1) a random or diffuse distribution of the flow of sound in the room and (2) a continuous absorption of sound by the boundaries of the room — conditions which are quite completely fulfilled in large reverberant rooms. It is to be expected therefore that these formulas would be satisfactory for the practical calculation of reverberation in " live " rooms, but that they would lead to only approximately correct results in " dead " rooms. A more general theory of reverberation, which applies to both *live* and *dead* rooms, has been derived by Schuster and Waetzmann,[3] and a part of this theory

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[2] A. Jaeger, "Zur Theorie des Nachhalls," Sitzungsber. d. Kaisl. Akad. d. Wiss. in Wien, Math.-Natur Klasse, 120, Abt. 2a (1911). See also Eckhardt, Jour. Frank. Inst., **195**, 799–814 (June, 1923); and Buckingham, Bureau of Standards Bul. No. 506 (May 26, 1925).

[3] K. Schuster and E. Waetzmann, "Reverberation in Closed Rooms," Ann. d. Phys., **1**, 671 (March, 1929). Schuster and Waetzmann regard existing theories of reverberation (such as those developed by W. C. Sabine and A. Jaeger) as unsatisfactory. They maintain that these theories concern only the path or "career" of a single sound ray in a room, and that the energy losses in the reflections at the boundaries are transferred to the average density of sound energy in the room. They state that the theory of reverberation should be based upon the wave equation for a three-dimensional continuum, and they define reverberation as the damped *free* vibrations of the enclosed volume of air in the room. Reverberation, according to their view, deals only with the *free* vibrations after the sound source in the room has stopped, since, after the source has stopped, there are no *external* forces acting upon the air particles. By making special assumptions concerning the distribution of the absorptive material in the enclosure and concerning the "order numbers" of the *free* vibrations, they obtain formulas for the rate of decay of the *free* vibrations of sound in a cubical cavity and in a cylindrical cavity (with diameter equal to length) which are in fair agreement with the Sabine and Jaeger formula for the decay of what might be termed the *forced* or *impressed* vibration of sound in the room. The author is of the opinion that the complete solution of the reverberation problem in a room will have to deal with both the *impressed* and the *free* vibrations. If we adopt the Huyghens' principle, the external or *impressed* vibration may not stop at the instant the source is stopped, but each wave front of the direct and reflected waves of sound may be regarded as a secondary source of sound which *impresses* the original vibra-

has been independently worked out and experimentally verified by Eyring.[4]

In the present section, consideration will be given to the approximate reverberation theory — which holds for the *impressed* vibrations, and for *live* rooms — following essentially the method developed by Jaeger.

Assume a room of large size, compared with the wave length of sound, and with boundaries that are efficient sound reflectors, as plaster or concrete. When a source of sound is first started in such a room the sound energy spreads out almost spherically until it strikes the boundaries of the room. It is then partially absorbed and partially reflected. The reflected portion is scattered in many directions. After each reflection the distribution of sound energy becomes more nearly uniform in all parts of the room, and the direction of flow of sound energy becomes more and more diffuse. Ultimately, except in close proximity to the sound source, there is in the room a diffuse or random distribution in the direction of flow of sound energy. Further, when the equilibrium condition is reached, that is, when the rates of absorption and emission are equal, the *average* density of sound energy in the room attains a constant value which will depend only upon the rate of emission of the source and the equivalent absorption of the room and its boundaries. If the source of sound is a single frequency, that is, a pure tone, the density of sound energy will not be uniform throughout the room but there will be large fluctuations from point to point owing to the phenomena of interference. If now we assume that the source of sound is a uniform band of frequencies at least one half an octave wide, in-

tion upon the continuum. The *impressed* vibrations excite the *free* vibrations of the continuum, and it is possible that in many rooms the rates of decay for the *impressed* and the *free* vibrations are different. For example, the measured reverberation time in a small test room was 2.5 seconds, whereas in accordance with the Sabine-Jaeger theory the reverberation time should have been reduced to about 0.75 second. It was obvious, from listening to the decadent sound in the room, that the *impressed* vibrations were quickly damped and that the *free* vibrations were soon predominant and were the ones which were very slowly damped. Fortunately, such phenomena are not so likely to occur in large rooms, and, practically, they can be eliminated in all rooms, provided the absorptive material be distributed on the different surfaces of the room in such a manner that the rates of decay of sound will be approximately the same in the three principal directions in the room. Under these circumstances, the reverberation formulas based upon the rate of decay of the *impressed* vibrations (such as will be derived in the following pages) will be satisfactory for calculating the reverberation times in practically all architectural interiors. (See also Ref. 11, p. 132, and author's paper on " Resonance in Rooms " presented before the Acoustical Society of America, in New York, May, 1932.)

[4] C. F. Eyring, "Reverberation Time in 'Dead' Rooms," Jour. Acous. Soc., 1, 217 (January, 1930).

stead of a single frequency, the effect of interference just mentioned will be largely overcome, so that when the steady state is reached the density of sound energy, and therefore the intensity, will be almost uniform at all points in the room not too near the source; but there will still be a haphazard or random distribution in the direction of the flow of sound energy in the room, and, on the average, the same amount of sound energy will flow in all directions. When it is recalled that in a room of moderate size each ray of sound which proceeds from the source is reflected 20 or more times each second, and that these reflections are likely to continue several seconds before the steady state is reached, the assumption of equal probability of flow in all directions becomes fairly plausible, especially in *live* rooms.

In the following theory a further assumption will be made which is equivalent to assuming that the mean free path of the sound is four times the volume of the room divided by the interior surface of the room — an assumption which is remarkably valid for rectangular rooms of conventional dimensions, but which is only approximately true for peculiarly shaped rooms. (See Sec. 55.) Finally, it will be assumed that the effects of interference, echoes, resonance, and the change of phase at the boundaries can be neglected — assumptions which are acceptable for nearly all rooms. For the present, the absorption of sound in the air will be neglected.

Before proceeding with the derivation of the theory for the steady state and for the growth and decay of sound in a room it will be advantageous to define the symbols and terms which will be used, as follows:

V = volume of the room.

$S_1, S_2, S_3, \cdots$ = exposed areas of the different materials which comprise the interior boundaries of the room. $S = S_1 + S_2 + S_3 + \cdots$ = total interior surface of the boundaries of the room.

$\alpha_1, \alpha_2, \alpha_3, \cdots$ = coefficients of sound-absorption of the different materials which comprise the boundaries of the room.

a = total absorption of the boundaries $= \alpha_1S_1 + \alpha_2S_2 + \alpha_3S_3 + \cdots$.

E = rate at which sound energy is emitted from the source.

c = velocity of sound in the room.

ρ = amount of sound energy per unit volume (volume density) in the room at any time t during the growth or decay of sound.

ρ_0 = volume density in the room when the sound has built up to a steady state.

t_{60} = time of reverberation in the room, that is, the time required for the sound to decay 60 db.[5]

The first step in the derivation is to determine the rate at which sound

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[5] This assumes that there is only one rate of decay of sound in the room, which will be the case for a simple rectangular room in which the absorptive material is uniformly distributed on all surfaces, and in which there are no pronounced resonant phenomena.

energy strikes the interior boundaries of the room. Obviously this will be proportional to ρ and c. The method of determining this rate is essentially the same as that used in the kinetic theory of gases for determining the rate at which molecules in an enclosed vessel hit against the inner walls of the vessel, and may be developed as follows: Suppose that *abcd* (Fig. 72) is one of the boundary surfaces in the room, dS a small element of surface, and dV a small element of volume a distance r from dS making an angle θ with the normal to dS. The total sound energy in dV is $\rho\, dV$, which, according to an assumption which was shown to be plausible, is free to radiate equally in all directions. Only a small fraction of the sound energy in dV will strike the small surface dS, the fraction being given by $d\omega/4\pi$, where $d\omega$ is the solid angle subtended by the surface dS from a point at dV, and 4π is the total solid angle surrounding dV. That is, the fractional part of the energy in dV which will ultimately strike dS is given by the probability which the sound rays in dV have of moving in the small angle $d\omega$. Since $d\omega = dS \cos\theta/r^2$, the amount of energy in dV which will be directed toward dS is given by

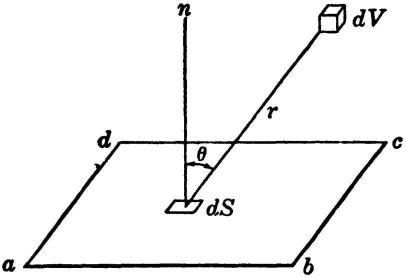

FIG. 72.

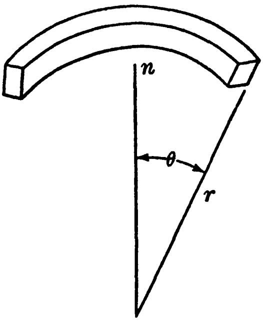

FIG. 73.

$$\rho\, dV \frac{d\omega}{4\pi} = \frac{\rho\, dV\, dS \cos\theta}{4\pi r^2}. \tag{11}$$

In order to include in dV all elements of volume separated a distance r from dS and making an angle θ with the normal to dS, it is necessary to regard dV as a small annular ring, a portion of which is shown in Fig. 73. The thickness of this ring is dr, the width is $r\, d\theta$, and the radius is $r \sin\theta$; so that the volume dV of the entire ring is the area of cross section times the circumference, that is, $r\, d\theta\, dr \times 2\pi r \sin\theta = 2\pi r^2 \sin\theta\, dr\, d\theta$. Hence, the amount of energy in this annular ring which will ultimately strike dS is

$$\frac{2\pi r^2 \rho \sin\theta \cos\theta\, dS\, dr\, d\theta}{4\pi r^2} = \frac{\rho \sin\theta \cos\theta\, dS\, dr\, d\theta}{2}. \tag{12}$$

Now the total energy which will strike dS in one second will be made up of all such contributions from all the elements of volume dV that are within a distance c from dS, that is, the distance sound travels in one second, and within an angle θ between 0 and $\pi/2$. This energy is given by a definite integral of (12), in which r has the limits of 0 and c, and θ has the limits of 0 and $\pi/2$, namely

$$\frac{\rho\, dS}{2}\int_0^c dr \int_0^{\pi/2} \sin\theta \cos\theta \, d\theta = \frac{\rho c\, dS}{4}. \tag{13}$$

Hence, the amount of sound energy striking unit area per second will be simply $\rho c/4$, and the amount of sound energy striking the entire interior surface of the room per second will be $\rho cS/4$. (The quantity $\rho c/4$ is also the flux of sound energy through each square centimeter per second, which by definition is the intensity of sound in the room.) Hence, the total amount of sound energy absorbed per second by the interior boundaries of the room will be

$$\frac{\rho c}{4}(\alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \cdot \cdot \cdot) = \frac{\rho c a}{4}. \tag{14}$$

The total amount of sound energy in the room at any instant during the growth or decay of the sound is $V\rho$, and the rate at which it increases or decreases is given by the difference between the rate of emission from the sound source, namely E, and the rate of absorption by the boundaries, namely $\rho ca/4$. If the changes of ρ, owing to absorption at the boundaries, occur in such small steps that the growth or decay of sound in the room may be regarded as continuous, the rate of change of the total sound energy in the room is given by $d/dt\,V\rho$. This condition will be approximated if only a small fraction of the sound energy is absorbed at each reflection. Hence, for *live* rooms,

$$\frac{d}{dt}V\rho = V\frac{d\rho}{dt} = E - \frac{\rho c a}{4},$$

or

$$V\frac{d\rho}{dt} + \frac{ca}{4}\rho = E. \tag{15}$$

This is a fundamental differential equation for the flow of sound energy in a room, and, although certain assumptions and approximations impose limitations upon it, it is of prime importance in architectural acoustics. The equation is so much like the equation for the growth and decay of electrical current in a circuit comprised of inductance L and resistance R that it will be of interest, especially to those who are familiar with electrical problems, to compare the two equations. The corresponding electrical equation is

$$L\frac{di}{dt} + Ri = e, \tag{16}$$

where i is the current and e the electromotive force. It will be seen by comparing (15) and (16) that the two equations are identical in form, and that there is the following correspondence

V corresponds with L
ρ " " i
$\frac{ca}{4}$ " " R
E " " e

Every student of electrical theory is familiar with the solution of (16). The method of solving (15) is identical with that of solving (16), and is accomplished by a simple separation of the variables. Thus (15) may be written

$$\frac{V\,d\rho}{E - \frac{\rho ca}{4}} = dt, \tag{17}$$

which is readily integrable. Performing the integration,

$$-\frac{4V}{ca}\log_e\left(E - \frac{\rho ca}{4}\right) = t + \text{constant}. \tag{18}$$

The constant of integration can be determined by introducing the initial condition for the growth of sound energy, namely, that when $t = 0$, $\rho = 0$. Hence, the constant of integration is $-4V/ca \log_e E$. Introducing this constant in (18),

$$\log_e \frac{E - \frac{\rho ca}{4}}{E} = -\frac{ca}{4V}t;$$

$$E - \frac{\rho ca}{4} = Ee^{-\frac{ca}{4V}t},$$

and finally the value of the energy density of sound during the growth of sound in the room is

$$\rho = \frac{4E}{ca}\left(1 - e^{-\frac{ca}{4V}t}\right). \tag{19}$$

The steady state value of the energy density in the room, ρ_0, will be given by putting $t = \infty$ in (19). The result is

$$\rho_0 = \frac{4E}{ca}, \tag{20}$$

and, since the steady state value of the intensity I_0 is $\rho_0 c/4$,

$$I_0 = \frac{E}{a}. \tag{21}$$

Although theoretically the steady state is reached only after an infinite time, practically it is reached in most rooms in only a few seconds. In accordance with (20) and (21), the average density of sound energy or the sound intensity in a room is independent of the volume and shape of the room, and depends only upon the rate of emission E and the total absorption of the room a. This, of course, does not hold true in rooms in which there are sound foci, as in spherical rooms, cylindrical rooms, curved rooms, or rooms coupled together by an opening.

The equation for the decay of sound in a room is obtained directly by putting $E = 0$ in (17), since the source is off during the decay. The constant of integration in (18) is determined by introducing the initial condition, namely, that when $t = 0$, $\rho = \rho_0$. Hence, for the decay of sound in a room, there results

$$\rho = \frac{4E}{ca} e^{-\frac{ca}{4V}t} = \rho_0 e^{-\frac{ca}{4V}t}. \tag{22}$$

The Sabine reverberation equation can be obtained readily from (22), by determining the value of t required for ρ/ρ_0 to be equal to 10^{-6}; that is, by determining the time required for the sound to decay to one millionth of its initial steady state value. Thus,

$$t_{60} = \frac{4V}{ca} \log_e \frac{\rho_0}{\rho} = \frac{55.3V}{1125a},$$

or

$$t_{60} = \frac{0.049V}{a}. \tag{23}$$

In (23) V is in cubic feet and a is in sabines.[6] If the volume be given in cubic meters and the absorption in square meters, (23) becomes

$$t_{60} = \frac{0.161V}{a}. \tag{23'}$$

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[6] The sabine is a unit recently proposed for the absorption of sound. A surface has 1 sabine of absorption if it absorbs sound at the same rate as does 1 square foot of perfectly absorbing surface, as an open window. (See Appendix I.)

It should be borne in mind that these equations apply to rooms in which there are a sufficient number of reflections during the growth or decay to provide the uniform distribution in intensity, the random distribution in direction, and the continuous absorption upon which these equations were derived; that is, these equations apply to rooms which are relatively reverberant and free from pronounced focusing effects. It is obvious that the equations for growth and decay would not hold in the limiting case when the boundaries have an absorptivity of unity, in which case, for example, the reverberation time must be zero, whereas according to (23) it would be $0.049V/S$, where S is the interior surface of the room; and it is obvious that they would be only approximately valid in very *dead* rooms. Thus, in the example worked out in Sec. 51 for a room having a mean free path of 51 feet and boundary surfaces which reflect 50 per cent of the incident sound, Eq. (23) would lead to a calculated time of reverberation of about 1.27 seconds instead of 0.91 second.

53. More General Reverberation Formula.[7] A more general reverberation formula than that developed by Sabine and Jaeger, and one which applies to both live and dead rooms, has been proposed by a number of investigators, notably by Norris and by Eyring in the United States and by Schuster and Waetzmann in Germany. A simple derivation of this formula by Norris is given in Appendix II. Eyring arrives at this formula by assuming that the intensity of sound in a room — during the growth, steady state or decay — is given by summing up the contributions of radiant sound energy from all possible images which surround the source of sound. Thus, according to this view, when the source in the room is started, all the images are simultaneously started; and the building up of the sound consists of the accumulation of successive increments from the first order images, the second order images, and so on, until all the image sources, of any appreciable magnitude, have contributed their portion to the room. At this time the steady state is reached, and the rates of absorption and emission of sound are equal. Similarly, when the source in the room is stopped, all the images of the source are simultaneously stopped; and the decadent sound results from the successive losses of radiant energy, first from the source, then the first order images, the second order images, and so on, until all the images, of any appreciable magnitude, have radiated their energy to the room. According to this view, the duration of audibility of the

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[7] Here again the treatment of the reverberation problem deals only with the rate of decay of the *impressed* vibrations. (See note 3, p. 121.) That is, the treatment does not deal with the rate of decay of the damped *free* vibrations which are excited by the impressed vibrations.

decadent sound is equal to the time required for sound to arrive at the room from the order of images which is so far removed from the room that all images beyond this order will just contribute enough energy to the room to produce the threshold intensity. Thus, if the time of reverberation for a certain room is 5.0 seconds, it means that all the images beyond 5625 feet from the room will supply one millionth of the sound energy which is supplied by the source and all its images. In such a room, therefore, it is necessary to consider all images which are closer than about one mile from the room in order to specify the rate of growth or decay, or the steady state of sound in the room. According to this view, absorption, and therefore the rate of decay of sound, does not occur continuously but in discrete steps. Thus, an observer listening to the decadent sound would first sense a large drop in intensity when no more sound reaches him from the source, a somewhat smaller drop when no more sound reaches him from the first order images, a still smaller drop when no more sound reaches him from the second order images, and so on.

If this process of reckoning the growth and decay of sound in a room be correct, and it is certainly more nearly correct than the process which is based upon the assumption of *continuous* absorption, it can be shown[8] that the equation for the growth of sound in a room is

$$\rho = \rho_0\left(1 - e^{\frac{cS \log_e (1-\alpha)}{4V} t}\right); \tag{24}$$

the equation for the decay of sound in a room is

$$\rho = \rho_0 e^{\frac{cS \log_e (1-\alpha)}{4V} t}; \tag{25}$$

and the reverberation formula (in British units) is

$$t_{60} = \frac{0.049V}{-S \log_e (1-\alpha)}; \tag{26}$$

where, as before, S is the total interior surface of the room and α is the average value of the coefficient of absorption of the entire interior surface. It will be noted that Eqs. (24), (25), and (26) would be identical with the corresponding Sabine-Jaeger equations, (19), (22), and (23), if the total absorption a in these latter equations were replaced by $-S \log_e (1 - \alpha)$. For small values of α, $-\log_e (1 - \alpha)$ is nearly equal to α, and therefore the two sets of equations become identical for very reverberant rooms. There is, however, an appreciable divergence between the two sets of formulas for dead rooms, and even for the rooms

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[8] The interested reader should consult Eyring's paper for his derivation of the reverberation formula.

encountered in practice. Thus, Eq. (26) gives about 10 to 30 per cent shorter times of reverberation than does the corresponding Eq. (23) for all rooms having shorter reverberation times than about 3.0 seconds. Further, (26) gives zero time of reverberation, as it should, for the limiting case of a room bounded by completely absorptive surfaces. Eyring has shown by the measurement of reverberation in a dead room that (26) is in much better accord with the observed facts than is (23). This same conclusion has been confirmed by the author in measurements of reverberation in many churches, theatres, and school rooms. Although (26) is admittedly only an approximate reverberation formula, it is in better agreement with measurements than is (23), and for this reason it generally will be used for calculating the reverberation time in rooms. It should be mentioned, however, that Eqs. (24), (25), and (26) are strictly valid only for rooms in which all the boundaries have the same coefficient of absorption.

The equations for the steady state of sound in a room, according to this more general theory of reverberation, are the same as those given by the Sabine-Jaeger theory, namely Eqs. (20) and (21).

54. Effect of the Absorption of Sound in Air upon Reverberation. In the foregoing theory of reverberation only the absorption by the boundaries of the room has been considered; that is, the absorption of sound in the air has been neglected. But it is known that every type of wave motion, including sound, loses a part of its energy as it is propagated through a ponderable medium. Thus, the intensity of a plane wave after traveling a distance x in a homogeneous medium is $I_0 e^{-mx}$, where I_0 is the intensity of the wave at the position $x = 0$, and m is the attenuation or absorption coefficient for the plane wave in the medium. The attenuation constant m depends upon viscosity, heat conduction and radiation, wave distortion, and possibly molecular absorption.[9]

If the effect of the absorption in the air be introduced in Eq. (25), which describes the decay of sound in a room, it becomes

$$p = p_0 \left(e^{\frac{cS \log_e (1 - \alpha)}{4V} t} \right) e^{-mx}. \tag{27}$$

And since $x = ct$,

$$p = p_0 e^{\left[\frac{S \log_e (1 - \alpha)}{4V} - m \right] ct}. \tag{28}$$

If (28) be solved for t, when $p_0/p = 10^6$, we obtain the reverberation formula which includes the effect of absorption in the air, namely

$$t_{60} = \frac{0.049 V}{-S \log_e (1 - \alpha) + 4mV}. \tag{29}$$

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[9] See Rayleigh, "Theory of Sound," **2**, 312–323; Herzfeld and Rice, Phys. Rev., **31**, 691 (1928); Bourgin, Phil. Mag., **7**, 821 (1929), and Phys. Rev., **34**, 521 (1929).

The second term in the denominator, $4mV$, represents the effective absorption in the room contributed by the losses in the air. When m is negligibly small, as it is for frequencies below about 1000 cycles, Eq. (29) reduces to Eq. (26), which does not take account of the absorption in the air. For frequencies above about 1000, m increases almost with the square of the frequency, and consequently it becomes very important at high frequencies. At 4096 cycles, for example, the absorption in the air in a large auditorium may amount to as much as 30 per cent of the absorption of the boundaries of the room; and in a reverberation chamber with concrete walls, floor, and ceiling the absorption in the air at frequencies above 4000 cycles may be several times as great as the surface absorption of the boundaries.

The coefficient m is dependent not only upon the frequency but also upon the humidity and possibly upon the temperature of the air. The approximate values of m for frequencies of 2048, 3000, 4096, and 6000 cycles, and for relative humidities between about 20 per cent and 70 per cent (at a temperature of 21° C. or 70° F.), are given in Fig. 74. It will be seen that the coefficient m is very much dependent upon the humidity, so that the reverberation of high-pitched sounds in rooms will be influenced by the humidity of the air. The variation of reverberation time with relative humidity in the reverberation chamber at the University of California at Los Angeles is shown in Fig. 75. It will be noted that the reverberation time increases with the relative humidity up to about 80 per cent humidity, and then decreases slightly for greater humidities. The points of inflection in these curves occur at humidities at which condensation appeared on the painted and varnished walls, and it is believed that the decrease of reverberation time at high humidities is attributable to increased surface absorption.[10]

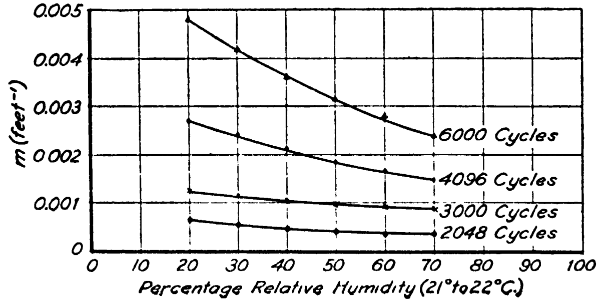

FIG. 74. Curves giving the values of the attenuation constant m for different frequencies and relative humidities.

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[10] V. O. Knudsen, Jour. Acous. Soc., **3**, 126 (July, 1931).

In making calculations of reverberation in rooms it is usually sufficient to take account of the absorption in the air at frequencies of and above 2048 cycles, and to neglect the air absorption at all lower frequencies. That is, Eq. (26) may be used for calculating reverberation times for all frequencies below about 2000 cycles, but Eq. (29), with the appropriate value of m, should be used for all higher frequencies.

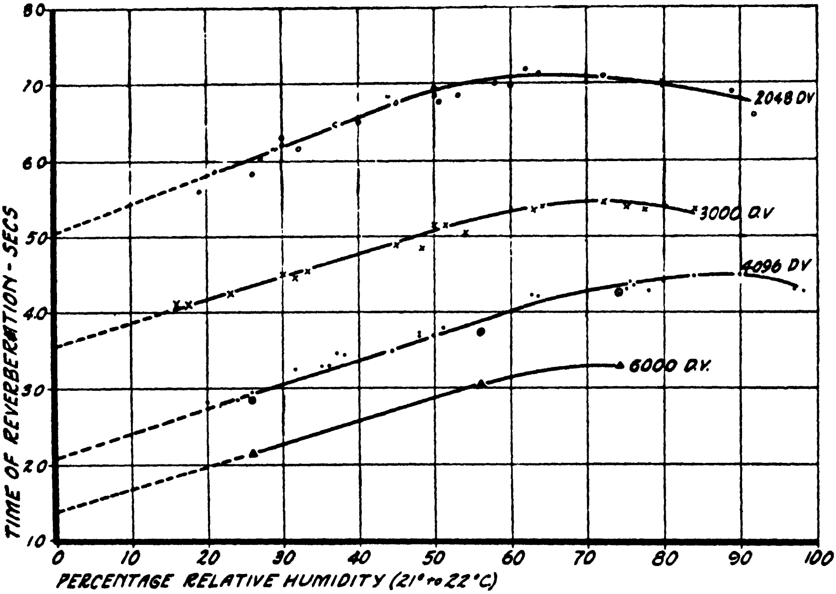

FIG. 75. Variation of reverberation time with the change of relative humidity in a reverberant room.

55. Effect of the Shape of a Room on Reverberation. Although the reverberation formula (26) is in good agreement with the measured times of reverberation in rooms of conventional rectangular shape, such as lecture rooms, music studios, and small auditoriums without balconies, it is not strictly applicable to rooms of peculiar or complex shape. The reverberation formulas (23) and (26) are dependent only upon the volume of the room, the areas of the interior surfaces which comprise the boundary of the room, and the absorption coefficients for the interior surfaces; they take no account of the shape of the room.[11] Obviously,

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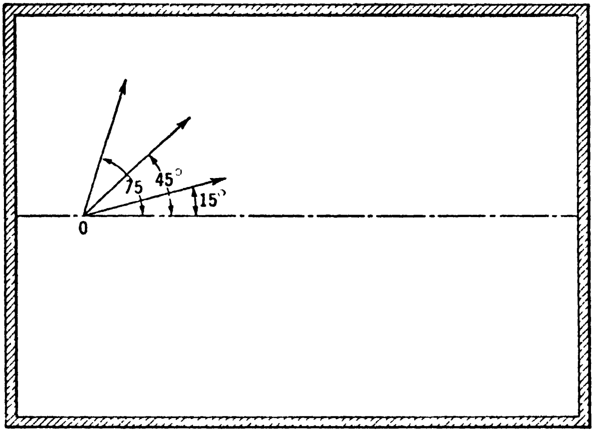
[11] M. J. O. Strutt, Z. ang. Math. Mech., **10**, 360 (1930), in a theoretical paper on the acoustics of large spaces, shows that from a consideration of the forced and free vibrations in a room, having an arbitrary distribution of absorption, the time of reverberation, at least for high-frequency sounds, is proportional to the volume of the room divided by the total absorption in the room, and *does not* depend upon the shape of the room.

the rate of decay of the *impressed* vibrations depends upon the mean free path and upon the distribution of absorptive material in the room. According to the approximate theory we have considered — in which it is assumed that the sound is diffuse and the intensity uniform in all parts of the room — the mean free path is $4V/S$ for the rectangular room of conventional shape. But the mean free path in many rooms, especially for the first few reflections, is dependent upon the location of the source and upon the shape and the architectural treatment of the interior of the room, and is not always given by $4V/S$, as is implied in (23) and (26). Thus, in the case of a spherical room (with source at the centre), the mean free path is $6.0V/S$, and presumably the mean free paths for a cubical room and for a cylindrical room (with the sources at the centre) differ from $4V/S$. (See articles referred to in notes 3 and 4 of this chapter.) It is necessary therefore to replace the constant 0.049, which appears in (26) with a constant k which is proportional to the mean free path for each room. The reverberation formula therefore may be written in the form

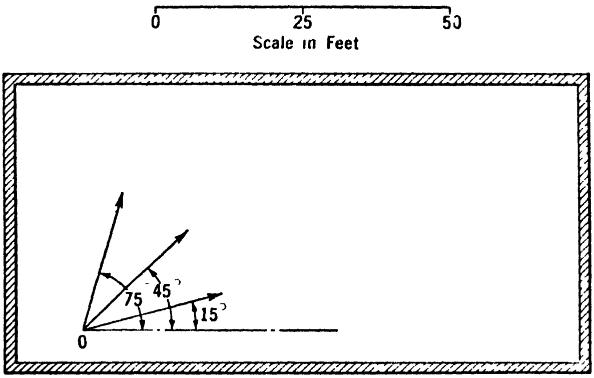
$$t_{60} = \frac{kV}{-S \log_e (1 - \alpha)}. \tag{30}$$

For the conventional rectangular room, and at ordinary room temperatures, k is 0.049; and for practical calculations which arise in building design it is generally assumed that $k = 0.05$ for the conventional room. It will be shown in this section that this value of k is approximately correct for nearly all types of room which arise in practice.

The values of the mean free path and of k for different shaped rooms have been determined experimentally by constructing, with fibre board, three-dimensional models, to a scale of $\frac{1}{2}$ inch = 1 foot, and measuring the lengths of successively reflected rays of light in the model. A source of plane parallel light is first located at the most probable position for the source of sound in the room. This source is an improved miniature flash light consisting of a good concave lens with a straight filament lamp at the focus of the lens. The flash light casts on a distant wall an image of the filament, and this image is reflected by a small plane mirror which is held against the wall by means of a thumb tack cemented to the back of the mirror. The distance from the source to the first image on the wall is measured and recorded. The source is then moved to the position of the first image, directed along the path of the first reflection, and the mirror moved to the new position of the image on the wall. The path length of this ray of light is then measured and recorded, as before. This process is continued for 25 successive reflections. The average of the 25 path lengths gives approximately the mean free path for a particular ray of sound, which however depends upon the original direction of the ray. Thus, if the original ray had started along the longitudinal axis of a rectangular room with parallel walls, the mean free path for this ray would be the length of the room. In order to obtain a more accurate value of the mean free path it is necessary to make measurements of successive path lengths on a number of rays, all of which have been started in directions which, taken in the aggregate, will be representative of all probable directions for the rays of sound from a point source. By choosing 9 representative directions for the original ray, all confined within a single quadrant, and making measurements of 25 successive path lengths for each of the 9 rays — 225 measurements in



PLAN



LONG SECTION

Fig. 76. Plan and section of simple rectangular model showing position of source and original directions of rays for determining "mean free path."

all — it is possible to attain an accuracy in the determination of the mean free path which is sufficiently good for most practical purposes. The 9 representative directions within one quadrant have azimuths of 15°, 45°, and 75°; and elevations of 15°, 45°, and 75° for each of the three azimuth angles.

It is possible also to record the number of reflections which occur from the ceiling, side walls, end walls, floor, balcony soffit, or any other reflecting surface, and thus determine the effectiveness of different surfaces for absorptive treatment. Thus, in a very large room with a low ceiling, it would seem probable that the total number of reflections from the ceiling and floor (provided only the first few reflections be considered) would be greater than would be predicted on the assumption that all surfaces in the room have the same probability of being hit by sound rays (which was the assumption made in the derivation of the reverberation formula).

A sample set of measurements for a simple rectangular room, without balcony, 70 feet by 96 feet by 48 feet, is given in Table II. Fig. 76 is a plan and longitudinal section of the model showing the position of the source and the directions of the original rays. The individual path lengths,[12] the average for each series of 25 measurements on the 9 different rays, the average for the 225 measured path lengths (the " mean free path "), and the number of reflections from each surface are tabulated. For this model the measured mean free path is 44.0 feet, which agrees remarkably well with the theoretical value $4V/S$, namely 43.7 feet.

With regard to the distribution of reflections from the different surfaces it will be noted that there are relatively more reflections from the ceiling and floor than there are from the walls. If the number of reflections from each of the different surfaces be divided by the areas of the corresponding surfaces, the resulting quotients will give relative values of the probabilities of reflections from the different surfaces, provided of course that a sufficiently large number of starting directions and reflections have been tabulated to warrant the application of the theory of probability. From the limited data for this model, the ceiling and floor are situated in such a manner as will give more reflections of sound per unit area of surface than will the side or end walls. However, these results must be taken qualitatively rather than quantitatively. The number of original directions, namely, 9, and the total number of measured and charted reflections in each model, namely, 225, is far too few to warrant any accuracy in determining the probability of reflections from the different surfaces in that model. However, the data from three

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[12] The individual path lengths are recorded for the first 3 rays, and to conserve space, only the average values are given for the remaining 6 rays.

TABLE II

MEAN FREE PATH MEASUREMENTS IN RECTANGULAR ROOM

Model built to scale of ½ in. = 1 ft. 0 in. Room dimensions = 70 ft. by 96 ft. by 48 ft.
Symbols: S = side walls, E = end walls, F = floor, C = ceiling.

Path Number	Azimuth angle = 15° Angle of elevation = 15°		Azimuth angle = 45° Angle of elevation = 15°		Azimuth angle = 75° Angle of elevation = 15°	
	Path Length, ft.	Surface Hit	Path Length, ft.	Surface Hit	Path Length, ft.	Surface Hit
1	90	E	55	S	39	S
2	42	C	71	E	75	S
3	61	E	11	C	75	S
4	60	F	16	S	8	C
5	13	S	100	S	65	S
6	28	E	17	F	55	E
7	102	E	8	E	17	S
8	13	C	72	S	72	S
9	88	E	29	C	52	F
10	71	F	69	S	20	S
11	29	E	4	E	37	E
12	35	S	39	F	35	S
13	66	E	48	S	70	S
14	38	C	79	E	70	S
15	67	E	5	S	71	S
16	74	F	38	C	72	S
17	10	S	44	S	73	S
18	21	E	84	S	5	F
19	106	E	10	F	70	S
20	14	C	42	E	48	E
21	88	E	29	S	29	S
22	15	S	79	S	73	C
23	77	F	9	C	4	S
24	11	E	69	S	80	S
25	100	E	74	E	37	S
	Average path length = 52.8 ft.		Average path length = 44.0 ft.		Average path length = 50.0 ft.	

TABLE II — (*Continued*)

Azimuth angle = 15°
Angle of elevation = 45°
Average path length = 45.2 ft.

Azimuth angle = 45°
Angle of elevation = 45°
Average path length = 38.8 ft.

Azimuth angle = 75°
Angle of elevation = 45°
Average path length = 37.6 ft.

Azimuth angle = 15°
Angle of elevation = 75°
Average path length = 41.2 ft.

Azimuth angle = 45°
Angle of elevation = 75°
Average path length = 44.2 ft.

Azimuth angle = 75°
Angle of elevation = 75°
Average path length = 41.8 ft.

Average of the total 225 path lengths, or " mean free path " = 44.0 ft.
Theoretical value of " mean free path " = $4V/S$ = 43.7 ft.

Number of reflections from

ceiling =	65
side walls =	56
end walls =	42
floor =	62
Total =	225

other models (see *b*, *c*, and *d* in Table III) which were of the same general shape and dimensions, but which differed only in that two of the models had balconies and the third had both a balcony and a gabled ceiling, also indicate that the probability of reflections from the ceiling or floor is, in general, greater than the probability of reflections from all the surfaces in the room, and the total number of reflections in the four models — namely, 900 — is large enough to warrant a fair degree of accuracy in determining the probability of reflections from different surfaces. Thus it is found that the probability of reflections from the ceiling and floor in these four rectangular models is 1.04 whereas the probability of reflections from the walls in the same models is 0.94, which means that absorptive material in the ceiling (in rooms of this shape) will be about 10 per cent more effective in reducing reverberation — at least during the first part of the decay — than will the same amount of absorptive material on the walls.

A summary of results of mean free path measurements in a number of typically shaped models of auditoriums is given in Table III. Figs. 77 and 78 are photographs of two of the models which were constructed for the purpose of obtaining these data.[13] Plan and sectional sketches

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[13] The author wishes to acknowledge the help given him in this investigation by Mr. C. H. Johnson.

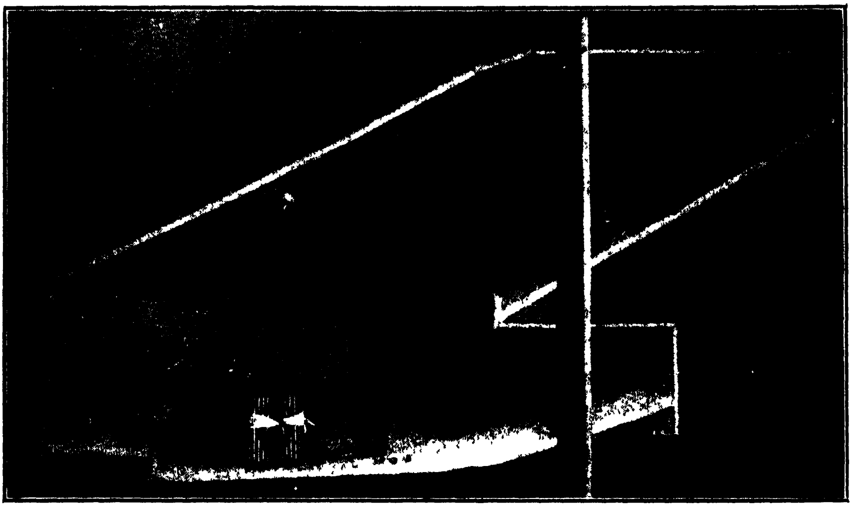


FIG. 77. Model of a fan-shaped theatre.

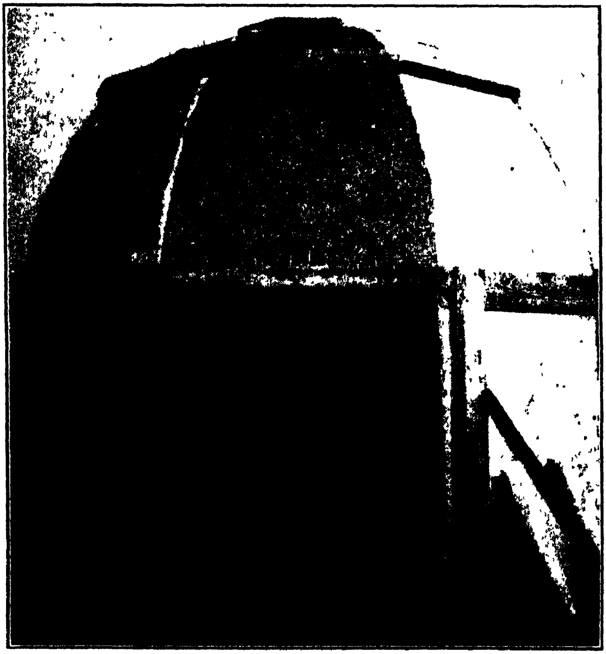


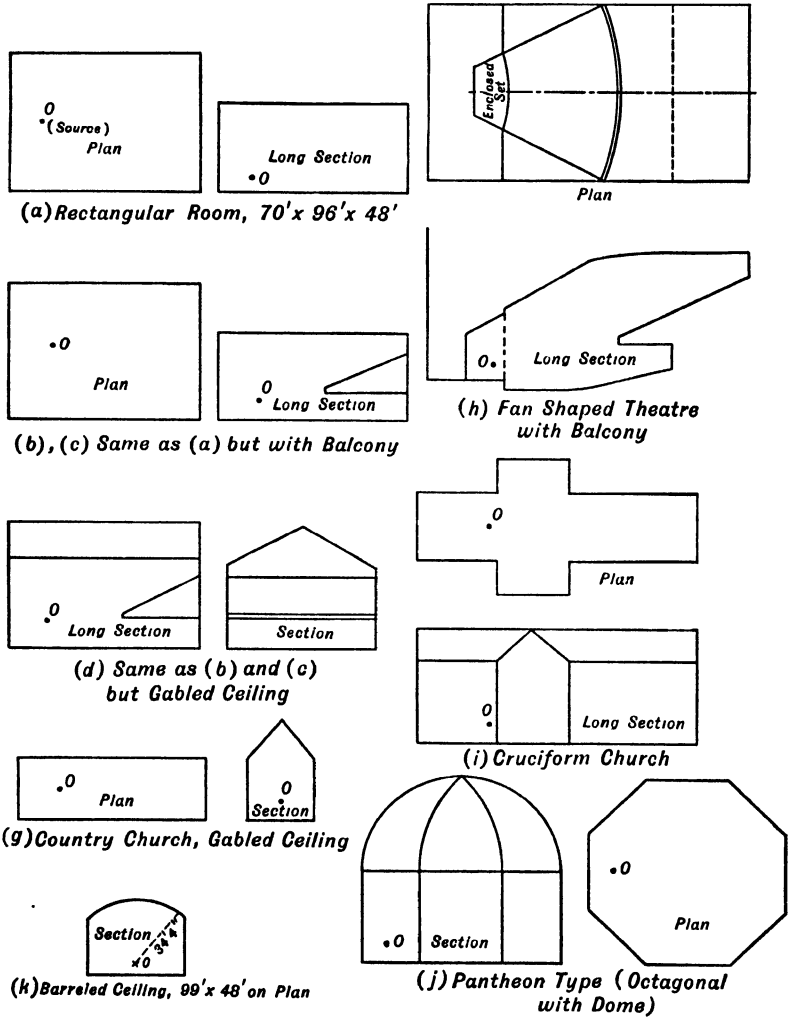
FIG. 78. Model of octagonal auditorium with domed ceiling.

of these auditoriums are shown in Fig. 79. A brief description of the type of auditorium is given in the first column of Table III (further described by the sketches in Fig. 79). The volume and inner surface are given in the next two columns. The average of the 225 path lengths, that is, the experimentally determined mean free path, is given in the fourth column; and the theoretical value of the mean free path, that is, $4V/S$, is given in the fifth column. In the sixth column is given the experimental value of the reverberation factor k which should be used in the more general reverberation equation (30). The factor k is determined by first expressing the mean free path as a constant times V/S, and then multiplying this constant by 0.01225. In the last column are some comments on the distribution of reflections from the various surfaces in the room.

It will be seen that the experimentally determined reverberation factor k does not differ more than about 8 per cent from the " theoretical " value in Eqs. (23) and (26), that is, 0.049. For a commercial room about 48 feet by 31 feet by 12 feet the value of k is about 0.046, and for rooms having a larger floor area but about the same ceiling height it is probable that the value of k may be as low as 0.044 or 0.045, especially for the first few reflections. Further, since the probability of reflections from the ceiling of such a room is greater than the probability of reflections from the walls, it is obvious that the reverberation formula (26) will not give the correct time of reverberation in rooms of this shape, or in rooms which differ widely from the conventional shapes listed in Table III. Thus, if the ceiling of a large office or commercial room (with a low ceiling) be treated with absorptive material, it is probable that the measured reverberation time in the room may be as much as 20 per cent shorter than the time calculated by means of Eq. (26). About 8 or 10 per cent of the " error " would be attributable to the use of a high value of k (namely, 0.049 instead of 0.044 or 0.045), and the remainder might easily be attributed to the favorable location of the material.

It seems obvious therefore that an exact formula for the rate of decay of the *impressed* vibrations in a room will require (1) a factor k, as the one in the numerator of Eq. (30), which will take account of the shape of the room, that is, the mean free path for the room; and (2) certain weighting factors for summing up the absorption contributed by different surfaces, which will take account of the probabilities of reflections from the different surfaces in the room. Sufficient data are not yet available to apply these corrections to all types of room which arise in practice, but the values of k given in Table III will indicate the nature and order of magnitude of the corrections for rooms of different shape;

and more data on the probability of reflections from different surfaces will suggest the corrections which should be made because of the loca-



(a) Rectangular Room, 70′x 96′x 48′

(b), (c) Same as (a) but with Balcony

(h) Fan Shaped Theatre with Balcony

(d) Same as (b) and (c) but Gabled Ceiling

(i) Cruciform Church

(g) Country Church, Gabled Ceiling

(k) Barreled Ceiling, 99′x 48′ on Plan

(j) Pantheon Type (Octagonal with Dome)

FIG. 79. Plan and sectional sketches of typical auditoriums. "Mean free path" data for these auditoriums are given in Table III.

tion of the source and the absorptive materials in rooms of different shape. It should be borne in mind, however, that these corrections are so small as to be of little practical significance in most of the convention-

TABLE III

Type of Auditorium	V cubic feet	S square feet	Mean Free Path, feet	$\frac{4V}{S}$	k	Comments on Distribution of Reflections
(*a*) Rectangular, 70 ft. by 96 ft. by 48 ft., no balcony	322,600	29,400	44.0	43.7	0.049	Probability of reflections from ceiling and floor about 10 per cent greater than from walls
(*b*) Same as (*a*) but with balcony, regarding balcony opening as a reflecting surface	223,000	24,600	36.2	36.4	.049	
(*c*) Same as (*b*) but regarding space under balcony as part of a single cavity	284,000	32,600	35.6	34.8	.050	
(*d*) Same as (*c*) but with gabled ceiling	338,000	34,800	39.8	38.8	.050	
(*e*) Cube, 70 ft. by 70 ft. by 70 ft.	343,000	29,400	48.4	46.6	.051	
(*f*) Office room 48 ft. by 39 ft., 4 in. by 11 ft., 8 in.	17,600	4,860	13.6	14.5	.046	Most reflections from ceiling and floor
(*g*) Country church 96 ft. by 32 ft. on plan, 50 ft. to top of gabled ceiling	127,000	16,600	30.8	30.6	.049	
(*h*) Fan-shaped theatre, with balcony	470,000	46,300	40.6	40.6	.049	
(*i*) Cruciform church (no aisles or trusses)	354,000	36,400	42.0	38.9	.053	
(*j*) Pantheon type, with domed ceiling	690,000	41,500	69.6	66.5	.051	
(*k*) Barreled ceiling, 99 ft. by 48 ft., on plan	172,000	19,300	34.7	35.6	.048	

ally shaped rooms encountered in practice (in which Eq. (26) will give a nearly correct value of the reverberation time), and are pertinent, from the practical standpoint, only in large rooms with very low ceilings, in long, narrow rooms, or in rooms which have pronounced peculiarities of shape.

56. Reverberation in Coupled Spaces. The introduction of a balcony in a room divides the room into at least two coupled spaces — the main body of the room and the space under the balcony. Most auditoriums of the theatre type are divided into at least three coupled spaces — the stage, the main portion of the auditorium, and the space under the balcony. Office space is often divided into a number of coupled spaces; and a great complexity of coupled spaces often will be found in cathedrals, consisting of nave, transepts, choir, sanctuary, aisles, chapels, balconies, and organ chamber. If the mean free path can be determined for such coupled spaces, and if all surfaces have approximately the same absorption coefficients, Eq. (30) will give the time of reverberation for the entire room, where V and S are the total volume and the total interior surface of the room. But it is not always feasible to determine the mean free path for a complicated combination of coupled spaces, and it is very improbable that all surfaces will have even approximately the same coefficients of absorption. It sometimes becomes necessary therefore to consider the reverberation in each of the several coupled spaces, and to adjust the reverberation time in each space to the optimal condition.

Consider the following typical case: A high-school auditorium seating 1800 persons has the conventional rectangular shape, a high gabled ceiling, and a deep recess under the balcony. The entire ceiling is treated with a very absorptive material which provides a fairly satisfactory condition of reverberation in the front part of the auditorium and in the balcony. The walls under the balcony, the soffit of the balcony, and the entire main floor are poured concrete. The seats are of wood, not upholstered. As a result, the space under the balcony, especially when only a few persons are sitting in this section, is very reverberant. During the growth or decay of sound in such an auditorium there is a transfer of energy between the two coupled spaces, with different rates of growth or decay in the two spaces. During the steady state the rate of transfer of sound from the *dead* space to the *live* one is equal to the rate of transfer in the opposite direction, that is, from the *live* space to the *dead* space. During the very early stages of the decay these rates of transfer are nearly equal, but since the sound decays much more rapidly in the main part of the auditorium than it does under the balcony, there soon will be established an excess rate of flow from the live to the dead space, and the result is that the reverberation is prolonged in the main part of the auditorium as well as in the space under the balcony. In order to overcome this undesirable condition it is necessary that the rates of decay in both spaces be nearly equal (or that the rate of decay in the smaller space under the balcony be greater than the rate of decay in the main part of the auditorium). This involves a determination of the reverberation in both spaces, which in turn necessitates the assignment of coefficients of absorption to the opening which couples the two spaces. It is not possible, as yet, to assign precise coefficients to these openings. The coefficients will depend, in general, upon the size and shape of the opening, the depth under the balcony, and the amounts of absorption under the balcony and in the main part of the auditorium. But if both spaces have approximately the same rates of growth, as they should for good acoustics, the " effective coefficients " will be of the order of 0.40 to 0.80 — nearer the lower limit for shallow recesses which contain a relatively small amount of absorption.[14] Similar considerations apply to the stage opening which couples the stage and the main part of the auditorium.

Many theatres, churches, memorial halls, and other auditoriums are often coupled, by means of door openings or archways, to rooms or corridors which are excessively reverberant. In such auditoriums, even though the reverberation in the audience space has been adjusted to the proper value, there will be a " feed back " of reverberation from the adjacent reverberant rooms into the main auditorium. Thus, auditors in a theatre who are seated near an opening to a reverberant corridor, foyer, or anteroom will be disturbed by the excessive reverberation in the adjacent room. It is advisable in all such cases either to close the openings, or to use an adequate amount of absorption in all spaces which are coupled to the audience room.

In most auditoriums made up of coupled spaces, as in the theatre with balcony and stage recesses, it is possible, provided the absorptive material be distributed fairly uniformly in all parts of the room, to regard the room as a single space and apply the reverberation formula (26) or (30). The volume V then includes the volume under the balcony and the volume of the enclosed set on the stage.

57. Graphical Representation of the Growth and Decay of Sound in a Room. By means of Eqs. (24) and (25) in Sec. 53 it is possible to obtain a graphical representation of the growth and decay of sound in a room, and thus gain a clearer notion of the extent of overlapping of the successive sounds of speech and music in reverberant and non-reverberant rooms.

Fig. 80 shows such a graphical representation of the growth to 60 db and decay to 0 db in which the energy or volume density of the sound is plotted as a function of the time of growth and decay, in a room having a volume of 100,000 cubic feet and a time of reverberation of 5.0 seconds. Since the sensation of sound is nearly proportional to the logarithm of the energy density ρ, it is advantageous to plot ρ on a logarithmic scale,

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[14] See paper by Eyring, Society of Motion Picture Engineers (May, 1930). In this same paper Eyring discusses conditions which may give rise to two or more rates of decay in the same room. See also paper by Eyring, Jour. Acous. Soc., Oct., 1931.

as is done in Fig. 80. It will be seen that the sound builds up very rapidly, attaining practically the steady state value in about 1 second. The source is supposedly turned off after it has been sounding for 3 seconds, and it will be seen that the rate of decay (with the logarithmic plot of ρ) is uniform throughout the entire period of audible decay, namely, 5.0 seconds. These curves represent approximately the manner in which the ear senses the growth and the decay of the loudness of sound in a reverberant room. The sound, as heard in a reverberant room, seems to build up very quickly, and to die away very slowly. There are, of course, irregularities in the growth and decay, owing to resonance and interference phenomena, but the curves shown in Fig. 80 represent the average processes of growth and decay.

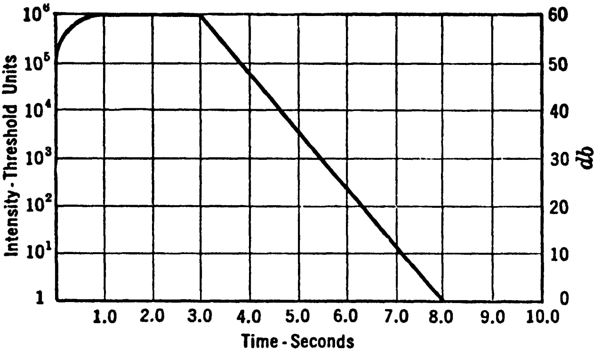

FIG. 80. Graphical representation of the growth and decay of sound in a reverberant room.

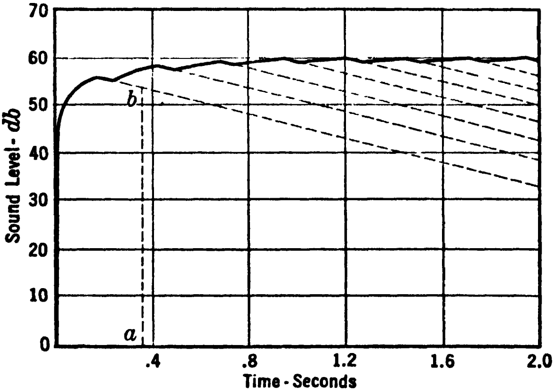

FIG. 81. Graphical representation of the growth and decay of the sounds of articulated speech in a reverberant room.

It will be of interest now to consider a graphical representation of the growth and decay of speech in this same room which has a volume of 100,000 cubic feet and a time of reverberation of 5.0 seconds. Suppose each syllable consists of a steady and constant emission of sound for 0.2 second followed by an interval of 0.05 second of no emission of sound, and that the average sound level ultimately builds up to about 60 db. Fig. 81 shows a graphical representation of the manner in which these separate syllables would impress themselves upon the ear; that is, the ordinates represent the sound levels, in decibels, of the successive syllables. The first syllable builds up to about 56 db in 0.2 second; and then during the interval of 0.05 second it dies away at a rate of 12 db per second, or only 0.6 db. When the second syllable is half uttered, that is, at the instant that it is being impressed upon the ears of the auditors, the first syllable is at a sound level of about 53 db (as shown by the dotted line *ab*), or only about 3 db below the level of the syllable to which the auditors are listening. As is shown in the figure, there is very little variation in the sound level throughout the entire sequence of syllables and intervals, and consequently there is very poor *definition* or *resolution* of the separate syllables in speech. Obviously, it would be difficult — or almost impossible — to hear the separate syllables of articulated speech under such a condition of reverberation.

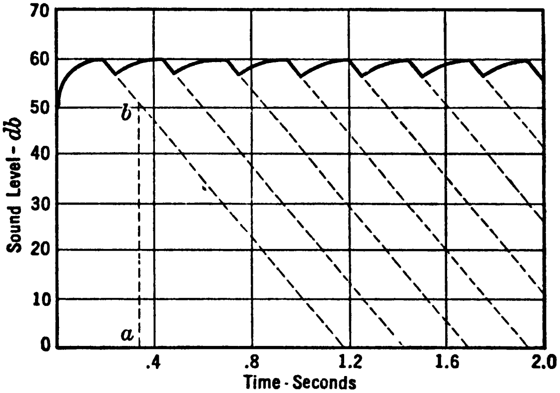

FIG. 82. Graphical representation of the growth and decay of the sounds of articulated speech in a room having a time of reverberation of 1 second.

Fig. 82 shows the manner in which these same syllables would build up and die away in a room having a volume of 100,000 cubic feet but a time of reverberation of only 1.0 second. Under this condition, when auditors listen to the second syllable, for example, the first syllable has fallen to a level nearly 10 db below that of the second syllable. The first syllable may be regarded as a masking noise which has a "noise level" of about 10 db below the speech level of the syllable to which one is listening. This amount of masking is readily tolerable, but when the level of the syllable to which one is listening is not more than about 8 or 10 db above that of the preceding syllable, the masking effect of the preceding syllable constitutes a confusing disturbance which interferes with the hearing of speech. As is shown in Fig. 82, there is an appreciable variation in the sound level throughout the entire sequence of syllables and intervals, and consequently under such conditions there is very good *definition* or *resolution* of the separate syllables of speech. Obviously, it is not difficult to hear the separate syllables of articulated speech under such a condition of reverberation.

The graphs shown in Figs. 80 to 82 are based upon reverberation formulas which ignore the effects of interference and room resonance, and therefore they are only approximations. A more precise record of the growth and decay of sound in a room can be determined by obtaining oscillograms of speech or controlled sound in the room. The oscillograms shown in Figs. 83, 84, and 85, obtained by Schindelin and Scharstein,[15] exhibit very clearly the nature of the growth and decay of sound in a reverberant and in a non-reverberant room. In the interpretation of these oscillograms, and in comparing them with the growth and decay curves in Figs. 80 to 82, it should be borne in mind that the oscillograms exhibit pressure changes in the sound field, whereas the plotted curves in Figs. 80 to 82 exhibit changes in the sound level. In all the oscillograms the curve marked *t* is a time curve, each cycle representing $\frac{1}{32}$ second. Curve *b* is a record of the audio-frequency alternating current which actuated the loud speaker — the source of sound in the room. As curve *b* indicates, the loud speaker is made to sound intermittently, so that it is emitting sound for, say, 0.1 second and then is silent for 0.4 second; and in some cases the loud speaker is sounding for 0.4 second and then silent for 0.1 second. The record marked *a* is an oscil-

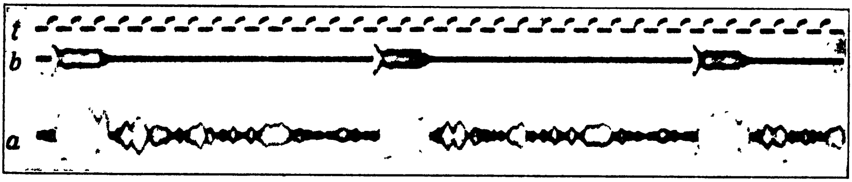

FIG. 83. Oscillogram of the growth and decay of a 512-cycle tone in a reverberant room. (*Scharstein.*)

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[15] Schindelin and Scharstein, Ann. d. Phys., **2**, Nr. 2, 129–200 (1929).

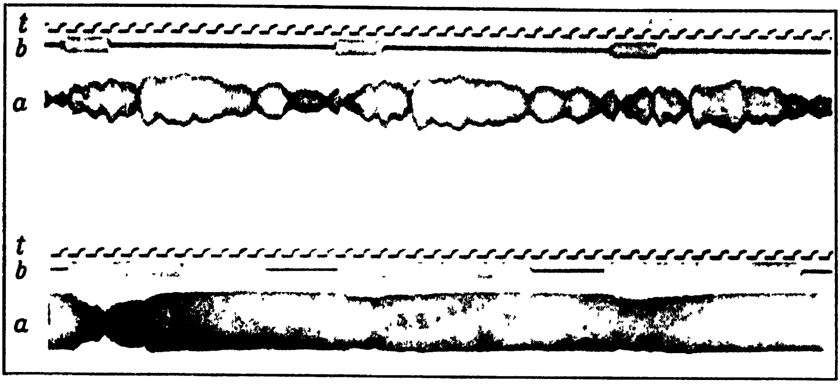

FIG. 84. Oscillograms of the growth and decay of a 410-cycle tone in a reverberant room. The 410-cycle tone corresponds to one of the natural or free vibrations of the room. (*Scharstein.*)

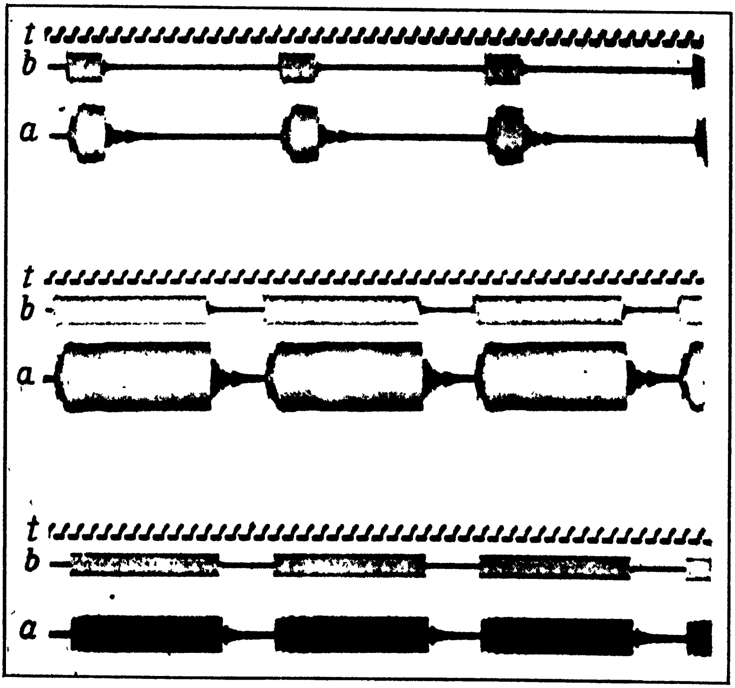

FIG. 85. Oscillograms of the growth and decay of sound in a radio broadcast room having a short period of reverberation. The two upper oscillograms are for a tone of 450 cycles, and the lower oscillogram is for a tone of 980 cycles. (*Schindelin.*)

lographic record of the sound vibrations produced in the room. These vibrations are picked up by a condenser microphone, amplified by a vacuum-tube amplifier, and photographically recorded by the oscillograph. It will be noted from Figs. 83 and 84 that in a reverberant room there is very little resemblance between the sound generated at the source and the resulting sound vibration in the room. Although the source consists of discrete durations of sound followed by discrete intervals of quiet, the sound picked up by the microphone is an irregular but a continuous sound vibration. In the lower oscillogram in Fig. 84, where the intervals of quiet are shorter than the intervals of emission, as shown by record *b*, there is an almost imperceptible variation in the intensity of the sound picked up by the microphone, as is shown by record *a*. When one examines these oscillographic records, and notes the marked dissimilarity between the discrete pulses of sound produced by the source and the continuous flow of sound at the microphone, one wonders how it is at all possible to recognize any of the sounds of speech in a reverberant room — and one is reminded of chanted prayers heard in reverberant cathedrals where indeed it is utterly impossible to recognize the prayers unless they have been memorized. It is obvious that such excessively long periods of reverberation cannot be tolerated in rooms which are to be used for speaking purposes.

The improvement in the acoustics of a room, at least for the hearing of speech, attained by lining the interior walls of the room with absorptive material is shown by the records in Fig. 85. These records were obtained in a small radio broadcasting studio which had a time of reverberation of less than 1 second. It will be noted from these records that the variations of the sound picked up by the microphone resemble closely the variations in the current which actuated the loud speaker; that is, the sound picked up by the microphone is a fairly faithful reproduction of the sound emitted by the loud speaker. The addition of absorptive material to a room, that is, the reduction of the reverberation time in a room, is thus seen to contribute most beneficially to the *definition* or *resolution* of articulated sounds, such as speech or music.

58. Reverberation at Different Frequencies. The initial work of W. C. Sabine on reverberation was limited to a single frequency of 512 cycles, although later his experiments included measurements between 64 and 4096 cycles. Custom has attached so much importance to the frequency of 512 that when the term *time of reverberation* is used, without the specification of frequency, it is generally understood that *the time of reverberation* refers to a pure tone of 512 cycles. In fact, so many measurements in architectural acoustics are referred to this tone that it has become a venerable standard, especially in the calculation of the reverberation time in a room. Although the calculation of reverberation at a single frequency, as 512 cycles, will suffice to represent the reverberation in a room at other frequencies provided the absorptive material in the room has nearly the same absorptivity at all frequencies, it is obvious that such is not the case if the absorptive material have widely different absorptivities at different frequencies. Thus, an acoustical plaster, ¼ inch thick, may have coefficients of absorption of 0.06 at 128 cycles, 0.36 at 512 cycles, and 0.72 at 2048 cycles. If this plaster should be applied to the entire inner surface of a room (a thin carpet on the floor would have nearly the same absorption characteristic as the acoustical plaster), the reverberation time at 128 cycles would be at least six times as long as the reverberation time at 512 cycles, and the time at 2048 cycles would be less than one half of the 512-cycle time. If the reverberation time in such a room be 1.25 seconds at 512 cycles, it will be at least 7.5 seconds at 128 and less than 0.62 second at 2048 cycles. To describe this room as one having a time of reverberation of 1.25 seconds — which is regarded as close to the optimal time for good acoustics — certainly does not describe the reverberatory properties of the room; and it will be found that such a room is not satisfactory in regard to acoustics — there will be complaints of excessive reverberation, and indeed the room will be excessively reverberant for the bass notes of music, and even the low-frequency components of speech will be reverberant and over-emphasized. On the other hand, the higher tones and harmonics in music will be suppressed owing to over-absorption at the high frequencies.

It is necessary therefore to specify and calculate the reverberation time, at least in speech and music rooms, for representative frequencies throughout the entire frequency range used in speech and music. It will be found, however, that if calculations be made at 128, 512, and 2048 cycles, that is, at low-, medium-, and high-pitched tones, the resulting reverberation times will give a satisfactory description of the reverberatory properties of the room for all practical purposes. In the design of all speech and music rooms consideration should be given to the reverberation times at these three frequencies; in important theatres, opera houses, and concert halls the reverberation times throughout the entire audible range should be considered, and optimal reverberation times should be planned for at least 128, 512, and 2048 cycles. The optimal times of reverberation at different frequencies will be considered in Chaps. XVII and XVIII. For the present it will suffice to remark that, in general, the reverberation time at 128 cycles should be about twice as long as the time at 512, and that the reverberation time above 512 should remain nearly constant. In office rooms and in all other rooms where absorptive treatment is used as an expedient for reducing noise, it will suffice to use an average coefficient of absorption — the arithmetical mean of the coefficients at 128, 512, and 2048 cycles — and make a single calculation of the reverberation time based upon this average coefficient.

A large measure of success or failure in the acoustical design of important speech and music rooms will depend upon the selection of interior materials which will give the proper reverberatory characteristics throughout the entire range of frequencies used in speech and music, and therefore the architect or engineer, in whose hands is placed the responsibility of acoustics, should base his selection of interior materials upon calculations of reverberation at several representative frequencies, as 128, 512, and 2048 cycles, rather than at the single frequency of 512 cycles.

CHAPTER VI

THE ABSORPTION OF SOUND — GENERAL AND THEORETICAL CONSIDERATIONS

59. Introductory. Because of the importance of reverberation, and its fundamental dependence upon absorption, the absorbent nature of the interior surfaces and the furnishings in a room is the most potent of all factors which affect the acoustical quality of that room. Many of the building materials used in modern structures, such as concrete, hard plaster, and stone, absorb only 1 or 2 per cent of the incident sound which strikes their surfaces. The remaining 98 or 99 per cent is reflected back into the room. As a consequence, buildings in which the interiors are finished with such materials are very poor acoustically because the separate sounds of speech and music are absorbed so slowly — 100 or more successive reflections may be necessary to reduce the intensity of the sound to inaudibility. The absorption of sound is not only the most important factor in determining the acoustical quality of a room but it is also one of the most potent means of reducing noise in offices and all public buildings. It is necessary therefore that the elementary facts concerning the nature of sound-absorption be given some consideration.

60. Nature of Sound-Absorption. It was shown in Chap. II that when a sound wave strikes an obstacle in a room, such as a wall, it is either reflected, transmitted, or absorbed. So far as concerns an observer in the room, all the sound energy in the wave which is not reflected is absorbed; in other words, as was explained in Chap. II, the absorbed portion includes also the portion which is transmitted. However, in rigid, heavy walls, the transmitted portion is infinitesimally small — amounting in most cases to not more than 0.01 per cent of the incident sound energy. Under these circumstances, it can be said that that sound which is not reflected is absorbed. The absorbed portion of the sound is by some mechanism converted into other forms of energy, and ultimately into heat. It is the purpose of the present chapter to discuss this mechanism by means of which the sound waves are converted into heat. If a material is impervious to air, the sound waves experience great difficulty in penetrating the material. The sound waves exert an alternating pressure against the wall and force it into vibration of a corresponding frequency. The resulting flexural vibration of the wall uses up a certain amount of the incident sound energy, which is either converted into heat or radiated as sound from the opposite side of the wall. The amount of energy converted into flexural vibrations of the wall is exceedingly small for rigid walls, but it may become very considerable if the wall is made of a thin, flexible material, like a stretched rubber or oilcloth membrane, or even thin panels of wood or glass.

Many wall materials, and especially such materials as acoustical felt or acoustical plaster, have many small interstices or pores penetrating deeply into their interiors. The sound waves can readily propagate themselves into these pores, where a portion of the sound energy is converted into heat by frictional or viscous resistance within the capillary pores. If the material be sufficiently porous and of appropriate thickness, as much as 90 or even 95 per cent of the incident sound wave may be absorbed in this manner. This mechanism of sound-absorption is utilized in the manufacture of nearly all acoustical materials, and consequently it will be of interest to consider certain theoretical aspects of the subject.

61. Theory of Sound-Absorption by Porous Materials. A mathematical approach to the subject of sound-absorption by porous materials has been made by Lord Rayleigh and extended further by I. B. Crandall.[1] The theory is based upon the assumption that absorption is a result of viscous forces incident to the flow of air through the small capillary pores of the material. The sound waves which impinge upon the surface of the porous material produce an alternating pressure which forces the air within the pores into a vibratory motion. Small tubes offer a high resistance to the flow of air through them, principally because the interior surface of the small pores is relatively large compared with the conducting area of the pores.

The flow of gases through capillary tubes is a branch of physics which has been quite thoroughly investigated, and it is well known that the resistance to flow in a single tube is given by $R = 8\mu/r^2$ (known as Poiseuille's Coefficient), where μ is the coefficient of viscosity of the gas and r is the radius of the tube. By introducing this relation into the equation for the propagation of a plane wave through small tubes, Crandall has obtained an equation for the reflection coefficient β of a porous material in terms of the radius of the pores[2] and the frequency

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[1] Crandall, "Theory of Vibrating Systems and Sound," 185–191 (Van Nostrand, 1926).

[2] It is assumed that all pores are cylindrical and of the same radius, an ideal condition which is only roughly approximated in certain selected materials, as felts and fibre boards, and certainly not even approximated in most acoustical plasters and tiles. However, the theory is important in indicating such properties as the effect of the size of the pores on the absorption at different frequencies.

of the incident sound waves; namely,

$$\beta = -\frac{2M^2 - 2M + 1}{2M^2 + 2M + 1}. \tag{31}$$

And, since the sound energy which is not reflected is absorbed, the absorption coefficient is given by $1 - \beta$. M is defined by the equation

$$M = \frac{2}{r}\sqrt{\frac{\mu}{\rho\omega}}, \tag{32}$$

in which ρ is the density of the air and ω is 2π times the frequency of the incident sound. It will be noted that M, which according to this theory determines the absorptive properties of porous materials with rigid walls, is dependent upon the viscosity and density of the air, the radius of the pores, and the frequency of the incident sound waves. For air, μ/ρ is approximately 0.13, so that if the size of the pores of an absorptive material, for example hair felt, be known, it is possible to calculate the coefficients of sound-absorption for sound waves of different frequencies. Crandall has made some calculations for hair felt, on the assumption that the felt is a closely packed honeycomb structure of circular pores, having an average diameter of 0.02 centimeter. The results are given in the following table:

TABLE IV

Frequency of Sound Wave	$M = \frac{2}{0.02}\sqrt{\frac{.13}{\omega}}$	Reflection Coefficient β	Absorption Coefficient $\alpha = 1 - \beta$
200 cycles	2.00	0.38	0.62
400	1.41	.28	.72
800	1.00	.20	.80
1600	0.707	.17	.83
3200	0.500	.20	.80
6400	0.354	.28	.72

The values of the coefficients of absorption given in the last column are in fair agreement with the measured coefficients for a very thick (6-inch) blanket of felt. It is assumed in the theory that all the sound that penetrates into the material is absorbed. In order that this hold true, it is necessary that the pores be several inches deep for the low-frequency components of sound. The theory is not satisfactory for thin absorptive materials because the low-frequency components of sound are much more slowly damped as they are propagated through the pores of the material, so that they are reflected from the hard wall behind the absorptive material and, after propagation through the pores again, unite with the sound which was reflected from the front surface of the absorptive material.

In spite of these limitations in this elementary theory of absorption by porous materials, it is very useful in suggesting the various factors which affect the absorption of sound. For example, it will be noted in the table, and it can be shown from Eq. (31), that the maximal absorption of a porous material occurs when M is equal to $1/\sqrt{2}$, or 0.707, and that the absorption coefficient is then 0.83, which for the hair felt here described occurs at a frequency of 1600 cycles. Further, if the size of the pores is increased, the maximal absorption will occur for a correspondingly lower frequency. Thus, if the size of the pores had been 0.04 centimeter instead of 0.02 centimeter, the maximal absorption of 0.83 would have been for a frequency of 400 cycles, instead of the 1600 cycles indicated in the table. The size of the pores is thus seen to afford a means of controlling, within certain limits, the absorptive characteristic of a material. If it is desired to obtain an absorptive material with maximal absorption in the low frequencies, the pores in the material should be relatively large; and if maximal absorption is desired in the high frequencies, the pores should be relatively small. It should be borne in mind, however, that the theory on which these conclusions are based applies only to porous materials in which the pores are so small that the inertial resistance of the air within the pores is small in comparison with the viscous resistance of the air within the tiny pores. When the pores become large, say with radii as large as 0.10 centimeter, the inertia of the air within the pores becomes very appreciable and the theory here outlined is no longer applicable. Measurements on the absorptive properties of acoustical plasters having pores with radii of about 0.10 centimeter confirm this statement. The absorption is much less than would be predicted on the basis of the foregoing theory.

62. Absorption of Sound by Flexible Materials. Although the absorption of sound in most acoustical materials is attributable to the dissipation of sound in the pores and interstices of the material, a considerable amount of sound energy, especially sounds of low frequency, is absorbed by the flexural vibrations of the material. For example, fibre board materials, as standard " Celotex," " Insulite," or " Masonite," are very much more absorptive at frequencies of 128 and 256 cycles when they are nailed to wood strips than they are when they are cemented or fastened against a rigid surface. (See Table XV, Chap. VIII, on the absorption coefficients of fibre boards.) Also such materials as hard or acoustical plaster are more absorptive when they are applied to wood lath or metal lath over wood studs or channel iron than they are when they are applied directly to concrete or solid masonry walls. That these materials are set into flexural vibrations by the excitation of the sound waves in the room can be readily demonstrated by placing one's finger tips against the surfaces when a loud low-pitched sound is produced in a room in which these materials constitute a part of the boundary.[3]

In general, the amount of sound energy absorbed by flexible materials will be proportional to the square of the product of the amplitude times the frequency of vibration of the panel and directly proportional to the internal damping coefficient of the material. Materials which are set into vibration not only absorb sound but also re-emit sound, and if the internal damping coefficient be very small, it is possible that the amount of re-emitted sound may transcend the amount of sound absorbed by the vibration. This is likely to be the case especially at frequencies for which the vibrating material is resonant. Measurements of the coefficients of sound-absorption of flexible materials, such as wood veneer flats which are used for the erection of " sets " in the making of talking pictures, show rather pronounced peaks and hollows in the curves which give the coefficient of sound-absorption as a function of frequency. Some data on materials of this type will be given in Table XV, Chap. VIII. The peaks may be attributable to resonant vibrations at frequencies for which there is a relatively large coefficient of internal damping, whereas the hollows in the curves may be attributable to resonant vibrations at frequencies for which the internal damping coefficient is relatively small, and therefore the amount of re-emitted sound becomes predominant. The absorption of sound by flexible materials is exhibited not only by such materials as have been mentioned but also by such materials as wood paneling, wood flooring, window panes, hair felt, and acoustical tile.

63. Effect of Adding Holes in Absorptive Materials. The addition of holes in absorptive materials, such as the drilled or punched holes in " Acousti-Celotex " and the stippling of acoustical plaster with a wire brush, has the effect of greatly increasing the absorptivity of the material. The addition of such holes not only greatly increases the superficial area of the porous material exposed to the sound waves, and thus exposes the interior interstices of the material to the pressure variations in a sound

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[3] The actual amplitudes of vibration of a number of flexible and rigid walls have been measured recently by E. Meyer (Sitzungsber. d. Preus. Akad. d. Wiss., Phys.-Math. Klasse, 1931, IX). Thus, the amplitude of vibration of a 3½-inch brick and plaster wall, actuated by sound waves having a r.m.s. pressure of 10 bars, was 10^{-5} centimeter for frequencies around 100 cycles, and was only 10^{-8} centimeter for frequencies around 4000 cycles.

wave, but it also provides an irregular boundary at the surface of the material. These surface irregularities are not so much a matter of topographical variation, since the dimensions of the holes are usually small in comparison with the wave lengths of sound, but the holes introduce irregularities of density and elasticity which contribute effectively to the loss of reflected sound at the boundary. More exact quantitative theory is necessary to account for the increased absorption produced by the addition of holes in porous materials, but such qualitative effects as have been discussed in this section will readily account for the observed facts in connection with such materials as " Acousti-Celotex " and stippled acoustical plaster. The quantitative effects of the addition of these holes will be indicated by the tables of coefficients of sound-absorption which will be given in Chap. VIII.

CHAPTER VII

THE ABSORPTION OF SOUND — METHODS OF MEASURING REVERBERATION AND ABSORPTION

64. Measurement of Sound-Absorption — General Considerations. Although the theory considered in the preceding chapter is of value in understanding the nature of sound-absorption by certain materials, and especially porous materials, it is not sufficiently exact or quantitative to make possible a determination of the coefficients of sound-absorption of building materials from a consideration of the structural and porous properties of the materials. It is also inadequate as a means for determining the total amount of sound-absorption in a room. These quantities can be determined more readily, and with greater accuracy, by experimental methods. Some of the practical and commonly used methods of measuring sound-absorption will be described in this chapter.

It was shown in Chap. V that if a sustained sound, such as the tone from an organ pipe, be produced in a room, it builds up in intensity until the rate at which the sound energy is absorbed by the boundaries and contents of the room is equal to the rate at which the sound energy is generated by the source of sound. The sound energy in the room has then reached a steady state, or a condition of equilibrium. If the source of the sound is then stopped, the sound energy will gradually die away to inaudibility; that is, the total amount of sound energy in the room ultimately will be absorbed by the boundaries and contents of the room. This process of the growth and decay of sound, which was considered in detail in Chap. V, leads to several useful methods for measuring the total amount of sound-absorption in a room, and also the coefficients of sound-absorption of acoustical materials.

Eq. (15), Chap. V, namely,

$$V\frac{d\rho}{dt} + \frac{ca}{4}\rho = E, \tag{15}$$

which is a fundamental equation for the flow of sound in a reverberant room, yields two equations which are serviceable for determining the sound-absorption in a room. The first and simpler of these equations, which applies to the steady state when the rates of emission and absorption are equal, is

$$a = \frac{4E}{c\rho_0}, \tag{33}$$

which follows immediately from Eq. (20). (The symbols all have the same meanings which were assigned in Chap. V — see p. 123.) The second of these equations, which applies to the decay of sound in a reverberant room after the source has been stopped, is

$$p = p_0 e^{-\frac{ca}{4V}t}, \tag{22}$$

which is Eq. (22), Chap. V. However, it must be remembered that Eq. (22) applies only to reverberant rooms, and that the more general equation for the decay of sound in any rectangular room of conventional shape is (neglecting the absorption in the air)

$$p = p_0 e^{\frac{cS \log_e (1 - \alpha)}{4V}t}, \tag{25}$$

which is Eq. (25). Eq. (25), which gives the rate of decay of sound in a room, suggests two methods for determining a: (1) measurement of oscillograms of the decadent sound in a room, or (2) measurement of the time required for a sound to be reduced to a known fraction of its initial steady state value. This latter method, known as the reverberation method, is the one chosen and developed by W. C. Sabine, and it has been used almost exclusively by all subsequent investigators. It is customary to use the ear as the detector in these measurements.[1] The observer stops a tone of predetermined intensity (usually about one million times the minimal audible intensity) and measures the duration of audibility.

It is necessary that the sound in the room be thoroughly diffuse during the decay so that all the sound energy in the room will have the same probability of being propagated in every direction. A large rotating vane or paddle in the room is beneficial for providing the required degree of " mixing."

W. C. Sabine and many subsequent investigators, including Paul E. Sabine at the Riverbank Laboratories, have used organ pipes for the source of test tones in their reverberation measurements. When W. C. Sabine began his investigation of architectural acoustics more than thirty years ago a set of organ pipes was probably the most satisfactory apparatus for producing nearly pure tones of the pitch and loudness range required for the investigation of acoustical problems. However, the development of the thermionic tube and thermionic-tube circuits during the past fifteen years has made available more convenient and precise apparatus for acoustical measurements. For example, the

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[1] During the past two years there has been a growing tendency, in the making of reverberation measurements, to replace the ear with a microphone and amplifier. See Sec. 69.

vacuum-tube oscillator, with appropriate filters and a high-quality loud speaker, as described in Chap. II, will produce approximately pure tones of any required pitch and loudness, and the pitch and loudness can be readily controlled and measured. The use of such thermionic-tube circuits for making fundamental measurements in architectural acoustics has become more and more popular during recent years, and because of the many advantages of such circuits a typical set-up for reverberation measurements will be described.

65. Measurement of Reverberation by Means of Thermionic-Tube Circuits, Using the Ear as the Detector. In Fig. 86 is shown a diagrammatic set-up of apparatus which has proved highly satisfactory for reverberation and absorption measurements in rooms having a time of reverberation longer than about 2.0 seconds. The audio-frequency vacuum-tube oscillator is a typical Hartley circuit, similar to the one described in Chap. II. The alternating current generated by the oscillator passes through a suitable low-pass filter, where all undesirable harmonics are eliminated, thus providing a pure sinusoidal current. The current output from the filter is measured by a thermocouple and galvanometer,[2] and it then passes through an electrical attenuator and finally actuates a high-quality electrodynamic loud speaker, which is located in the room in which the reverberation or absorption measurements are to be made. Since the loud speaker is of the electrodynamic type, the acoustical energy developed by it will be very nearly propor-

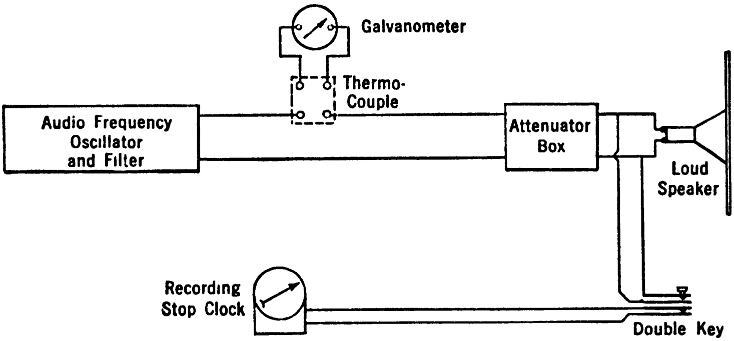

FIG. 86. Diagrammatic arrangement of apparatus for making reverberation measurements by ear.

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[2] During the past two years the thermocouple and galvanometer have been replaced by an electrostatic voltmeter (designed by L. P. Delsasso) which is connected across the input to the attenuator. The voltmeter is a convenience, especially in field work, since it does not have to be mounted so carefully as does a galvanometer. Further, the voltmeter is a rugged instrument, and can be read easily and quickly.

tional to the electrical energy which actuates the loud speaker, provided the speaker is not overloaded and is free from all parasitic currents, such as might arise from imperfect shielding or balancing. The electrical attenuator, which is calibrated at all test frequencies, will then provide a means of changing the intensity of the generated tone by any required amount, and the change of the acoustical intensity in the room, in decibels, will be the same as the change in decibels on the attenuation box. Thus if the attenuator, which is usually calibrated in decibels, is changed 60 db, the sound level of the tone will be changed by that same amount.

It is customary in making reverberation measurements with the ear first to adjust the attenuator so that for the average position of a listener in the room the tone is reduced to the minimal threshold of audibility, and then increase the level of the tone 60 db. The tone then has a standard intensity or loudness level; that is, it has an intensity equal to one million times the intensity of a tone of the same pitch which is just barely audible in the room. The time required for such a tone to die away to inaudibility in the room is a measure of the reverberation time for that particular tone.

The tone generated by the loud speaker can be stopped or started at will by means of the double contact key shown in the figure. This key also operates a stop clock which has an electromagnetic control. When the observer closes the double contact key, the tone in the room is stopped and at the same time the recording stop clock is started. The clock runs as long as the key is depressed. When the key is opened, which is done at the moment the tone has decayed to the threshold of audibility, the clock stops, and the tone in the room is started again. This operation can be performed as many times as desired, and the clock will register the separate times of reverberation, or the total time for several consecutive measurements.

By means of this apparatus, reverberation measurements are made in a room in the following manner: Measurements are first conducted to determine the amount of attenuation required in the attenuation box to produce a barely audible tone at the average position in the room. Because of the sound-interference pattern in the room, it is often necessary to make as many as 25 separate determinations of minimal audibility, distributed in all parts of the room. After the adjustment for minimal audibility has been made, the electrical energy input to the loud speaker is increased one million fold, that is, 60 db is taken out of the attenuation box. The tone in the room is then of standard intensity. It is advisable to have the loud speaker in several representative positions in the room during the measurements of both minimal audibility and the time of reverberation, or to rotate it by means of a silent motor, or have it oscillate as a simple or conical pendulum. If the loud speaker is kept in one position in the room, the amount of energy it will radiate will depend upon the interference pattern surrounding the loud speaker; whereas if it is moved about, the effect of the interference pattern is averaged, and consequently more accurate results will be obtained.

For most practical purposes it is sufficient to obtain 25 different measurements of the time of reverberation for each test tone. When precise work is required, it is advisable to take as many as 50 different measurements for each tone. These can be taken in rapid succession by means of the double contact key. The observer holds the key in his hand, and when the tone has built up to its steady state, he depresses the key which stops the tone and starts the clock. He holds the key down until the tone dies away to the threshold of minimal audibility, at which instant he releases the key, which stops the clock and starts the tone again. The tone is then allowed to build up for several seconds — it should be allowed to build up for a time equal to at least one half of the time of reverberation — then the operation for each measurement is repeated as many times as required. During a series of measurements, the observer moves to all representative positions in the room, so that the average time of reverberation is based upon measurements taken in all parts of the room.

The apparatus and method just described have the following advantages:

1. The intensity of the test tone can be adjusted to a standard level of 60 db, or more or less if desired, in any room just prior to the taking of the reverberation measurements. This is accomplished by simple adjustments of the attenuator, provided the electrical potential at the input of the attenuator be kept constant.

2. Since the threshold of minimal audibility is determined at the time and under the existing conditions of the test, the establishment of test tones of definite loudness is less dependent upon residual noises in the room than would be the case with the use of, for example, organ pipes, which are usually calibrated with considerable labor and under perfectly quiet conditions.

3. The use of suitable filters and a high-quality loud speaker provides test tones which are practically free from undesirable harmonics; that is, the tones are pure. On the other hand, test tones generated by organ pipes are accompanied by a whole series of prominent harmonics; that is, the tones are impure. The presence of harmonics in the test tones is most objectionable and leads to erroneous results,

especially for low-frequency measurements. Thus, suppose a test tone of 128 cycles has a harmonic component of 512 cycles. If the amplitude of this harmonic be as great as one tenth the amplitude of the fundamental, it will be heard louder than the fundamental — owing to the increased sensitivity of the ear at 512 cycles as compared with the sensitivity at 128 cycles. Hence, the fundamental tone of 128 may die away to inaudibility before the 512 harmonic does; and consequently measurements of reverberation with such an impure test tone would apply more nearly to the harmonic of 512 than they would to the fundamental of 128 cycles. It is obvious therefore that pure tones are required for precise measurements of reverberation, and these can be approximately obtained with oscillators and loud speakers provided the alternating current has been suitably filtered.

4. The thermionic-tube apparatus is convenient to operate, is portable, and can be set up in about 20 or 30 minutes. It also is fairly dependable in the hands of persons who possess only a general knowledge of vacuum-tube circuits.

In testing the reverberatory properties of a room it is usually sufficient to make reverberation measurements at frequencies of 128, 512, and 2048 cycles.

66. Measurement of Sound-Absorption in a Room by the Reverberation Method, Using the Ear as the Detector. The apparatus described in the preceding section is also useful for the measurement of sound-absorption in a room. The amount of absorption in a room, for a certain frequency, is related to the time of reverberation in the room in a manner indicated by Eq. (30), namely

$$t_{60} = \frac{kV}{-S \log_e (1 - \alpha)}. \qquad (30)$$

The volume of the room V, and the total interior surface S, are determined by simple measurements; and the time of reverberation t_{60} is determined by a method similar to the one described in the preceding section. The value of k for most rooms is 0.049. The value of α, the average coefficient for the entire boundary of the room as tested, can then be obtained from (30). The total absorption in the room is then given by αS.

For example, the reverberation chamber in the Acoustical Laboratory at the University of California at Los Angeles has a volume of 6080 cubic feet, an interior surface of 2008 square feet, and a time of reverberation of 12.65 seconds at 512 cycles. Substituting these values in (30), $\alpha = 0.0119$, and the total absorption in the empty room is therefore 0.0119 × 2008, or 23.9 sabines. Now suppose that 100 square feet of an absorptive material, the coefficient of sound-absorption of which is to be determined, be brought into the room.[3] The intensity of the test tone is again adjusted to a sound level of 60 db, and the reverberation time is again measured. Let us suppose that the measured time of reverberation at 512 cycles is 4.5 seconds. Then the total amount of absorption in the room can be determined by solving (30) for α, and multiplying this value of α by S. The result is 64.0 sabines. The total absorption added to the room by the addition of the 100 square feet of test material is then equal to 64.0 − 23.9, or 40.1 sabines. The amount of absorption contributed by each square foot of the acoustical material would then be 0.401 sabine. Since the acoustical material covered 100 square feet of floor area, which in this particular room had a coefficient of 0.012, the amount of absorption supplied by 1 square foot of the acoustical material would be 0.413 sabine. The coefficient of sound-absorption of the acoustical material is therefore rated at 0.413, or usually at 0.41, since the errors of measurement amount to at least 3 or 4 per cent. These measurements apply to a frequency of 512 cycles. Similar measurements are made at 128, 256, 1024, 2048, and 4096 cycles. The resulting data will give the absorptive characteristic of the material.

In order to make accurate measurements of the coefficients of sound-absorption of acoustical materials, by the reverberation method just described, the room should be large, and should have a time of reverberation of at least 5 or 6 seconds, so that the error in timing short intervals will not be appreciable. Further, the amount of material tested should be of such an area that its total absorption will reduce the time of rever-

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[3] As was shown in Chap. V, the location of the material will have an effect upon the time of reverberation in the room and consequently upon the effective absorption which the test material adds to the room. But the dimensions of this room, 19 feet by 20 feet by 16 feet, are such that all surfaces have nearly the same probability of being hit by the decaying sound, and therefore the location of the material will not be a very important factor in affecting the rate of decay of sound in this room. As a rule, the material is made up into a panel in a manner comparable with its use in buildings, and placed upon the floor of the reverberation room. The test panel should have large dimensions in comparison with the wave lengths of the test tones. This condition is realized for frequencies above about 256 cycles, but for lower frequencies there are appreciable errors owing to the diffraction around the edges of the panel, and to the arrangement of nodes and loops in the room when the test frequency is nearly coincident with one of the free or natural frequencies of the room. It is also important that only a relatively small portion of the floor area be covered with the test (absorptive) material. Thus, if the entire floor be covered with absorptive material, there will be a two-dimensional reverberation between the walls which will tend to prolong the reverberation. In routine tests, the author uses a test area of 72 square feet, in the form of a rectangle 8 feet by 9 feet.

beration in the room to approximately one half of the reverberation time for the empty room.

The reverberation method just described is a simple and useful method for determining the total amount of absorption in a room, or for determining coefficients of sound-absorption of acoustical materials. When it is not possible or convenient to adjust the test tone to a level of 60 db, the following somewhat more general method may be utilized. It is necessary to have a source of sound, the rate of emission of which, E, can be varied by a known ratio. Then, if the duration of audibility of the residual sound for two values of E be determined, the total absorption in the room can be calculated. Thus, let E_1 and E_2 be the rates of emission of the source, the ratio E_2/E_1 being known. (Sabine used one and four identical organ pipes, separated from each other sufficiently to neglect the mutual coupling between them, so that the four pipes emitted four times as much energy as one pipe. A suitable loud speaker, actuated by a filtered oscillator current, will usually prove more convenient and more satisfactory.)

Now let t_1 and t_2 be the durations of audibility of the two sources having rates of emission of E_1 and E_2, respectively; and let I_m be the minimal audible intensity for an observer in the room. Then, since the intensity ratio I_2/I_1,[4] for the steady states, is equal to the ratio of the rates of emission of the source E_2/E_1 it follows from Eq. (25) that

$$\frac{I_m}{I_1} = e^{\frac{cS \log_e (1-\alpha)}{4V} t_1},$$

$$\frac{I_m}{I_2} = e^{\frac{cS \log_e (1-\alpha)}{4V} t_2}.$$

Whence, by division, and solving for $\log_e (1 - \alpha)$

$$-\log_e (1-\alpha) = \frac{4V}{cS(t_2 - t_1)} \log_e \frac{E_2}{E_1}. \qquad (34)$$

In the organ-pipe experiments of Sabine, E_2/E_1 is usually four, the number of pipes used. In experiments using a loud speaker as the source, E_2/E_1 can and should be at least 100. The only measurements necessary besides V, the volume of the room, S, the interior surface of the room, and c, the velocity of sound, are t_1 and t_2, which can be determined by the ear and a suitable stop clock. It is an advantage to have E_1 and E_2 large, as this increases the accuracy in measuring t_1 and t_2, since the times to be measured will be correspondingly longer. It is an even

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[4] This ratio is also equal to the ratio ρ_2/ρ_1, where ρ_2 and ρ_1 refer to the volume densities of sound energy in the room.

greater advantage to have the ratio E_2/E_1 large, since this will reduce the error in the difference $t_2 - t_1$. This method of determining the total absorption in a room, or the absorptivity of a material brought into the room, will yield fairly accurate results, provided as many as about 50 measurements of t_1 and t_2 be taken, and provided further that the test room be completely free from noise.

The reverberation method for measuring sound-absorption has the following advantages[5]:

1. The decadent sound in the room, after the source has been stopped, becomes more and more mixed up as time goes on, so that near minimal audibility the intensity is nearly uniform in all parts of the room.
2. The pertinent measurements consist simply of time measurements, usually of two or more seconds' duration.
3. The apparatus requirements are simple — a standard source of tone, with means for adjusting the intensity, and a suitable chronograph comprise the necessary apparatus.

There are, however, a number of limitations to the reverberation method, and some of them are objectionable or difficult to control. There is, for example, an inherent error in judging just when the sound has reached minimal audibility. Two elements contribute to this error: first, the poor sensibility of the ear to small changes of intensity near the threshold of audibility; and second, the actual fluctuation of intensity resulting from the interference pattern in the room. Under ideal conditions, the smallest discernible change of intensity near minimal audibility is in excess of 40 per cent,[6] and may be as large as 200 per cent[7] for very low frequencies. Under actual working conditions, it is probable that even greater changes than these are nearer the practical limit. This would appear, on first thought, to be a serious source of error; but for a tone of usual intensity, that is, one having an intensity of one million times the minimal audible intensity, the error in the measurement of individual measurements of t_{60} would be approximately 5 per cent. The actual fluctuation of intensity resulting from the ever-changing interference pattern in the room will also introduce an error in the observer's judgment of just when minimal audibility is reached, the magnitude of

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[5] These are supplementary to the advantages already mentioned on pp. 161 and 162, which referred principally to the advantages of thermionic-tube circuits compared with organ pipes. The advantages mentioned at this point refer to the general reverberation method, irrespective of the source of test tones.

[6] V. O. Knudsen, "Sensibility of the Ear to Small Differences of Intensity and Frequency," Phys. Rev. (ser. 2), **21**, 84 (1923).

[7] R. R. Riesz, Phys. Rev., **31**, 867 (1928).

which depends upon the nature of the room and the experimental equipment. The rotation of a large reflecting surface in the room, as is used by Paul E. Sabine in the Riverbank Laboratories, minimizes this error. However, measurements of reverberation in an ordinary room, without a rotating reflector or other means for "mixing" the decadent sound, would be subject to an error of about 5 to 10 per cent owing to lack of diffuseness and the shifting interference pattern in the room. The errors arising from the poor sensibility of the ear and from the shifting interference pattern will be quite regularly distributed, and therefore, by taking the average of a large number of separate measurements, the result will be sufficiently accurate for most practical purposes.

A more serious limitation to the reverberation method for measuring the absorption in a room is the necessity for absolute quiet in the test room. The masking effect of any slight residual noise upon a feeble tone approaching minimal audibility is sufficient to introduce objectionable errors[8] in the measurement of t_{60}. Since a noise comprises an almost continuous spectrum of all audible frequencies, it is capable of producing a masking effect upon a tone of any pitch. Even a very feeble noise of only 5 to 10 db would be sufficient to introduce an error of nearly 10 per cent in the measurement of the time of reverberation. Noises of this loudness are prevalent in many rooms which are regarded as practically quiet. The limitations resulting from noise can be removed by providing a soundproof test room, or by choosing the quiet hours of the night, if there be any, as was done by W. C. Sabine. But the rooms in which absorption measurements are to be made are not always soundproofed, and the task of making routine measurements between midnight and 4:00 A.M. is not attractive.

Another objection to the reverberation method is attributable to psychological errors on the part of the observer, who must decide just when the intensity has decayed to the threshold of audibility. Although a trained observer becomes adept at judging just when the decadent sound has reached the threshold, he is not infallible. There are a number of factors, such as judgment, attention, fatigue, reaction time in closing or opening the key associated with the chronograph, actual changes of hearing sensitivity, and even such factors as prejudices and preconceived notions, all of which introduce errors in the measurement of t_{60}. In fact, the human element in the reverberation method for measuring the absorption of a room is probably its greatest weakness. Confidence in the accuracy of any measurements is increased if they can be made

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[8] See article by R. L. Wegel and C. E. Lane, "Auditory Masking of One Pure Tone by Another and Its Probable Relation to the Dynamics of the Inner Ear," Phys. Rev., **23**, 266 (February, 1924).

independently of fallible judgments of the sense organs. Anyone who has made reverberation measurements is certain to realize the limitations imposed by the use of his ear in judging just when a sound has reached minimal audibility, especially if there be any disturbing noise in the room.

The reverberation method, besides having the limitations mentioned, is laborious, and requires the utmost care and patience on the part of the observer. Finally, the method becomes very inaccurate in rooms having a short time of reverberation.

But in spite of these limitations, the reverberation method is capable of yielding very useful results, accurate to about 3 per cent under the most favorable conditions, and about 5 to 10 per cent under conditions more commonly encountered in the average room. The most fundamental data and principles in the field of architectural acoustics have been obtained by this method, and until recently it has afforded the only means for investigating the important problem of reverberation in auditoriums.

67. Measurement of Reverberation and Sound-Absorption by the Oscillograph Method. Eq. (25), which describes the rate of decay of sound in a room, indicates that the absorption of a room can be determined by measuring the rate of decay of the sound after the source is stopped. Perhaps the most obvious method for obtaining a graphic record of the rate of decay is to obtain oscillograms of the decadent sound. Suppose the curve in Fig. 87 to be the envelope of a typical oscillogram[9] representing the nearly logarithmic decay of diffuse sound in a room. If the ordinates in Fig. 87 be measured for the same successive intervals of time t', the ratios of corresponding ordinates separated by these time intervals will be nearly constant. Let I_0'/I' represent the nearly constant ratio of any ordinate (which must be expressed in intensity units) to a successive one t' seconds later; then the average coefficient of absorption of the interior surface of the room can be determined from

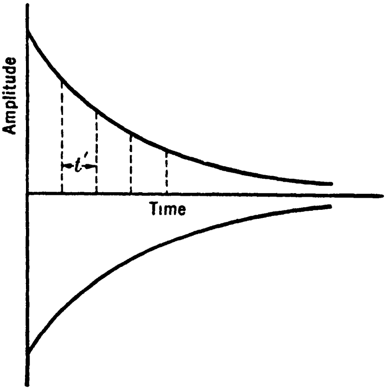

FIG. 87. Logarithmic decay curve showing the approximate manner in which sound decays in a room.

$$-\log_e (1 - \alpha) = \frac{4V}{cSt'} \log_e \frac{I_0'}{I'}. \tag{35}$$

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[9] This represents an ideal case in which the effects of interference and room resonance are neglected.

This equation can be solved for α, and the total absorption in the room is then, at least approximately, αS. In the oscillograms the ordinates would represent the pressure amplitude or the displacement amplitude of the sound and not the intensity I, which is proportional to the square of the amplitude. I_0'/I' is therefore the square of the corresponding ordinates measured on the oscillogram. In general, in making measurements from oscillograms, it is necessary to extend the measurements over a considerable time of decay so that irregularities in the rate of decay will be " averaged out."

The advantages of the oscillograph method of determining the absorption of a room are:

1. The method is an absolute one, and therefore no calibration is required.
2. The measurements are made on a photographic record, and therefore can be made with a high degree of accuracy.
3. The error in determining the absorption is nearly proportional to the logarithm of the intensity ratio I_0'/I', and therefore should be small.
4. The photographic record is permanent and compact, and can be filed for future reference.

There are two limitations to this method for determining the absorption in a room. First, the decay is not uniform. The interference pattern in the room is pronounced and is in a state of rapid change; successive maxima and minima are presented to the detector, and consequently the oscillogram is a complex record showing the effects of interference as well as the decay of the sound. After the source of sound has been stopped the residual sound becomes somewhat more uniform, but the successive maxima and minima are never completely eliminated.

The second limitation to this method comes from the interfering effect of any noise in the room. Since it is necessary to extend the measurements to relatively long periods of decay it often becomes necessary to use that portion of the oscillogram which corresponds to sound intensities comparable with the noise level in many rooms. To avoid this source of error it is necessary that the room be relatively quiet — a condition which cannot always be realized in commercial buildings.

An interesting adaptation of the oscillograph method for measuring reverberation has been developed by E. Meyer and P. Just.[10] Many

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[10] Erwin Meyer and Paul Just, "Zur Messing von Nachhalldauer und Schallabsorption," Elektrischen Nachrichten-Technik, 5, Heft 8, 293 (1928).

other investigators have used this method recently.[11] The detecting apparatus used by Meyer and Just is shown schematically in Fig. 88. As a source of sound they use a band of frequencies generated by the beat frequency from two high-frequency oscillators. A motor-driven rotating condenser, which is rotated at a rate of about 5 to 7 revolutions per second, is connected in the tuning circuit of one of the high-frequency oscillators. This produces a periodic variation in the capacitance of the tuning circuit, and thus a periodic variation in the beat frequency. In this manner, cyclically varying frequency bands of 150 ± 50 cycles, 600 ± 100 cycles, and other bands up to 4800 ± 300 cycles, are generated. As indicated in Fig. 88, the sound is picked up by a microphone, amplified by a three-stage amplifier, and then rectified. The rectified current operates a galvanometer, and the deflection of the galvanometer is recorded photographically upon a moving film. The effective width of the film is very greatly increased by means of a relay placed between the second and third stages of the amplifier. When the amplitude of the decadent sound has been reduced to about one tenth of its initial value, the relay, which is operated by a time-delay circuit shown at C and R, increases by ten fold the input to the third stage of the amplifier. By this device, the length of the decay is doubled so that it is possible to obtain a record of decay of at least 40 db.

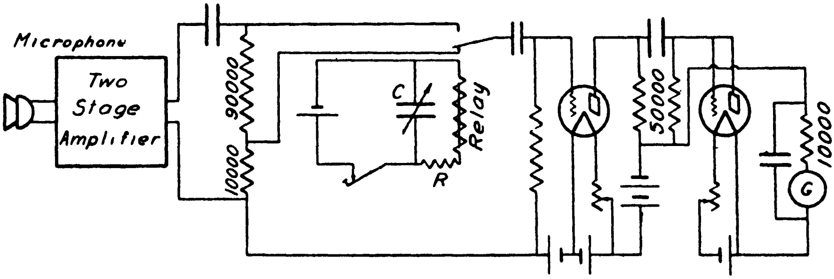

FIG. 88. Schematic arrangement of apparatus used by Meyer and Just for measuring rate of decay of sound in a room.

A typical series of records obtained by Meyer and Just is shown in Fig. 89. It will be seen that there are many irregularities in the decay curves, even with the rather wide frequency bands which were used for " mixing " the sound in the room. The irregularities, however, are not

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[11] See, for example, V. O. Knudsen, Phil. Mag., **5**, 1240 (1928); W. Schindelin, Ann. d. Phys., **5**, 2, 129 (1929); E. Scharstein, Ann. d. Phys., **5**, 2, 169 (1929); W. Linck, Ann. d. Phys. **5**, 4, 1017 (1930); W. Kuntze, Ann. d. Phys., **5**, 4, 1058 (1930); Chrisler and Snyder, Bureau of Standards Research Paper, No. 242 (October, 1930).

so great as those obtained from a single-frequency source. It will be seen also that the low frequencies die away much more slowly than do the high frequencies. This is characteristic of nearly all rooms.

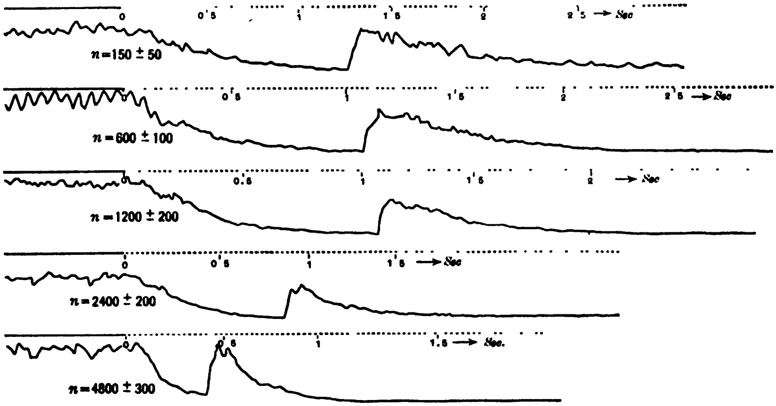

FIG. 89. From photographic records of the decay of sound in a room. (*Meyer and Just.*)

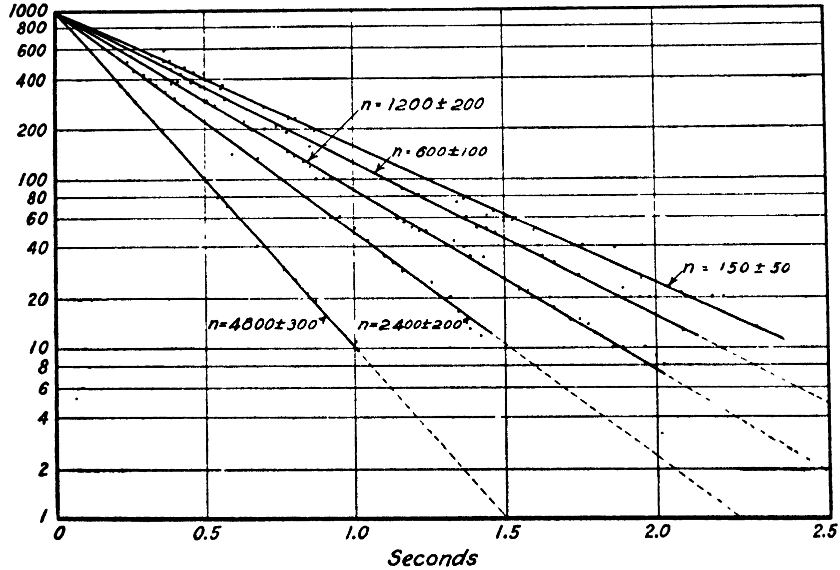

FIG. 90. Plotted results of the decay curve shown in Fig. 89. (*Meyer and Just.*)

The method of interpreting and measuring the photographic records is indicated by Fig. 90. It will be noted that the amplitude of the decay curve is plotted to a logarithmic scale, so that the decay curves thus plotted should be approximately straight lines. Further, these lines are extrapolated until the amplitude has been reduced to one thousandth of its initial value; that is, until the intensity has been reduced to one millionth of its initial value. As plotted, the intersection of these straight lines with the time axis gives the time of reverberation for the room — that is, the time required for residual sound in the room to decay to one millionth of its initial intensity. For example, the reverberation time at 4800 ± 300 cycles is 1.5 seconds. The technique developed by Meyer and Just thus provides an objective method for determining the time of reverberation or the sound-absorption in a room. The method appears to be fairly accurate, particularly at high frequencies. It is, however, rather laborious, as is evidenced by the number of separate points plotted in Fig. 90. Further, it is necessary to take the average of a number of such records — usually about five — in order to attain a requisite degree of accuracy.

68. Measurement of Sound-Absorption by the Intensity Method. Another method for measuring the total absorption in a room, and therefore a method for measuring coefficients of sound-absorption of acoustical materials, is based upon Eq. (33), which is $a = 4E/c\rho_0$. This method is called the intensity method because the essential measurements consist of determining the average intensity of sound in a room. According to Eq. (33), the volume density ρ_0 of sound in a room is directly proportional to the rate of emission of sound energy E and inversely proportional to the total amount of absorption a in the room. Hence, if the rate of emission of the sound source be kept constant, it is possible to make measurements of the total absorption in the room simply by measuring ρ_0, the average value of the volume density of the sound. This is accomplished by making two sets of intensity measurements, one with the room as it is to be tested, and another with a known amount of absorption added to the room. It then becomes unnecessary to know the rate of emission of the source, provided it remains constant for the two sets of measurements. The equations for these measurements are obtained from (33). Suppose measurements of ρ_0 be made in an empty room having a total absorption a. Then

$$a = \frac{4E}{c\rho_0}.$$

Now suppose a known amount of absorption a' has been added to the room. Then

$$a + a' = \frac{4E}{c\rho_0'},$$

where ρ_0' is the resulting steady state density of sound energy. Whence,

$$a = \frac{a'}{\frac{\rho_0}{\rho_0'} - 1}. \tag{36}$$

As is indicated by (36), it is not necessary to know the value of E provided it is known that E remains constant while both ρ_0 and ρ_0' are determined. Further, it is not necessary to know the absolute value of ρ_0 and ρ_0'. Since they enter only as a ratio, it is sufficient to measure any quantities which are proportional to the volume densities ρ_0 and ρ_0'.

This method of determining the absorption of sound in a room has a number of obvious advantages:

1. All the measurements are instrumental, and thus independent of the ear of an observer.
2. The error in determining the absorption of sound is the same as the error in measuring the average intensity of sound in the room, and with suitable apparatus it is possible to reduce this error to a tolerable degree.
3. The disturbing effect of residual noise can be made negligible. If the intensity of the test tone be one thousand times greater than the intensity of the residual noise in the room, the noise introduces an error of only 0.1 per cent. It is an easy matter to produce test tones of this required intensity in an average room. Elaborate sound-insulation, or the making of the measurements during the quiet part of the night, is thus obviated.

The method of measurement appears simple and precise, and indeed would be were it not for the difficulties encountered in determining the average value of ρ_0. But the interference pattern in the room affects both the volume density (or intensity) in the proximity of the detector (a microphone) and the impedance load on the source (a loud speaker).[12] It is necessary, therefore, thoroughly to " mix " the sound and to make measurements at several positions in the room if reliable measurements of average intensity are to be made.

An arrangement of apparatus which has proved satisfactory, although laborious, for making measurements of sound-absorption by the intensity method is shown schematically in Fig. 91. The oscillator shown in the figure is an audio-frequency oscillator with a motor-driven variable inductance. The oscillator may be replaced by a beat-frequency oscillator, similar to the one described in the preceding section. By means of either oscillator it is possible to generate frequency bands, approxi-

[12] See Phil. Mag., 5, 1242 (1928).

mately one half octave in width, in the vicinity of the following frequencies: 128, 256, 512, 1024, 2048, and 4096 cycles. For the frequency band in the vicinity of 512, for example, the frequency varies periodically from 408 to 629 and back again to 408 cycles, and the frequency goes through approximately five such cycles each second, that is, the warble frequency is five cycles per second. In a reverberant room, as is used for test purposes, such a rapid variation produces essentially a continuous band of frequencies from 408 to 629 cycles. With a band of frequencies of this width, the interference pattern in the room is very considerably smoothed out, so that on the average there is a nearly uniform distribution of sound energy throughout the room, not too near the source.

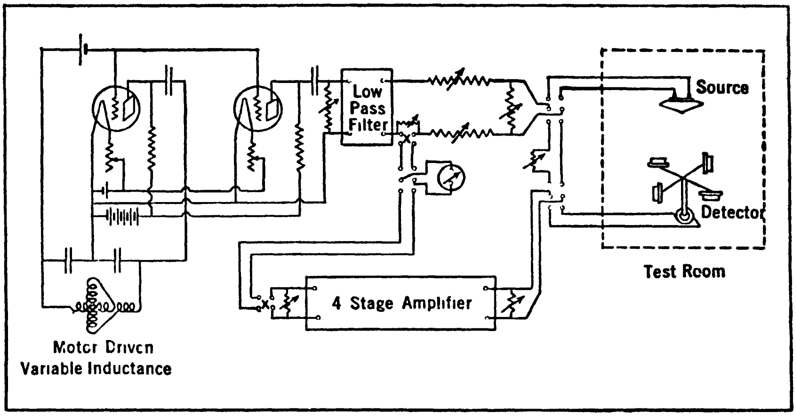

FIG. 91. Schematic diagram of circuit and apparatus used for determining the average intensity of sound in a room.

Determinations of the amount of sound-absorption in a room by the intensity method give values which are in good agreement with the values obtained by the reverberation method. For example, a long series of measurements on the same acoustical material, using both the intensity method and the reverberation method, gave a coefficient at 512 cycles of 0.43 by the reverberation method and 0.44 by the intensity method.

As a further indication of the reliability of the intensity method, the results of a series of intensity measurements with different amounts of absorptive material in a room are given in Fig. 92. The small circles in the figure indicate the measured values of the intensity, expressed in terms of the deflection of the galvanometer in the output of the thermocouple. The solid line curve is a rectangular hyperbola, based upon

Eq. (33), which states that the volume density (and consequently the intensity) in a room is inversely proportional to the total amount of absorption in the room. The close agreement between the observed intensities and the hyperbolic curve seems to support the reliability of using the intensity method for the measurement of the sound-absorption in a room. These measurements also support the validity of Eq. (33), which states that the average density of sound energy in a room, provided the acoustical energy output from the source remain constant, is inversely proportional to the total absorption in the room. This conclusion is important in connection with the use of absorptive materials for the reduction of noise in buildings.

Dr. Paul Sabine[13] and also Mr. Wallace Waterfall[14] recently have made adaptations of the intensity method for the rapid comparison of the absorptivity of small specimens of acoustical materials. A source having a constant rate of emission radiates sound on a specimen, and the sound reflected from the specimen affects the intensity of sound which falls upon a microphone. The intensity, as measured by the microphone and amplifier, is a function of the absorptivity of the specimen. The apparatus is calibrated by using specimens of known absorptivity.

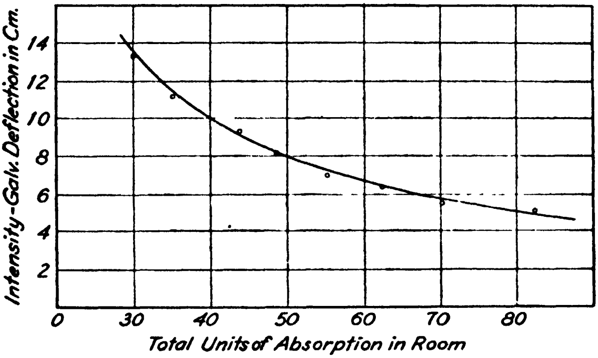

FIG. 92. Curve showing the relation between the intensity of sound in a room and the total amount of absorption in the room. The curve gives the theoretical value of the intensity based upon the assumption that the intensity is inversely proportional to the total amount of absorption in the room. The small circles indicate measured values of intensity with different amounts of absorption in the room.

69. Recently Developed Objective Methods of Measuring the Rate of Decay of Sound in a Room. During the past two years there has

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[13] P. Sabine, "A Device for Direct Measurement of Sound-Absorption Coefficients," reported at the May, 1931, meeting of the Acoustical Society of America. (Abstract, Jour. Acous. Soc., **3**, 11 [1931].)

[14] W. Waterfall, not published.

been a pronounced development of instrumental methods for measuring the rate of decay of sound in rooms — a quantity which, as we have seen, facilitates the determination of the total amount of absorption in a room or the determination of coefficients of sound-absorption of materials brought into the room. The methods of measuring sound-absorption described in the two preceding sections are instrumental, but they are laborious if accuracy is required. What is wanted is accuracy of measurement without an excessive amount of labor. And nearly everyone who has worked in the field of architectural acoustics has felt the necessity of developing objective methods which would be free from the inherent errors in the use of the ear in the reverberation method.

The recent developments in objective methods of measuring sound-absorption, both in America and in Europe, have been very much along the same line. For example, such laboratories as the Heinrich-Hertz Institut für Schwingungsforschung,[15] in Berlin; the Bell Telephone Laboratories,[16] New York; the Electrical Research Products, Inc.,[17] in New York and in Los Angeles; the Bureau of Standards,[18] Washington, D. C.; the Naturkundig Laboratorium der N. V. Philips' Gloeilampenfabrieken,[19] Eindhoven; and the Acoustical Laboratory at the University of California at Los Angeles[20] have developed reverberation meters which have many features in common. In fact, to describe one of these meters is sufficient to give the general principles involved in all the meters, although there are of course many differences in detail. For example, all but one of these meters use warble frequencies for the test tone; all use a condenser or electro-dynamic microphone for picking up the sound in the test room; and all use an amplifier and some sort of chronograph or recording meter, operated by a relay, to record the time required for a decay of a specified number of decibels. In some of the instruments the time of decay is indicated for successive decays of about 3 to 10 db, and in this way a graphic record of the nature of the decay is obtained.[21] At the other laboratories the chronograph usually measures the time required for a decay in the room of 20 to 60 db.

The method in use at the Acoustical Laboratory at the University of California at Los Angeles follows very closely the method used by the Electrical Research Products, Inc. This method has been adopted

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[15] E. Meyer, Zeits. für Tech. Phys., **7**, 253 (1930).

[16] Wente and Bedell, Jour. Acous. Soc., **1**, 422 (1930).

[17] F. L. Hopper, Jour. Acous. Soc., **2**, 499 (1931).

[18] Chrisler and Snyder, Jour. Acous. Soc., **3**, 12 (1931).

[19] M. J. O. Strutt, E.N.T., **7**, 280 (1930).

[20] V. O. Knudsen, Jour. Acous. Soc., **3**, 126 (July, 1931).

[21] See, for example, C. F. Eyring, Soc. Motion Picture Engineers (May, 1930), in which it is shown that many rooms have more than one rate of decay of sound.

following the testing of various other methods, and is found to be satisfactory for routine tests. The arrangement of the test room and the adjacent measuring room is indicated in Figs. 93 and 94, which show a

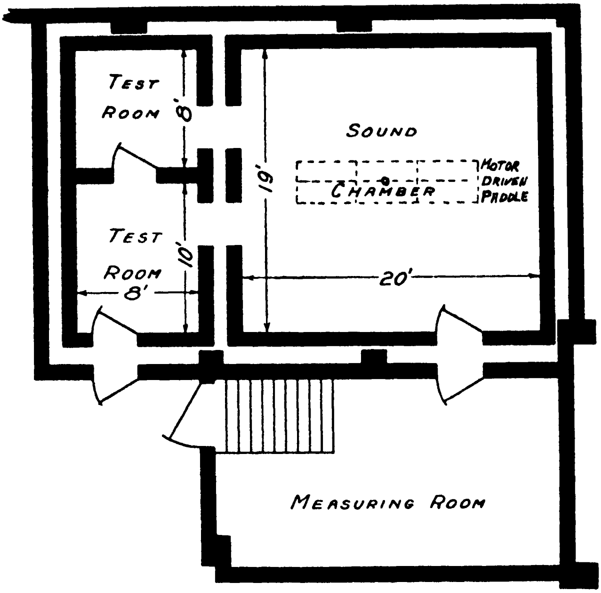

Fig. 93. Plan of the acoustical laboratory at the University of California at Los Angeles.

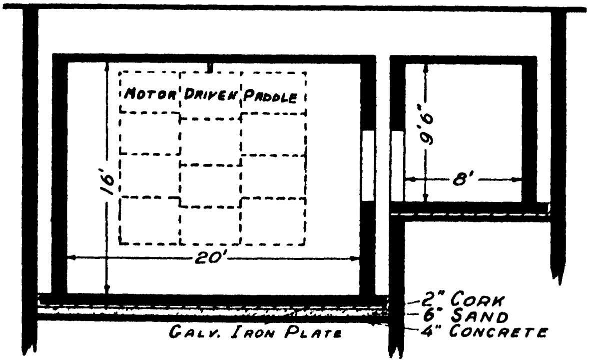

Fig. 94. Section through reverberation room and test room of the acoustical laboratory at the University of California at Los Angeles.

plan and a typical section of the Acoustical Laboratory at the University of California at Los Angeles. This laboratory is used for both absorption and insulation measurements, but only the features of the laboratory which apply to absorption measurements will be discussed at the present time. The reverberation chamber is 19 feet by 20 feet by 16 feet high, and is made of reenforced concrete. The walls are 12 inches thick, and the ceiling slab is 6 inches thick. This room is enclosed inside another concrete room the walls of which are a part of the main Physics Building. The reverberation room is separated from the earth by 6 inches of dry sand and 2-inch cork strips which effectively eliminate solid-borne vibrations which might come through the earth or from other parts of the building. A large motor-driven paddle of sheet steel is rotated in the reverberation room. This helps to " mix " the sound in the room and insures a more uniform reverberation. The source of sound, an electrodynamic loud speaker, and the condenser microphone are in the reverberation room. The rest of the equipment is in the measuring room. All connections between the two rooms are by means of shielded leads. A schematic arrangement of the equipment is shown in Fig. 95. There are two parts: (1) the generator, and (2) the detector. The generator consists of a beat-frequency oscillator with auxiliary rotating condenser for generating the warble frequencies, a power amplifier, and an electrodynamic loud speaker. An electrostatic voltmeter is connected across the input of the loud speaker in order to maintain a constant rate of power supply to the loud speaker. The detector consists of a condenser microphone with an associated three-stage amplifier, an attenuator box calibrated in decibels, a two-stage amplifier with a vacuum-tube rectifier, a relay which operates at 0.5 milliampere, and a special synchronous motor chronograph. The synchronous motor is provided with a system of reducing gears which, when engaged with the

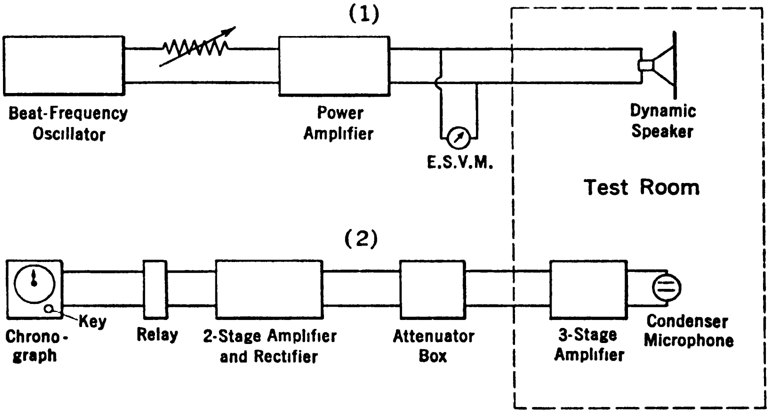

FIG. 95. Schematic arrangement of apparatus for measuring the rate of decay of sound in a room.

dial on the chronograph, will rotate the pointer on the dial at a rate of one revolution per second. The dial is graduated into 100 parts so that the chronograph reads directly in hundredths of a second. An auxiliary dial counts the total number of seconds.

A series of measurements is taken in the following manner: First the warble tone in the test room is allowed to build up to a steady state. Then attenuation is added to the attenuator box until the rectified current which operates the relay has been reduced to 0.5 milliampere, which is read on a small milliammeter. Then a certain amount of attenuation — usually 30 db — is taken out of the attenuator, which greatly overloads the two-stage amplifier and provides a current to the relay much in excess of the current at which it operates. The key on the chronograph is then pushed, which simultaneously stops the warble tone in the test room and starts the chronograph. The chronograph continues until the rectified current has diminished to 0.5 milliampere, at which instant the chronograph is stopped by an electromagnet operated by the relay. This is repeated until a series of 10 measurements has been taken. The microphone is then moved to another position in the room and another series of 10 readings is taken. In precise work it is customary to take at least 5 such series of measurements for each warble tone, thus giving a total of at least 50 separate measurements of the time required for a decay of the number of decibels which had been cut out on the attenuator. In some instances, successive times of decay are measured for drops of 10, 20, 30, 40, and 50 db, and the results plotted in a manner similar to that shown in Fig. 90. In this way, a graphic record is obtained of the manner in which the decay takes place. During the measurements, the intensity of the warble tone is frequently checked, and if necessary adjusted, so that the extent of the decay in the room corresponds to the amount indicated on the attenuation box. Such a series of measurements, when plotted as in Fig. 90, gives the time required for a decay of 60 db, which is the time of reverberation in the room for the particular frequency band at which the measurements are taken. It is also a simple matter to calculate either the total amount of absorption in the room (from Eq. [30]), or the coefficient of absorption of a material which has been added to the room (by making measurements of the reverberation times with and without the material in the room). The equipment is fairly portable, and therefore is useful for making measurements in the field as well as in the laboratory. It is possible to make all measurements at sound levels above 35 or 40 db, so that measurements can be made in rooms in which the noise level is less than about 35 db. The measurements therefore can be conducted under nearly all conditions which are met in practice.

The coefficients of sound-absorption of many materials which will be listed in the next chapter have been measured either by the method just described or by methods similar to it. In addition, the absorptive and reverberatory properties of many rooms have been investigated with equipment of this type. The equipment is particularly useful for the measurement of reverberation in " dead " rooms, since a reverberation time as short as 0.3 second can be readily measured with a probable error of not more than 5 per cent.

70. Field Measurements of Reverberation and Sound-Absorption with the Use of Organ Pipes and a Stop Watch. The methods described in the preceding sections for measuring reverberation and sound-absorption require rather expensive vacuum-tube equipment, and call for considerable experience and skill on the part of the one who makes the measurements. It is possible to make measurements, sufficiently accurate for many purposes, with organ pipes and a stop watch: and the technique of making the measurements can be easily acquired even by those who have had no special training in electric circuits or acoustics. Three organ pipes — tuned to 128, 512, and 2048 cycles — will be sufficient for most purposes. The rates of emission of the pipes should be determined by blowing them in a calibrated reverberation chamber and measuring their durations of audibility. Each pipe should be blown at an intensity just below the point at which the prominent overtone is produced. With a little experience it will be found that the same pipe can be blown repeatedly so as to produce always the same sound level in the same room, within 2 or 3 db. If, for example, the duration of audibility of the 512 pipe should be found to be 16 seconds in a room which has a reverberation time of 12 seconds at that frequency, the sound level of the 512 pipe in this room will be $60 \times 16 \div 12$, or 80 db. This corresponds to 10^8 threshold units. Then the intensity this same pipe will produce in any other room will be $10^8\ a'/a$, where a is the total absorption in this room at 512 cycles, and a' is the total absorption in the reverberation chamber in which the pipe was calibrated, at the frequency of 512 cycles. Thus, if $a' = 25$ sabines and $a = 2500$ sabines, the 512 pipe will produce an intensity of 10^6 threshold units in a room having an absorption of 2500 sabines. That is, the sound level produced by the 512 pipe in such a room will be 60 db. If the amount of absorption in the room be not known, it can be determined approximately by measuring the duration of audibility of a tone produced by the pipe in the room, and regarding this time as the approximate time of reverberation in the room. By substituting this " approximate time of reverberation " (in most large rooms it will not differ by more than 20 or 30 per cent from the true time of reverberation) in Eq. (30), it is possible to solve for the approximate value of a, which is equal to αS. This approximate value of a can then be used as a means of obtaining (to a sufficiently high degree of accuracy) the true time of reverberation, as follows: Let t = measured duration of audibility of the tone produced by the pipe in the room (which must be quiet), and let t_{60} = time for a decay of 60 db. Then for the 512 pipe in this room,

$$t_{60} = \frac{60}{10 \log_{10} 10^8 \frac{a'}{a}} t. \qquad (37)$$

Since an error of 20 or 25 per cent in the value of a will introduce an error of less than 2 per cent in the value of t_{60}, it is obvious that the "approximate value" of a, as determined above, is sufficiently accurate for the use to which it is put in Eq. (37). The value of t_{60} obtained from Eq. (37) can then be used in Eq. (30) to obtain a more accurate value of the total absorption in the room, which will now be accurate to the same degree as is t_{60}, and this is sufficient for all practical purposes.

Measurements at other frequencies, for example at 128 and 2048 cycles, should be made in a manner similar to that which has been outlined for 512 cycles. With a set of three calibrated pipes and a stop watch, as described, it is possible to make most of the reverberation and sound-absorption measurements required for the practical problems which arise in architectural acoustics. If there is some residual noise in the room where the measurements are made, it is necessary to determine the masking effect of this noise for the frequencies at which the measurements of reverberation are made. This can be done by calibrated tuning forks having the same frequencies as the organ pipes. The manner of making these corrections will be explained in Sec. 87.

71. Measurement of Absorptivity by the Tube Method. When a sound wave, incident vertically upon a plane surface, is reflected, the incident and reflected sound unite to form what is called a stationary wave pattern. That is, at certain positions in front of the reflecting surface, the two waves meet in phase, and conspire to produce maxima; and at other positions located half way between the maxima, the two waves meet in contrary phase, and thus oppose each other to produce minima. If A represent, say, the pressure amplitude of the incident wave, and B the pressure amplitude of the reflected wave, the maxima in the stationary wave pattern have amplitudes of $A + B$, and the minima have amplitudes of $A - B$. This is shown in Fig. 96, which also illustrates the so-called tube or stationary wave method of measuring sound-absorption. In the upper part of the figure the reflecting end of the tube is closed with a perfectly reflecting surface, so that the resulting amplitudes in the stationary wave pattern are $2A$ at the maxima and 0 at the minima. The lower part of the figure represents a case in which the closed end of the tube consists of an absorbent material which reflects only a portion of the incident wave, with an amplitude B, so that the resulting amplitudes in the stationary-wave pattern are $A + B$ for the maxima and $A - B$ for the minima. Various methods have been devised to measure the amplitudes $A + B$ and $A - B$, by Tuma,[22] Weisbach,[23] Taylor,[24] Paris,[25] the Bureau of Standards,[26] Heimberger,[27] and Wente and Bedell.[28]

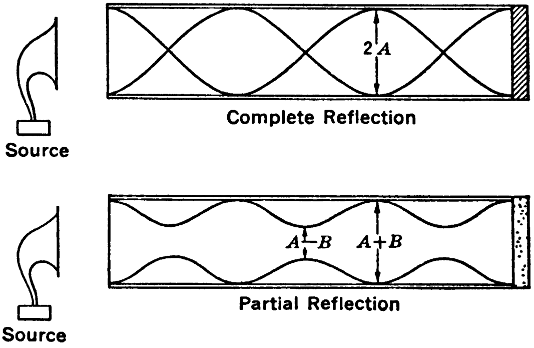

FIG. 96. Stationary waves in tube showing perfect reflection in upper part of figure, and partial reflection from an absorptive material in lower part of figure. (*Paris.*)

It can be demonstrated, from a simple consideration of the theory of wave motion as applied to the union of the incident and reflected waves in a tube closed at one end, such as is shown in Fig. 96,[29] that the coefficient of absorption of the partially reflecting surface is given by

$$\alpha = \frac{4}{2 + \frac{a}{b} + \frac{b}{a}}, \tag{38}$$

where a/b is the ratio of the maximal amplitude to the minimal amplitude. Thus, since in Eq. (38) $a/b = (A + B)/(A - B)$, and since $\alpha = (A^2 - B^2)/A^2$, it follows at once that α is given by Eq. (38). This equation is the form given by Hawley Taylor and is in convenient form

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[22] J. Tuma, "Eine Methode zur Vergleichung von Schallstarkung und zur Bestimmung der Reflexionsfahigkeit verschiedenen Materialen," Sitzungsber. d. Kaiserl. Akad. d. Wiss., III, Part 2A, 402 (1902).

[23] F. Weisbach, "Versuche über Schalldurchlassigkeit, Schallreflexion und Schallabsorption," Ann. d. Phys. **33**, 763 (1910).

[24] Hawley O. Taylor, "A Direct Method of Finding the Value of Materials as Sound Absorbers," Phys. Rev., **2**, 270 (1913).

[25] E. T. Paris, "On the Stationary-Wave Method of Measuring Sound-Absorption at Normal Incidence," Proc. Phys. Soc., **39**, Part 4, 269 (June 15, 1927).

[26] Eckhardt and Chrisler, "Transmission and Absorption of Sound by Some Building Materials," B. of S. Sci. Papers, No. 526 (April 28, 1926).

[27] G. Heimberger, "Simple Method of Finding the Sound Absorbing Power of a Building Material," Phys. Rev., **31**, 275 (1928).

[28] Wente and Bedell, "The Measurement of Acoustic Impedance and the Absorption Coefficients of Porous Materials," Bell Syst. Tech. Jour., **7**, 1 (1928).

[29] See, for example, E. T. Paris, *loc. cit.*, p. 272.

for determining α. It is only necessary to make measurements of $A + B$ and $A - B$, which is usually done with a small exploring tube connected to a suitable microphone, amplifier, and galvanometer. In general, several maxima and several minima are measured, and average values are used for the computation of α; or continuous measurements can be made along the axis of the tube which when plotted will give a continuous curve (almost sinusoidal) varying in amplitude from $A + B$ to $A - B$. The tube should be long enough to give at least two or three maxima and the same number of minima, and since the maxima or minima are separated by distances equal to one half the wave length, the tube should have a length equal to at least two times the wave length for which the tube is to be used. For example, if measurements are to be made at frequencies as low as 128 cycles, the tube should be at least 10 feet long.

The chief use of the tube method is for the comparison of coefficients of sound-absorption of small samples of materials which are fairly homogeneous in composition. Thus, the diameter of the tube rarely exceeds 1 foot, so that the sample tested need not be larger than about 1 square foot; but it should be typical of the material it represents. This is often a convenience for comparing samples, where the cost and labor of making tests on large samples are prohibitive. However, in many materials, such as acoustical plasters, a specimen 1 foot square may not be representative of the absorptivity of a large surface of acoustical plaster, since the texture and porosity of a small sample may differ from a large surface of plaster applied to a wall. Finally, it should be mentioned that measurements of sound-absorption by the tube method give the coefficients for perpendicular incidence of the sound waves, whereas measurements in a room give the coefficients for random incidence which is more comparable with actual conditions in a room.

72. Porosity Measurements of Acoustical Materials. It often becomes necessary to know whether the absorptivity of an acoustical material as installed in a room is comparable with specimens of the material which have been tested in the laboratory and approved for use in the room. For example, such materials as acoustical plasters require a considerable amount of care on the part of the plasterer in order to impart to the plaster the required amount of absorption. Since the absorptivity of an acoustical plaster depends almost entirely upon its porosity — assuming that the size of the pores is determined by the nature of the aggregate material, and that the plaster has been applied to the specified thickness — measurements of the porosity of the plaster will give a good index of its absorptivity. A simple device which has proved very satisfactory for such purposes is illustrated in Fig. 97. It consists of a 5-

gallon bottle, a foot bellows (or a bicycle pump with a check valve, or even a normal pair of lungs), a U-tube mercury manometer, and a 2-inch glass funnel with a collar for sealing (usually with putty) the funnel onto the specimen to be tested. The porosity of the material is then determined by measuring the time required for a certain amount of air to be discharged through the specimen, that is, the time required for the pressure of the air in the bottle to be reduced a specified amount. A pressure drop of from 7 centimeters above to 1 centimeter above atmospheric pressure has proved satisfactory for practical measurements. Tests with this apparatus on different plaster surfaces show that there is practically no diffusion of air through hard gypsum or lime plasters, whereas the bottle will discharge its contents of air (from 7 centimeters down to 1 centimeter pressure) through acoustical plasters in times ranging from about 1 minute down to 1½ seconds. In general, if it requires as long as 1 minute for the contents of the bottle to be discharged through an acoustical plaster, the plaster is not very absorptive. If the air is discharged in about 15 to 20 seconds, the pumice type of plaster (such as California Stucco Acoustical Plaster), ½ inch thick, will have a coefficient of about 0.15 to 0.18 at 512 cycles; if the air is discharged through the plaster in about 10 seconds, the plaster will have a coefficient of about 0.19 to 0.22 at 512 cycles; and if the air is discharged through the plaster in 1½ seconds (as it is in the case of "Kalite," for example), the material has a coefficient of approximately 0.35 to 0.40 at 512 cycles. Such porosity tests should be made with a great deal of caution, since so much will depend upon the size, number, and inter-

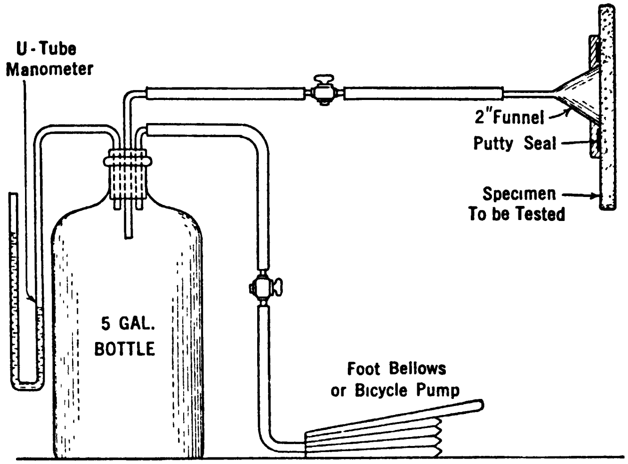

FIG. 97. Simple device for measuring porosity of acoustical materials.

communicability of the pores. On the other hand, if the tests are conducted intelligently, they will reveal pertinent information concerning the absorptive character of acoustical plasters.

Similar tests with this apparatus on fibre boards, such as standard " Celotex," " Insulite," " Masonite," and other fibre boards of this type, indicate that if about 20 seconds are required for the air to be discharged through the ½-inch-thick fibre board (which should be exposed to the air on the opposite side) the material has a coefficient of approximately 0.25 at 512 cycles, whereas if the air is discharged through the fibre board in about 8 to 10 seconds, the material has a coefficient of approximately 0.30 at 512 cycles.

Although these porosity tests are very crude, they are often of great value in ascertaining the approximate absorptivity of materials which are being installed in a building. For example, by making porosity tests of specimens of materials at the time they are tested by more precise methods in the laboratory and again when the materials are being installed in a building it is possible to determine whether the material, as installed, is equivalent to the material tested in the laboratory. It is often feasible to plaster a small test room in the building before the larger and more important rooms are plastered. The porosity of the plaster in this small room can then be tested before it is approved for use in the more important rooms in the building. The method is also very convenient for making a quick comparison of the effects produced by the application of different kinds of paint to acoustical plaster, fibre board, or even some types of acoustical tile.

73. Frequency Range Required for Measurements of Sound-Absorption Coefficients. Coefficients of sound-absorption of building materials usually are determined at frequencies of 128, 256, 512, 1024, 2048, and 4096 cycles, and in some instances this range is extended about an octave at each end. The measurements at frequencies below 128 and above 4096, however, are not very reliable. At very low frequencies the natural frequencies of the test room are comparable with the frequencies of the test tones, and, as Strutt has shown,[30] the reverberation formula becomes of doubtful validity. At very high frequencies, the absorption in the air becomes such a large portion of the total absorption in the room (and the air absorption is subject to rather wide variations with small changes of humidity) that the measurements of the absorptivity of the test material will not be very reliable. For most practical purposes therefore it is necessary and sufficient to determine the coefficients at octave intervals between 128 and 4096 cycles. For thin, flexible materials, as wood or glass panels, which may have pronounced resonant

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[30] M. J. O. Strutt, *loc. cit.*

frequencies, it is desirable to determine the coefficients at smaller intervals than the octave, especially in close proximity to the resonant frequencies.

For all measurements of sound-absorption at frequencies of and above 2048 cycles, it is necessary to make appropriate corrections for the humidity, and possibly the temperature, of the air (see Sec. 54), or better, to calibrate the empty room at the time each material is tested.

74. Choice of Methods for Measuring Reverberation and Sound-Absorption. Several methods of measuring reverberation and sound-absorption have been considered in the preceding sections, and it is possible that those who may wish to make similar measurements will experience difficulty in choosing the method which will be best suited to the requirements and limitations of both skill and apparatus. It probably will be appropriate therefore to conclude this chapter with some comments and suggestions concerning the choice of method. If one is not familiar with vacuum-tube circuits, it probably will be advisable to make approximate measurements with organ pipes and a stop watch, following the method described in Sec. 70. Carefully made measurements with three calibrated organ pipes — pitched at 128, 512, and 2048 cycles — will reveal the pertinent facts concerning the times of reverberation and the sound-absorptive properties of most rooms in which the times of reverberation at all three frequencies are in excess of 2.0 seconds.

For making more precise measurements, especially in rooms having short periods of reverberation, and for laboratory measurements of absorptive materials, the self-registering instruments and methods described in Sec. 69 are recommended. These methods are not only objective and therefore independent of the ear of the observer, but they also provide a quick and reliable means of determining both the rate of decay (i.e., the slope of the reverberation curve during its various phases) and the time for a decay of 60 db. The apparatus is rather delicate and costly, and, until it is made more rugged and "fool-proof," it should be used only by those who are familiar with thermionic-tube circuits.

For investigating the precise manner in which sound is absorbed or dies away in a room, and for revealing the irregularities owing to interference and resonance phenomena, the oscillograph method described in Sec. 67 is recommended. The required apparatus is both delicate and costly, and considerable skill is required for proper operation of the equipment. Although precise measurements of reverberation and sound-absorption can be made by the oscillograph method by determining the rate of decay from at least five oscillograms, each registering a decay of at least 30 db, the method is laborious and therefore is not recommended for routine measurements.

The intensity method described in Sec. 68 has a strong appeal because of the apparent simplicity of the theory underlying the measurements, but requires the utmost care in providing a thoroughly mixed and uniform distribution of sound energy in the room and in maintaining absolute constancy of both the sound generator and the sound detector. The method has possibilities of future development, but at the present it is of interest primarily because it demonstrates that the average intensity of sound in a room is inversely proportional to the total amount of absorption in the room. The method, as simplified by P. Sabine and by Waterfall, is useful for making a rapid comparison of the absorptivities of small specimens of materials.

For making rough measurements of the porosity of acoustical plasters and fibre boards, as installed and decorated in buildings, and comparing the porosity with specimens of the same materials which have been tested in the laboratory, the measurement of the rate of diffusion of air through the materials, as described in Sec. 72, is extremely helpful in protecting a building against defects in the application of acoustical plaster or against difficulties which might result from decorating porous materials with non-porous paints. The apparatus is extremely simple and inexpensive, and can be operated by the architect, building superintendent, or any skilled workman. The proper use of such a simple device will save many buildings from acoustical ruin.

CHAPTER VIII

THE ABSORPTION OF SOUND — MEASUREMENTS, COEFFICIENTS OF ABSORPTION, AND OTHER PROPERTIES OF ACOUSTICAL MATERIALS

75. Introductory. In the last two chapters, consideration was given primarily to the nature of sound-absorption and to methods of its measurement. In the present chapter the principal results of sound-absorption measurements by different investigators will be presented. In the first part of the chapter there will be given the results of measurements which indicate how such factors as the thickness of the absorptive material, the porosity, the density, the perforation of the material with small holes, and the use of multiple layers separated by air spaces, affect the coefficients of sound-absorption of a material. In the latter part of the chapter there will be given, in tabular form, a fairly complete listing of the coefficients of sound-absorption of materials which are used in building construction, and especially for acoustical purposes.

In many instances the same material has been measured by different investigators, and the results are not always in good agreement. This lack of agreement can be attributed to several factors, such as actual differences in the samples, differences in the methods of measurement, differences in the purity of the test tone used, and probably other factors which have not yet been fully determined. In such cases, the author has taken certain liberties in obtaining average results. The justification for this exercise of judgment in arriving at average values is based upon an attempt to give results for all materials which will be as nearly comparable as possible. In general, the results of different authorities are not seriously discordant, but where average results are given they represent what the author believes to be the most probable values of the absorption coefficients.

The results given in the tables are based upon the measurements of such authorities as W. C. Sabine, Paul E. Sabine, F. R. Watson, V. L. Chrisler[1] and W. F. Snyder,[1] E. T. Paris,[2] V. O. Knudsen, and others. There are included in the tables results of measurements on materials and combinations of materials obtained by the author and not heretofore published. This is made possible through the generous per-

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[1] Bureau of Standards, Washington, D. C.

[2] Building Experiment Station, London.

mission of many concerns for whom the measurements initially were made.

76. Relation between Sound-Absorption and Thickness of Felted Materials and Plasters. Many measurements have been made by different investigators to ascertain how the thickness of an acoustical material affects the coefficients of sound-absorption. In Fig. 98 are

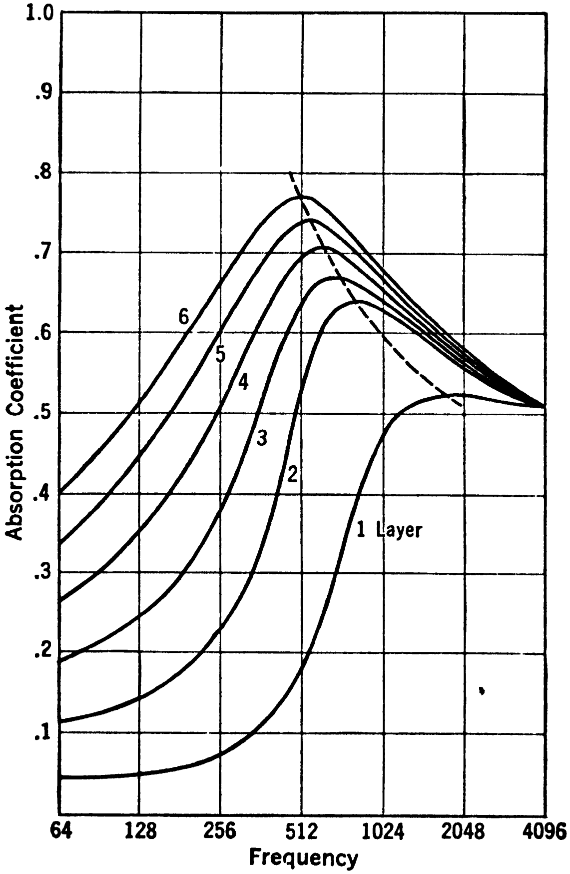

FIG. 98. Curves showing the absorption characteristic of hair felt of different thicknesses. (*W. C. Sabine.*)

shown the results of W. C. Sabine for the coefficients of sound-absorption of different thicknesses of hair felt from 1.1 centimeters (0.43 inch) in thickness to 6.6 centimeters (2.60 inches). It will be noted that the principal effect of increasing the thickness is to increase the absorption at the low frequencies. The coefficient of sound-absorption at 4096 is practically independent of the thickness of the material. It will be noted also that the maximal absorption occurs at a frequency which is dependent upon the thickness, shifting toward lower frequencies as the thickness of the felt increases. This shift in the frequency at which maximal absorption occurs suggests that there is some sort of resonance, probably caused by flexural yielding, that is, by the vibration of the entire felted material. As the thickness of the material increases, the mass increases proportionately, and therefore it is to be expected that the resonant frequency, which is inversely proportional to the square root of the mass or inertia factor, will shift toward lower frequencies as the thickness (or mass) of the material is increased.

In Fig. 99 are shown the results of Wente and Bedell on the absorption coefficients of hair felt of different thicknesses. The measurements given by Wente and Bedell were obtained by the "tube method" of measuring sound-absorption. (See Sec. 71.) There is a fair agreement between these results and those obtained by W. C. Sabine, although resonance peaks are not conspicuous in Wente and Bedell's curves, and the agreement is not very good for frequencies above 1000.

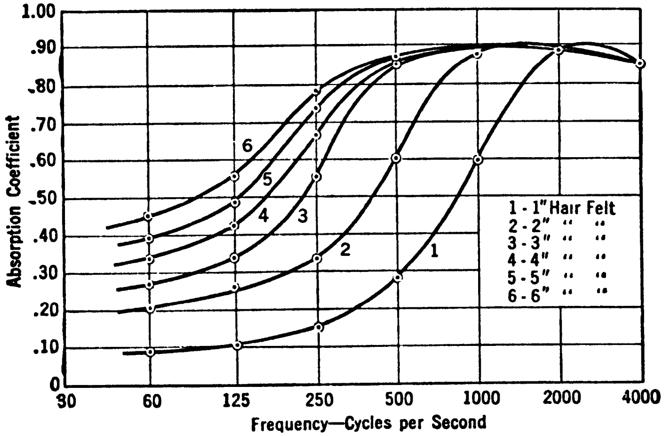

FIG. 99. Curves showing the absorption characteristic of hair felt of different thicknesses. (*Wente and Bedell.*)

In Table V are shown the results of measurements by E. T. Paris, also obtained by the tube method, which exhibit the effect of the thickness of hair felt upon the coefficients of sound-absorption. The sample of felt investigated by Paris consisted of one to four layers of hair felt, each layer having an average thickness of 0.46 inch and a weight of 8.5 ounces per square foot. The samples were tested at a frequency of 512.

TABLE V

Number of Layers	Approximate Thickness, inches	Coefficients of Sound-Absorption at 512 cycles
1	0.5	0.21
2	0.9	0.52
3	1.4	0.69
4	1.8	0.69

In Fig. 100 are shown the results of measurements at 512 cycles on different thicknesses of hair felt obtained by W. C. Sabine, by Wente and Bedell, by E. T. Paris, and by V. O. Knudsen. The results of Wente and Bedell and of Paris were obtained by the " tube " or " stationary-wave " method, whereas the results of W. C. Sabine and of Knudsen were obtained by the reverberation method. It is reasonable to expect that the results obtained by these two methods are not directly comparable. In the stationary-wave method the sound waves strike the absorbing surface only at normal incidence, whereas in the reverberation method the sound waves strike the absorbing surface at all possible angles of incidence. The almost perfect agreement between the results of W. C. Sabine and

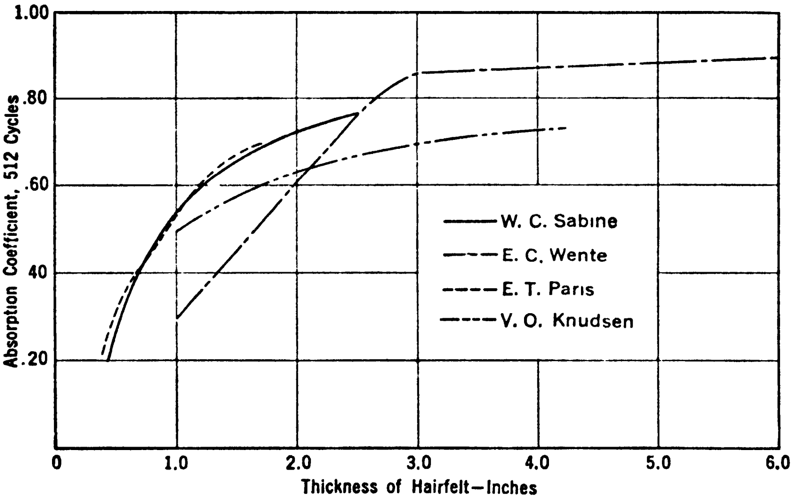

FIG. 100. Summary of absorption measurements on hair felt made at different laboratories showing not only the effect of thickness but the order of agreement of measurements made at different laboratories.

those of Paris is probably accidental, and is not typical, unfortunately, of the lack of agreement which is characteristic of most absorption measurements. For example, a comparison of absorption coefficients obtained at the Bureau of Standards on the same materials by the reverberation method and by the tube method will show discrepancies of more than 100 per cent. In general, however, the agreement among the results from different laboratories is about as good as is indicated by the four curves in Fig. 100, and fortunately this is sufficiently good for nearly all practical purposes.

The results of measurements on the absorption coefficient for hair felt of different thicknesses indicate in general that the absorption increases with the thickness of the absorbing material, especially at low frequencies. For frequencies below 512, the absorption coefficient is nearly proportional to the thickness of the hair felt, for thicknesses of less than 3 or 4 inches. For frequencies above 512, the absorption increases up to a thickness of 1 or 2 inches, above which thickness the absorption coefficient remains nearly constant. All the results indicate that in order to obtain a fairly uniform absorption throughout the range of frequencies from 128 to 4096 cycles by means of porous felted materials, it is necessary to use a thickness of at least 4 to 6 inches. However, a thickness of 1 to 2 inches will give the type of absorption characteristic required for most speech and music rooms.

The data in Table VI show the effect of thickness upon the coefficients of sound-absorption of balsam wool.

TABLE VI

Thickness, inches	Coefficients of Sound-Absorption				
	128 cycles	256 cycles	512 cycles	1024 cycles	2048 cycles
½	0 06	0 22	0 41	0 58	0 57
1	10	.25	46	62	60
2	21	38	58	69	70
4	34	48	65	75	76

It will be noted that the results for the balsam wool of different thicknesses are not essentially different from those obtained for hair felt; that is, an increase in thickness has a more pronounced effect upon the absorption at the low frequencies than it does upon the absorption at the high frequencies.

In Table VII are shown the results of measurements on a certain brand of acoustical plaster, ½, ¾, and 1 inch thick.[3] (Data by the author.)

TABLE VII

Thickness, inches	Coefficients of Sound-Absorption					
	128 cycles	256 cycles	512 cycles	1024 cycles	2048 cycles	4096 cycles
½	0.09	0.14	0.17	0.18	0.20	0.28
¾	.11	.16	.18	.19	.20	.29
1	.13	.17	.18	.19	.20	.26

It will be noted that acoustical plaster becomes somewhat more absorptive at the low frequencies as the thickness is increased, but that the increase of absorption with thickness is not so pronounced as it is for hair felt or balsam wool. Thus, whereas the absorption coefficient at 128 cycles for hair felt and balsam wool was nearly proportional to the thickness, the coefficient for the plaster increased from only 0.09 to 0.13 when the thickness was doubled. This is no doubt attributable to differences in the sound-transmission characteristics of the two materials — the sound is quite readily transmitted into the porous structure of the felt but not so readily into the plaster.

77. Effect of Stippling Acoustical Plaster. In Table VIII are shown the effects of stippling an acoustical plaster with a wire brush. (Data by the author.) The holes produced by the stippling were spaced approximately ¼ inch on centres both ways. It will be seen that the stippling increases the absorption of the acoustical plaster. The results are somewhat similar to those obtained by drilling holes in an acoustical fibre board. Thus, a piece of ordinary cane fibre board, 1¼ inches thick, has an absorption coefficient at 512 cycles of approximately 0.30, whereas the same material with many holes drilled deeply into it has a coefficient of approximately 0.70 at 512 cycles.

78. Effect of Varying the Amount of Binder in Acoustical Plasters. The absorption coefficients of such materials as acoustical plasters are

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[3] In another series of tests conducted by the author for the purpose of determining the effect of thickness on the absorptivity of a certain brand of acoustical plaster, it was found that a ½-inch thickness was more absorptive than a ¾-inch thickness of the same plaster. This probably means that the manner of mixing and applying the plaster has a potent influence on the resulting absorptivity, and indeed experience with numerous installations of acoustical plaster has confirmed this inference.

Table VIII

Description	Coefficients of Sound-Absorption				
	128 cycles	256 cycles	512 cycles	1024 cycles	2048 cycles
$\frac{1}{2}$ in. thick, float finish...	0.11	0.16	0.20	0.30	0.36
$\frac{1}{2}$ in. thick, lightly stippled	.14	.18	.22	.31	.37
$\frac{3}{4}$ in. thick, stippled to depth of $\frac{3}{8}$ in.	.16	.20	.25	.37	.45

very much dependent upon the composition. Most acoustical plasters contain either pumice or slag as the aggregate material, and either magnesite, cement, gypsum, lime, or special preparations as the binder material. In Table IX are given the results obtained by E. T. Paris on different specimens of acoustical plaster, in which the relative amounts of slag and magnesite were varied. All three specimens were of a uniform thickness of 1 inch, and were backed by a thin layer of cement.

Table IX

Description of Specimen	Coefficients of Absorption		
	380 cycles	512 cycles	650 cycles
Acoustical Plaster ($3\frac{3}{4}$ parts slag to 1 part magnesite).. . .	0.18	0.25	0.27
Acoustical Plaster ($4\frac{3}{4}$ parts slag to 1 part magnesite)	.18	.27	.30
Acoustical Plaster ($6\frac{1}{12}$ parts slag to 1 part magnesite).	.21	.31	.36

It will be noted, as would be expected, that the absorption coefficient increases as the amount of binder is decreased. That is, the absorption coefficient increases as the material becomes more and more porous.

Frequently special chemicals are added to acoustical plasters which form bubbles or slowly evolve gas as the plaster takes its initial set. This expedient often will increase the porosity and consequently the absorptivity of the plaster.

79. Effect of " Packing " in Felted and Loose Materials. The effect on the absorption coefficient of packing a loose material, like hair felt, is shown in Fig. 101, which gives the results of tests by Wente and Bedell on a layer of hair felt which has a normal thickness of 1 inch. The felt was tested at its normal thickness, when it was expanded to a thickness of 2 inches, and when it was compressed to a thickness of $\frac{5}{8}$ inch. It will be seen that the chief effect of expanding the felt, so that it is very loosely packed, is to increase the absorption coefficient between about 200 and 2000 cycles, and to decrease slightly the absorption coefficient at frequencies below 200 cycles. Somewhat similar results on the effect of changing the density of a material like rock wool are shown in Table XIV, p. 210.

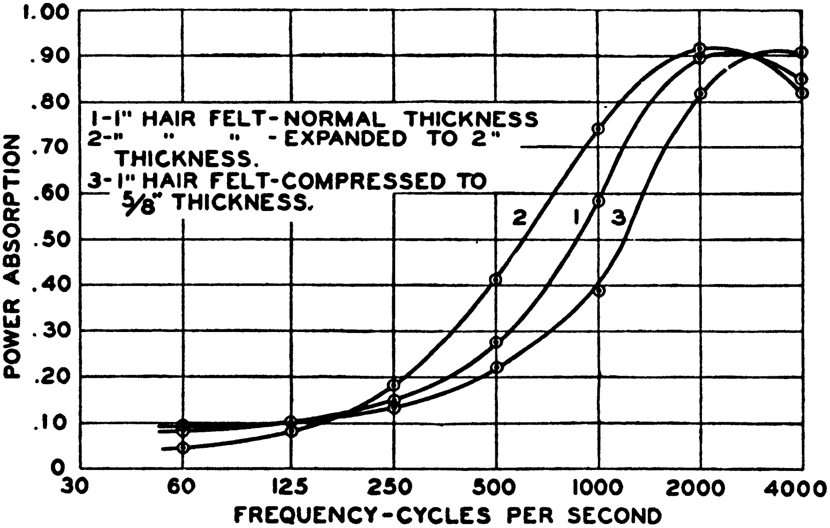

FIG. 101. Effect on absorption of "packing" of a loose felted material. (*Wente and Bedell.*)

80. Effect of Painting Acoustical Plasters and Fibre Boards. The matter of decorating acoustical materials is a problem of prime importance. It is apparent that materials which owe their sound-absorptive properties to their porous structure may be greatly impaired by any treatment with oil or water paint, varnish, distemper, or other materials which will close, or partially close, the surface pores. The results of painting acoustical plaster with one and two coats of distemper are shown in Table X. (Data by Paris.) See also data on painted " Kalite," Table XII, p. 199, which show that three coats of lacquer reduce the absorptivity about 15 per cent.

TABLE X

Condition of Acoustical Plaster	Coefficients of Absorption	
	256 cycles	512 cycles
Unpainted	0 16	0 29
One coat of distemper	06*	13
Two coats of distemper	05*	11

* These figures are to be regarded as upper limits to the coefficients, since, on account of the small amount of sound absorbed, the measurements become inaccurate with the stationary-wave method.

The application of one and two coats of distemper is thus seen to impair greatly the absorption coefficients of acoustical plaster. Other heavy or non-porous paints will be fully as injurious. Many installations of acoustical plaster have been ruined by decoration with such paints as oil and lead, casein, and heavy water paints. Viscous or heavy paints *bridge over* or *close* the surface pores.

On the other hand, there are various methods of decorating acoustical plaster without impairing its absorptive value. For example, thin aniline dyes, gasoline or kerosene stains, thin lacquer sprays, and dry paint dusted onto the plaster with a pounce-bag are found to offer satisfactory means of decoration without impairing the absorptive value of the plaster. Actual tests made on a specimen of acoustical plaster decorated with a thin kerosene spray indicated no measurable loss in absorption after one and two applications of the stain.

Fibre boards are subject to the same decorative limitations as are acoustical plasters. When decorated with non-porous paints these fibre boards lose a large portion of their absorptive value. However, the thin stains and sprays recommended for acoustical plaster are also suitable for fibre boards. Tests on fibre boards decorated with kerosene, gasoline, or alcohol stains have shown that these decorative agents can be used without more than a 10 per cent impairment of the absorptive value of the fibre board.

81. Spacing and Pattern Effects. The absorption contributed to a room by a certain amount of absorptive material depends upon its location and distribution in the room. There are always diffraction effects around the edges of an absorptive material, so that the shape and distribution of the material will affect the total amount of absorption supplied by the material. Acoustical material installed in panels, for example, will provide a greater amount of absorption than will a continuous surface of the same area. In addition, the shape of the room and the location of the material in the room will determine, as was shown in Sec. 55, the number of encounters the decaying sound waves will make per second against the absorptive material, and hence will determine the effective absorption of the material in the room.

The effect of spacing and pattern has been investigated by Parkinson[4] in a series of tests conducted at the Riverbank Laboratories. The effective absorption of 48 square feet of 1-inch " Akoustikos Felt " was determined first when the material was in a single panel 6 feet by 8 feet, and then when the material was broken up into small squares and rectangles of different sizes and with different spacings. The coefficients of absorption for the material (that is, the total absorption contributed by the material divided by the area of 48 square feet), corresponding to different arrangements of the material, are given in Table XI. The pattern and spacing are seen to affect very considerably the effective absorption a certain amount of material will contribute to the room.

TABLE XI

Area of Each Unit	Width of Spacing	Absorption Coefficients					
		128 cycles	256 cycles	512 cycles	1024 cycles	2048 cycles	4096 cycles
6 ft. by 8 ft.	No spacing	0 11	0 31	0 59	0 68	0 58	0.46
2 ft. by 2 ft.	2 ft.	.07	.30	.78	0 96	.78	48
2 ft. by 2 ft.	4 ft.	.11	32	.93	1 17	86	.62
1 ft. by 8 ft.	1 ft.	.10	.30	.73	0 82	76	.71
1 ft. by 8 ft.	2 ft.	.11	.30	.78	0 94	79	.70
1 ft. by 8 ft.	3 ft.	.11	.32	.85	1 15	.84	.66
2 ft. by 8 ft.	1 ft.	.09	.30	.74	0 79	68	.60
2 ft. by 8 ft.	2 ft.	.09	.31	.76	0.84	.71	.65
2 ft. by 8 ft.	4 ft.	.11	.31	.79	1 05	.74	.60

82. Tabulated Results on Coefficients of Sound-Absorption of Building Materials.

In the following tables are given the results of sound-absorptive measurements on nearly all the important materials now used in building construction, and especially the materials which are used for the acoustical treatment of architectural interiors. As mentioned earlier

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[4] J. S. Parkinson, "Area and Pattern Effects in the Measurement of Sound-Absorption," Jour. Acous. Soc., 2, 112 (July, 1930).

in this chapter, the tabulated results indicate what the author considers the most probable values of the coefficients of sound-absorption obtained by investigators in the United States and England. Data also are given for different types of chairs and for a seated audience.

Included in the tables are brief descriptions of the composition or special features of the material. Such features as structural strength, maintenance, adaptability, and other features are discussed in a section following the tables of coefficients. In addition, a large number of photographs are reproduced which show the general appearance, texture, and some of the structural details of representative types of material.

It should be mentioned that owing to the active interest in acoustics at the present time improvements of existing materials and developments of new materials are announced almost every week. Likewise, many materials are being discontinued, so that it is an almost impossible task to tabulate those (and only those) materials which are actively used in building construction. The author has attempted to make a fairly complete tabulation of all materials which have been used, which are being used, or which are available for use, in the building industry. Naturally, such a tabulation includes a large number of materials, many of which may be unimportant or even destined for obsolescence. The reason for including such materials is that they may be found in existing buildings, in which case the coefficients may be useful in connection with questions in acoustics which may arise in these buildings. Finally, it should be mentioned that because of the rapid and remarkable developments in acoustical materials, tests which were made on a material two or three years ago may not represent the absorptivity of that material today. For example, many acoustical plasters which had coefficients (at 512 cycles) of 0.15 to 0.20 a year ago may have been improved so that their coefficients today are in excess of 0.35. On the other hand, many of the staple products of the larger acoustical concerns have not changed for several years, and it is likely that many of these products will be continued for several years without appreciable change of absorptivity.

In order to facilitate quick and convenient use of the tables the materials have been grouped as follows: Table XII, Acoustical Plasters; XIII, Acoustical Tiles; XIV, Acoustical Felts, Wools, and Granulated Materials; XV, Fibre and Wall Boards; XVI, Hangings, Floor Coverings, and Miscellaneous Materials; XVII, Hard Plasters, Masonry, Wood, and Other Standard Building Materials; XVIII, Combinations of Acoustical Materials; and XIX, Audience, Individual Persons, Chairs and Other Objects. The different materials or objects in each table have been arranged in alphabetical order.

Table XII

ACOUSTICAL PLASTERS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Acoustico	¾	0.17	0 23	0 28	0 36	0 64		Bureau of Standards	1930
Akoustolith	¼	.18	20	.24	.30	34	41	C. M. Swan	
Akoustolith	½	.21	24	.29	.33	37	42	"	
Akoustolith, float finish	½	.17	.21	.27	33	38	.40	Average	
Ambler Sound Absorbing Plaster	.	.03	.06	.14	.17	19	.11	F. R. Watson	1926
Blue Diamond Acousticoat, gypsum base	½	.07	..	.13	..	.19	.	V. O. Knudsen	1929
Blue Diamond Acousticoat, lime base, float finish	½	.11	.16	.18	.26	30	..	"	1928
Blue Diamond Acousticoat, over metal lath.	¾	.31	.39	.42	.47	.50	.45	"	1931
Blue Diamond Acousticoat, over hardwall on metal lath	½	.29	.37	.36	.60	.75	74	"	1931
Blue Diamond Acousticoat, over hardwall on metal lath	1	.38	.50	.60	.75	.70	.72	"	1931
Blue Diamond Acousticoat, over scratch coat on metal lath	½	.21	.24	.35	.50	.55	.64	"	1931
Blue Diamond Acousticoat, over scratch coat on metal lath	¾	.33	.42	.46	.61	.60	.55	"	1931
Blue Diamond Acousticoat, over scratch coat on metal lath	1¼	.42	.47	.55	.62	.64	.67	"	1931
Calacoustic, floated	½	.08	.12	.17	.21	.24	.29	"	1926
Calacoustic, deeply stippled	1	.16	.19	.23	.30	.40	.43	"	1926

TABLE XII — (*Continued*)

ACOUSTICAL PLASTERS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Eclipse.... .	1/2	0 12	0.15	0.19	0.24	0.26	0.29	V. O. Knudsen	1930
Eclipse, over scratch coat	1/2	.16	.	.25	.	.26	..	"	1930
Gimco..........	3/4	.	32	.30	36	.42	..	F. R. Watson	1930
Halico, floated...... .	1/2	17	.14	14	.16	.15	..	Bureau of Standards	1930
Halico, stippled.... .	1/2	.16	.19	.25	.36	.44	..	"	1930
Kalite, No. 1, on plaster board	3/4	27	.30	.37	.55	.57	.64	V. O. Knudsen	1930
Kalite, No. 100, on metal lath	3/4	.44	..	.55	..	.70	..	"	1930
Kalite, No. 102, on metal lath..	3/4	.37	.45	.39	.47	.53	.65	"	1930
Kalite, over hardwall on metal lath, No. 102 finish coat.....	1/2	.16	..	.21	.	.29	.	"	1930
Kalite, No. 103, on metal lath	3/4	39	..	.40	..	.48	..	"	1930
Kalite, No. 104, as installed in a room	1/2	.18	..	.24	..	.30	..	"	1931
Kalite, as installed in a room........	5/8 11/16	.16	..	.31	..	.38	..	"	1931
Kalite Cast Acoustic Plaster Tamped.......	1 1/4	.29		.60	..	.71	..	"	1931
Kalite Super Plaster A, three coats on metal lath............	1 1/4	.50	.59	.64	.61	.67	.83	"	1930
Kalite, unpainted......	3/4	.41	..	.51	..	.59	..	"	1930
Kalite, with one coat lacquer............ .	3/4	.37	..	.46	..	.51	..	"	1930
Kalite, with three coats lacquer........	3/4	.35	..	.43	..	.45	..	"	1930
Macoustic, float finish.	..	.09	.13	.19	.21	.26	.27	Bureau of Standards	1929

TABLE XII — (*Continued*)

ACOUSTICAL PLASTERS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Macoustic, stippled with fibre brush....	½	0 09	0 14	0 22	0 27	0 41	0 55	Bureau of Standards	1929
Macoustic, stippled to depth of ½ in....	.	12	20	31	39	58	65	"	1929
Malone, on ¼-in. wall board backing. "Left under the rod."	⅝	15	29	27	28	28	30	V. O. Knudsen	1931
Malone, over hardwall on ⅜-in. plaster lath	⅜	13	14	20	46	48	.45	"	1931
Malone, over hardwall on ⅜-in. plaster lath .	⅝	15	17	33	58	52	45	"	1931
Malone, over special scratch coat on metal lath.	..	39		50		56		"	1931
Mineral Wool Acoustic Plaster.. . .	½	15		38		35		"	1930
National, stippled ..	⅝	13	17	22	29	34	46	"	1930
National, Type S ..	¾	15	22	46	52	64	43	"	1930
National, Type S, over hardwall scratch coat on wire lath... .	½	.235	25	31	42	53	48	Electrical Research Products*	1931
Nephi, smooth finish	¾	08	12	14	20	24	.	V. O. Knudsen	1927
Nephi, rough dash finish.......	¾	10	13	16	23	.28		"	1928
Nephi, on metal lath .	½	.16	40	.43	.44	.49	52	"	1931
No-Echo, smooth finish	½	.05	08	.13	22	.35	.	"	1929
No-Echo, rough float. .	¾	.11	.15	17	.21	.32		"	1929
No-Echo, on metal lath.	1¼	.	..	.50	..	..	.	"	
Reverbolite, stippled with large pins........	½	.07	.15	.34	.47	.65	..	Bureau of Standards	1930
Sabine Plaster, fixed as tiles...	¾	.07	.07	.23	.43	.27	.41	Building Research Station	

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* Sound-absorption coefficients from Electrical Research Products Laboratories are for frequencies of 125, 250, 500, 1000, 2000, and 4000 cycles.

TABLE XII — (*Continued*)

ACOUSTICAL PLASTERS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients, cycles per second: 128	256	512	1024	2048	4096	Authority	Year Tested
Sabine Plaster, modified by Building Research Station, trowel applied	1	0 11	0 11	0 29	0 47	0 29	0 38	Building Research Station	
Sabinite	½	08	14	.18	.25	31	35	Average	Before 1930
Sabinite ..	½		20	34	48	49	47	P. E. Sabine	
Sabinite, improved standard			20	31	39	.38	43	"	
Sabinite, No. 38, for swimming pools		10	24	38	.42	41	.41	"	
Simphonic, stippled	¾	10	12	.16	.21	24	.27	V. O. Knudsen	1929
Stucoustic, float finish	½	.12	16	.19	.24	31	..	"	1929
Stucoustic, float finish	½	.18	.	.24	.	26	.	"	1930
Western Acoustic Plaster, drag finish	½	25		32		50	..	"	1931
Zono. . .	..	..	.30	31	.29	.30	.24	Anderson University of Toronto	
Zonolite.	¾	.16	22	.25	.32	.38	..	V. O. Knudsen	1929

TABLE XIII

ACOUSTICAL TILES

Brand or Make	Thickness, in.	Sound-Absorption Coefficients, 128 cycles per second	256	512	1024	2048	4096	Authority	Year Tested
Acoustex, composition tile made of excelsior and magnesium oxychloride	1	0 16	0 23	0 37	0 64	0 65	0 55	C. M. Swan	1928
Acoustex	1	.		37				F. R. Watson	1929
Acoustex, 60	1	10	23	54	74	63	55	P. E. Sabine	1930
Acoustex, 60, spray painted	1	16	24	51	71	72	60	Bureau of Standards	1930
Acoustex, 70	1½	14	34	68	82	63	52	P. E. Sabine	1930
Acoustex, 70	1½	16	34	75	85	84	93	Bureau of Standards	1931
Acoustex, 70, painted, four coats	1½		29	.73	90	85		"	1931
Acoustex, spray painted	1½	22	.31	59	.73	73		"	1930
Acoustex	2	22	41	64	86	84		"	1930
Acousti-Celotex, Type A	13/16	.14	.16	24	23	23	23	Average	Before 1929
Acousti-Celotex, Type B	13/16	22	28	47	53	62	62	"	Before 1929
Acousti-Celotex, Type BB	1¼	28	42	.65	.73	77	77	"	Before 1929
Acousti-Celotex, Type C	⅜	14	.16	.30	45	57	55	"	Before 1929
Acousti-Celotex, Single B	⅝	.11	25	.45	.61	.68	.74	"	1931
Acousti-Celotex, Double B	11/16	.17	32	57	.72	.69	70	"	1931
Acousti-Celotex, Triple B	1¼	20	.41	.75	.86	67	.59	"	1931
Acousti-Celotex, Mineral Fibre Tile	1¼	.22	.32	.84	.80	.87	.87	Bureau of Standards	1931
Acoustone, No. 46	½	..	.19	.46	55	.48	.	P. E. Sabine	1930
Acoustone, No. 62	¾	..	.30	.62	.64	.55	..	"	1930
Acoustone, No. 60	1	..	.41	.60	.64	.53	..	"	1930
Acoustone, No. 47	½	..	.17	.44	.59	.60	..	Bureau of Standards	1930
Acoustone, No. 56	¾	..	.27	.53	.62	.60	..	"	1930

Table XIII — (*Continued*)

ACOUSTICAL TILES

Brand or Make	Thickness, in.	Sound-Absorption Coefficients, cycles per second: 128	256	512	1024	2048	4096	Authority	Year Tested
Acoustone, No. 61....	1		0 37	0.59	0 64	0 61		Bureau of Standards	1930
Acoustone..	½		18	48	.62	59	52	Average	Before 1931
Acoustone ...	¾	.	.28	.62	66	70	.53	"	Before 1931
Acoustone..	1		.42	65	67	69	.53	"	Before 1931
Akoustolith	⅞	.10	21	30	.42	46	42	"	Before 1930
Akoustolith A	1	14	19	.48	.72	.83	.	Bureau of Standards	1931
Akoustolith B...	1	10	.14	28	65	73		"	1929
Akoustolith C...	1½	12	.19	44	61	66		"	1930
Akoustolith C...	2	19	.26	53	64	.70	.	"	1930
Akoustolith D...	1	08	.13	25	54	67		"	1930
Akoustolith D.	2	15	.26	59	.74	52		"	1930
Akoustolith Sound-Absorbing Stone	1	.06	14	38	.52	.53	35	C. M. Swan	
Alltite Acoustical Blocks	1½	28	46	60	64	.62	.64	V. O. Knudsen	1930
Alltite Acoustical Tile	1½	38	.55	69	.75	81	.85	"	1929
Armstrong Cork Board, .875 lb. per square foot.	1		.08	.30	.31	.28	.	F. R. Watson	Before 1927
Armstrong Cork Board, like above, sprayed with cold water paint	1	.	.07	.30	.28	.29	..	"	Before 1927
Armstrong Cork Board, 1.6 lb. per square foot.	2	.	.17	.35	27	.34	..	"	Before 1927
Calicel, undecorated...	1	.23	.33	.72	.75	.71	.46	Electrical Research Products*	1931
Calicel, one coat lacquer................	1	.25	.32	.71	.73	.70	.48	"	1931

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* Sound-absorption coefficients from Electrical Research Products Laboratories are for frequencies of 125, 250, 500, 1000, 2000, and 4000 cycles.

TABLE XIII — (*Continued*)

ACOUSTICAL TILES

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Calicel, two coats lacquer	1	0 22	0 35	0 70	0 76	0 72	0 48	Electrical Research Products*	1931
Corkoustic	1½	.08	13	32	34	40	50	V. O. Knudsen	1929
Fir-Tex Decorated Board	½	.14	.19	.38	.64	.80	.68	"	1932
Fir-Tex Decorated Board	1	.20	32	.69	.73	.85	.70	"	1932
Herman, E. T., Acoustical Tile	1¼	.09	15	23	.33	50	.75	"	1931
Insulite Acoustile, nailed to wood strips, 12-in. o.c.	¾	.21	.30	.38	.44	.46	.50	"	1930
Insulite Acoustile: ¾-in. low density board with sanded surface glued to 13/16-in. Standard Insulite board; ⅛-in. air space between boards	1 11/16	.26	.42	.50	.57	.61	.59	Bureau of Standards	1931
Kendall and Delaney's Rock Wool Tile	1	.38	.45	.43	49	63	.59	V. O. Knudsen	1931
Laminated Acoustic Tile	1	.14	.26	.54	.68	.75	..	Bureau of Standards	1930
Laminated Acoustic Tile	1½	.22	37	60	.72	76	..	"	1930
Mutetile		.46	.71	.76	.94	.67	.53	"	1932
Nashtile	¾	..	..	.38	..	.	..	Johns-Manville	Before 1931
No-Echo Tile	¾	.13	.21	.39	.50	.51	.55	V. O. Knudsen	1930
No-Echo Tile (Zonolite)	⅞	.21	.27	.35	.40	.43	.45	"	1929
Porolith Rock Wool Tile	7/16	.10	.23	.56	.84	.87	.89	Bureau of Standards	1931
Porous breeze concrete blocks, set in 1 : 3 cement-sand mortar	2	.15	.21	.43	.37	.39	.51	Building Research Station	

TABLE XIII — (*Continued*)
ACOUSTICAL TILES

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Rockoustile . .	1	0 18	0 38	0 57	0 65	0 72	0.80	Bureau of Standards	Before 1931
Rumford Tile	1	09	.18	29	34	.34	30	W. C. Sabine	Before 1915
Sanacoustic Tile .	1¼	19	.46	79	82	74	.56	Average	1931
Sanacoustic Tile, enameled steel or enameled aluminum	.	.		82			.	Johns-Manville	Before 1931
Slagbestos slabs, ¾ in. from wall. .	1½	32	38	.65	73	30	29	Building Research Station	
Slagbestos slabs, 1½ in., with canvas cover 1 in. distant............	2½	42	49	80	78	47	42	"	
Soundex	1	11	13	27	50	.63	.40	P. E. Sabine	1929
Soundex	2	09	35	60	67	.45	.53	"	1929
Soundex, spray painted	1 3/16	.10	22	36	53	72	.	Bureau of Standards	1929
Soundex, spray painted	1 7/16	.21	26	48	68	.75	.	"	1929
TMB Acoustic Metal Tile with 1¼-in. Gimco rock wool filler. . .	. ..	.	62	80	79	.70	.	F. R. Watson	1931
TMB Acoustic Metal Tile with 1¾-in. Gimco rock wool pad......	..	.39	50	86	90	81	.75	Bureau of Standards	
Transite Acoustical Tile..................	..	.19	.39	81	.77	.72	.55	"	Before 1931
Trutone...............	1	22	.30	.39	.47	.53	..	V. O. Knudsen	1929
Trutone.....	2	.29	.35	.47	.49	.55	..	"	1929
Trutone, on ⅜-in. plaster board..	1⅛	.31	.39	.57	.70	.64	.52	"	1931
Zenitherm: cork granules compressed into a porous tile; 2.07 lb. per square foot.......	1.14	.03	.13	.33	.42	.42	.15	F. R. Watson	1927

Table XIV
ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Acoustic Flexfelt.	1¼		0 46	0 57		0 72		F. R. Watson	
Acoustic Flexfelt	1	27	40	.56	.65	68		Knudsen	1929
Acoustic Flexfelt	1½	.40	49	.61	.67	69		"	1929
Acoustic Flexfelt ...	6	.53	.59	.69	.61	.67		"	1929
Acoustic Flexfelt, 1 in. layer separated from 1½-in. layer by 1-in. air space	3½	51	60	65	71	73		"	1929
Auditec, on 1-in. furring strips 16 in. o.c.	⅜	.07	16	25	44	47	51	P. E. Sabine	1930
Auditec, de Luxe, on 1 in. by 2 in. furring strips, 24 in. o.c.. ..	¾	10	23	.45	.72	58	50	"	1931
Auditec, de Luxe, hung 1½ in. from wall . . .	¾	10	28	.52	81	67	53	"	1931
Balsam Wool, 0.258 lb. per square foot........	1	.12	25	49	63	65	60	Average	
Balsam Wool, 0.52 lb. per square foot.......	2	.23	40	.58	69	70	66	V. O. Knudsen	1928
Balsam Wool, 1.03 lb. per square foot	4	.36	50	.65	.75	.76	.72	"	1928
Balsam Wool, scrim facing............. ...	1	.18	.36	55	.65	67	..	Bureau of Standards	1930
Blast Hair Blanket, 8 oz. per square foot....	2	..	.	85			..	Johns-Manville	Before 1931
Blast Hair Blanket, 8 oz. per square foot, hung in curtain form against wall..........	2	.285	.595	765	82	765	665	P. E. Sabine and Bureau of Standards	
Broadcasting and Recording Studio Treatment........	4	..	..	.695	..	..	..	Johns-Manville	Before 1931
Cabot's Quilt, three-ply, two layers 1½ in. from wall with canvas cover 1 in. from Quilt.		.22	.42	.74	.77	.69	.44	Building Research Station	

TABLE XIV — (*Continued*)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Cushocel. . . .	¾		0 14	0 35	0 33	0 22	.	F. R. Watson	1930
Dry-Zero: kapok fibres covered with burlap	2	38	.51	.62	.63	65	. .	V. O. Knudsen	1929
Dry-Zero, in burlap .	2	22	.35	61	80	91	98	Bureau of Standards	1929
Dry-Zero, in muslin	2½	28	48	68	82	98	97	"	1929
Felt, Asbestos-Akoustikos: hair and asbestos fibre	½	09	14	.29	.50	.62	.56	Average	
Felt, Asbestos-Akoustikos	¾	11	21	.40	.64	.68	62	"	
Felt, Asbestos-Akoustikos .	1	15	29	.54	.70	73	62	"	
Felt, Asbestos-Akoustikos.	1½	.13	41	73	.73	.58	.46	P. E. Sabine	
Felt, Asbestos-Akoustikos. .	2	24	48	74	79	.76	65	Average	
Felt, Asbestos-Akoustikos	3	35	57	78	84	78	67	"	
Fibrofelt	½	. .	.	.43				C. F. Burgess Laboratories	1928
Fibrofelt.............	1	.	.	62				"	1928
Flax Wool..	. .	.09	18	.48	73	.50	.33	Wente and Bedell	Before 1928
Hair felt, 100 per cent hair....	1	.12	32	51	.62	.60	.56	Average	
Hair felt, as above. . .	2		. .	.68	. .	. .	. .	"	
Hair felt, as above . .	4	.	. .	.79	.		. .	"	
Hair felt, cloth membrane (0.87 oz. per square foot) stretched near surface.........	. .	.20	.40	.65	.27	.14	.11	Building Research Station and W. C. Sabine	Before 1915
Hair felt, membrane (2.58 oz. per square foot) stretched near surface.............	. .	.29	.41	.32	.19	.11	.08	"	Before 1915

TABLE XIV — (*Continued*)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Hair felt, as above, 2 in. from wall	.	0 11	0.26	0 62	0 73	0 66	0 45	Building Research Station and W. C. Sabine	Before 1915
Hair felt, as above, 4 in. from wall	.	13	30	66	74	66	45	"	Before 1915
Hair felt, as above, 6 in. from wall	..	15	35	68	75	66	.45	"	Before 1915
Jute-felt	½	05	08	.17	48	52	51	W. C. Sabine	Before 1915
Jute-felt	1	15	22	54	63	57	.52	"	Before 1915
Jute-felt	1½	24	38	.63	65	57	52	"	Before 1915
Jute-felt	2	34	50	69	67	.58	52	"	Before 1915
Jute-felt	2½	43	59	75	67	58	52	"	Before 1915
Jute-felt	3	50	66	77	68	58	52	"	Before 1915
Linofelt, commercial	1	.17	.24	.41	.50	57	.70	V. O. Knudsen	1930
Nashkote A, perforated after erection	½	.08	15	.43	.62	65	58	Bureau of Standards	1929
Nashkote A, as above	¾	.11	.21	.51	.68	.71	.68	"	1929
Nashkote A, as above	⅞	..	..	.67	..	..	..	"	Before 1931
Nashkote A, as above	1	.13	.26	.58	.73	.77	.71	Bureau of Standards	1929
Nashkote A, as above	1	.12	.33	.68	.75	.66	.54	Average	1929
Nashkote AIS	½	.07	.19	.30	.40	.42	.33	Bureau of Standards	1929
Nashkote AIS	¾	.09	.25	.36	.44	.48	.39	"	1929
Nashkote AIS	1	.10	.32	.41	.50	.56	.47	"	1929
Nashkote AIS	½	..	..	.31	..	..	..	"	Before 1931

TABLE XIV — (*Continued*)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Nashkote AIS	¾			0.38				Bureau of Standards	Before 1931
Nashkote AIS	⅞			46				"	"
Nashkote ACS	½			31				"	"
Nashkote ACS	¾			38				"	"
Nashkote ACS	⅞			46				"	"
Nashkote B-322	1	0.15	0.28	59	0.79	0.77	0.63	"	"
Nashkote B-332	½			43				"	"
Nashkote B-332	¾			53				"	"
Nashkote B-332	⅞			67				"	"
Nashkote B-085	½			36				"	"
Nashkote B-085	¾			47				"	"
Nashkote B-085	⅞			.60				"	"
Nashkote B-068	½			39				"	"
Nashkote B-068	¾			48				"	"
Nashkote B-068	⅞			63				"	"
Nashkote B-045	½			39				"	"
Nashkote B-045	¾			49				"	"
Nashkote B-045	⅞			64				"	"
Nashkote C	½	10	12	30	.54	75	71	"	1929
Nashkote C	¾	.13	15	41	62	.85	76	"	1929
Nashkote C	½	08	.13	.31	54	.66	62	Average	1929
Nashkote C	¾	.11	.18	.42	63	73	.64	"	1929
Nashkote C	1	17	20	.50	73	91	80	Bureau of Standards	1929
Nashkote F	½	07	.18	35	58	58	.47	P. E. Sabine	1928
Nashkote F	¾	10	24	49	74	.59	.47	"	1928
Nashkote F	1	.11	.33	.65	77	60	47	"	1928
Nashkote F	1½	.13	.40	.72	.77	.60	.47	"	1928
Nashkote F	2	.19	.52	.76	.78	.60	.47	"	1928
Nashkote F	3	.34	.53	.77	.79	.61	.47	"	1929
Nashkote OMC, painted with flat wall paint with Nash Blotting Pad Method	¾	.065	25	.46	.74	.73	.55	"	1928

Table XIV — (*Continued*)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Nashkote OMC, sprayed with two coats architectural lacquer	1	0 11	0 31	0 66	0 74	0 56	0 50	P. E. Sabine	1928
Penn Acoustic Felt....	½	.07	15	31	44	50	40	"	1930
Pumice No. 2, 6-in. fill between 2 in. by 6 in. studs, 16 in. o.c., backed with wood flooring	6½	42	48	53	54	53	55	V. O. Knudsen	1928
Rock Wool, felted, 10 to 12 lb. per cubic foot	1	26	.45	61	72	75		"	1928
Rock Wool, as above	2	38	54	65	76	78		"	1928
Rock Wool, granulated, 12 lb. per cubic foot, filled between 2 in. by 4 in. wood studs 16 in. o.c., covered with cheesecloth	4	.43	53	59	69	70		"	1928
Rock Wool, packed between 2 in. by 4 in. studs, finished with sheetrock, perforated with 1-in. holes 1½ in. o.c., finished with B-068 Kribble Kloth..	4	.34	.56	.76	80	56	.43	P. E. Sabine	1929
Rock Wool, granulated, 12 lb. per cubic foot, filled between 2 in. by 6 in. wood studs, 16 in. o.c., covered with cheesecloth.	6	50	.58	.63	.68	.69	.68	V. O. Knudsen	1929
Rock Wool, packed to 7 lb. per cubic foot, as above...............	6	.47	.53	.60	.62	.58	.56	"	1929

TABLE XIV — (*Continued*)

ACOUSTICAL FELTS, WOOLS, AND GRANULATED MATERIALS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients, cycles per second: 128	256	512	1024	2048	4096	Authority	Year Tested
Rock Wool, two 1-in. layers separated by 1¾-in. air space	3¾	0 50	0 63	0 70	0.81	0.83	..	V. O. Knudsen	
Sanacoustic Holorib Roof Deck	3	..	.	70	..		..	Johns-Manville	Before 1931
Sanacoustic Panels. .	1¼			82				"	"
Silent-Ceal .. .	.	29	74	68	.67	.75	64	Bureau of Standards	1930
Slag Wool, 12 lb. per cubic foot, between 2 in. by 4 in. studs, covered with cheesecloth ..	4	48	53	58	65	70	..	V. O. Knudsen	
Sprayo-Flake.. ..	1	24	37	46	47	.48	..	"	1929
Sprayo-Flake...... .	1½	27	36	.47	49	50	.	"	1929
Sprayo-Flake, between wood studs, covered with ½-in. mesh hardware cloth . .	4	38	43	57	58	55	54	"	1929
Sprayo-Flake, as above	6	44	49	59	60	57	54	"	1929
Therminsul .. .	1	20	29	46	54	55	.59	"	1930
Upson Blue Stripe Insulation...	½	.18	.32	50	.46	36	.30	"	1930
Westfelt, on 1-in. furring strips.	¼	.06	.12	.19	40	.43	.44	P. E. Sabine	1929
Westfelt, on 1-in. furring strips...........	½	.08	.17	.34	.62	55	.52	"	1929
Westfelt....	1	.09	.22	.48	.64	.55	.52	"	Before 1930
Zonolite, granulated, loosely compacted between 2 in. by 4 in. studs, backed with Masonite, covered with fly screen........	4¼	.34	.45	.58	.57	.56	.56	V. O. Knudsen	1928

Table XV
FIBRE AND WALL BOARDS, AND MATERIALS USED FOR SETS IN SOUND PICTURE STUDIOS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Absorbege	1¼	0.38	0.40	0.45	0.53	0.66	0.91	Bureau of Standards	1931
Acoustolic		.44	.24	.31	.44	.48	..	"	1930
Acoustolic, tinted with water-soluble aniline color	..		.29	.28	.41	.	.	"	1930
Acoustolic, tinted with water-color paint . .	..	.40	.33	.31	.38	.37	.	"	1930
Arborite, low-density material, sanded surface	..	.21	.48	.34	.31	.41	..	"	1930
Arborite, regular material, sanded surface.	..	.16	.40	.27	.29	.39	..	"	1930
Balsa Wood.......	7/16	.15	..	.19		.28	.	V. O. Knudsen	1928
Celotex, standard .	7/16	.16	.20	.24	.22	.23	.22	Average	Before 1930
Celotex B'd, light density, loosely felted, on wood studs	½	.29	.28	.28	.32	.33	.38	V. O. Knudsen	1930
Celotex Absorption Board, two 7/16-in. layers separated by ¾-in. by 1¾-in. furring strips, 18 in. o.c..........	1⅝	.24	.27	.30	.31	.33	..	"	1928
Cork Insulation Company Material, beveled ⅜ in. on edge, one coat water-color paint..	1½	.09	.09	.35	.26	.28	.36	Electrical Research Products*	1931

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* Sound-absorption coefficients from Electrical Research Products Laboratories are for frequencies of 125, 250, 500, 1000, 2000, and 4000 cycles.

TABLE XV — (*Continued*)

FIBRE AND WALL BOARDS, AND MATERIALS USED FOR SETS IN SOUND PICTURE STUDIOS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Fir-Tex, on 2 in. by 4 in. wood studs, 16 in. o.c. .	½	0.25	0.26	0.30	0.29	0.25	0.39	V. O. Knudsen	1930
Fir-Tex, on 2 in. by 4 in. wood studs, 16 in. o.c.	½	.22	.21	.28	.31	.44	.55	"	1931
Fir-Tex, on 2 in. by 4 in. wood studs, 16 in. o.c.	1	.32	.36	.39	.43	.41	.50	"	1930
Fir-Tex . .	1	..	.32	.37	.42	.58	.	F. R. Watson	1930
Flax-li-num (flax fibre felted into semi-stiff board) nailed on 2 in. by 4 in. wood studs, 16 o.c.	½	.12	.21	.33	.45	.46	.44	Average	
Flax-li-num, as above....	¾	.16	.24	.36	.46	.48	.46	"	
Flax-li-num, as above	1	.15	.30	.55	.60	.58	.54	"	Before 1929
Flax-li-num, two layers of ½ in. and one layer of 1 in. all separated by 1-in. air spaces...	4	.32	.36	.44	.45	.50	..	V. O. Knudsen	1928
Flax-li-num, in TMB Tile, on 13/16 in. by 2-in. furring strips 16 in. o.c.	½	.11	.19	.58	.68	.69	..	Bureau of Standards	1930
Flax-li-num, as above...	1	.17	.34	.61	.72	.68	..	"	1930
Flax-li-num, as above....	½ and 1	.32	.46	.67	.69	.71	..	Bureau of Standards	1930

Table XV — (*Continued*)

FIBRE AND WALL BOARDS, AND MATERIALS USED FOR SETS IN SOUND PICTURE STUDIOS

Brand or Make	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Flax-li-num, as above	Two 1	0.41	0.59	0.70	0.72	0.74		Bureau of Standards	1930
Inso Board, against wood flooring	7/16	.14	.22	.26	.27	.28		V. O. Knudsen	1929
Insulite, on 2 in. by 4 in. studs, 16 in. o.c.	1/2	.22	.26	.29	.33	.37	.38	Average	
Insulite, as above, painted with one coat Aztec Acoustical Paint.	1/2	.18	.23	.26	.27	25		V. O. Knudsen	1928
Masonite, against concrete surface	7/16	.10	.21	.29	.30	.29		"	1928
Masonite, on 2 in. by 4 in. studs, 16 in. o.c.	7/16	.18	.25	.32	.35	.33	.31	Average	
Masonite, two layers separated by 1 in. by 2 in. furring strips, 16 in. o.c.	1 7/8	.23	.32	.31	.31	.32	.	V. O. Knudsen	1928
Masonite, three layers, as above	3 5/16	.31	.35	.32	.31	.34	.	"	1928
Nu-Wood, two 7/16-in. layers, separated by 1 in. by 2 in. furring strips 16 in. o.c.	1 7/8	.20	.28	.30	.32	.31	..	"	1929
Weatherwood Insulating Board, against concrete surface	7/16	.16	.20	.29	.32	.31	.30	"	1929
Thermatex	..	.30	.39	.34	.43	.53	..	Bureau of Standards	1930

TABLE XV — (*Continued*)

FIBRE AND WALL BOARDS, AND MATERIALS USED FOR SETS IN SOUND PICTURE STUDIOS

Description	Thickness, in.	Sound-Absorption Coefficients 128 cycles per second	256	512	1024	2048	4096	Authority	Year Tested
Set Materials									
Veneered flats, papered with crepe paper	..	0.116	0.109	0.062	0.081	0.091	0.121	V. O. Knudsen	1930
Veneered flats, as above, and hard wall paper over crepe paper... ..	..	.104	.101	.061	.071	.071	.071	"	1930
Masonite, papered with crepe paper	$\frac{7}{16}$	.179	.174	.113	.099	.117	.115	"	1930
Masonite, as above, with one coat studio flat paint ..	$\frac{7}{16}$	.158	.169	.109	.090	.073	.073	"	1930
Celotex, papered with crepe paper..	$\frac{7}{16}$	.166	.143	.106	.111	.119	.109	"	1930
Celotex, as above, with one coat water paint..........	$\frac{7}{16}$	.175	.161	.112	.111	.129	.089	"	1930
Cast plaster, applied to burlap, one coat thin shellac..	$\frac{3}{8}$ to $\frac{1}{2}$	.098	.092	.050	.069	.092	.053	"	1930
Cast stone, similar to above, except irregular surface .	..	.241	.233	.102	.146	.153	.093	"	1930
Zonolite, brushed over burlap on chicken wire......	$\frac{1}{16}$ to $\frac{1}{8}$	.376	.370	.252	.230	.245	.221	"	1930
Zonolite, troweled over burlap and chicken wire......	$\frac{1}{4}$	.197	.145	.103	.078	.063	.050	"	1930

Table XVI
HANGINGS, FLOOR COVERINGS, AND MISCELLANEOUS MATERIALS

Description	Thickness, in.	Sound-Absorption Coefficients, cycles per second: 128	256	512	1024	2048	4096	Authority	Year Tested
Canvas, 6 in. from wall	..	0.10	0.12	0.25	0.33	0.15	0.35	Building Research Station	
Carpets, lined	..	.10†		.25		.40†		W. C. Sabine	
Carpets, unlined	..	.08†		.15	.	.25†		"	
Carpet, Amritza, on concrete	7/16	.09	.06	.24	.24	.28	.11	Building Research Station	
Carpet, Cardinal Batala, on concrete	7/16	.12	.10	.28	.42	.21	.33	"	
Carpet, pile, on concrete	3/8	.09	.08	.21	.26	.27	.37	"	
Carpet, pile, on 1/8-in. felt	3/8	.11	.14	.37	.43	.27	.25	"	
Carpet, pile, on 1/8-in. felt on 3/4-in. polished cork on concrete	3/8	.17	.14	.35	.42	.23	.34	"	
Carpet, pile, on 1/8-in. felt on 3/4-in. pine blocks on concrete	3/8	.11	.13	.38	.45	.29	.29	"	
Carpet, rubber, on concrete	3/16	.04	.04	.08	.12	.03	.10	"	
Cocoa Matting	..	.08†		.17	.	.30†		W. C. Sabine	
Cork flooring slabs, glued down	3/4	.08	.02	.08	.19	.21	.22	Building Research Station	
Cork flooring, like above, waxed and polished	3/4	.04	.03	.05	.11	.07	.02	"	
Cork tile	1/4	.04†	..	.06	..	0.7†	..	V. O. Knudsen	

† These coefficients are estimates made by the author.

TABLE XVI — (*Continued*)

HANGINGS, FLOOR COVERINGS, AND MISCELLANEOUS MATERIALS

Description	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Cotton fabric, 14 oz. per square yard, draped to half its area . ..		0.07	0.31	0.49	0.81	0.66	0.54	P. E. Sabine	
Cotton fabric, like above, draped to three fourths its area	..	.04	.23	.40	.57	.53	.40	"	
Cotton fabric, like above, draped to seven eighths its area...........	..	.03	.12	.15	.27	.37	.42	"	
Cretonne cloth .	..			.15		.		W. C. Sabine	
Curtains, chenille	..	.05†		.23	.	.30†	.	"	
Draperies, cotton fabric, 10 oz. per square yard, hung straight, in contact with wall ..	..	.03	.04	.11	.17	.24	.35	P. E. Sabine	
Draperies, 14 oz. per square yard, hung as above.. .	..	.04	.07	.13	.22	.32	.35	"	
Draperies, velour, 18 oz. per square yard, hung as above............	..	.05	.12	.35	.45	.38	.36	"	
Draperies, like above, hung straight, 4 in. from wall.........	..	.06	.27	.44	.50	.40	.35	"	
Draperies, like above, hung straight, 8 in. from wall.........	..	.08	.29	.44	.50	.40	.35	"	
Draperies, like above, draped to one half area......	..	.14	.35	.55	.72	.70	.65	V. O. Knudsen	

† These coefficients are estimates made by the author.

Table XVI — (*Continued*)

HANGINGS, FLOOR COVERINGS, AND MISCELLANEOUS MATERIALS

Description	Thickness, in.	Sound-Absorption Coefficients, cycles per second: 128	256	512	1024	2048	4096	Authority	Year Tested
Elastic Cotton, under canvas and short nap plush	.	0.61	0.62	0.76	0.91	0.73	0.47	W. C. Sabine	
Hair, under canvas and leatherette	.	.42	.47	.72	.47	.27	.16	"	
Hair, long, under canvas and plush	..	.36	.41	.67	.62	.51	.34	"	
Linoleum	..	.02†	.	.03	..	.04†		V. O. Knudsen	
Openings, balcony	.		.25	to	.80		.	Average	
Openings, stage, depending upon stage furnishings	..	..	.25	to	.40	.	.	F. R. Watson	
Oregon pine flooring	¾	.09		.08	.	.10		V. O. Knudsen	
Ozite, 0.167 lb. per square foot	¼	.033	.10	.13	.25	.37	.47	P. E. Sabine	1929
Ozite, 0.266 lb. per square foot	⅜	.051	.12	.17	.33	.45	.47	"	1929
Ozite, 0.386 lb. per square foot	½	.058	.13	.20	.42	.47	.47	"	1929
Ozite, 0.362 lb. per square foot	¾	.08	.19	.285	.51	.56	.47	"	1929
Paintings, oil, including frames				.28	..	.	.	W. C. Sabine	
Rug, Axminster	..	.11	.14	.20	.33	.52	.82	Wente and Bedell	Before 1928
Rug, Oriental	..	.10†	..	.29	..	.40†	.	W. C. Sabine	
Vegetable fibre, under canvas and cloth	..	.28	.39	.54	.59	.53	.45	"	
Ventilators, 50 per cent open	..	.30†	..	.50	..	.50†	..	F. R. Watson	
Wood blocks, Gurjan, laid in mastic	¾	.03	.04	.07	.14	.09	.15	Building Research Station	
Wood blocks, pitch pine, laid in mastic	¾	.05	.03	.06	.09	.10	.22	"	

† These coefficients are estimates made by the author.

TABLE XVII

HARD PLASTERS, MASONRY, WOOD, AND OTHER STANDARD BUILDING MATERIALS

Description	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Brick wall, unpainted .. .	18	0.024	0.025	0.031	0.042	0.049	0.07	W. C. Sabine	
Brick wall, painted	18	.012	.013	.017	.02	.023	.025	"	
Clay tile, burned	1	†.015		.028		†.035	.	V. O. Knudsen	
Glass ..		†.035		.027	.	†.020	..	W. C. Sabine	
Interior stucco, smooth finish .	½	†.03		.04	.	†.04	..	V. O. Knudsen	
Marble		†.01		.01	.	†.015	..	F. R. Watson	
Plaster, gypsum, on hollow tile	..	.013	.015	.020	.028	.040	.050	W. C. Sabine	
Plaster, gypsum, scratch and brown coats on metal lath on wood studs		.020	.026	.040	.062	.058	.028	P. E. Sabine	
Plaster, gypsum, scratch and brown coats on wood lath on wood studs	¾	.016	.032	.039	.050	.030	.028	"	
Plaster, gypsum, scratch, brown and finish coats, on wood lath on wood studs .	¾	.020	.022	.032	.039	.039	.028	"	
Plaster, lime, sand finish, on metal lath..........	¾	.038	.049	.060	.085	.043	.056	V. O. Knudsen	
Plaster, lime, on wood lath........	..	.020	.024	.034	.030	.028	.043	W. C. Sabine	
Plaster, lime, with finishing coat, on wood lath.........	..	.012	.013	.018	.045	.028	.055	"	

† These coefficients are estimates made by the author.

TABLE XVII — (*Continued*)

HARD PLASTERS, MASONRY, WOOD, AND OTHER STANDARD BUILDING MATERIALS

Description	Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Plaster, lime, scratch and brown coats, on wood lath on wood studs	¾	0.027	0.046	0.060	0.085	0.043	0.056	P. E. Sabine	
Plaster, as above, smooth finish	¾	.024	.027	.030	.037	.019	.034	W. C. Sabine	
Plaster, lime, scratch, brown and finish coats on wood lath on wood studs..	..	.024	.046	.060	.085	.043	.056	P. E. Sabine	
Poured concrete, unpainted...	..	.010	.012	.016	.019	.023	.035	V. O. Knudsen	
Poured concrete, painted and varnished.. . .	..	.009	.011	.014	.016	.017	.018	"	
Teak panels, three-ply, 3 ft. by 2 ft. 2 in., framed in wood, 1 in. from wall	..	.09	.17	.17	.15	.15	.15	Building Research Station	
Travertine, artificial	..	.02†	..	.05	.	.07†	..	V. O. Knudsen	
Water, as in swimming pool.........	..	.008	.008	.013	.015	.020	.025	"	
Wood sheathing, pine..............	¾	.098	.11	.10	.081	.082	.11	W. C. Sabine	
Wood, varnished...	..	.05†	..	.03	..	.03†	..	F. R. Watson	

†These coefficients are estimates made by the author.

Table XVIII
COMBINATIONS OF ACOUSTICAL MATERIALS

Description (The innermost material is named first, the exposed material last)	Total Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Fibre building board, 1-in. air space, fibre building board	3	0.25	0.41	0.75	0.77	0.71	0.80	Wente and Bedell (Tube Method)	Before 1928
Fibre building board, 1-in. air space, fibre building board, 1-in. air space, fibre building board.	5	.41	.87	.74	81	.59	.83	"	"
Fibre building board, 1-in. air space, 1-in. felt, 1-in. air space, 1-in. fibre building board.... .	5	.39	.83	.82	.64	.59	.80	"	"
Hair felt, 1 in., fibre building board......	2	.18	.36	.71	.79	.82	.85	"	"
Hair felt, 1 in., 1-in. air space, fibre building board	3	.24	.46	.77	.92	.89	.85	"	"
Hair felt, 1 in., 2-in. air space, fibre building board .	4	.37	.62	.88	.92	.78	.84	"	"
Hair felt, 1 in., 1-in. air space, 1-in. felt, 1-in. air space, fibre building board	5	.39	.82	.94	.92	.91	.85	"	"
Hair felt, 1 in., 1-in. air space, 1-in. building board, 1-in. air space, fibre building board....	5	.37	.79	.91	.82	.89	.86	"	"

Table XVIII — (*Continued*)
COMBINATIONS OF ACOUSTICAL MATERIALS

Description (The innermost material is named first, the exposed material last)	Total Thickness, in.	Sound-Absorption Coefficients						Authority	Year Tested
		128	256	512	1024	2048	4096		
		cycles per second							
Hair felt, 1-in. fibre building board, 1-in. air space, fibre building board, 1-in. air space, fibre building board .	6	0.55	0.92	0.69	0.83	0.86	0.86	Wente and Bedell	Before 1928
Hair felt, 2 in., no air space, fibre building board ..	3	.28	.51	.81	.92	.90	.84	"	"
Mineral wool, 1½ in., covered with very porous acoustical tile, ½ in. thick ...	2	.39	.45	.56	.59	.61	.55	V. O. Knudsen	1929
Mineral wool, 2½ in., 1-in. air space, 1½-in. Sprayo-Flake........ .	5	.49	.56	.66	.67	.70	.	"	1929
Rock wool, 1 in., covered with ⅝-in. perforated acoustical plaster.......	1⅝	.31	..	.38	..	.43	..	"	1928
Rock wool, 1½ in., covered with ½-in. perforated acoustical plaster......	2	.28	.37	.40	.38	.39	..	"	1928

TABLE XIX
AUDIENCE, INDIVIDUAL PERSONS, CHAIRS AND OTHER OBJECTS

Description	Sound-Absorption Coefficients						Authority	Year Tested
	128	256	512	1024	2048	4096		
	cycles per second							
Audience, as ordinarily seated, per unit area	0.72	0.89	0.95	0.99	1.00	1.00	W. C. Sabine	
Audience, mixed, seated in theatre chair, heavily upholstered, per person			3.9	4.7		.	Bureau of Standards	Before 1930
Audience, mixed, seated in theatre chair, single padding on back		3.5	4.1	4.9	4.2		“	“
Audience, mixed, seated in church pews		2.7	3.3	3.8	3.6		“	“
Chairs, American Loge, full upholstered in mohair			4.5	.			“	“
Chair, box spring, pantasote seat and back, plywood on rear; seats up		1.4	1.6	1.3	0.71		F. R. Watson	“
Chair, like above, except panel back of velour		1.7	1.6	1.7	2.1		“	“
Chair, Chicago Civic Opera (special), fully upholstered in mohair; upholstered side panels in standards; seats up		.	3.5				“	“
Chair, plywood seat, plywood back; seats up	..	.19	.24	.39	.38	.	“	“
Chair, spring edge mohair seat and back, plywood panel on rear; seat down	..	3.1	3.0	3.3	3.5		“	
Chair, like above; seat up		2.8	2.8	3.0	3.2	..	“	
Chair, like above, with mohair covering the plywood rear	.	3.2	3.0	3.0	3.4	.	“	
Chair, like above, with thick completely covered seat and back; seat up	..	3.3	3.5	3.7	3.8	..	“	

TABLE XIX — (*Continued*)

AUDIENCE, INDIVIDUAL PERSONS, CHAIRS AND OTHER OBJECTS

Description	Sound-Absorption Coefficients						Authority	Year Tested
	128	256	512	1024	2048	4096		
	cycles per second							
Chair, spring edge, velour seat and back, plywood on rear; seat down . . .		3.1	3.1	3.4	3.7		F. R. Watson	
Chair, like above; seat up .		2.7	2.7	3.0	3.1		"	
Chair, theatre, heavily upholstered . . .		3.4	3.0	3.3	3.6		Bureau of Standards	Before 1930
Chair, theatre, single padding on back		3.0	2.5	2.9	3.1		"	"
Person, adult	1.8		4.2		5.5		V. O. Knudsen	1928
Person, adult, seated in American Loge chair			5.5				Bureau of Standards	Before 1930
Person, child, high school	1.6		3.8		5.0		V. O. Knudsen	1928
Person, child, junior high school .	1.5		3.5	..	4.6	.	"	"
Person, child, grammar school	1.3		2.8		3.8	.	"	"
Person, man, without coat, seated in open-back cane chair	1.3	2.1	4.1	5.5	7.4	..	Bureau of Standards	Before 1930
Person, man, with coat, seated as above	2.3	3.2	4.8	6.2	7.6	..	"	"
Person, woman, without coat, seated as above . .	.7	1.3	2.3	3.6	4.6	..	"	"
Person, woman, with coat, seated as above . ..	1.3	2.4	4.0	5.8	6.7	..	"	"

83. Practical Considerations of Sound-Absorptive Materials. The foregoing tables give the absorption coefficients for a large number of materials from which the architect or engineer may choose those suitable for the acoustical treatment of almost any type of building. In making a choice of absorptive materials there are a number of factors which must be considered besides the coefficients of sound-absorption. Good acoustics is only one of many qualities which should be secured in every building. Thus, besides the absorptive characteristics of a material, it is necessary to consider such factors as the following: structural strength; decorative possibilities; adaptability to the surface available for, or requiring, absorptive treatment; maintenance; sanitation; ease of application; fire hazard; absorption of water; attraction for vermin; " fool-proofness "; durability; and cost. In general, each room requires

Fig. 102. Microphotograph of a section through Kalite Acoustical Plaster, magnified about five fold.

a certain number of units of sound-absorption, and in addition certain surfaces in some rooms require absorptive treatment. These two considerations usually limit the choice of absorbents to those materials having coefficients within certain specified limits. In most cases, however, there will be many materials having coefficients within these limits. This allows considerable freedom in the choice of materials which will provide the required amount of absorption and also meet the requirements of appearance, durability, cost, and possibly other factors. The choice of the best acoustical materials for a certain room should be based upon careful consideration of all these acoustical, decorative, structural, and economic factors. In Part III there will be found numerous examples of buildings which have been designed for good acoustics,

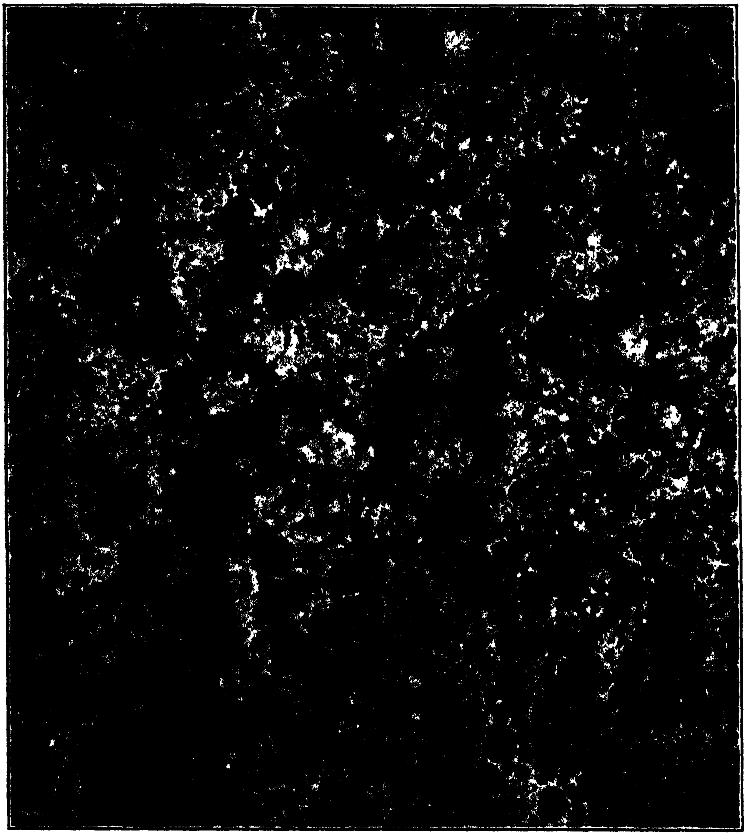

FIG. 103. Microphotograph of surface of Kalite Acoustical Plaster, showing the many pores which penetrate into the interior. Magnified four fold.

and in which the selection of acoustical materials has been guided by all the factors just mentioned. The examples illustrate the adaptability of different acoustical materials to rooms of different type, and will illustrate how many specific problems which arise in practice can be worked out satisfactorily.

Architects and builders are often persuaded into an unfortunate choice of acoustical materials by reason of data furnished by certain manufacturers' representatives, which show that their particular product is more absorptive than the material of a competitor. It is important therefore that the architect have an acquaintance with the structural and decorative properties of different acoustical materials, since he will then be in a better position to assess the relative merits of these materials. For this reason, it seems advisable at this point to give a brief description of the principal properties, and to discuss the advantages and disadvantages, of different types of acoustical materials.

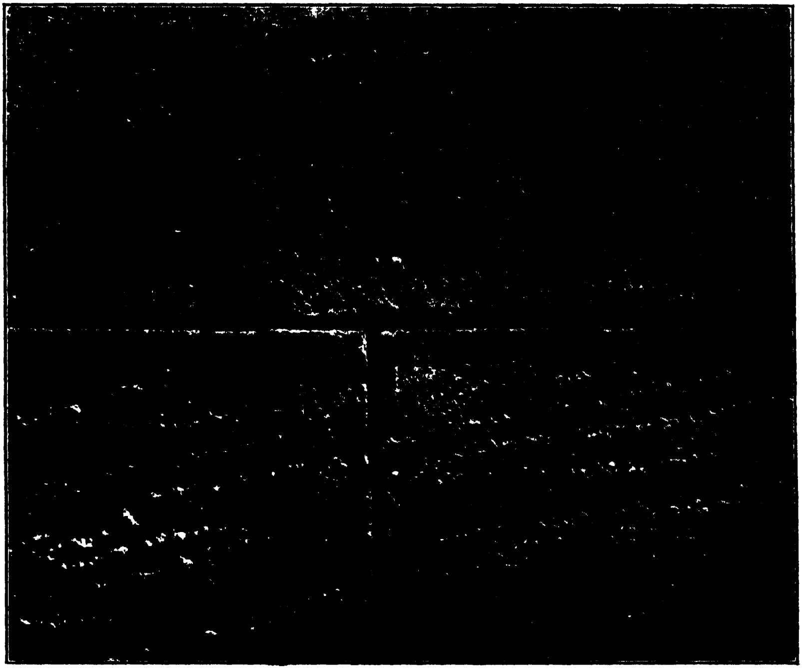

FIG. 104. Macoustic Plaster showing surface texture and markings for tile effect.

(*a*) *Acoustical Plasters.* Many acoustical plasters, in order to obtain great porosity, are made with small amounts of binding material, and consequently the tensile strength is often less than that required for

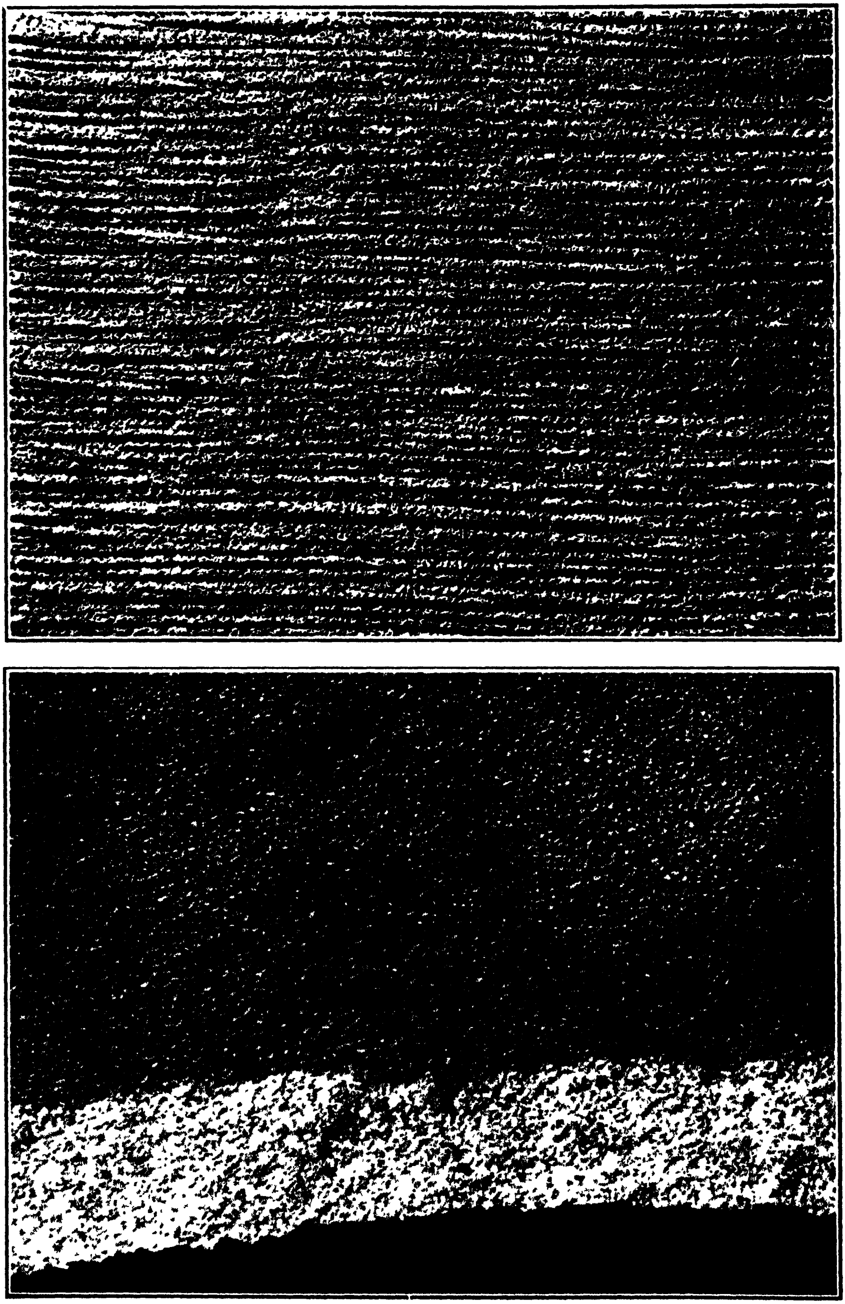

FIG. 105. Special textures obtainable in "Akoustolith."

adequate structural bond. Under such circumstances, the plaster may dust or pop off the wall.[5] In making a choice of an acoustical plaster it is therefore desirable to consider its adhesive and cohesive properties, its resistance to abrasion, its ease of application, its texture, and its maintenance (such as cleaning and decorating), as well as its coefficients of sound-absorption.

If it becomes necessary to use an acoustical plaster which will not withstand the wear and abrasion to which the walls near the floor will be subjected, it is a good plan to use a wainscot of harder material, as wood or hard plaster. The wainscot should extend up to a height of about six feet above the floor.

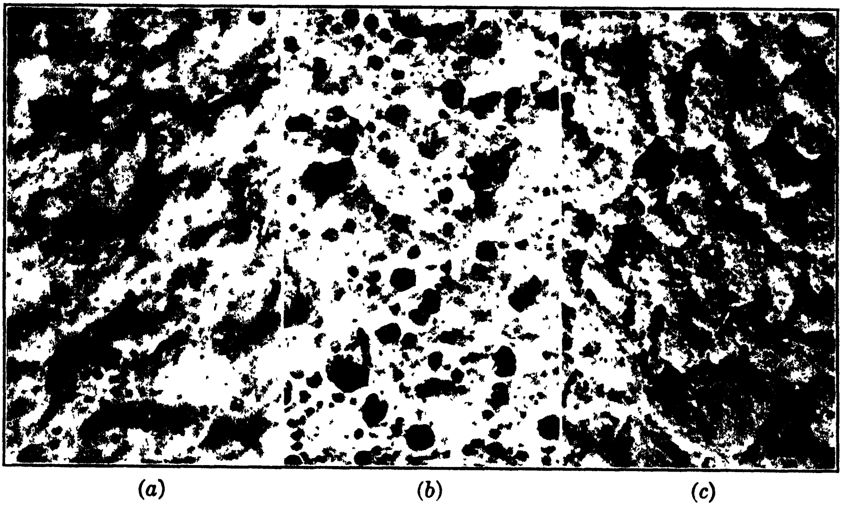
(*a*) (*b*) (*c*)

FIG. 106. Microphotographs showing the effect on acoustical plaster of suction by the under coat. (*a*) shows the surface (magnified 10 fold) of an acoustical plaster applied over a hard wall under coat immediately after the under coat has taken its initial set. (*b*) shows the surface of the same kind of acoustical plaster applied after the under coat has dried for one day. (*c*) shows the surface of the same kind of acoustical plaster applied after the under coat has dried for four days. The dry under coat sucks out the excess water from the acoustical plaster, thus rendering it porous. (*O. A. Malone.*)

Since the absorption coefficients of acoustical plasters are dependent upon such factors as the *suction* behind the plaster, the pressure applied to the trowel, and the manner of floating, texturing, or stippling the plaster, the plasterers should be instructed to exercise great care in applying

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[5] The tensile strength of acoustical plaster should not be less than about 50 pounds per square inch. Recently, some acoustical plasters have been developed which have tensile strengths as high as 75 to 110 pounds per square inch.

and finishing the plaster.[6] It is a good plan to require the contractor to submit to the architect or acoustical engineer a small panel of the proposed plaster, applied and textured as contemplated for the building. After this specimen has been tested and approved by the architect or engineer, the plastering contractor should be required to apply the plaster in the building in such a manner that it will duplicate the tested panel with respect to both porosity and texture.[7]

FIG. 107. Half size detail of Johns-Manville "Nashkote," Type "B-045." Acoustical felt finished with perforated "Sanitas."

Unless these simple precautions are observed, the use of acoustical plaster may prove disappointing for the control of reverberation in

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[6] A large measure of the success or failure which attends the application of acoustical plaster depends upon the *drying out* of the plaster. The surface to which the acoustical plaster is applied must provide a high degree of *suction*. Accordingly, it is advisable to prepare scratch and brown coats which will *draw* the water from the acoustical plaster and thus prevent the formation of a non-porous film on the finished surface of the acoustical plaster. It is also advisable to provide good drying conditions for the plaster, and to *float* or *drag* the surface of the plaster just before it takes its initial set. See Fig. 106.

[7] A suitable and simple method for testing both the specimen of plaster and the finished plaster is described in Sec. 72.

rooms. On the other hand, if these precautions are carefully followed, acoustical plasters which are now on the market will be found to be very well adapted to many types of building where the amount of surface available for treatment is sufficient to reduce the reverberation to the optimal time. The use of selected types of acoustical plaster already has proved highly satisfactory for the treatment of offices, school rooms, corridors, and many public buildings. It can be used in nearly every place where ordinary plaster can be used, and without altering the architectural effects which have been obtained in the past with the use of ordinary lime or gypsum plaster. Acoustical plaster is entirely fireproof, is an integral building material, and its cost installed is about one dollar

FIG. 108. Half size detail of Johns-Manville "Nashkote," Type "C." White-faced acoustical felt sized. Stenciled decorations applied directly to the surface of the felt.

per square yard above the cost of ordinary plaster. Acoustical plaster is a relatively new building material, and a certain amount of caution is advisable in the use of any new material, especially if it is not properly sponsored. The use of acoustical plaster for the control of sound in buildings is increasing at a rapid rate. As the product is improved and as the correct manner of its application is more universally understood by plasterers its use will be extended to more and more buildings.

(*b*) *Acoustical Tile.* Perhaps the most outstanding feature of an acoustical tile is its " built-in " absorptive value. The tile is a factory-made product, and the degree of porosity, and therefore its absorption, is a relatively uniform and standard quantity. This gives to acoustical tile a " fool-proof " feature which is highly important for the acoustical treatment of rooms. The amount of absorption added to a room by an acoustical tile is quite independent of the skill or lack of skill of the persons who install the material.

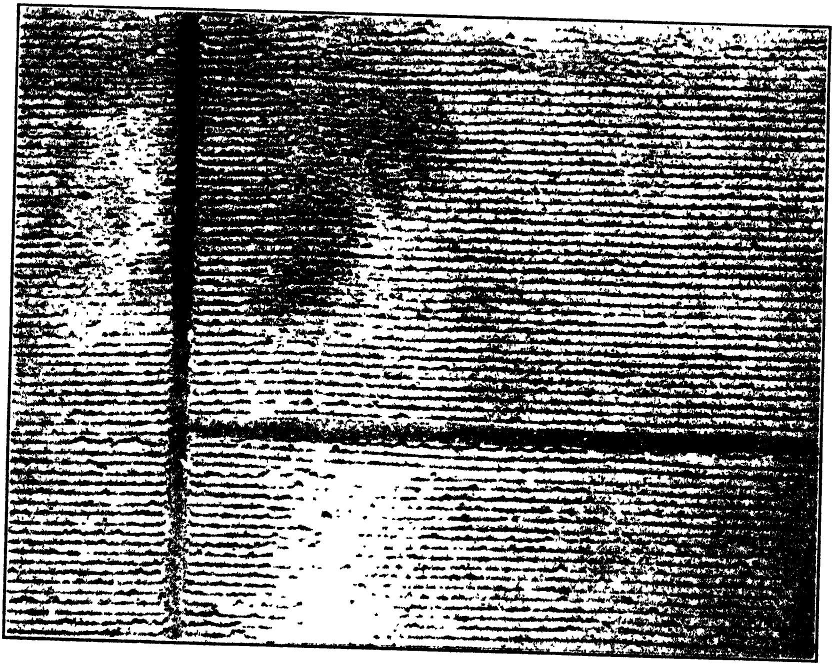

FIG. 109. Half size detail of Johns-Manville "Nashkote," Type "ACS." Acoustical felt finished with muslin, painted with oil paint mixed with sand, and textured with a graining comb.

Another merit possessed by acoustical tile is its relatively high absorption. In a factory-made product it is possible to control such factors as porosity, flexibility, and the punching or drilling of holes — factors which are paramount in determining the absorptivity of materials, and factors which may be difficult to control in certain types of plastic materials. In addition, acoustical tiles can be given structural and decorative properties which are well adapted to the requirements for artistic interiors.

Several acoustical tiles on the market, notably " Acousti-Celotex " and " Sanacoustic Tile," enjoy a unique advantage in that they can be decorated with oil and lead, or with any other kind of paint, without impairing their high absorptivity. This is made possible by the mechanically made holes in the tile, which permit the sound waves to reach the interior of the tile and thus be absorbed by the viscous forces in the tiny pores of the material. Laboratory and field tests have shown that " Sanacoustic Tile " and " Acousti-Celotex " are as absorptive decorated with an oil and lead paint as they are unpainted. This imparts to these materials a high degree of surety against loss of absorption by decoration.

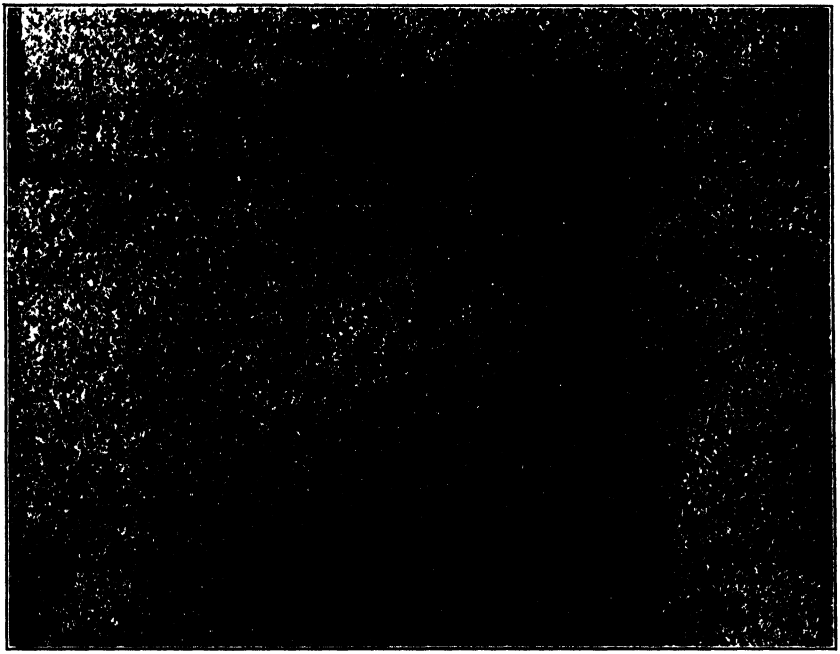

FIG. 110. Close-up view of Johns-Manville "Nashtile," showing surface texture.

Because of the highly absorptive value of acoustical tile, it is particularly well adapted to rooms requiring a low period of reverberation or rooms in which a relatively small surface is available for acoustical treatment. Theatres which are used for talking pictures, radio broadcast studios, and studios for the recording of sound, all require a relatively low period of reverberation, and for this reason acoustical tiles having high coefficients of sound-absorption often are well adapted for the acoustical treatment of such rooms.

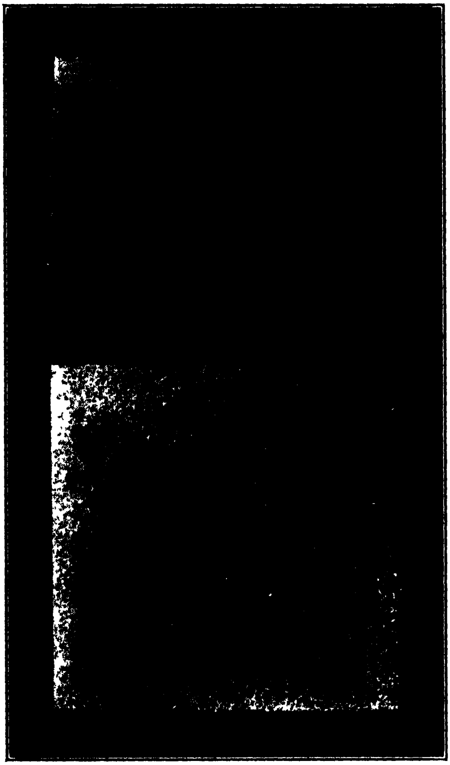

FIG. 111. "Trutone Acoustical Tile." The material is made porous by the evolution of gas within the plastic mixture while it takes its initial set.

The principal disadvantages of an acoustical tile are its limitations for architectural treatment, and its cost compared with other acoustical materials. It is quite impossible to conceal satisfactorily the joints between adjacent pieces of tile, and for this reason acoustical tile is limited to treatments which give a tile or ashlar effect. However, by using tight joints in high ceilings, and by decorating the entire surface, it is possible to secure the appearance of a continuous or monolithic surface. But in rooms with low ceilings, the tile effect is noticeable with any type

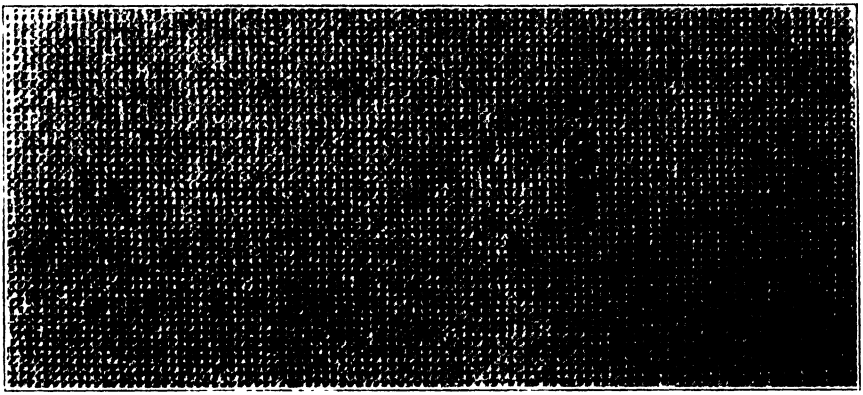

FIG. 112. "Flax-li-num," showing surface texture.

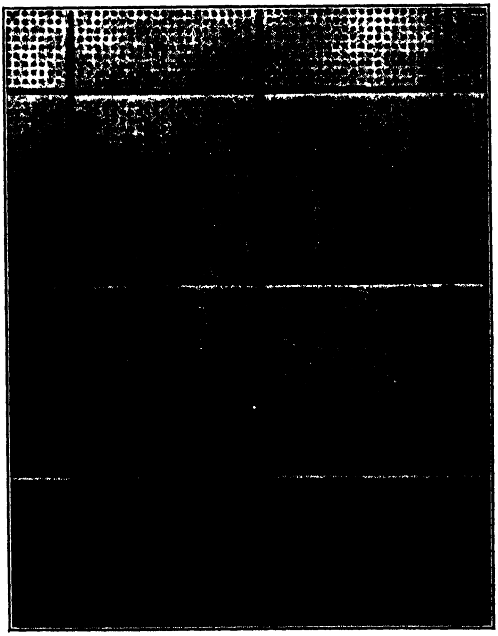

FIG. 113. "Acousti-Celotex," showing texture, perforations, and joints. Each tile is 1 foot square.

of decoration. For this reason, it is customary to make a beveled edge around the tile and thus emphasize rather than attempt to conceal its *masonry* effect.

Most types of acoustical tile on the market are relatively costly. As a rule, the cost is between about thirty-five and seventy cents a square foot, installed. In comparing the cost of acoustical tile with other types of acoustical treatment it should be borne in mind that the cost per square foot should not be considered alone. For example, acoustical tiles often are two or three times more absorptive than acoustical plasters, and for this reason 1 square foot of acoustical tile may supply as much absorption to a room as will 2 or 3 square feet of acoustical plaster.

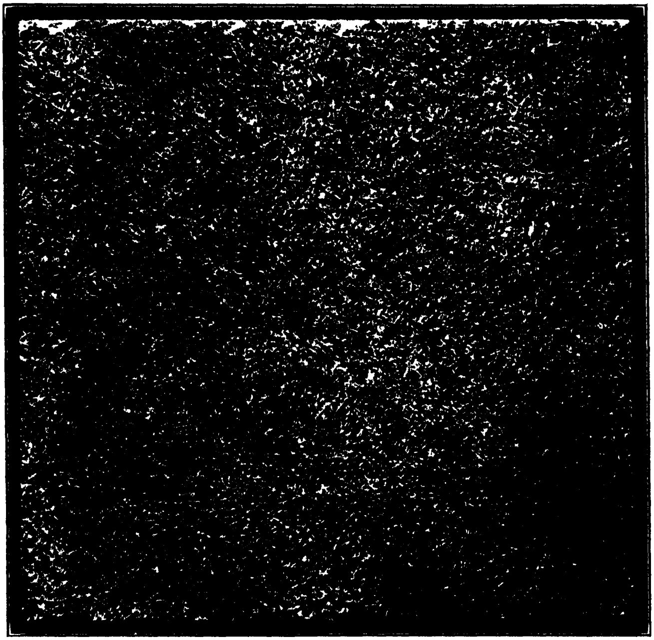

FIG. 114. "Acoustex," showing surface texture.

(*c*) *Acoustical Fibre Boards.* Acoustical fibre boards provide a means of obtaining a rather large amount of absorption in a room at a relatively low cost. The material usually does not cost more than about six to eight cents a square foot, installed, and the absorption coefficient of the material is of the order of 0.25 to 0.30 at 512 cycles. In general, these fibre boards are not fireproof. They usually come in large boards, 4 feet wide, and 8, 10, or 12 feet long, so that it is generally necessary to apply such material in the form of panels, with suitable strips or ornaments covering the joints. The use of these fibre boards also offers a difficulty in the matter of decoration. Oil and lead paints, and other non-porous paints, will close the surface pores of the material and hence destroy the absorptive value. On the other hand, thin dyes and stains, stencil designs with heavier paint, or dry paint dusted on with a pounce-bag can be used without impairing the acoustical value of the material. There is, however, the danger that a subsequent decoration with a non-porous paint may greatly impair the absorptive value of the fibre board. But, in spite of these limitations, acoustical fibre board is often a practical material for the control of reverberation in buildings. There are many schools and industrial jobs, where cost is an important consideration, in which these fibre boards may be used to advantage.

FIG. 115. United States Gypsum Company's "Acoustone Tile," carved with a penknife. It reveals not only the texture of the tile, but shows the possibility of obtaining low relief work with material of this type.

(*d*) *Acoustical Felts.* Acoustical felts have been used extensively in the past for the control of reverberation in rooms. A large portion of the early correction work which was done under the supervision of Wallace C. Sabine, and many of his successors, was accomplished with hair felt covered with a suitable membrane. Acoustical felts are usually covered with a cloth membrane or with a plastic membrane consisting of flexible or porous paint. The Johns-Manville Corporation has developed a number of acoustical felts which are covered with a dyed muslin, a perforated "Sanitas," or with "Nashkote," a special preparation which preserves or even enhances the absorptive value of the felt. When hair felt is covered with a coarse mesh cloth, such as cider press cloth, the cloth may be decorated with oil and lead without impairing the acoustical value of the felt, since the mesh of the cloth is so coarse that the paint does not close over the individual meshes. The decorative effects which can be executed on such a membrane are comparable with those which can be obtained by painting on canvas. This type of treatment has been used successfully, and with good artistic effects, in many rooms having curved surfaces. It gives a highly absorptive surface — the coefficient being of the order of 0.60 to 0.80 at 512 cycles. The felt treatment covered with the perforated "Sanitas" has the advantage that the "Sanitas" surface can be cleaned. The principal advantage of the "Nashkote" treatment lies in the nature of the surface which can be obtained with its use. A textured surface, resembling a plaster or tile surface, can be obtained without sacrificing the absorptive value of the felt. This type of treatment should be handled only by persons who are competent to apply the plastic membrane in such a manner as will preserve the porous and flexible structure of the felt.

(*e*) *Other Types of Acoustical Treatment.* In many instances it may be advantageous to use two or more different acoustical materials in the same room. For example, the reverberation may be reduced suitably in a large auditorium by treating portions of the ceiling with a very absorptive acoustical tile or felt, and by treating the walls with a less absorptive material, as acoustical plaster. Such a combination in the use of acoustical materials has proved very satisfactory in several large auditoriums, as in the B'Nai B'Rith Temple in Los Angeles. (See Sec. 170.)

For the acoustical treatment of sound-recording studios, such as are used by the motion-picture industry, it is often feasible to use thick mineral wool for the treatment of the walls and ceilings. Loose, granulated wool, placed between 2 inch by 4 inch wood studs, and covered with cheesecloth and hardware cloth, provides a type of absorption which is uniformly high throughout the entire range of frequencies used in speech and music. This type of absorption, when properly used (see Sec. 195), provides very good conditions for the recording of either speech or music. The use of thin absorptive materials in such rooms is not feasible, since the high-frequency components of speech or music are absorbed four or five times as much by such materials as are the low-frequency components. In the available equipment for the recording and reproducing of sound there are inherent limitations which tend to under-emphasize the high-frequency components. Under such circumstances, it would be a mistake to use materials which over-absorb the high-frequency components and leave unabsorbed the low-frequency ones.

84. Summary of Absorption Coefficients and Other Physical Properties of Acoustical Materials. In Table XX are summarized a number of pertinent data relative to the absorptive and other physical properties of materials which have become fairly well established and recognized for their dependability. The absorption coefficients are given for three frequencies only — 128, 512, and 2048 cycles — the three frequencies which should be used routinely in calculating for acoustics. The name of the manufacturer, composition, sizes and thickness (in cases of tiles, felts, et cetera), weight, structural strength, method of decoration, heat insulation, light reflection, and special comments are given for each material.[8] The materials have been listed in alphabetical order.

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[8] Data on many of the materials listed in the table were not available. It is also probable that the author has omitted from this table materials which, because of their merit or promise, should have been included. Such omissions, he hopes, will be pardoned in view of the many and varied developments of new acoustical materials.

TABLE

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Acoustex 60, 1"	0 16	0 37	0 65	Approximately 2 lb. per sq. ft.	A pre-cast tile of cement and wood fibre, compressed and baked	1", 1½"	6"×12" 12"×12" 12"×24" 24"×24" Sheets 2′ wide up to 8′ long
Acoustex 60, 1", spray painted	16	51	72				
Acoustex 70, 1½"	14	68	63	Approximately 3 lb per sq ft.			
Acoustex 70, 1½", spray painted	22	59	73				
Acousti-Celotex, Single B, ⅝"	11	45	68	13 oz per sq ft	Cane fibre tile perforated with 441 holes per sq ft.	⅝", 13/16", 1¼"	6"×12" 12"×12" 12"×24"
Acousti-Celotex, Double B, 13/16"	17	57	69	15 oz. per sq. ft.			
Acousti-Celotex, Triple B, 1¼"	20	75	67	1 lb., 3 oz per sq ft.			
Acoustic Flexfelt	.27	56	68		Rock wool felted between metal netting and stucco lath	Required thickness	4′×4′ 4′×8′
Acoustico Plaster	17	28	64	83 lb. per cu. ft., dry	Dolomitic lime with sound-absorbing aggregate	⅜" to 1" over ordinary brown coat	
Acoustite Plastic, ½"	15	38	35	20 lb. per cu. ft., bulk	Made of processed mineral wool pellets with inorganic binder	Recommended thickness of application, ¼", ½"	
Acoustone, ½"		48	.59	1¼ lb. per sq. ft.	Artificial stone filaments bonded together in tile form in a large variety of shapes and colors	½", ¾", 1"	6"×6" 6"×12" 12"×12" 9"×18" Special sizes up to 24"×36" available
Acoustone, ¾"		.62	70	1½ lb. per sq. ft.			
Acoustone, 1"		.66	.69	1¾ lb. per sq. ft.			

XX
OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
Satisfactory	0.76	0.68	Spray painted	Fire resistant	Housing Company Boston, Massachusetts
Very high	32	0.65 to .78 with white or light cream interior paints	Decorated with any type of paint including lead and oil	Installed by cementing and nailing. Can be painted many times without loss of absorption	The Celotex Company, Chicago, Illinois
			No decoration required for most uses. Can be covered with a porous fabric, as Monks cloth	Fire and vermin proof	General Insulating and Manufacturing Company, Alexandria, Indiana
		0.76	Integrally mixed color or thin sprays		Ohio Hydrate and Supply Company, Woodville, Ohio
	.30 at 90°	Depends on color	Color intermixed, or spirit dyes	Not changed by contact with carbon dioxide. Non-fading colors. Non-combustible, inorganic, vermin-proof, nothing to deteriorate	Coast Insulating Company, Torrance, California
Satisfactory		Std. white, 0.63. Std. tile up to 0.80	Integrally colored in pastel shades. May be stained with thin paint	Looks like natural stone. Fireproof. Tile may be vacuum cleaned	United States Gypsum Company Chicago, Illinois

TABLE XX

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Akoustolith Plaster ½"	0.21	0.29	0.37		Light weight plastic material	Applied ½" in thickness over usual ground coats	
Akoustolith Plaster, ½" float finish	17	27	38				
Akoustolith A, Tile, 1"	14	48	83	About 4 lb per sq ft.	Artificial stone	1", 1½", 2"	3"×16" 4"×8" 5"×10" 12"×12" 8"×16" for 1" thickness Can be made in any size up to 15"×30", 1½", 2"
Akoustolith B, Tile, 1"	10	28	73				
Akoustolith C, Tile, 1½"	12	44	66				
Akoustolith D, Tile, 2"	15	59	52				
Alltite Basket Tile	38	69	81	2½ lb per sq ft.	Wire baskets filled with 1½" layer of stone wool. Either plywood or sheet metal back	1⅜"	24"×24"
Auditec, De Luxe, ⅜"	10	45	58	60 oz. per yd.	Jute pad, needled to sized cotton De Luxe facing	Standard, ⅜" De Luxe, ⅝"	Panels of any size
Balsam Wool, 1"	15	52	66	320 lb. per 1000 sq. ft.	Balsam wool mat covered one side with a Kraft paper liner, other side with fireproof cloth mesh	1"	Packed in rolls 34" wide, containing 124 sq. ft.
Blue Diamond Acousticoat, ½" over hardwall on metal lath	29	36	75	41 lb. per cu. ft., dry. 40 lb. per cu. ft., set on wall	Plaster composed of pumice, gypsum, fibre, and special chemicals		
Blue Diamond Acousticoat, 1" over hardwall on metal lath	38	.60	.70				

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OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
Satisfactory		Depends on color	Mortar colors added by plasterer, or tinted after installation	Can be washed with soap and water. Properly mixed, 100 sq. yd per ton, ½″ thick. Not recommended for other than plain surfaces	R. Guastavino Company, Boston, Massachusetts
Satisfactory		Natural, 0 56 Depends on color	Pre-colored Resembles natural stones ranging from gray white through buff, and brown, and other natural stone colors	Fine granular surface. Noncombustible masonry. Can be water washed	R Guastavino Company, Boston, Massachusetts
Satisfactory	23	Depends on color	Sprayed or stained with thin dyes or lacquers	Has special interlocking back. Can be applied to old or new surface May be applied directly to metal channels on furred down ceilings	Coast Insulating Company Torrance, California
Satisfactory		Depends on color	Decorated or stenciled at factory with aniline colors	Low cost acoustical treatment. Chemically treated to prevent carrying flame	National Rug Mills, Milwaukee, Wisconsin
		0.42 as furnished. Varies with color	Decorative cloth membrane	Applied directly to walls or ceiling, between 1½″ furring strips 34″ o.c. Wool chemically treated to make fire resistant	Wood Conversion Company, Chicago Illinois
65 lb. per sq. in.		Depends on color	Integrally colored or lacquer sprayed	Good plasticity 67 per cent voids	Blue Diamond Company, Los Angeles, California

TABLE XX

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Caliœl, 1"	0 23	0 72	0 71	2¼ lb. per sq. ft.	Cellular silicate of lime and alumina, expanded from 20 to 40 volumes. Refractory bonding agent. Moulded under high pressure	¾", 1", 1¼"	12"×12" 16"×16" 6"×12" 9"×18" Other sizes obtainable
Felt, Akoustikos 1"	15	54	73	About 1 lb. per sq. ft.	Punched felt of goat hair and asbestos fibre	½", ¾", 1"	
Fir-Tex, 1"	32	.39	41	1.2 lb. per sq. ft.	Made from Douglas Fir. Contains about 10 per cent of bark. 0.1 per cent resin for fibre waterproofing set upon fibre by 0 1 per cent alum solution giving considerable fireproofing	1", 1½"	12"×12"
Flax-li-num, 1"	15	55	58	1 15 lb. per sq. ft.	Manufactured from the long tough fibres of the flax plant	¼", ½", ¾" 1"	Specially cut dimensions up to maximum of 48"×10'
Halico Plaster, stippled	16	25	44			½" in two or more layers over scratch, or scratch and brown coats	
Insulite Acoustile, Type 37	.21	38	46	750 lb. per 1000 sq. ft.	Wood fibre fabricated into tiles	¾"	Sizes range from 6"×6" up to 24"×24"
Insulite Acoustile, Type 44	.26	50	.61	1400 lb. per 1000 sq. ft.		1⅜"	

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OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
	0 53	Natural light, .54 Ivory washable lacquer, .68	Can be brushed or sprayed with thin oil or flat paints and lacquers. Additional coats do not appreciably alter absorption	Appearance of tile not affected by water or flame. Can be cleaned by vacuuming or wiping with wall paper cleaner	General Insulating Company, Hammond, Indiana
	Low	Depends on membrane	Decorative cloth membrane		Johns-Manville Corporation, New York City
90 to 190 lb. per sq. in.	.28 to 31	Natural color is brown	Can be stained or decorated with acoustical paints		Fir-Tex Insulating Board Company, St. Helens, Oregon
	.31	Depends on color	Decorating not recommended, although can be done with kalsomine or special acoustical paint	Low in cellulose composition, high in fibrous. Very small expansion or contraction with moisture changes	Flax-li-num Insulating Company, St. Paul, Minnesota
25 to 45 lb. per sq. in.			Integrally colored. Stencil or border designs with thin paint	Best acoustical results obtained by stippling with rice root brushes	Hachmeister-Lind Company, Pittsburgh, Pennsylvania
150 to 200 lb. per sq. in.	30	.64	Benzol and alcohol stains and thin water paints	Can be furnished in practically any desired size or shape	Insulite Company, Minneapolis, Minnesota

TABLE XX

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Kalite No. 102, ¾", on metal lath	0 37	0 40	0 53	About one half of ordinary plaster	Made of graded sizes of a special pumice mixed with a gypsum binder. The inherent porosity of the pumice together with the method of mixing gives a plaster with many communicating channels Calcined gypsum ($CaSO_4.\frac{1}{2}H_2O$), 34.85 per cent; pumice 60.33 per cent	Can be applied in thicknesses of ½", ¾", 1"	
Kalite, ¾"	41	51	59				
Kalite, ¾", with three coats lacquer	35	43	45				
Macoustic Plaster, stippled to depth of ½"	12	31	58	2 lb. per sq. ft.	A fibrous plaster	Applied ½"	
Macoustic Plaster, float finish	09	19	26				
Malone Plaster, ⅜", ½" wall board backing. "Left under the rod"	15	27	28	37 lb. per cu. ft	Composed of lime, Keene's cement, and a pumice gravel. Should be applied to dry undercoating in order to develop maximal absorptivity		
Malone Plaster, 1", over special scratch coat on metal lath	39	50	56				
Masonite	.18	32	33	700 lb. per 1000 sq. ft.	Made chiefly of longleaf pine and southern gum	7/16"	4'×12'
Nashkote A, Perforated, 1"	12	68	66		Akoustikos felt cemented to surface to be treated, covered with a membrane secured by Acoustical Size. Membrane is painted muslin (Types A, AIS, ACS); Kribble Kloth (Types B-332, B-085, B-068, B-045); awning cloth, burlap, etc. (Type F); or no membrane and surface sized (Type C).	Type C, ½", ¾"; Type F, ½", ¾", ⅞", 1½", 1¾", 3"; Types A, AIS, ACS, and all B-types, ½", ¾", ⅞"	No limitation to size of units
Nashkote B-322, 1"	.15	59	77				

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OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
50 to 75 .lb per sq. in.		Depends on color	May be colored or tinted by integral mixing or can be sprayed or hand-painted with non-bridging lacquers	Supplied in three grades (1) regular, with smooth trowel finish; (2) No. 102, with egg-shell finish; (3) Kalite hydraulic, a Portland cement plaster for use in swimming pools, etc. Plaster not affected by washing	Kalite Company, Ltd., Pasadena, California
110 lb. per sq. in.		White, .65 Light cream, .58 Ivory, .56 Buff, .54	Spray painting with water colors	110 yd. per ton coverage	Macoustic Engineering Company, Inc., Cleveland, Ohio
50 to 100 lb. per sq in.		Depends on color	Natural color, light cream tone. Integrally mixed pastel shades. May be decorated by thin stains	Slow setting properties give ample time for plaster joinings; also add to workability	Malone Stucco Products Company Los Angeles, California
225 lb. per sq. in.	33	Depends on color	"Masonite Acoustical White" stippled on with a sponge. May be stenciled		Masonite Corporation, Chicago, Illinois
			Types A, AIS, ACS may be painted and perforated. B- types may be painted. Type C should be spray painted	Type A resembles smooth plaster; Type AIS, rough plaster; Type ACS, Caen Stone; Numerals in B- types refer to size of perforations. Type F must be dry or vacuum cleaned; all other types washable. Fire resistant.	Johns-Manville Corporation, New York

TABLE XX

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Nephi Super-Acoustic Plaster, ½", on metal lath	0 16	0 43	0 49	41.8 lb. per cu. ft., bulk 47 lb. per cu ft., dry set	Combination of fibrous and porous aggregates	Usually applied to thickness of ½"	
Reverbolite Plaster	07	34	65	24 lb. per cu ft , dry. 44 lb. per cu ft , set and dried (on job)	Fibrous material, small pellets of rock wool, and gypsum base	½"	
Rockoustile, 1"	18	57	72	1.5 lb. per sq. ft.	Rock wool product	1"	6"×12" 12"×12"
Sabinite		34	49	2 to 3 lb per sq. ft	Gypsum base plaster No stippling or special art in application required. No. 38 is a special humidity resisting material, utilizing a hydraulic binder, for the acoustical treatment of natatoria and similar humid rooms	Applied in two coats, about ½"	
Sabinite, No. 38, for swimming pools	10	38	41				
Sanacoustic Tile	19	.79	.74	2 lb. per sq. ft. (aluminum) 2.5 lb. per sq. ft. (steel)	Perforated sheet metal tiles finished in baked enamel, containing special rock wool element	1½"	12"×12" 12"×24" 8"×16" 16"×16"

— (*Continued*)

OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
108 lb. per sq. in.		.27 to .62 depending on color	Integrally colored. May be stenciled or spray tinted. Supplied in seven stock colors	Highly resistant to mechanical abrasion. May be stiff brushed for cleansing, or washed with soap and water	Nephi Plaster Manufacturing Company, Salt Lake City, Utah
58 lb. per sq. in.	.76 to .80	Depends on color	Furnished in color or natural. Can be sprayed with dye colors or cold water paint manufactured by American Gypsum Company. May be stained with aniline or water dyes	Can be textured. May be cast and applied for ornamental effects. Fire resistant.	American Gypsum Company, Port Clinton, Ohio
		Depends on color	Furnished in two colors, buff or gray	Resembles Travertine. Can be vacuum cleaned or sandpapered	Johns-Manville Corporation, New York City
		Natural white, .65	Supplied in color May be spray painted with kalsomine or thin lacquer; or brush painted with Acoustical Textone	Fireproof, decorative, easy to apply. No. 38 requires special base coat; will not disintegrate or be otherwise affected in humid rooms	United States Gypsum Company, Chicago, Illinois
Satisfactory			Can be decorated with any type of paint. Furnished pre-decorated in various colored designs in 16″× 16″ size only	Tile of perforated steel, or perforated aluminum for use under damp and humid conditions. Fireproof. Washable. Individual units snap into special metal T bars secured to surface to be treated	Johns-Manville Corporation, New York City

TABLE XX

PHYSICAL PROPERTIES

Material	Sound-Absorption Coefficients			Weight	Composition	Thicknesses	Stock Sizes
	128	512	2048				
Silent-Ceal	0 29	0 68	0 75	3 lb. per sq. ft.	Rock wool fill, special metal furring; No. 20 gauge perforated metal primary membrane, fabric secondary membrane	Determined by requirements of job	
Stucoustic Plaster	18	24	26	35 lb. per cu ft.	Keene's cement and dolomitic lime base with pumice aggregate plus other materials for workability and plasticity	Any thickness desired	
Transite Tile, 1″	19	81	72	3 lb. per sq ft	1″ sound-absorbing block faced with perforated Transite, 3/16″, asbestos paper	1 3/16″	6″×6″ 12″×12″
Trutone Tile	31	57	64		Precast porous gypsum tile with ¼″ plaster board backing	1¼″	12″×12″ and larger as required

— (*Continued*)

OF ABSORPTIVE MATERIALS

Tensile Strength	Heat Conductivity in B.T.U. per in.	Light Reflection Coefficients	Recommended Methods of Decoration	Comments	Name of Manufacturer
Satisfactory		78	Special sponge stipple paint	Complete ceiling construction; rock wool fill may be zoned to give more absorption at one place than another	Acoustical Corporation of America, Philadelphia, Pennsylvania
Satisfactory		Depends on color	Thin dyes or sprays	Good workability	California Stucco Products Company, Los Angeles, California
Satisfactory		Depends on color	Furnished in three colors natural variegated gray, natural variegated buff and cream white enamel	Washable	Johns-Manville Corporation, New York City
Satisfactory		Depends on color	Furnished in any solid color integrally mixed. May be stenciled with water color paints or colors mixed with nonbridging lacquer	May be cast in ornamental forms. Fibrous. Inorganic. Washable. Furnished with beveled or straight edges	Acoustone Company, Ltd., Los Angeles, California

CHAPTER IX

INSULATION OF SOUND — NOISE IN BUILDINGS AND OUT-OF-DOORS

85. Introductory. Freedom from the harassing effects of noise is one of the finest qualities a building can possess. Now, more than ever before, the architect is obliged to seek, by every possible means, for those types of construction which will impart to his buildings exceptionally quiet living or working conditions. An intelligent approach to the problem of constructing buildings which will be free from the disturbance of noises originating either inside or outside of the building must be based upon a knowledge of the intensity and frequency characteristics of these noises. In some instances it is feasible to make measurements of the noise near the site or within the building before designing the type of structure which will insulate adequately these inherent noises. In most instances, however, it is sufficient to be familiar with the results of noise surveys which have been made in metropolitan cities, both in buildings and out-of-doors.

During recent years, both acoustical engineers and civic authorities have given considerable attention to the questions of noise surveys and noise abatement. The city of New York has taken the lead in this matter, and has recently published a volume which gives an account of some comprehensive surveys of noises in New York City, together with many technical proposals for the abatement of noise.[1] The data obtained from these surveys, and published in " City Noise," give the intensity and frequency distribution of most kinds of noise in typical parts of metropolitan New York. Every architect and acoustical engineer should be acquainted with these data, for they reveal very clearly the degree of sound-insulation which must be built into various buildings if these buildings are to provide adequate protection against the insidious noises of the machine age. It is true that some alleviation from these noises will come from efforts to reduce them at their sources, but there will always be a certain unavoidable level of noise, and the architect is obliged to provide insulation against this level.

In the design of theatres or metropolitan opera houses, of churches or schools near main traffic arteries, of office and industrial buildings, or

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[1] "City Noise," Noise Abatement Commission, Dept. of Health, City of New York (1930).

of hotels and apartment houses, it is necessary that the architect know (1) the amount and character of the noise against which he is to provide insulation, and (2) the amount of noise which can be tolerated in different types of building. Thus, it may be stated as a general rule that the difference between the existing noise and the amount which can be tolerated indicates the amount of insulation which should be provided in the building. Thus, if the noise in the vicinity of a building have a level of 60 db, and a level of 20 db can be tolerated in the building, it is necessary that the building provide an insulation of 40 db.

Just what is meant by a noise level of, for instance, 60 db and an insulation of, for instance, 40 db, requires further elucidation. The evaluation and measurement of insulation will be considered in Chap. X. For the immediate purpose of the discussion of noise in and near buildings it will be sufficient to consider the evaluation and measurement of noise. First of all, it is necessary to define the unit or units of noise.

86. Units of Noise. Noise may be evaluated either in physical units by specifying the pressure variations of the sound wave for all audible frequencies, or in sensation units by specifying the sound level or loudness for all audible frequencies. For purely physical investigations, a physical unit, such as the peak and average pressure in bars, would be the most satisfactory. But such a unit fails to convey to the non-technical person a proper notion of the magnitudes of different noises. For example, for two noises characterized by average pressures of 0.01 bar and 1 bar, at a frequency of about 1000 cycles, experience shows that the non-technical person will not judge the 1-bar noise to be 100 times as loud as the 0.01-bar noise. If these same two noises are rated in terms of their sound levels, the corresponding levels, at a frequency of 1000 cycles, will be about 25 and 65 db above the threshold of audibility. These two numbers give a better notion of the magnitudes of the two noises, as judged by the average person, since they are proportional to the logarithms of the sound pressures. If the average sound levels of these same two noises are specified at other representative frequencies throughout the audible range, the two noises will be described in terms of numbers which correspond approximately with the loudness levels at the representative frequencies,[2] and the numbers (sound levels in decibels) will be very convenient for calculating the amounts of noise which will penetrate through different types of walls and partitions. For most practical problems in connection with noise measurement and the insulation of sound it is sufficient to specify the

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[2] The sound levels should be converted into loudness units (see Sec. 37) in order to correspond better with our generally established notions of loudness. Such a conversion will affect only the frequency components below about 700 cycles.

sound levels for low, medium, and high frequencies; for example, for frequency bands in the vicinity of 128, 512, and 2048 cycles.

It is convenient, and attempts are often made, to evaluate the loudness of a noise in terms of a single number, as for example by specifying the sound level of a pure tone of 700 or 1000 cycles which would be judged to be of the same loudness as the loudness of the noise. Such evaluations, however, do not describe the character of the noise, and if used at all in problems of sound-insulation they should be used only with a knowledge of the frequency distribution of the noise and the insulative properties of the insulating medium. It happens that most noises have their maximal sound level within the octave between 512 and 1024 cycles, so that if the sound level of the noise and the insulative value of the insulating medium be specified for this region it is possible to predict approximately the amount of noise which will be transmitted through the boundaries of a room. For approximate calculations in sound-insulation it will suffice to use these single frequency, or even average frequency, values, but for more precise calculations, such as should be made for all important buildings, it is advisable to specify the noise in terms of its peak and average sound levels at frequencies of say 128, 512, and 2048 cycles, and to make calculations of the transmitted noise at these frequencies.

87. Methods of Measuring Noise. Several practical methods have been developed for the measurement of noise.[3] At a recent symposium on noise measurement conducted by the American Institute of Electrical Engineers in April, 1931, eight different instruments for the measurement of noise were presented. Three of these methods will be considered briefly in this section: (1) the tuning-fork method, (2) the audiometric method, and (3) the acoustimeter method. The tuning-fork method, described by Davis,[4] is extremely simple, but gives quite satisfactory results if used with proper care. Davis used a single fork having a frequency of 640 cycles, but the same type of measurements can be made with several forks. In general, it is advisable to use at least three forks — tuned to, say, 128, 512, and 2048 cycles. The 2048 fork, at least, should be a massive steel fork, or a fork of the "Duratone" type with a low rate of damping. Ordinary steel forks are quite

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[3] E. E. Free, "Practical Methods of Noise Measurement," Jour. Acous. Soc., **2**, 18 (1930); R. H. Galt, "Results of Noise Surveys — Noise Out-of-Doors," Jour. Acous. Soc., **2**, 30 (1930); R. S. Tucker, "Noise in Buildings," Jour. Acous. Soc., **2**, 59 (1930); J. S. Parkinson, "Vehicle Noise and Noise Reduction," Jour. Acous. Soc., **2**, 65 (July, 1930).

[4] A. H. Davis, "Measurement of Noise by Means of a Tuning Fork," Nature, **125**, 48 (January 11, 1930).

satisfactory at 128 and 512 cycles. First of all, the forks must be calibrated. It is necessary to know the sound level, in decibels, of each fork immediately after it has received a standard blow or excitation. If the fork be allowed to fall from a vertical position, through an arc of 90°, hitting a suitable pad (such as soft rubber or felt for the low-pitched forks and hard rubber for the high-pitched forks), the initial intensity can be reproduced very easily to an accuracy of 1 or 2 db. It is then necessary to know the rate of decay of the three forks. In general, the rate of decay of intensity is essentially logarithmic, so that the rate of decay will be a constant number of decibels per second. The rate of decay can be determined very readily by means of any of the reverberation meters described in Sec. 69. The 512 steel fork will give, when held close to the ear, an initial sound level of about 70 or 80 db, and it will decay at a rate of about 1.0 to 1.7 db per second. Lower-pitched forks decay more slowly and higher-pitched forks decay more rapidly than does the 512 fork. In a perfectly quiet room steel forks may remain audible, when held close to the ear with the broad side of the prong toward the opening of the ear canal, from about 50 to 80 seconds, and " Duratone " forks will remain audible a hundred seconds or longer. If the rate of decay in decibels per second and the duration of audibility in a *quiet* room have been determined for a fork, its initial sound level will be equal to the rate of decay times the duration of audibility. Thus, if the rate of decay for a fork is found to be 1.1 db per second, and the duration of audibility after it has been given a standard hit is 60 seconds, the initial sound level of the fork will be 66 db above the threshold of the individual making the measurements. The hearing acuity of this individual should then be compared with the normal (by means of a calibrated audiometer) and an appropriate correction applied to the initial sound level of the fork. In many cases it is possible to have the forks calibrated by the manufacturer or by qualified laboratories, such as the Bureau of Standards. After the forks are calibrated, the method of measuring any noise is very simple. The observer, in the presence of the noise, strikes the fork a standard blow and at the same instant starts a stop watch. The fork is then held in front of the ear canal, moving it back and forth slightly, until the tone of the fork is just completely masked by the noise, at which instant the stop watch is stopped. This measurement is then repeated two or three times, and the average of all readings will give a good measure of the level of the noise at that particular frequency. Thus, suppose that the fork gives an initial sound level of 66 db, and that its tone decays at a rate of 1.1 db per second. Then if the fork remains audible only 20 seconds, it means that the masking effect of the noise at this frequency is 66 − 22 or 44 db.

Similar readings are obtained at other frequencies, and the resulting data will give an approximate audiogram of the measured noise. Measurements of this type, made with 128, 512, and 2048 forks, give a very satisfactory description of the intensity and frequency distribution of different types of noise. Both the apparatus and the method of measurement are extremely simple and reliable.

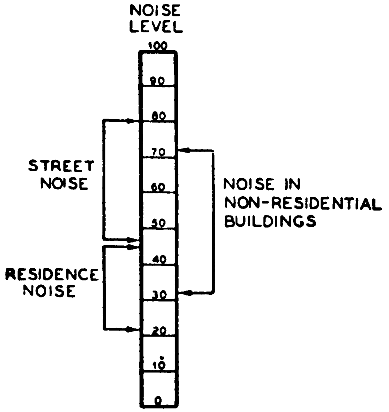
A somewhat similar and also a very convenient method for making an approximate measurement of noise is made possible by means of a buzzer audiometer, such as the Western Electric Company's 3A Audiometer. The buzzer in this instrument has a fundamental frequency of 160 cycles, and it has an abundant supply of overtones (see Fig. 10), so that its noise is quite representative of most noises encountered in practice. The receiver of the audiometer is equipped with an off-set receiver cap so that the ear of the observer hears both the noise of the audiometer and the noise which is to be measured. The observer first determines the amount of attenuation (in decibels) which must be introduced in the audiometer to reduce the buzzer sound to inaudibility when listening in a quiet place. He then makes a similar measurement when listening in the presence of a noise which is to be measured. The difference in the two readings of the audiometer, in the quiet place and in the noise, then gives a rough measure of the masking effect of the noise. The masking effect of the noise, as measured by the threshold shift on the audiometer dial, will usually be about 5 to 10 db less than the sound level of the noise.

FIG. 116. Schematic diagram of noise meter developed by Bell Telephone Laboratories. The weighting network is designed to give the same meter deflection for any pure tone having a loudness of 30 db.

In the acoustimeter method of measuring noise the noise vibrations are picked up by a microphone, amplified by a vacuum-tube amplifier, passed through a frequency-weighting network, and registered or recorded by a suitable galvanometer. Fig. 116 shows a schematic diagram of an acoustimeter developed by Bell Laboratories. This instrument has been used extensively in the survey of noises in New York, and most of the records which will be given in the following two sections were obtained with this instrument. The frequency-weighting network is based upon the sensitivity and sensibility characteristics of the normal human ear, so that the deflections registered or recorded by the instrument will be comparable to those which would be heard by the ear. A single reading of the instrument will therefore give a fairly reliable measure of the " noisiness " of the noise, although the effect of the frequency-weighting network will introduce certain errors owing to variations of intensity and frequency distribution in different noises. Such an instrument is extremely useful for obtaining a continuous record over an extended period of time. The band-pass filters shown in Fig. 116 provide a means for determining the sound levels over four frequency bands — below 500 cycles, 500 to 1500 cycles, 1500 to 3000 cycles, and above 3000 cycles.

88. Noise in Buildings. In connection with the noise survey carried out by the New York Noise Abatement Commission, Mr. R. S. Tucker, of the American Telephone and Telegraph Company, has made a number of noise measurements in residential and non-residential locations, including private homes, apartments, and various industrial rooms. The order of magnitude of the noises encountered in different buildings and in the streets of New York is shown in Fig. 117, which is based upon the survey of the New York Noise Abatement Commission and the joint survey of the National Electric Light Association and the American Telephone and Telegraph Company. Thus, the average street noise level in New York varies from about 47 to 80 db; the average noise level

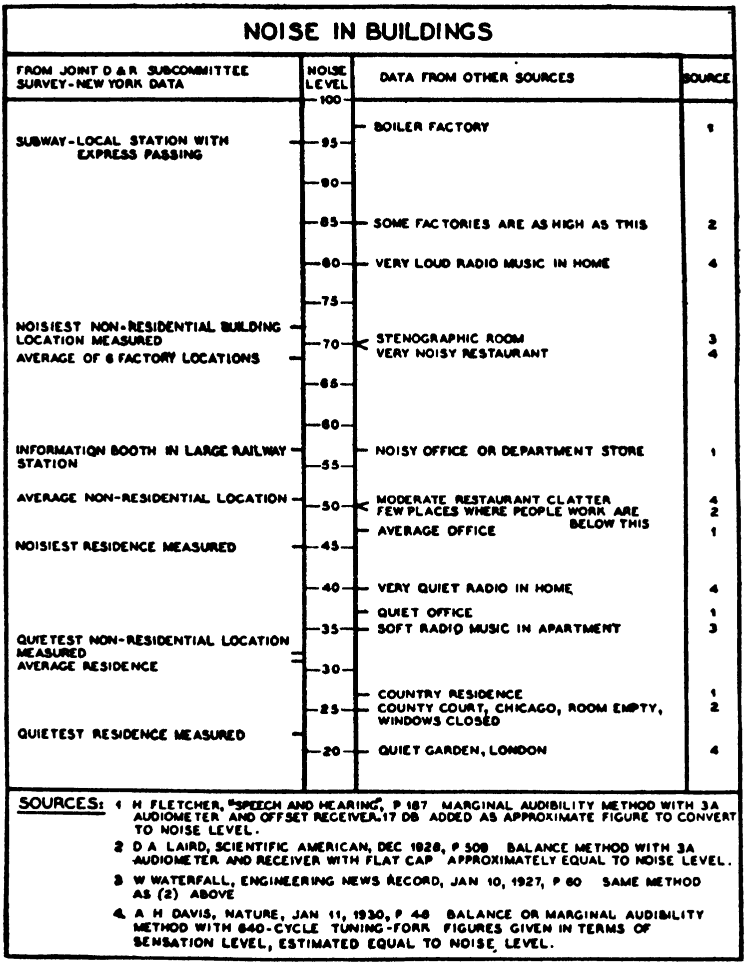
RANGES OF NOISE LEVELS FOUND IN NEW YORK CITY



VALUES FOR STREET NOISE FROM NOISE ABATEMENT COMMISSION SURVEY; FOR OTHER NOISES, FROM N E L A -A T &T CO SURVEY ALL VALUES ARE AVERAGES FOR THE LOCATIONS TESTED

FIG. 117. Approximate noise levels in New York City. (*Tucker.*)

in non-residential buildings varies from about 32 to 72 db; and the average noise level in residences varies from about 22 to 45 db. The average of all residential locations was 31 db, and the average of all non-residential locations was 51 db; so that in general it may be stated that the noise level in non-residential buildings is approximately 20 db higher than that in residential buildings.



SOURCES:
1 H FLETCHER, "SPEECH AND HEARING", P 187 MARGINAL AUDIBILITY METHOD WITH 3A AUDIOMETER AND OFFSET RECEIVER. 17 DB ADDED AS APPROXIMATE FIGURE TO CONVERT TO NOISE LEVEL.
2 D A LAIRD, SCIENTIFIC AMERICAN, DEC 1928, P 508 BALANCE METHOD WITH 3A AUDIOMETER AND RECEIVER WITH FLAT CAP APPROXIMATELY EQUAL TO NOISE LEVEL.
3 W WATERFALL, ENGINEERING NEWS RECORD, JAN 10, 1927, P 60 SAME METHOD AS (2) ABOVE
4 A H DAVIS, NATURE, JAN 11, 1930, P 48 BALANCE OR MARGINAL AUDIBILITY METHOD WITH 640-CYCLE TUNING-FORK FIGURES GIVEN IN TERMS OF SENSATION LEVEL, ESTIMATED EQUAL TO NOISE LEVEL.

FIG. 118. Noise levels in buildings. (*Tucker.*)

In Fig. 118 are shown the results of noise measurements in a wide variety of buildings obtained from the sources named at the bottom of the figure. Thus, the noise in a boiler factory is about 97 db; the noise

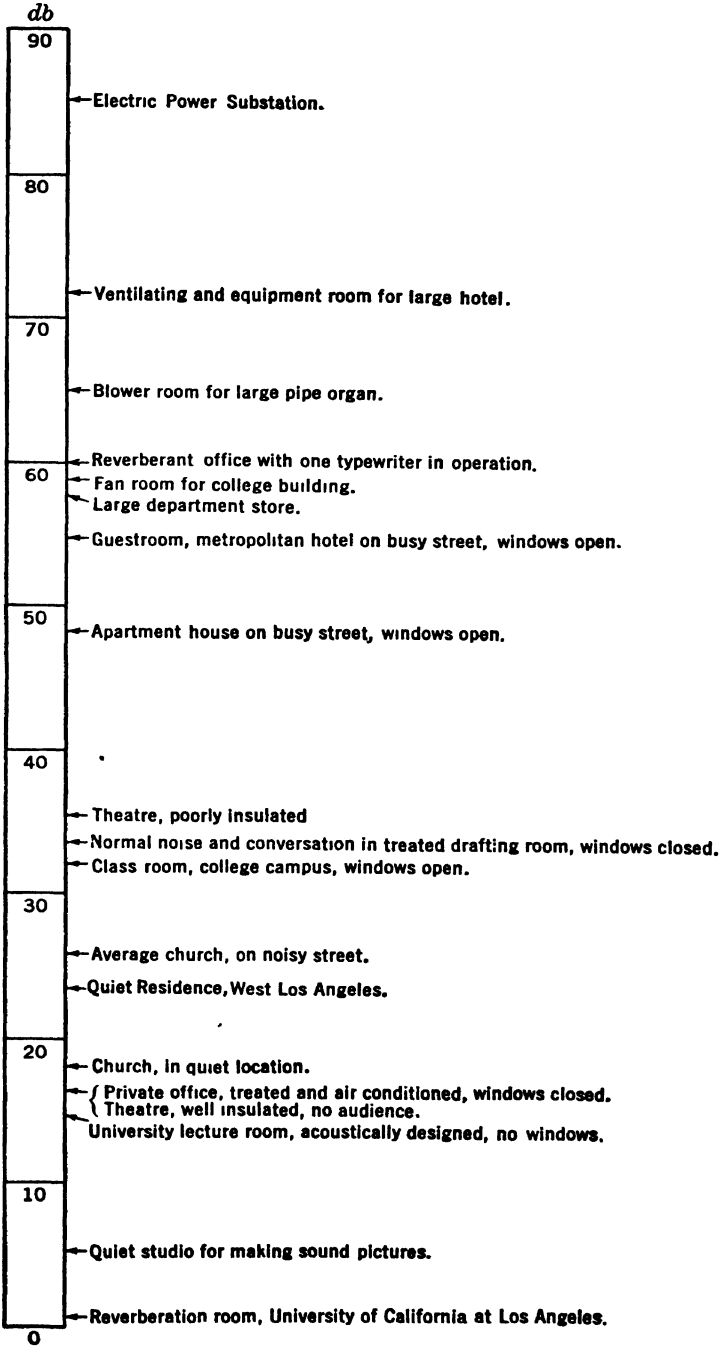
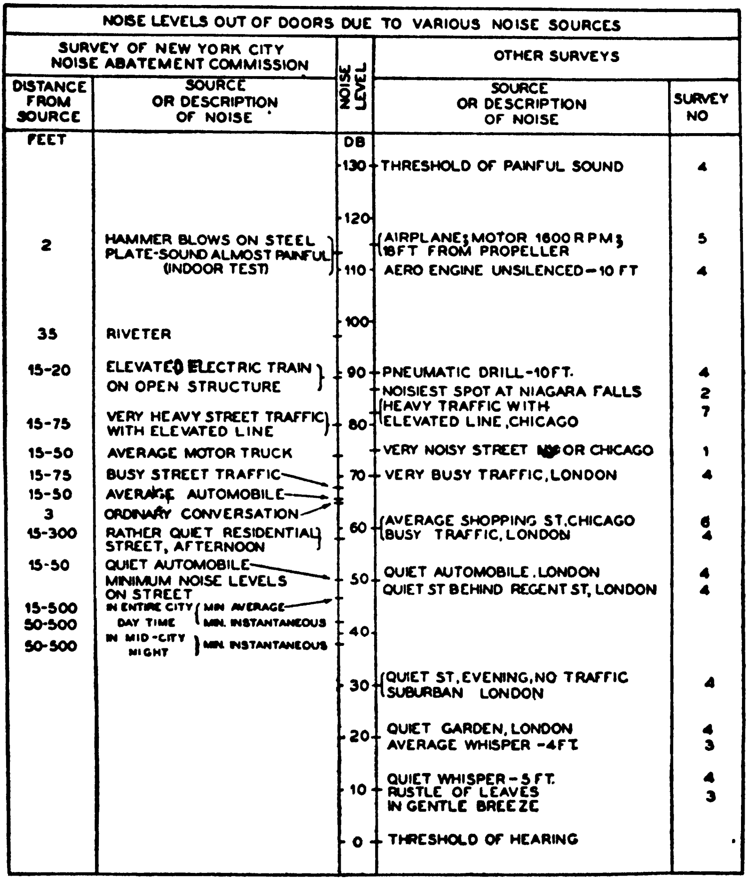


Fig. 119. Noise levels in various buildings in Los Angeles.

on a subway station with a passing express train is 95 db; very loud radio music in the home is 80 db; very quiet radio in the home is 40 db; a very noisy restaurant is 70 db; and a quiet garden in London is only 20 db.

In Fig. 119 are given the results of a number of noise measurements in buildings in and near Los Angeles. The measurements were made with



NOISE LEVELS OUT OF DOORS DUE TO VARIOUS NOISE SOURCES

SURVEY OF NEW YORK CITY NOISE ABATEMENT COMMISSION		NOISE LEVEL	OTHER SURVEYS	
DISTANCE FROM SOURCE	SOURCE OR DESCRIPTION OF NOISE		SOURCE OR DESCRIPTION OF NOISE	SURVEY NO
FEET		DB		
		130	THRESHOLD OF PAINFUL SOUND	4
		120		
2	HAMMER BLOWS ON STEEL PLATE-SOUND ALMOST PAINFUL (INDOOR TEST)		AIRPLANE; MOTOR 1600 RPM; 18 FT FROM PROPELLER	5
		110	AERO ENGINE UNSILENCED—10 FT	4
		100		
35	RIVETER			
15-20	ELEVATED ELECTRIC TRAIN ON OPEN STRUCTURE	90	PNEUMATIC DRILL-10FT.	4
			NOISIEST SPOT AT NIAGARA FALLS	2
15-75	VERY HEAVY STREET TRAFFIC WITH ELEVATED LINE	80	HEAVY TRAFFIC WITH ELEVATED LINE, CHICAGO	7
15-50	AVERAGE MOTOR TRUCK		VERY NOISY STREET N.Y. OR CHICAGO	1
15-75	BUSY STREET TRAFFIC	70	VERY BUSY TRAFFIC, LONDON	4
15-50	AVERAGE AUTOMOBILE			
3	ORDINARY CONVERSATION			
15-300	RATHER QUIET RESIDENTIAL STREET, AFTERNOON	60	AVERAGE SHOPPING ST, CHICAGO BUSY TRAFFIC, LONDON	6 4
15-50	QUIET AUTOMOBILE	50	QUIET AUTOMOBILE. LONDON	4
	MINIMUM NOISE LEVELS ON STREET		QUIET ST BEHIND REGENT ST, LONDON	4
15-500	IN ENTIRE CITY DAY TIME: MIN AVERAGE			
50-500	IN ENTIRE CITY DAY TIME: MIN. INSTANTANEOUS	40		
50-500	IN MID-CITY NIGHT: MIN. INSTANTANEOUS			
		30	QUIET ST, EVENING, NO TRAFFIC SUBURBAN LONDON	4
		20	QUIET GARDEN, LONDON	4
			AVERAGE WHISPER -4 FT	3
		10	QUIET WHISPER - 5 FT	4
			RUSTLE OF LEAVES IN GENTLE BREEZE	3
		0	THRESHOLD OF HEARING	

FIG. 120. Noise levels in various out-of-door locations. (*Galt.*)

tuning forks of 128, 512, and 2048 cycles per second. The data in Fig. 119 give only the average masking effect of the noise as measured with the 512 fork. In all cases the masking effect was less for the 128 and the 2048 forks than it was for the 512 fork.

89. Noise Out-of-Doors. In Fig. 120 is a summary, prepared by Mr. Galt, of noise measurements made in the open by a number of investigators. A large number of interesting data are contained in this chart, Thus, the noise of an airplane at a distance of 18 feet from the propeller is 115 db, which is only 15 db below the painful threshold; street noises vary from about 30 db in suburban London to 75 db in very noisy streets in New York or Chicago.

Fig. 121 shows how the noise level varies at Forty-eighth Street near Eighth Avenue, in New York City, over an interval of twenty-four hours. The heavy dots show the average values, and the small dots the minimal and maximal noise levels recorded in each twenty-minute test period. It will be noted that the average noise level varies from about 53 to 63 db, and that extreme variations lie between approximately 40 and 80 db. In order to provide practical insulation against these noises, a building should provide an insulation of at least 60 or 65 db. With this amount of insulation all average sound will be excluded, and only occasional loud outside sounds will reach the interior of the building with a maximal level of 15 to 20 db. Owing to the unavoidable noises in the interior of the building, which would rarely if ever fall below a level of 15 or 20 db, an insulation of 60 to 65 db would provide satisfactory insulation against these outside noises for practically all purposes. By

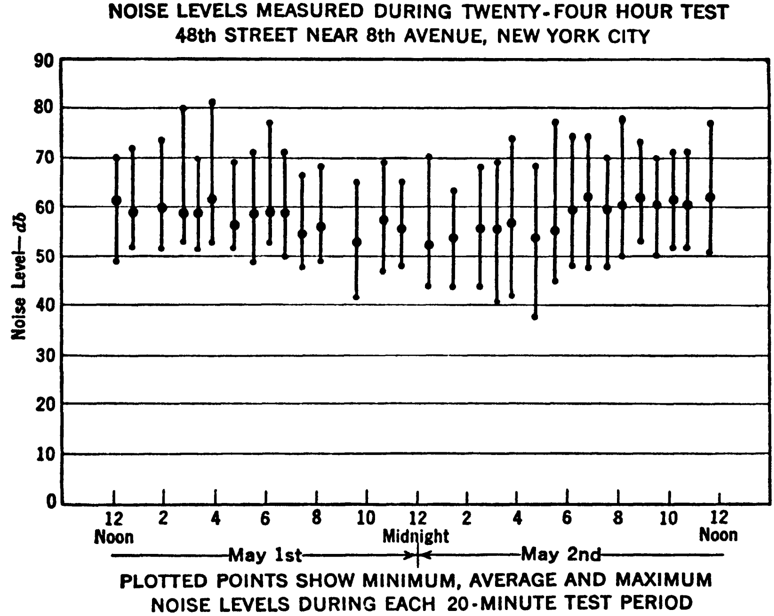


FIG. 121. Variation in street noise in metropolitan New York for a twenty-four-hour period. (*Galt.*)

making a noise survey, such as the one which is recorded in Fig. 121, at the site of any proposed building, it would be possible to predict in advance of construction just how much sound-insulation would be needed in order to provide any desired degree of insulation against these outside noises. This is often very important in connection with the design of theatres, churches, school buildings, and music buildings.

The frequency distribution of some typical noises measured in the streets of New York is shown in Figs. 122 and 123. It will be noted that in general the greatest loudness of noise lies in the frequency band between about 500 and 1500 cycles, although the loudness level is fairly uniform throughout the entire audible range of frequencies. In Fig. 124 are shown the results of some tests conducted out-of-doors in and near Los Angeles, using the tuning-fork method described in the first part of Sec. 87. In comparing data obtained by this method with data obtained by the acoustimeter it should be borne in mind that the tuning-fork method is essentially a *masking* method in which the noise just barely masks the tone of the fork, and for this reason the noise will always be louder than the tone which it masks. Experience indicates that for ordinary traffic noises it is necessary to add about 10 db to the tuning-fork measurements in order to convert them into data which will be comparable with the acoustimeter data. Further, the tuning-fork method, as described, gives the sound level rather than the loudness level of the noise. By means of Fig. 44, however, it is a simple matter to convert sound levels into loudness levels — a procedure which is neces-

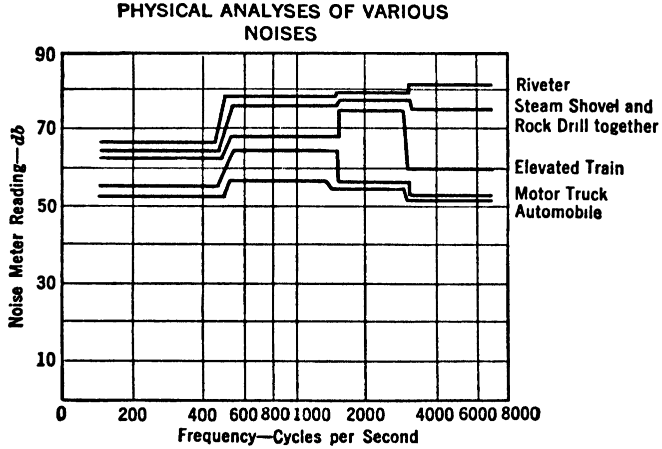


FIG. 122. Frequency distribution of some noises measured in the streets of New York. (*Galt.*)

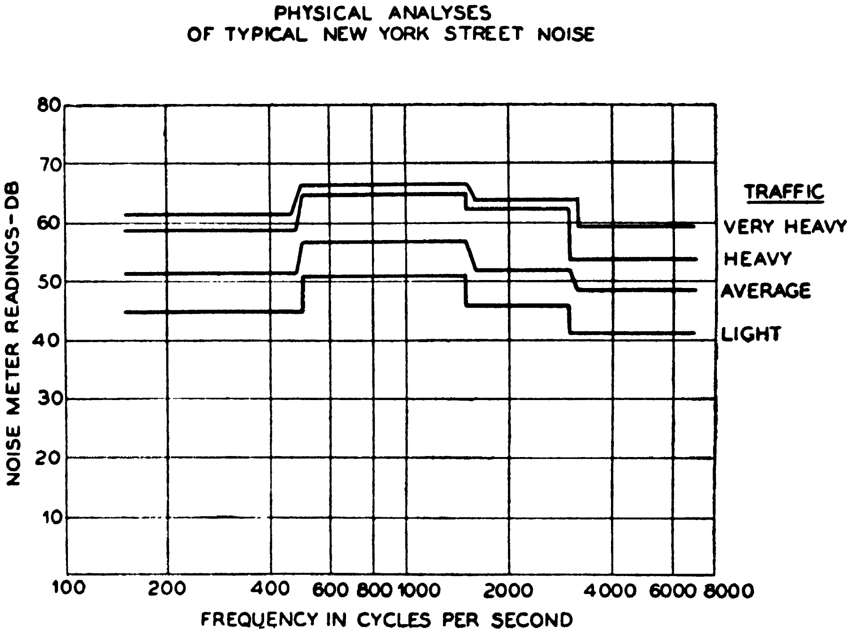


FIG. 123. Frequency distribution of composite street noise in metropolitan New York, corresponding to different densities of traffic. (*Galt.*)

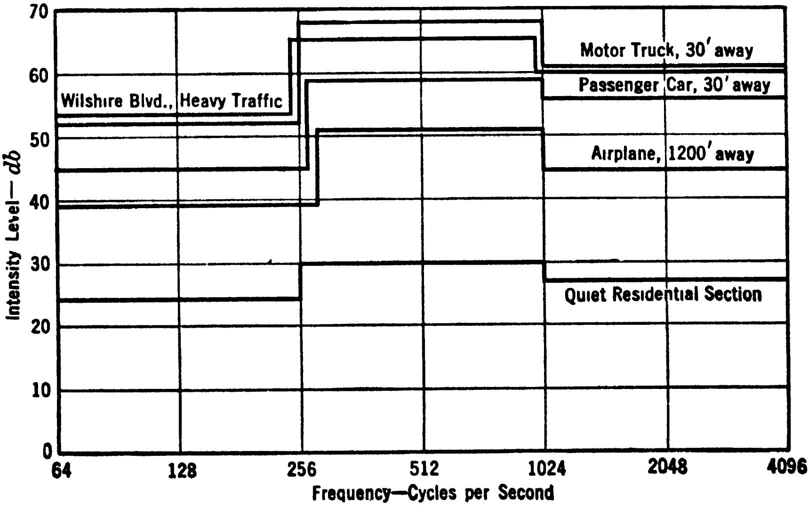


FIG. 124. Frequency distribution of out-of-door noises in Los Angeles.

sary only for the 128-cycle fork since loudness and sound levels are nearly identical for frequencies above 512 cycles. But, as stated in Sec. 86, it is better for the purpose of sound-insulation calculations to express the results of noise measurements in terms of sound levels rather than in terms of loudness levels.

CHAPTER X

INSULATION OF SOUND — FUNDAMENTAL PRINCIPLES

90. Introductory. One of the most baffling problems with which the building industry is confronted is the insulation of sound. Nearly every hotel, apartment house, office building, and residence is subject to the annoyance of noises which have their origin in adjacent rooms or outside. There is, therefore, a pressing need for a better understanding of this subject by architects and builders. Too frequently, architects and building engineers have received very meagre training in the problems of sound control in buildings, and therefore they are often dependent upon the help they can secure from sales engineers who have particular sound-insulating materials to sell. The prospectus of nearly every concern which sells sound-insulating materials is filled with proposed schemes of construction for sound-insulation. Some of these schemes possess definite merit, but others are of doubtful value. The trouble with many of the proposed types of structure is that they are based upon someone's notion of how to secure sound-insulation rather than upon plausible theories or exact measurements. One of the principal fallacies inherent in many of the proposed methods for sound-insulation is based upon the erroneous assumption that materials and methods which are effective for heat-insulation are also effective for sound-insulation. It is important that the architect and builder recognize that sound-insulation and heat-insulation are separate problems, although certain types of structure may be effective for both. In general, nearly all porous materials are good heat-insulators. Such materials are also, as a rule, good sound-absorbers, although they may not be good sound-insulators. However, when porous materials are properly used they may be effective in aiding sound-insulation by reason of their sound-absorptive properties. The uses of such materials in sound-insulation will be discussed later.

Although many difficulties and failures have beset the efforts of architects and builders to provide good sound-insulation in buildings, and although there are yet many things to be learned about the practical methods of sound-insulation, considerable information is now available in the form of data on the insulating properties of different materials and types of construction. In addition, the fundamental principles involved in sound-insulation are fairly well known. In the following sections of this chapter these fundamental principles will be treated, and in the following three chapters consideration will be given to the methods of measuring sound-insulation, to the available data on sound-insulation, and to the utilization of these data for calculating the insulation value of different types of construction.

91. Methods of Sound-Transmission through Partitions and Building Structures. In order to handle intelligently the problems of sound-insulation in buildings, it is necessary to have a clear conception of the mechanisms by which sound may be transmitted through building structures. The principal means for the transmission of sound through buildings are the following:

1. By means of openings, as windows, cracks around doors, ventilating ducts, or any other openings which will admit a free flow of air.
2. By means of the refraction or transmission through partitions. This is analogous to the refraction or transmission of light from air to water, or between any other two dissimilar media.
3. By means of the conduction of sound through solids. For example, "impact sounds," such as footfalls, hammering on walls or floors, or moving of furniture on hardwood floors, are conducted through the dense and rigid structural members of a building.
4. By means of the diaphragm action of walls which communicate sound from one side of a partition to the other side.

The refraction or transmission of sound from one medium to another, as from air to plaster or stone, is an almost negligible factor in building construction. For example, in Chap. II a calculation was made of the amount of sound which would be transmitted from air through a solid material like brick or stone, and it was found that the intensity of the transmitted portion was only about one millionth of the intensity of the incident wave. The transmission of sound through walls and partitions by this means is usually a negligible factor, and need not be considered unless the wall is very thick — thicker than about one foot.

92. Transmission through Openings. The transmission of sound through openings, on the other hand, is often the means by which sound is most readily transmitted from one portion of a building to another. It often happens therefore that the limiting factor in the amount of sound-insulation which can be attained, especially in hotels and apartments, is determined by the insulation supplied by such unavoidable openings as may be incidental to the use of windows and doors. If, for example, it is necessary to open windows for ventilating purposes, the sound-insulation between two adjacent rooms may be limited to about 20 or 30 db. Under such circumstances it would be futile to provide a relatively high insulation through the separating walls or partitions. Even very small openings, such as cracks around doors or around imperfectly fitting windows, are effective in transmitting a considerable amount of sound. The reasons for this are, first, that the sensation level of sound is proportional to the logarithm of the intensity, and second, that the sound which passes through a small opening is diffracted so much that it spreads out in all directions from the small opening as though the small opening were itself a source of sound. In order to make the first factor clear, suppose that an opening 10 inches wide will transmit sound to an adjacent room so that the transmitted sound attains a level of 50 db; then by reducing the opening to one tenth of its initial size, that is, to a width of 1 inch, the energy transmitted through the opening has been reduced ten fold (neglecting the effect of diffraction) which means that the level of the transmitted sound has been reduced only to 40 db. A further reduction in the width of the opening to 0.1 inch (again neglecting the effects of diffraction) would reduce the energy another ten fold, and the sound level would be reduced another 10 db, so that the resulting level would still be 30 db. Thus, although the width of the initial opening has been reduced a hundred fold, the level of the sound transmitted to the adjacent room is reduced only about 20 db. The complete closing of the opening will, by the same reasoning, produce a relatively large diminution in the loudness of the transmitted sound. It is apparent therefore that a high degree of sound-insulation is dependent, among other factors, upon the complete closing of all threshold cracks around doors and windows in buildings. This is an important factor in sound-insulation, and the neglect of it may vitiate the benefit which may be anticipated from carefully designed walls or partitions.

The transmission of sound through ventilating ducts often becomes a troublesome problem in the control of sound in buildings. There are three types of sound-transmission which must be controlled: (1) the noise from the fans, motors, and other air-conditioning equipment which is transmitted through the ducts and into the room; (2) the noise from an adjacent room which is transmitted from *opening* to *opening*, often through a short and highly conductive section of duct; and (3) the noise from adjacent rooms or outside which may be transmitted through the walls of the duct and thence through the ducts and into the room. The noise from the ventilating equipment room can be reduced suitably by (1) the selection of slow-speed, quietly operating equipment; (2) treating the walls and ceiling of the equipment room with highly absorptive material; and (3) introducing acoustical attenuation within the ducts, which can be accomplished by using very long ducts of small cross-sectional area and by lining the ducts with highly absorptive material.

Thus, tests which have been conducted at the Bureau of Standards on the transmission of sound through speaking tubes,[1] and tests which have been conducted elsewhere[2] on the transmission of sound through ventilating ducts, indicate that the acoustical attenuation (expressed in decibels) suffered by sound in being transmitted through tubes and ducts is proportional to the length of the tube or duct; is inversely proportional (in the case of a circular tube) to the *b*th power of the diameter of the tube, where *b* has a value between 0.76 and 1.00[3]; and is approximately proportional to the absorptivity of the material which comprises the interior surfaces of the tube or duct. Using these principles, it is possible to design filters which will provide any required amount of attenuation of the sound which is generated by the ventilating equipment and propagated through the ducts.

The noise-transmission from room to room, by means of the duct which connects two rooms, also can be reduced suitably by introducing similar filters or attenuators within the duct which connects the two rooms. This same expedient, together with the use of heavy, low-transmitting materials for the walls of the duct, will minimize noises which otherwise might be transmitted through the walls of the duct and thence along the interior of the duct and into the room. In all cases the amount of attenuation introduced in the duct system should be sufficient to reduce the noise entering the room to a level which will be tolerable. This amount of attenuation, in decibels, will be equal to the difference between the noise level at the source and the noise level which can be tolerated in the room. (See problem 10, Chapter XIII.)

93. Transmission of Solid-Borne Sounds. The ease with which sound travels through solids has already been noted, and is amply demonstrated in nearly every modern steel-frame or reenforced-concrete structure. For example, impact noises, such as hammering against a wall, which originate in a room two floors above the author's office, and at a distance of 200 feet, are transmitted to the office at a sound level of more than 40 db, an amount of noise which is definitely an annoyance. These solid-borne sounds travel through the structural members of a building, with but very little attenuation, and with a velocity of about a

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[1] Eckhardt, Chrisler, Quayle and Evans, "Transmission of Sound through Voice Tubes," Technologic Papers of the Bureau of Standards, No. 333 (1926).

[2] See, for example, G. L. Larson and R. F. Norris, Heating, Piping and Air Conditioning (January, 1931). Similar tests, as yet unpublished, have been conducted by the Carrier Engineering Corporation and by the author.

[3] There is yet some uncertainty concerning the exact value of this exponent *b*. According to tests conducted at the Bureau of Standards, it is 0.76 for circular tubes. More recent tests seem to indicate that this is too low, and that 1.0 is more probable. The exponent 1.0 is in accord with theory.

mile a second. They are not readily transmitted or refracted from the solid structure to the surrounding air, since the density and elasticity of the two media, the one a dense rigid wall, and the other a tenuous, readily compressible atmosphere, differ so enormously. However, the compressional wave in the solid is communicated to large surfaces, as the walls and partitions surrounding the room, and these large surfaces are made to vibrate like the sounding board of a piano. In this way, a large portion of the solid-borne sound wave may be radiated into a room, and often may attain a disturbing magnitude.

The most common sources of solid-borne sounds are footfalls or the moving of furniture on uncarpeted floors, the flowing of water in pipes which make rigid contact with the partitions of the building, machinery not properly insulated from the solid frame of the building, and repairs to buildings which involve hammering against, or drilling into, the solid frame of the building. Thus, it is *impact* or *contact* that is the source of these solid-borne sounds. It is often possible to control solid-borne sounds by means of adequate insulation against the *impacts* or *contacts*; for example, by the carpeting of floors; by the wrapping of pipes — especially where they touch the frame of the building — with flexible, porous materials, as hair felt or mineral wool; or by the proper mounting of machinery on flexible or elastic supports. In monolithic structures, however, it is almost impossible to eliminate such solid-borne sounds as the impacts against the walls or partitions of the building, unless rather drastic and costly measures be adopted.

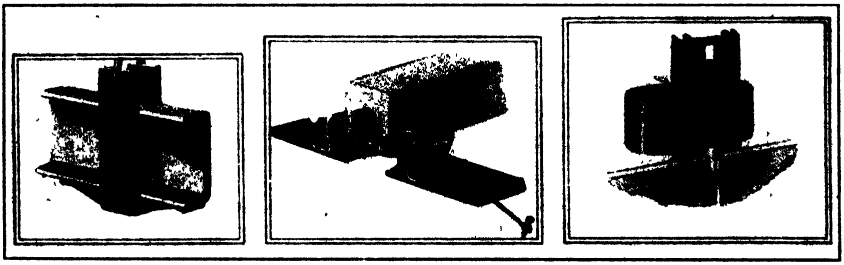
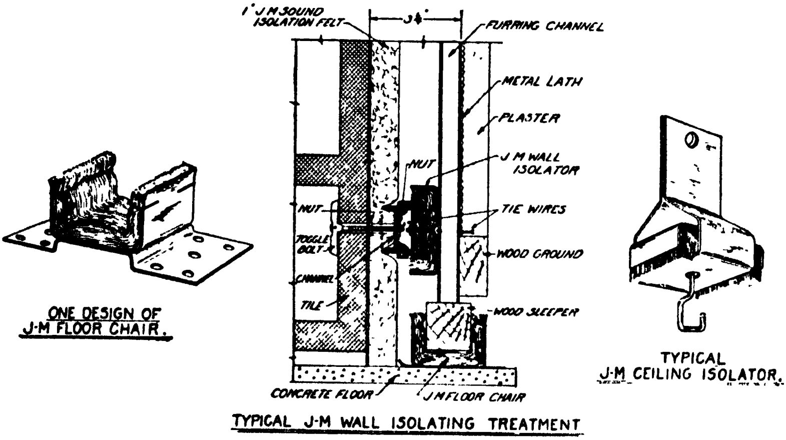


FIG. 125. Flexible ceiling saddle, wall clamp, and sleeper chair used by United States Gypsum Company.

Obviously, one of the most effective methods of eliminating these solid-borne sounds is to introduce discontinuities in the paths of the conducted sounds. These discontinuities should consist of materials which differ largely in elasticity and density from the solid structure of the building. For example, it is possible to suspend a ceiling by means of flexible or elastic supports; it is possible to build up inner walls in a room which are fastened to the monolithic frame by means of flexible ties; and it is possible to float the floor of the room upon flexible pads of cork or felt or other elastic material. In Figs. 125 and 126 are shown two types of flexible cushions, supports, and connectors which are effective for insulating solid-borne vibrations in buildings. The quantitative value of these flexible supports and connectors will be better understood after consideration has been given to the factors which affect the insulation of vibration. (See Sec. 94.)

A practice which is quite common but nearly always futile is to introduce porous materials, such as slag, pumice, or cinders, between studs or joists as a means of insulating both solid-borne and air-borne vibrations. Such expedients are of little or no value because the material itself is rigid, and as it is ordinarily employed, it does not introduce a discontinuity in the solid frame of the building, and it sometimes " bridges " partitions which otherwise would be separated.



ONE DESIGN OF J-M FLOOR CHAIR.

TYPICAL J-M WALL ISOLATING TREATMENT

TYPICAL J-M CEILING ISOLATOR.

FIG. 126. The Johns-Manville system of sound-insulation for ceiling, walls, and floors, showing a felt-lined floor chair, wall separator, and ceiling isolator.

Reenforced-concrete and steel-frame buildings give the greatest difficulty from the standpoint of solid-borne sounds, although wood-frame buildings may also prove troublesome in this respect. Masonry and brick structures, as a rule, do not transmit compressional sound waves so readily, principally because of the many discontinuities at the mortar joints, and therefore they are much freer from the defects of solid-borne sounds than are concrete or even wood-frame structures.

94. Insulation of Vibration. Closely associated with the insulation of solid-borne sound is the insulation of vibration. It was mentioned in the preceding section that many solid-borne sounds have their origin in vibrating machinery or equipment which, if properly mounted or supported, would not transmit an appreciable amount of vibration to the solid structure of the building. In the present section, special consideration will be given to the simple theory of the insulation of vibration, and to practical methods of insulating buildings, rooms, or building equipment from mechanical vibrations. The theory applies equally well to the problem of insulating the vibrations of mechanical equipment from parts of the building where such vibration should not be tolerated.

The simplest method of insulating any object, as a part of a building or a piece of equipment, from earth or building vibrations, consists of mounting the object on a suitable elastic support.[4] This is shown schematically in Fig. 127, in which an object of mass m is separated from another object of mass M by means of a flexible support which has certain elastic and damping properties.

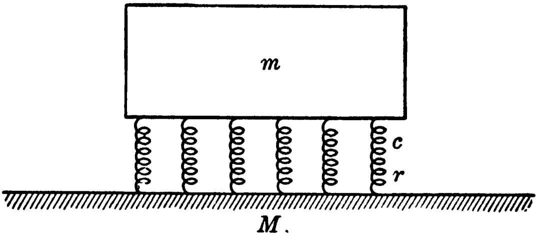


Fig. 127. Insulation of an object of mass m against vibrations in an object of mass M.

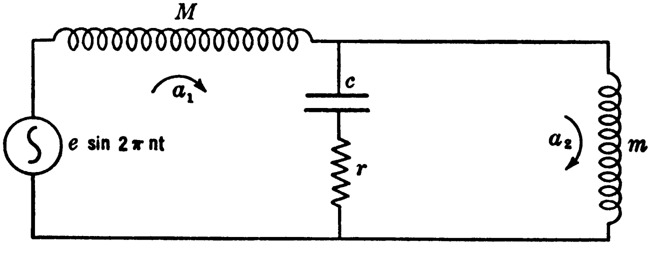


Fig. 128. Equivalent electrical circuit of the mechanical system shown in Fig. 127.

The similarity between mechanical and electrical circuits makes it possible to represent the mechanical system in Fig. 127 by the equivalent electrical circuit shown in Fig. 128. This circuit implies that when M is set into forced periodic vibration, these vibrations are communicated

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[4] See series of articles on this subject by C. R. Soderberg, beginning in the Electric Journal (January, 1924); S. Timoshenko, "Vibration Problems in Machinery" (Van Nostrand, 1928); V. O. Knudsen, Phys. Rev., **32**, 324 (1928); A. L. Kimball, Jour. Acous. Soc., **2**, 297 (1930); S. E. Slocum, "Noise and Vibration Engineering" (Van Nostrand, 1931). Slocum's book was published just as the author's manuscript was sent to press. It should be consulted.

to m principally by means of the elastic coupling between M and m, although the internal damping or resistance of the system also may contribute to the coupling. The elastic property of the flexible support is most conveniently specified by the compliance c, which is defined as the compression produced by the addition of unit force, as centimeters per dyne. The compliance may be regarded as an electrostatic capacitance in the equivalent electrical circuit, Fig. 128. The damping property, or resistance factor r, is specified by the rate at which the free vibrations of the mass m will be damped; it is analogous to electrical resistance in electrical circuits.

Suppose a vibromotive force — represented by $e \sin 2\pi nt$, where e is the maximal value of the vibromotive force and n is its frequency — be impressed upon M. This will set M, and consequently m, into vibrations of the same frequency as the impressed vibromotive force, and with velocity amplitudes of a_1 and a_2, respectively. It is possible, on the basis of the simple theory of network circuits, to write down the equivalent electrical equations for a_1 and a_2 in terms of $e \sin 2\pi nt$, M, m, c, and r, and then solve for the ratio of a_2 to a_1. If this be done, the resulting equation for a_2/a_1, which gives the ratio of the amplitude of vibration of the *insulated* mass m to that forced upon M, will be given by

$$\frac{a_2}{a_1} = \sqrt{\frac{r^2 + \dfrac{1}{4\pi^2 n^2 c^2}}{r^2 + \left(2\pi nm - \dfrac{1}{2\pi nc}\right)^2}}. \tag{39}$$

This equation has been tested experimentally for both supported and suspended systems and is in good agreement with the observed results.[5] The equation is useful for calculating the insulation value of different types of flexible supports. For values of n which are small compared with the natural or free vibration rate of m upon its elastic support, a_2/a_1 will be equal to unity; that is, m and M vibrate with the same amplitude, and the elastic support is neither advantageous nor detrimental as a means of insulating m from the vibrations of M. At the resonant frequency, that is, when $2\pi nm = 1/2\pi nc$ or $n = 1/2\pi\sqrt{mc}$, the value of a_2/a_1 is greater than unity, or the *insulating* support actually amplifies the motion imparted to m. In fact, for all values of n less than $1/\pi\sqrt{2mc}$ the value of a_2/a_1 will be greater than unity. However, for values of n greater than $1/\pi\sqrt{2mc}$ the value of a_2/a_1 becomes less than unity, and approaches the value $r/2\pi nm$ at frequencies which are high compared with the natural or resonant frequency. In general,

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[5] V. O. Knudsen, *loc. cit.* There is some uncertainty concerning the inclusion of r as a coupling factor, but experiments give a preference to its inclusion.

both m and c should be as large as possible if m is to be well insulated against the vibrations in M; that is, the support should be very elastic and loaded as heavily as possible. In other words, a type of insulating support should be chosen which will make the resonant frequency of m on its elastic support low compared with the frequencies of vibration which are to be insulated. It is apparent therefore that a mass, such as a building or a room or some special equipment, mounted on a flexible support, acts as a low-pass filter which will prevent external vibrations of all frequencies above about $1/\pi\sqrt{mc}$ from disturbing the *insulated* object. Reciprocally, the system acts as a low-pass filter which prevents similar vibrations which may be set up in m from disturbing M.

The discussion given in the preceding paragraphs has been limited to sustained periodic vibrations, such as might be produced by motors, elevators, ventilating fans, and other machinery. It is often important to provide insulation against transient as well as sustained vibrations. In order to provide a high degree of insulation against transient vibrations, the mass of the insulated object should be as large as possible and the resistance or damping factor of the flexible support should be relatively large. Under these conditions the transients will not impart an appreciable motion to the insulated object, and the large resistance in the flexible support will effectively damp out such vibration as may be imparted to the insulated mass.

Since the compliance c and the resistance[6] r of flexible materials determine the value of these materials for the insulation of vibration, it will be helpful to discuss briefly methods which may be used for determining c and r, and to give the values of c and r for a number of commonly used materials. The value of c can be obtained from static measurements of the displacement of the compressed support per unit of force. If this be done for a specimen of material of a certain thickness and area of cross section, the compliance can be determined for any other thickness or area by remembering that c will be directly proportional to the thickness and inversely proportional to the area of the flexible support.

When r is not too large, it can be determined by observing the successive amplitudes of the free vibrations of a mass m on the flexible support and solving for r by the usual log decrement method.[7] Or, if the damping be so great that the free motion of m is non-oscillatory, r can be ob-

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[6] The resistance factor is not so important as the compliance factor, and in many approximate calculations the value of r may be regarded as zero.

[7] The decrement in a damped periodic vibration, such as will occur with the mass m on its elastic support, if the system be oscillatory, is the ratio of one displacement to the immediately following displacement; that is, it is the ratio of the amplitude of vibration at any instant to the amplitude one half period later. The natural loga-

tained from measurements on the experimentally determined resonance curve of the forced vibrations of m, or from measurements of the rate of return of m when it is given an initial displacement. This last method, which may be regarded as a static method, is similar to the electrical method of determining the resistance R in series with an inductance L and a capacitance C by discharging the condenser through the inductance and resistance, and obtaining the *decay* curve or the *time constant* for the combination.

If the resistance of a certain specimen of material, as cork, felt, or rubber, has been determined by any of these methods, the resistance for any other thickness or area of the material can be approximately determined by assuming that the resistance will be inversely proportional to the thickness and directly proportional to the area of cross section of the flexible support. Having determined the values of c and r for a flexible material, it is possible to calculate, by means of (39), the amount of insulation that will be obtained from the use of this material as a flexible support for an object of mass m.

The manner in which Eq. (39) agrees with measured vibrations in a typical system is shown in Fig. 129. The curves in Fig. 129 apply to a system suspended by a damped spiral spring rather than one resting upon an elastic pad, but the same type of curves would result for either case. For the curves shown in Fig. 129, $m = 135$ grams, $c = 0.50 \times 10^{-5}$ centimeter per dyne, $r = 2480$ c.g.s. units.[8] For this system the resonant frequency was about 6 cycles, and it will be noted that for frequencies below about 8.2 cycles $a_2/a_1 > 1$, that is, the motion is amplified by the elastic suspension; but for frequencies above 8.2 cycles $a_2/a_1 < 1$, that is, the motion is reduced by means of the elastic support; and for frequencies above 20 cycles the motion is reduced more than five fold. Thus, such a system would provide a reduction in the audio-frequency range of 14 db at 20 cycles, 34 db at 200 cycles, and 63 db at 4000 cycles. Such a system therefore would be of considerable value for the insulation of audible vibrations.

The use of the foregoing theory in the prevention of vibrations in buildings has been demonstrated in numerous instances. The recently completed Acoustical Laboratory at the University of California at Los Angeles will serve as a typical example. It was desired to keep the

rithm of this *decrement*, called the log decrement, is equal to $rT/4m$, where T is the period of vibration of the mass m. Measurements are made of the period T and of successive displacements of the mass m; the appropriate quantities are then substituted in the defining equation for the log decrement; and the equation is solved for r.

[8] For the purpose of convenience, the author has used the c.g.s. system of units in the data and calculations on the insulation of vibration.

reverberation chamber free from earth and building vibrations, especially in the audio-frequency range. The chamber is constructed of 12-inch concrete walls and a 6-inch concrete ceiling slab, and this chamber is inside the main concrete frame of the building. The entire room is insulated from the ground and the main structure of the building by means of (1) a 6-inch fill of dry sand enclosed in a concrete pan, and (2) strips of 2-inch insulation cork placed directly under the concrete floor. The manner in which the heavy concrete room is supported by the cork and sand is shown in Fig. 94. The purpose of the sand is to offer a discontinuity in the path of earth-borne vibrations and to damp out transient vibrations. The purpose of the cork is to prevent sustained solid-borne vibrations, in the audible range, from reaching the chamber. The insulation value of the cork may be calculated as follows:

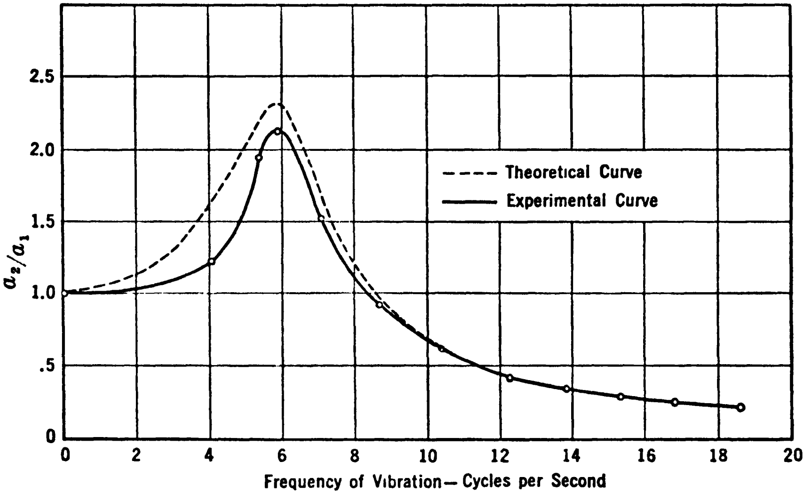

FIG. 129. Curves showing the order of agreement between predicted and observed amounts of insulation of vibration provided by flexible supports. Notice that for frequencies above 12 cycles the amplitude has been reduced to less than half, and that it diminishes more and more with increasing frequency.

Mass of insulated room = 151,000 pounds, or 68,600,000 grams.

Area of cork = 380 square feet, or 354,000 square centimeters.

Compliance of the 2-inch cork, per square centimeter, = 0.50×10^{-6} centimeter per dyne.

Or the compliance for the entire area of 354,000 square centimeters of cork would be $\frac{0.50 \times 10^{-6}}{354,000} = 1.4 \times 10^{-12}$ centimeter per dyne.

Resistance of the 2-inch cork, per square centimeter, = 0.22×10^5 c.g.s. units.

Or the resistance of the entire area of 354,000 square centimeters of cork would be $0.22 \times 10^5 \times 354,000 = 7.8 \times 10^9$ c.g.s. units.

If these values be substituted in (39) it will be found that some insulation will be provided for all frequencies above about 25 cycles. At 20 cycles, for example,

$$\frac{a_2}{a_1} = \sqrt{\frac{(7.8 \times 10^9)^2 - \dfrac{10^{24}}{4\pi^2 \times 400 \times 1.4^2}}{(7.8 \times 10^9)^2 - \left(2\pi \times 20 \times 6.86 \times 10^7 - \dfrac{10^{12}}{2\pi \times 20 \times 1.4}\right)^2}}$$
$$= 1.16;$$

at 200 cycles

$$\frac{a_2}{a_1} = \sqrt{\frac{(7.8 \times 10^9)^2 - \dfrac{10^{24}}{4\pi^2 \times 40{,}000 \times 1.4^2}}{(7.8 \times 10^9)^2 - \left(2\pi \times 200 \times 6.86 \times 10^7 - \dfrac{10^{12}}{2\pi \times 200 \times 1.4}\right)^2}}$$
$$= 0.091;$$

and at 2000 cycles

$$\frac{a_2}{a_1} = \sqrt{\frac{(7.8 \times 10^9)^2 - \dfrac{10^{24}}{4\pi^2 \times 4{,}000{,}000 \times 1.4^2}}{(7.8 \times 10^9)^2 - \left(2\pi = 2000 \times 6.86 \times 10^7 - \dfrac{10^{12}}{2\pi \times 2000 \times 1.4}\right)^2}}$$
$$= 0.009.$$

The resonant frequency is about 16 cycles, and at this frequency the value of a_2/a_1 is 1.3. Owing to the large damping coefficient of the cork, the resonant peak is very flat, and consequently there is no appreciable amplification of mechanical vibrations even for frequencies which are near resonance. This is shown in Fig. 130, which gives the values of a_2/a_1 for the insulated room for frequencies up to 2000 cycles. The insulation cork, as used, appears to afford effective insulation against all solid-borne vibrations within the audible range. Thus, at 200 cycles the effective reduction is about 20 db, and at 2000 cycles it is about 40 db. Although no exact quantitative tests have been made of the insulation value of the cork support under the reverberation room, a qualitative comparison of the extent of building-borne vibrations which reach this room with the vibrations in adjacent rooms, which rest directly upon the ground and are structurally a part of the concrete frame of the building, demonstrates that the cork support is very effective in preventing building vibrations from disturbing the reverberation room. A greater degree of insulation could have been obtained by using a more flexible material, like soft rubber, or by reducing the area of bearing surface on the cork, which would have increased its over-all compliance, but a compromise was made to insure a longer " life " to the cork.

In many instances cork or rubber has been used for insulating supports for large concrete platforms on which is mounted apparatus which is very sensitive to mechanical vibration, such as sound-recording equipment. Such equipment must be thoroughly insulated against all frequencies in the audible range. In one instance, measurements of the amount of vibration reaching an insulated platform compared with the vibration of the floor near the insulated platform were in good agreement with the predetermined insulation values based on Eq. (39).

The indiscriminate use of cork, felt, or rubber as an insulating medium may lead to disappointing results. For example, if the flexible support be very much underloaded, the natural or resonant frequency of the system may be as high as 100 cycles, in which case frequencies below 150 cycles may be amplified rather than diminished by the flexible support. In general, heavy-weight isolation cork should be loaded to about 25 to 50 pounds per square inch; light-weight insulation cork should be loaded to about 5 to 8 pounds per square inch; soft India rubber to about 3 to 6 pounds per square inch; and hair felt to about 1 to 2 pounds per square inch. This degree of loading will usually provide a high degree of insulation throughout the audio-frequency range, and at the same time the material will not break down or lose its elasticity.

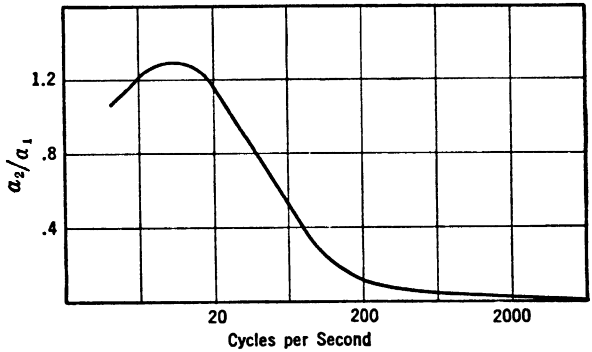

FIG. 130. Insulation of earth and building vibrations by means of a suitably loaded cork slab.

In the following table are given the values of the compliance c and, in some cases, the resistance r of a number of commonly used flexible materials. Different specimens of the same material will often vary more than 100 per cent, so that the data in the table give only the order of magnitude of c and r. In practice, measurements should be made of specimens of the materials which are contemplated for use.

TABLE XXI

COMPLIANCE AND RESISTANCE DATA FOR TYPICAL SPECIMENS OF FLEXIBLE MATERIALS

The compliance and resistance given in the table are for specimens 1 inch thick and 1 square centimeter in cross section.

Material	Description of Material	Approximate Upper Safe Loading in Lb. per Square Inch	Compliance, c, in Centimeters per Dyne	Resistance, r, in Absolute Units
Corkboard	1.10 lb. per board foot	12	0.25×10^{-6}	0.15×10^{5}
Corkboard	0.70 "	8	0.50 "	0.25 "
Flax-li-num	1.35 "	4 to 6	0.60 "	0.50 "
Celotex	Carpet lining	10	0.40 "	
Celotex	Insulating board	12	0.18 "	
Insulite	"	15	0.16 "	
Masonite	"	15	0.12 "	
Anti-Vibro-Block		5	0.60 "	1.5 "
Sponge Rubber	25 lb. per cubic foot	1 to 3	3.0 "	
Soft India Rubber	55 "	3 to 6	1.2 "	
Hair felt	10 "	1 to 2	1.5 "	

In the choice of materials for the insulation of vibration it is necessary to give consideration to the safe amount of loading the material will withstand without breaking down the structure of the material, or without compressing the material to the extent that its compliance is reduced beyond required limits. It also is important to select a material which will have a long life and which will not continue to compress or settle under the load which it supports. For example, if ordinary insulation cork be loaded as much as 20 or 30 pounds per square inch, the material will continue to compress indefinitely, and at the same time will become less and less compliant, until ultimately it not only loses its insulation value but also allows an amount of settling which cannot be tolerated. For example, a specimen of 1-inch insulation cork (0.70 pound per board foot), under a load of 20 pounds per square inch, settled 0.04 inch during the first 24 hours, 0.02 inch during the next 24 hours, and 0.11 inch during the first 5 months it was under compression. The same specimens, under a load of 10 pounds per square inch, settled only 0.01 inch during the first 24 hours, 0.005 inch during the next 24 hours, and only 0.03 inch during the first 5 months. In general, the most satisfactory material will be one which has a high compliance and very little tendency to settle under the influence of the load, and which tends to restore to its initial condition when the load is removed. Hair felt, cork, and rubber seem to be the best available materials which meet these requirements, although all these materials continue to settle, and become less and less compliant as they become older. Flexible steel supports and clips, such as those shown in Figs. 125 and 126, do not have these defects, and are proving to be very satisfactory not only for the insulation of floors and ceilings but also for insulating all sorts of equipment from the floor or the rigid frame of the building.[9]

Recently, the author had occasion to test the effectiveness of different types of flexible supports or cushions for insulating the noise of footfalls and other impacts against the floor of a gymnasium. The gymnasium floor (maple) was supported directly upon a concrete slab which separated the gymnasium from a large dining room located directly under the gymnasium. The impacts of a basket ball volleyed against the maple floor produced a noise level in the dining room of 45 db. It was proposed that an additional wood floor be *floated* above the existing maple floor, and accordingly tests were made to determine the added amount of insulation (against impacts) which would result from different methods of supporting the new floor. A model floor section, 8 feet by 8 feet, was constructed of ¾-inch sub-flooring and ¾-inch T & G finished flooring. This model section was floated on different types of fibre boards, blankets, and flexible steel chairs. The results of the tests are given in Table XXII.

TABLE XXII

Type of Insulation under Model Section	Sound Level of Transmitted Impacts, decibels	Insulation Value of Floated Floor, decibels
No insulation (impacts on maple floor).	45	.
Two layers ½-in. fibre board	34	11
One layer 1-in. fibre board	34	11
One layer 1½-in. cork	33	12
1-in. wool and ½-in. fibre board	37	8
Two layers of light-density fibre board	31	14
Flexible steel chairs	21	24

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[9] M. C. Rosenblatt has recently invented an isolating support which reduces the force against the foundation of machinery vibrations (1) by utilizing several alternate layers of rigid and flexible materials (as steel and felt), and (2) by using a bearing surface on the flexible and absorptive "pad" large enough to prevent excessive compression of the pad. (See Patent No. 1,819,039.)

These tests indicate that flexible steel chairs provide a better means of insulating a floor against impact noises than do blankets or fibre boards. This is a reasonable result, since the compliance of the flexible steel chairs is considerably greater than the compliance of the blankets or fibre boards.

95. Insulation of Sound by Porous and Porous-Flexible Materials. The insulation of sound by porous or porous-flexible materials, such as hair felt or mineral wool, is accomplished principally by losses of vibratory energy within the material. The transmitted sound wave is attenuated by viscous losses within the capillary pores of the material and by the vibration of the component parts of the material. The loss of energy owing to the flow of sound in small pores has already been considered (Sec. 61), and it is obvious that the vibration of the component parts, such as the hairs or fibres in felted materials, also will contribute to the dissipation of the transmitted wave. From the nature of these internal losses of sound energy, it is to be expected that the fractional loss of sound through, say, the first inch of a porous-flexible material will be the same as the fractional loss through the next inch of the material, and so on. In other words, if the sound energy be reduced ten fold through the first inch of the material, it would be reduced another ten fold through the second inch of the material; or the 2 inches of material would provide an energy reduction of one hundred fold; 3 inches would provide an energy reduction of one thousand fold; 4 inches would provide a reduction of ten thousand fold; and so on.

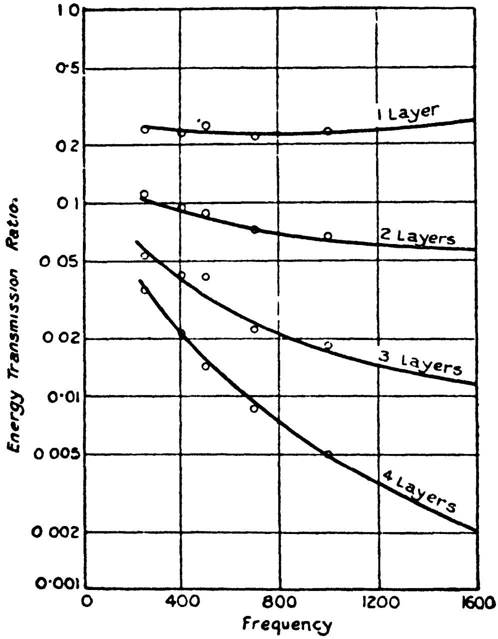

FIG. 131. The insulation of sound by one, two, three, and four layers of hair felt. The *energy transmission ratio* (or *transmission coefficient*) is plotted as a function of frequency. (*Davis and Littler.*)

Measurements of the insulation of sound by porous-flexible materials, such as hair felt, conform approximately to this anticipated result; that is, the logarithm of the energy reduction, or the decibel reduction, is roughly proportional to the thickness of the material. The degree of agreement between this anticipated result and experimental measurements obtained by Davis and Littler[10] is indicated in Fig. 131, which gives the transmission coefficients at different frequencies for one, two, three, and four layers of hair felt (density of felt, 12 pounds per cubic foot).

The results of insulation measurements on porous materials show that such materials, if used by themselves, do not provide a very large amount of insulation unless the insulating blanket or partition be very thick. Thus, as is indicated in Fig. 131, the coefficient of transmission at 700 cycles for four layers of hair felt (each layer is 0.58 inch thick) is about 0.01; that is, a sound wave of 700 cycles would be attenuated only 20 db in passing through 2.32 inches of hair felt. However, when such materials are used properly in conjunction with rigid partitions, they may contribute a considerable amount to the total insulation supplied by the wall structure. One of the most effective ways in which such materials may be used for the insulation of sound is by suspending or supporting the porous-flexible material in an air space between two rigid partitions. The amount of insulation provided by such structures will be given in Table XXXI, Chap. XII.

96. Insulation of Sound by Rigid Partitions. The transmission of sound through rigid partitions, as has already been mentioned, is accomplished principally by the forced vibration of the wall; that is, the entire rigid partition is forced into vibration by the impacts of the sound waves against it. The vibrating partition thus becomes a secondary source of sound and radiates a certain amount of sound to the space adjacent to the opposite side of the partition. On the basis that the transmission of sound through rigid partitions takes place in this manner, it is to be expected that the insulation value of a wall will depend primarily upon the mass or inertia of the wall, the stiffness of the wall, and the internal resistance or damping of the wall. Every partition of the type here considered will have certain characteristic or natural modes of vibration — the fundamental and a series of partials or overtones. If it were not for the internal damping in a rigid partition, there would be resonant peaks for frequencies corresponding to the fundamental and partials, and at these frequencies the panel would transfer, or transmit, a relatively large amount of energy to the opposite side of the panel.

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[10] Davis and Littler, "The Measurement of Transmission and Reflection of Sound by Partitions of Various Materials. I. Felt-like Materials," Phil. Mag., 3, 177 (January, 1927).

However, the internal damping is so large that these resonant frequencies are generally very much flattened out, and in general the ear does not detect any marked resonant effects, although they can be readily measured at low frequencies. Such instrumental measurements show that most rigid partitions do have a lower insulation at some frequencies than they do at others, owing to these resonant characteristics of the partition. The fundamental frequency for the structural partitions used in buildings is rather low, usually below 50 cycles, but the partial modes of vibration may give rise to overtones throughout two or three octaves above the fundamental. Meyer[11] has measured and calculated the fundamental frequency, and has measured the damping, for a number of rigid panels, each 2 meters square. The results are summarized in Table XXIII. As will be seen from this table, the fundamental frequency for typical wall partitions is not only low, but the damping is rather high. Consequently there can be no sharply defined resonant peaks in such partitions, and it is to be expected therefore that the sound-insulation of typical partitions will not be affected appreciably by the resonant properties of the panel.[12]

For all frequencies above the fundamental frequency of the partition, it is the mass of the partition rather than the stiffness or the damping which contributes principally to its insulation value, and even at the resonant frequency the mass factor is the dominant one for most partitions encountered in practice. The mass of a wall offers a reaction to the sound wave similar to the magnetic reaction of a self-inductance in an electrical circuit. In both the mechanical and electrical circuits the reaction increases with the frequency. On this basis, it would be expected that the mass of the partition would be the principal factor in determining the insulation value of the wall, especially at frequencies well above the fundamental frequency of the partition. Measurements on the insulation value of rigid partitions give credence to this general notion that the mass or inertia of a partition is the outstanding factor in determining its insulative properties. In the case of thin, flexible panels, the stiffness, the internal damping, the size of the panel, and the manner in which it is clamped around the edges, all contribute to the total amount of vibration which will be imparted to the partition, and therefore all these factors contribute to the insulation value of such panels. How-

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[11] E. Meyer, "Grundlegende Messungen zur Schallisolation von Einfach-Trennwänden," Sitzungsber. d. Preuss. Akad. d. Wiss, Phys.-Math. Klasse, IX (1931).

[12] Some measurements of the vibration of single panels, made by the author, indicate that in general the fundamental frequency is the only frequency for which the effects of resonance are great enough to have an appreciable influence upon sound-insulation.

Table XXIII

FUNDAMENTAL FREQUENCY AND DAMPING OF RIGID PANELS, 2 METERS SQUARE (6 FT. 6 IN. BY 6 FT. 6 IN.)

Type of Panel	Thickness in In.	Weight in Lb. per Square Foot	Natural Frequency in Cycles per Second		Damping in Decibels per Second
			Calculated	Measured	
Pine wood	0.2	0.45	7.8	7	9.5
Sheet iron	0.08	3.2	10.5	12	5.4
"Rabitzwand"	1.0	6.3	16	17	11.1
Pressed straw, plastered	3.5	13.8	24	30	41
"Schwemmstein-wand," plastered	4.7	24.8	32	38	54
Concrete, plastered	4.3	26.6	31	28	16
Brick (¼), plastered	3.5	31.0	27.5	29	87
Brick (½), plastered	5.8	46.4	45	48	69
Brick (1/1), plastered	10.6	93	75	51	48

ever, in the panels investigated by Meyer and referred to in Table XXIII (which included one thin wood panel), the mass seems to be the predominant factor in determining the insulation value of nearly all rigid panels and partitions encountered in practice. The importance of the mass factor is indicated in Fig. 132, which shows how the amplitude, velocity, and acceleration of a brick-and-plaster wall depend upon the frequency of the incident sound, the sound intensity being maintained at a constant pressure of 10 bars. It will be noted that although the amplitude and velocity of the brick wall tend to decrease with increasing frequency, the acceleration is nearly the same for all frequencies. Since the wall was excited by sound of a constant pressure (10 bars), and since the acceleration was nearly constant for all frequencies, it is evident that the wall reacts to the sound vibration as a system comprised essentially of mass. Meyer shows further, by equating the vibrational force acting on the panel to the product of the effective mass and acceleration, that the effective vibrational mass of rigid panels is of the order of one to two tenths of the total mass of the panels.

The manner in which the insulation value of rigid partitions depends upon the mass per unit area of the partition is shown by the plotted data in Fig. 133. These data are the results of measurements by the

Bureau of Standards, E. Meyer, the National Physical Laboratory, and V. O. Knudsen on a large number of rigid panels,[13] such as plate glass, plaster board, clay tile and plaster, and brick and plaster. The insulation value of each panel, expressed as the transmission loss in decibels (arithmetical mean for the octave frequencies between 128 and 2048 cycles), is plotted against the logarithm of the weight in pounds per square foot of the panel or partition. It will be noted that the curve

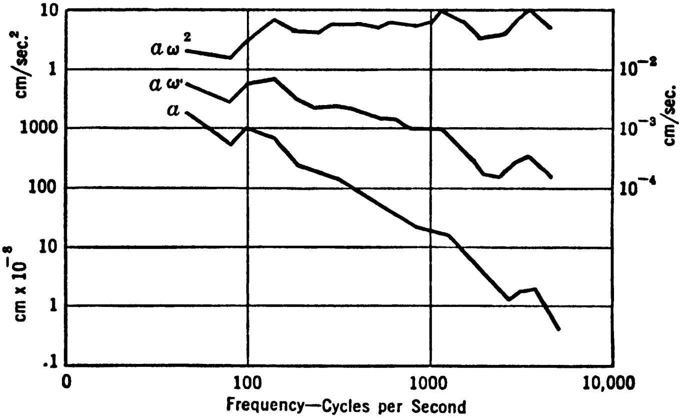

FIG. 132. Curves showing the amplitude (a), the velocity ($a\omega$) and the acceleration ($a\omega^2$) for a $3\frac{1}{2}$-inch brick and plaster wall when the wall is excited by sound having a pressure of 10 bars. (*Meyer.*)

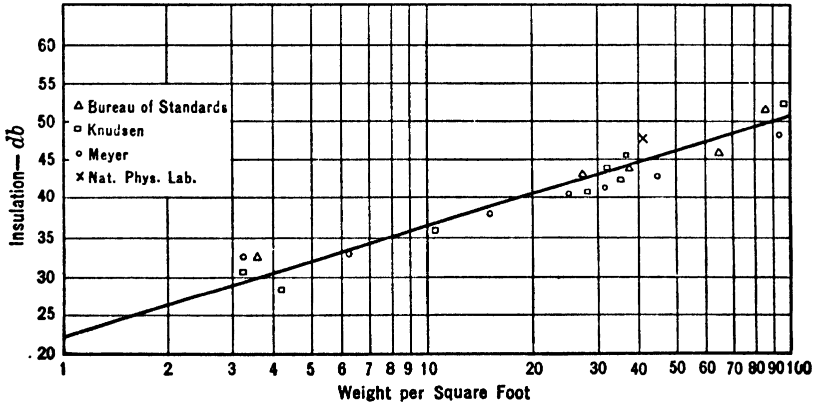

FIG. 133. Curves showing the relation between the insulation value of rigid partitions and the weight per square foot of the partition.

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[13] See author's article on "Measurement and Calculation of Sound-Insulation," Jour. Acous. Soc., **2**, 1, 129 (July, 1930).

passing through most of the points is approximately a straight line. This straight line indicates that the insulation value of rigid partitions is approximately proportional to the logarithm of the mass per unit area of the panel or partition. Thus, the transmission loss for a rigid panel which weighs 1 pound per square foot is about 22 db; the transmission loss for a rigid panel or wall which weighs 10 pounds per square foot of wall section is about 37 db; and the transmission loss for a rigid partition or wall which weighs 100 pounds per square foot of wall section is about 51 db. It will be noted by comparing Figs. 131 and 133 that added thickness to a rigid partition does not increase the insulation so rapidly as does added thickness to a porous-flexible partition, such as hair felt. Thus, whereas the insulation value of a hair-felt partition will increase ten fold (measured in decibels) when the thickness of the felt is increased ten fold, the same increase in the thickness of a rigid wall, for example, in the range from 10 to 100 pounds per square foot, will increase the insulation value from about 37 to 51 db, or less than two fold.

Because of the slow increase in insulation with increased mass or thickness of a rigid partition, it is not always feasible to secure a high degree of insulation by merely increasing the thickness of the wall. Thus, it would be necessary to increase the thickness of a concrete wall to nearly 4 feet in order to give to the wall an insulation of 60 db. When walls of high insulation are required, it is more feasible and economical to employ special structures which combine the two principles of sound-insulation which we have described: namely, absorption losses in porous-flexible materials, and inertial losses in rigid partitions. Thus, two or three rigid and relatively thin partitions separated from each other by felts or blankets can easily be composed in such a manner as to give an insulation of at least 60 db. The insulation value of many special forms of construction employing these and other principles will be found in Table XXXI, Chap. XII.

CHAPTER XI

INSULATION OF SOUND — METHODS OF MEASUREMENT

97. Introductory. In this chapter a number of different methods which are, or may be, used for measuring the insulation value of walls and partitions will be considered. It is important that the basic principles underlying these methods be clearly comprehended in order that the results obtained by different methods may be evaluated in such a manner that they will specify only the insulation value of the panel or partition, and thus be independent of the method of measurement and also of the size of the partition and the properties of the rooms in which the tests are made. The theoretical aspects of this problem have been considered by both Buckingham and Davis,[1] who have described quantitatively the different factors which are involved.

In all laboratory measurements it is necessary that the test panel be large enough, and be so fastened around its edges, that it will vibrate essentially as it would in actual types of building construction. It must be securely sealed around its edges so that no sound can leak through even the smallest of cracks. And the sound which is transmitted to the test room by other paths than through the test panel should be negligibly small. Finally the tests should be made at a sufficient number of frequencies, or bands of frequencies, to exhibit any possible resonant properties of the panel and to show its insulation value throughout the frequency range which is characteristic of speech, music, and noise.

Before proceeding with a description of the different methods of testing it will be necessary to choose and define a term which will serve as an absolute measure of the insulation value of different materials or types of structure. The term *coefficient of transmission* seems to be a logical choice. It already has been defined as the ratio of the intensity of the sound transmitted through the test panel or partition to the intensity of sound which is incident upon the source side of the test panel. If the panel or partition be large enough to vibrate essentially as it would

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[1] E. Buckingham, "Theory and Interpretation of Experiments on the Transmission of Sound through Partition Walls," Bureau of Standards Scientific Paper, No. 506, 193 (1925); A. H. Davis, "Reverberation Equations for Two Adjacent Rooms Connected by an Incompletely Soundproof Partition," Phil. Mag., **50**, 75 (1925); "The Basis of Acoustic Measurements by Reverberation Methods," Phil. Mag., **2**, 543 (1926).

in typical forms of construction, the coefficient of transmission, which is designated by τ, will be independent of the size of the test panel and the characteristics of the source and test rooms, and will depend only upon the material and structure of the panel. The insulative properties of any panel or partition will then be determined if the coefficients of transmission at representative frequencies throughout the audible range be known.

98. Beam Method. This is the method developed and used by F. R. Watson at the University of Illinois and later by A. H. Davis and T. S. Littler of the National Physical Laboratory. In this method, as in all methods, a source room and a test room are required. The two rooms are separated by a heavy wall which contains an opening in which the test panel is sealed. An approximately plane parallel beam of sound, of a certain frequency, obtained by means of a large parabolic reflector in the source room, is projected obliquely upon the opening between the source room and the test room. The walls of both rooms should be treated with highly absorptive material so as to minimize the effects of reflections from the walls. Measurements are made, usually by means of a microphone and amplifier, of the intensity of the sound along the transmitted beam in the test room first with the unobstructed opening and then with the test panel sealed in the opening. The first measurement gives a quantity which is approximately proportional to the rate at which the sound energy strikes the partition; and the second measurement gives a quantity which is approximately proportional to the rate at which the energy is transmitted through the test panel. The ratio of the second to the first quantity therefore gives the coefficient of transmission τ for the panel at a certain frequency. In general, the quantities which are measured directly are proportional to the pressure amplitude of the sound wave, and the intensities of the incident and transmitted beams would be proportional to the square of these pressure amplitude measurements. Thus, if p_1 be the average value of the pressure amplitude of the beam of sound in the test room when the panel is removed, and p_2 the average pressure amplitude when the panel is sealed in the aperture, then, approximately,[2]

$$\tau = \left(\frac{p_2}{p_1}\right)^2. \tag{40}$$

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[2] It is assumed that the rate of emission of the sound source is not affected by the presence of the panel in the aperture. This is approximately the case when the beam strikes the panel obliquely, but there would be an appreciable difference when the beam is normal to the panel, owing to the different *loading* on the source in the two cases. Both the test room and the source room should contain so much absorption that the panel either in or out will not appreciably alter the absorptive properties of the two rooms; or suitable correction should be made for the effect of the panel upon the amount of absorption in the rooms.

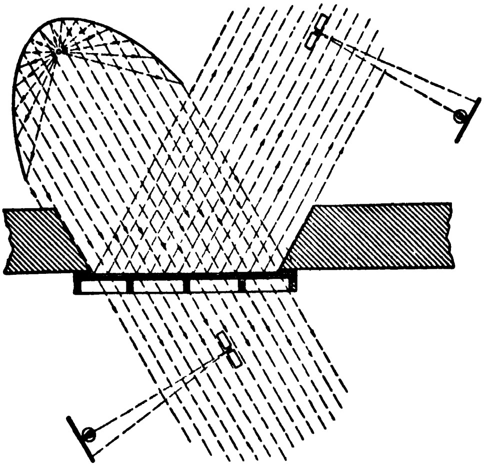

FIG. 134. Arrangement of apparatus used by Watson for measuring the insulation of a panel by the beam method.

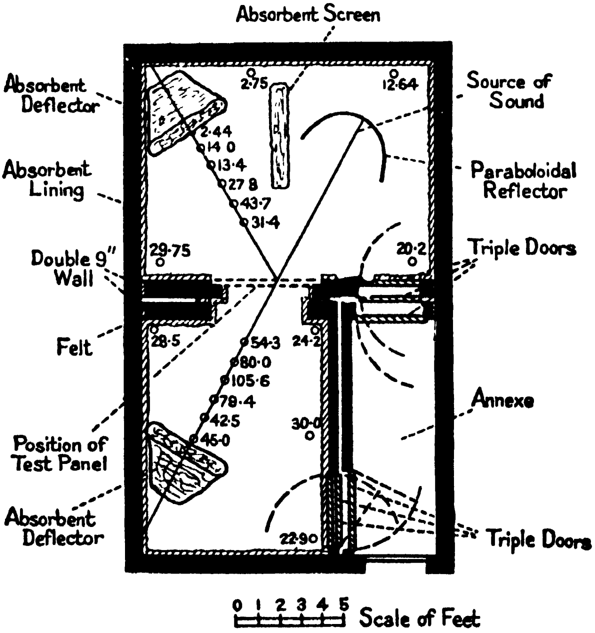

FIG. 135. Arrangement of apparatus used by Davis and Littler for measuring the insulation of a panel by the beam method.

Then the reciprocal of τ will give the number of times the energy is reduced by transmission through the panel; and the transmission loss in decibels, which the panel introduces in the beam of sound, will be given by

$$\text{T.L.} = 10 \log_{10} \frac{1}{\tau} = 10 \log_{10} \left(\frac{p_1}{p_2} \right)^2. \tag{41}$$

Hereafter, the abbreviation T.L. will be used for *transmission loss.* In Watson's method, the p_1 and p_2, or quantities proportional to them, are measured by means of the Rayleigh disc, and in the method used at the National Physical Laboratory p_1 and p_2 are measured with a condenser microphone and amplifier. Watson's arrangement of apparatus is shown in Fig. 134, and the arrangement used at the National Physical Laboratory is shown in Fig. 135. At the National Physical Laboratory the interior surfaces of both the source and test rooms are lined with highly absorptive felt so that reflections from the boundaries of the rooms are greatly minimized. In both laboratories the source of sound is a nearly pure tone generated by a vacuum-tube oscillator and electrical loud speaker.

99. Bureau of Standards' Method.[3] The method of measurement used at the Bureau of Standards is nearly the same as the beam method described in the preceding section, except that the source is not a single frequency, but a warble frequency, and the source of sound is not directed in a beam upon the panel. The sound in the source room — which is very reverberant — is of a diffuse nature, and the amount of sound energy which strikes the panel is determined therefore by the rate of emission of the source and the amount of absorption in the source room. The warble frequency tends to overcome the defects owing to the interference pattern in the room, and also minimizes any possible effects

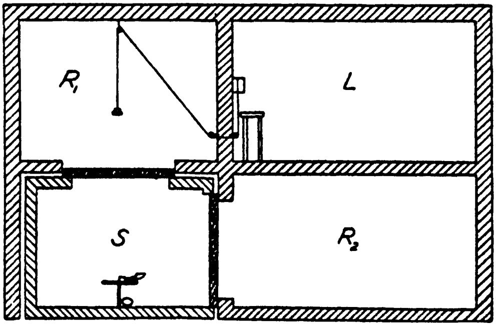

FIG. 136. Arrangement of rooms and apparatus used by Chrisler and Snyder for measuring the insulation of a panel. S is the source room, R_1 and R_2 are the test rooms, and L is the measuring room.

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[3] E. A. Eckhardt and V. L. Chrisler, "Transmission and Absorption of Sound by Some Building Materials," Scientific Papers of the Bureau of Standards, No. 526 (April 28, 1926); Chrisler and Snyder, "Transmission of Sound through Wall and Floor Structures," Bureau of Standards Journal of Research, **2,** 541 (March, 1929).

which might be attributable to room resonance or the excitation of the panel at one of its natural frequencies.

Measurements of the intensities of sound are made on both sides of the aperture, with and without the test panel in place. Suppose I_1 and I_2 represent the intensities in the source room and test room, respectively, when the panel is out. When the panel is inserted, I_1 will increase slightly, say to I_1', owing to the diminished absorption in the source room and the increased loading on the source; and I_2 will be diminished to I_2', owing principally to the insulative action of the panel. If the intensity in the source room remained the same with and without the panel in place, the coefficient of transmission would be given approximately by I_2'/I_2, but I_2' is slightly greater than it would have been if I_1 had remained constant during the two sets of measurements with and without the panel in place.[4] Making this required correction for I_2', the coefficient of transmission is given by

$$\tau = \frac{I_2'}{I_2}\,\frac{I_1}{I_1'}. \tag{42}$$

Or, if the measurements consist of pressure amplitude determinations, then,

$$\tau = \left(\frac{p_2'}{p_2}\right)^2 \left(\frac{p_1}{p_1'}\right)^2, \tag{43}$$

where, as before, the primed quantities refer to the measurements obtained when the panel is in place, and the unprimed quantities refer to the measurements with the panel removed. The amplitude measurements are made in the usual manner by means of a condenser microphone and vacuum-tube amplifier. It is necessary to take a sufficient number of measurements to *average out* any remaining variations of intensity owing to interference effects in both rooms.

100. Minimal Audibility Method. It is possible to simplify the method of measurement just described, but with a slight sacrifice in accuracy, by using an attenuator in the input of an electrodynamic loud speaker in the source room, and by making measurements of minimal audibility only in the test room. This requires a perfectly quiet test room, and the observer should be experienced in judging minimal audibility. The observer stationed in the test room introduces attenuation in the loud-speaker circuit until the intensity in the test room reaches the minimal threshold of audibility, first when the panel is out and then when the panel is in. If the insertion of the panel in the aperture does

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[4] The argument here given supposes that the test panel is less absorptive than the opening, which would be the case for nearly all panels which are of any practical interest.

not alter appreciably the amounts of absorption in the source and test rooms, then the difference between the two settings of the attenuator — one with the panel out and the other with the panel in — gives the T.L. in decibels for the test panel. If the insertion of the panel has diminished the absorption in both rooms, as it usually will, the effect will be to increase the average intensity of diffuse sound in both rooms. Thus, if E_1 be the required rate of emission of the source to give minimal audibility in the test room when the panel is in, and E_2 be the required rate to give minimal audibility in the test room when the panel is out, then the ratio of the intensities in the source room corresponding to the two conditions will be $E_1/E_2 \times a_1'/a_1$, where a_1' is the amount of absorption in the source room when the panel is out and a_1 is the amount when the panel is in. Also, since the presence of the panel in the aperture has diminished the total amount of effective absorption in the test room, the E_1/E_2 will be slightly smaller than would be the case if the amount of absorption in the test room had remained constant. Hence, the ratio of the intensity of the sound in the source room with the panel in and the intensity with the panel out, in order to allow the same amount of sound energy to flow into the test room in both cases, will be $E_1/E_2 \times a_1'/a_1 \times a_2'/a_2$, where a_2' is the amount of absorption in the test room with the panel out and a_2 is the amount when the panel is in. And this ratio gives simply the T.L. (in energy units) for the panel, the reciprocal of which is the coefficient of transmission of the panel at the frequency band used in the test. This result can be deduced more formally by the following considerations:

When the panel is in place, the rate of flow of sound energy against the panel, for minimal audibility in the test room, will be E_1A/a_1,[5] where A is the area of the panel. Therefore, if τ be the coefficient of transmission for the panel, the rate of flow of energy through the panel and into the test room will be $E_1A/a_1 \times \tau$. Hence, if I_m be the intensity of sound in the test room at minimal audibility, it follows that

$$I_m = \frac{E_1A}{a_1a_2}\tau. \tag{44}$$

When the panel is out, the rate of flow of sound energy into the test room at minimal audibility will be E_2A/a_1', and therefore

$$I_m = \frac{E_2A}{a_1'a_2'}. \tag{45}$$

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[5] This follows since E_1 has been defined as the rate of emission of the source required to produce minimal audibility in the test room when the panel is in, and the rate at which sound energy strikes unit area of the boundaries of the source room is, from Eq. (21), E_1/a_1. Hence the total energy which strikes the panel per second will be E_1A/a_1.

Equating (44) and (45), and solving for τ,

$$\tau = \frac{E_2}{E_1}\frac{a_1}{a_1'}\frac{a_2}{a_2'}. \qquad (46)$$

If the source and test rooms contain large amounts of sound-absorptive materials, a_1 will not differ appreciably from a_1', and a_2 will not differ appreciably from a_2'. Whence, approximately,

$$\tau = \frac{E_2}{E_1}. \qquad (47)$$

Or it is possible to add absorptive materials to both rooms when the panel is in, so that $a_1 = a_1'$ and $a_2 = a_2'$, in which case (47) will apply directly.

When an attenuator is used in the input of the electrodynamic loud speaker, as described, the ratio E_2/E_1 is given in terms of the decibels of attenuation introduced in the loud speaker. Thus, if the difference between the two settings of the attenuator be 30 db, the rates of the emission of the source differ one thousand fold, that is, E_2/E_1 would be 0.001. If the rooms are adjusted so that (47) is applicable, the difference between the two settings of the attenuator gives the T.L. for the panel in decibels. Slightly greater accuracy can be attained by using a microphone and amplifier in the test room and adjusting the attenuator until the output of the amplifier reads the same with or without the panel in place.

101. Measurement of Intensity on Both Sides of the Test Panel. It is often convenient to determine the coefficient of transmission of a panel by comparing the intensities of the sound on both sides of the panel. Thus, suppose the average intensity near the panel in the source room be I_1 and the average intensity in the test room be I_2. Then the rate of flow of energy against the test panel in the source room will be I_1A; and the rate at which energy will be transmitted through the panel into the test room will be $I_1A\tau$, which is the rate of emission of sound energy in the test room. Hence, when equilibrium is established, this rate of emission of sound energy will be equal to the rate of absorption in the test room, which is I_2a_2. Hence, $I_1A\tau = I_2a_2$, or

$$\tau = \frac{I_2}{I_1}\frac{a_2}{A}. \qquad (48)$$

The coefficient of transmission for the panel is thus seen to involve not only the ratio of I_2 and I_1, but also the area of the panel and the total amount of absorption in the test room.

If I_2, I_1, and a_2 can be measured by any means, (48) offers a simple means of determining τ. Several practical methods for measuring a_2 were described in Chap. VII. There are several satisfactory methods for measuring I_2 and I_1, some of which have already been described in this chapter. When the measurements must be made in the presence of some unavoidable noise, a masking method, with the help of an audiometer, will be found satisfactory and simple to operate.[6] The audiometer, with an offset receiver cap, is adjusted until it just masks the test tone, first when listening in the source room and then when listening in the test room. The difference between the two settings of the attenuator on the audiometer will give the intensity difference between I_2 and I_1 in decibels, and this difference is easily converted into the intensity ratio I_2/I_1.

E. Meyer measures the intensity on both sides of the panel by using a microphone in each room, either one of which can be connected to an amplifier. In this method one listens with a telephone headset connected to the output of the amplifier, and introduces attenuation in the amplifier when it is connected to the microphone in the source room in such an amount as will make the loudness of the tone in the headset the same as it is when the amplifier is connected directly to the microphone in the test room. In this manner, the acoustical attenuation of the panel is equalized by the electrical attenuation in a resistance network.

102. Reverberation Method. The method devised by W. C. Sabine, and further developed and used by Paul E. Sabine at the Riverbank Laboratories, is essentially a method for comparing the intensities of sound on the two sides of the test panel. The sound in the source room, which should be a very reverberant room, is stopped and allowed to decay. An observer then measures the duration of audibility in the source room (which will be designated by t_1) and also the duration of audibility in the test room (which will be designated by t_2). When the decaying sound in the source room has decayed for t_2 seconds the intensity of sound in the source room is of just sufficient strength to be barely audible on the other side of the panel. If the reverberant sound in the

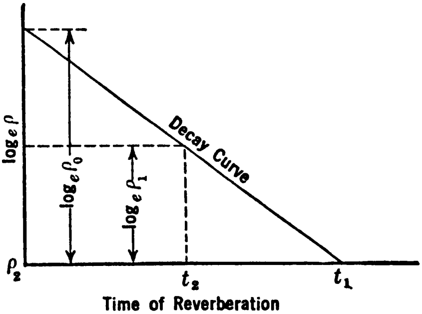

FIG. 137. Decay curve illustrating the reverberation method of measuring sound-insulation.

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[6] W. Waterfall, "An Audiometric Method for Measuring Sound-Insulation," Jour. Acous. Soc., **1**, 1, 209 (January, 1930).

test room be negligible in comparison with the direct beam of sound transmitted through the panel, the relations between the decay of sound in the source room, the transmission through the panel, and the times of decay are as shown in Fig. 137, which is a plot of the decay of sound in the source room. The steady state density of sound in the source room before the test tone is stopped is ρ_0. If the source room be very reverberant, $\log_e \rho/\rho_0 = -ca_1/4V_1 \times t$[7] will be the equation of the straight line shown in the figure. V_1 is the volume of the source room, and the other symbols have been defined. Hence, the volume density of the sound in the source room at the instant it is just barely audible in the test room, which will be designated by ρ_1, is given by the ordinate at t_2, and may be written

$$\log_e \frac{\rho_1}{\rho_0} = -\frac{ca_1}{4V_1} t_2. \tag{49}$$

At this instant, the intensity in the test room is reduced to minimal audibility, which will be designated by ρ_2, and is given by

$$\log_e \frac{\rho_2}{\rho_0} = -\frac{ca_1}{4V_1} t_1. \tag{50}$$

Whence,

$$\log_e \frac{\rho_1}{\rho_2} = \frac{ca_1}{4V_1}(t_1 - t_2). \tag{51}$$

Or

$$10 \log_{10} \frac{\rho_1}{\rho_2} = 10 \times 0.434 \frac{ca_1}{4V_1}(t_1 - t_2). \tag{52}$$

Sabine calls ρ_1/ρ_2 the *reduction factor* of the panel, and $10 \log_{10} \rho_1/\rho_2$ would be the reduction factor of the panel in decibels, which is the form Sabine has used for evaluating his results. It will be noted that although (52) provides a means of determining the relative insulation values of different materials and types of construction, it does not give directly the coefficient of transmission τ of the panel, so that *reduction factors* obtained by means of (52) should not be compared directly with results which are expressed in terms of the coefficient of transmission.

Buckingham[8] has developed an equation for determining the coefficient of transmission of a panel by means of reverberation measurements in two adjacent rooms separated by the test panel. This equation is based upon the consideration that the rate of decay of sound in the test chamber is equal to the difference between the rate of absorption of sound by the boundaries of the test room and the rate of supply of sound

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[7] If the room is not very reverberant, the a_1 must be replaced by $-S_1 \log_e (1 - \alpha)$ where S_1 is the total interior surface and α the average coefficient of sound-absorption of the interior surface of the source room. See Eqs. (22) and (25).

[8] *Loc. cit.*

energy through the test panel. The derivation of Buckingham's equation is beyond the scope of this book, but is obtained readily by solving the two simultaneous differential equations which give the rates of decay of sound in both the source room and the test room. If the transmission of sound from the test room back into the source room be small — and it always will be negligibly small for panels which have any practical insulation value — the coefficient of transmission is given by

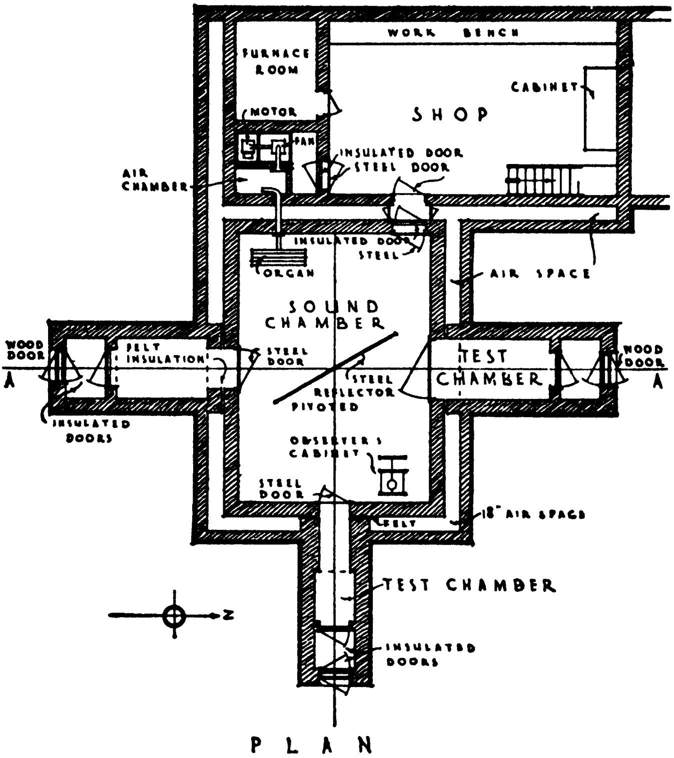
$$\tau = \frac{a_2(b_1 - b_2)e^{-b_1t_1}}{A(b_1e^{-b_2t_2} - b_2e^{-b_1t_2})}, \tag{53}$$

where $b_1 = ca_1/4V_1$, $b_2 = ca_2/4V_2$, and the other symbols have the significance heretofore assigned. If b_2 be considerably larger than b_1, as it is when the test room is smaller and less reverberant than the source room, (53) becomes, very approximately,

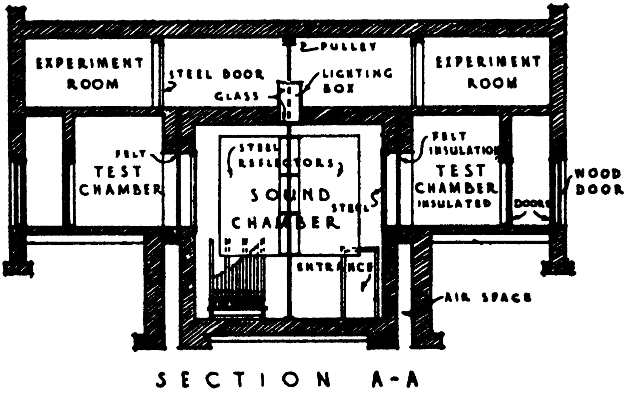
$$\tau = \frac{a_2}{A}\,\frac{b_2 - b_1}{b_2}\,e^{-b_1(t_1-t_2)}. \tag{54}$$

Eq. (54), like most of the other equations for determining τ, is based upon the assumption that the sound in both the source room and the test room is diffuse, and that observations are made in different parts of the rooms so that the average values based upon these observations represent average conditions in the rooms. In the reverberation method as used at the Riverbank Laboratory, the observer listens in the test room with his ear close to the panel, so that his ears are very close to the source of sound in the test room. Naturally, the intensity near the test panel is a little greater than it is at random positions in the room. By listening near the panel, in this manner, the observed value of the transmission loss for the panel would be somewhat less than it would have been if the observations had been made out in the central part of the test room.

The author has made a series of tests on two panels using the methods described in Secs. 99, 101, and 102. That is, the two panels were tested (1) by measuring the intensity in the test room with and without the test panel in the opening, (2) by measuring the intensity both in the source room and in the test room, and (3) by the reverberation method, using Eq. (54). The one panel was a ½-inch mineral-wool blanket covered on both sides with a heavy grade of wrapping paper; the other panel was ½-inch plaster board. Tests were made at frequencies of 128, 512, and 2048 cycles. The measurements of intensity were made in both the source and test rooms by introducing a sufficient amount of attenuation in the loud-speaker circuit to reduce the test tone to the minimal threshold of audibility. During the measurements, the loud speaker was



Plan of the Riverbank Acoustical Laboratories. (*P. E. Sabine.*)



Section of the Riverbank Acoustical Laboratories. (*P. E. Sabine.*)

FIG. 138.

swinging as a simple pendulum so that effects of interference were minimized. The results of these tests are given in Table XXIV. For each panel the T.L. is given for each of the three frequencies. In addition, the average T.L. (arithmetical mean) for the three frequencies and the average coefficient of transmission for the three frequencies are given for each panel. There is admittedly a weakness in obtaining the average value of the T.L. for any one panel by taking the arithmetical mean of the T.L.'s at several representative frequencies. In fact, it is impossible to give an accurate rating of the insulation value of a panel by any process of averaging, but it is convenient to be able to describe the insulation value of partitions by single numbers, and consequently *average values*, such as the ones given in Table XXIV, are commonly employed. They should be used only for purposes of approximate calculations, but with a proper understanding of what the *average* means and with a knowledge of the insulative properties of partitions at all frequencies, they will be found to be very convenient. It is fortunate for purposes of calculation, however, that these average values of T.L. usually correspond quite closely to the T.L. for the frequency range between 512 and 1024 cycles, that is, the range for which the sound level of most noises is a maximum.

TABLE XXIV

	Method 1 Intensity with and without Panel in Place	Method 2 Intensity on Both Sides of the Panel	Method 3 Reverberation Measurements	Average of the Three Methods
½-in. Mineral Wool Blanket				
T.L. (128 cycles)	11.4 db	12.8 db	13.0 db	12.4 db
T.L. (512 cycles)	14.2 "	15.2 "	15.7 "	15.0 "
T.L. (2048 cycles)	18.8 "	18.7 "	20.3 "	19.3 "
T.L. (average)	14.8 "	15.6 "	16.3 "	15.6 "
τ (average)	0.033	0.028	0.024	0.028
½-in. Plaster Board				
T.L. (128 cycles)	26.7 db	26.9 db	27.3 db	27.0 db
T.L. (512 cycles)	28.8 "	27.6 "	27.5 "	28.0 "
T.L. (2048 cycles)	32.7 "	32.7 "	33.6 "	33.0 "
T.L. (average)	29.4 "	29.1 "	29.5 "	29.3 "
τ (average)	0.00115	0.0013	0.0011	0.00116

As will be noted in the table, the results obtained by the three different methods of measurement are in very good agreement. The differences are no larger than the errors in the measurement of minimal audibility, namely, about 1 to 2 db. The good agreement obtained by these three different methods would seem to indicate that the results from different laboratories should be in fairly good agreement if all the test panels are made to the same specifications, and if all the data are reduced to the coefficients of transmission or the T.L.'s — quantities which do not depend upon the method of testing or the acoustical properties of the source and test rooms. Unfortunately, however, the agreement among the data from different laboratories does not turn out to be so good as the tests by the three different methods on these two panels would indicate. There are apparently a number of factors which enter into the making of sound-insulation tests which are not yet under proper control. In using the data, therefore, the architect should appreciate that there exist appreciable discrepancies among the results published by different investigators. In spite of these discrepancies, however, the existing data on the sound-insulation of different materials and different types of structure are of very great value in guiding the design of buildings where the insulation of sound is a prime requisite, and those which will be given in the following chapter are sufficiently accurate for all practical problems which arise in the design of sound-insulation for buildings.

CHAPTER XII

THE INSULATION OF SOUND — INSULATION DATA

103. General Considerations. The results of sound-insulation measurements obtained in different acoustical laboratories have been grouped into a number of tables which will be given in this chapter. Each table contains the data for materials or partitions having a number of properties in common. The data in each table have been further grouped so as to keep together the data from each laboratory. This facilitates comparisons of similar panels tested in the same laboratory. For convenience in referring to the tables, the names of the panels in each group have been alphabetized. Table XXV contains the data for porous-flexible materials, as felts, blankets, fabrics, and fibre boards; Table XXVI the data for thin rigid partitions, as plaster board, wood veneer, and sheet metal; Table XXVII, doors and windows; Table XXVIII, masonry and rigid partitions, as clay and gypsum tile, brick, and concrete; Table XXIX, wood stud or metal channel iron and plaster; Table XXX, floor and ceiling partitions; Table XXXI, composition partitions, such as combinations of rigid and porous-flexible materials, special wood partitions, sound-studio partitions, et cetera; and Table XXXII, double walls. In addition to the insulative properties of each partition there are given data on the composition of the partition, its mass per square foot of wall section, its thickness, and other special features.

The method of presenting the insulative data in the tables requires explanation. It would be very confusing to the architect if only the published data from the different laboratories were presented, since these data do not, as a rule, admit of direct comparison; and even where comparisons would seem to be warranted the agreement is not very satisfactory. The data from most laboratories give what has been called the *reduction factor* for the panel or partition tested. This *reduction factor*, in some instances, is the ratio of the intensities of the sound on both sides of the test panel, or ten times the logarithm of this ratio, and, as was shown in the preceding chapter, this ratio depends not only upon the insulative properties of the panel but also upon the size of the panel and the absorptive properties of the source and test rooms. In other instances, the *reduction factor* is given in terms of the coefficients of transmission or the T.L.'s for the panels. An attempt has been made therefore to adjust the data from different laboratories in such a manner as to give comparable ratings for all the materials and partitions listed in the tables. In spite of the rather large discrepancies among the data from different laboratories it is possible, in most instances, to make adjustments so that the data from all laboratories will be approximately comparable. The manner in which these adjustments have been made is indicated by the experimental curves for rigid panels shown in Fig. 139. The various broken lines in this figure show the *reduction factors*,[1] reported by different investigators, plotted as a function of the logarithm of the mass per unit area of the rigid partition. It will be noted that nearly all investigators find a direct proportion between the *reduction factor* and the mass per unit area of the rigid partitions, as is indicated by the straight lines which seem to give the best interpretation of the data. The straight lines, however, differ both in slope and in their intercepts.[2] The data from Meyer, the Bureau of Standards, Holtsmark,

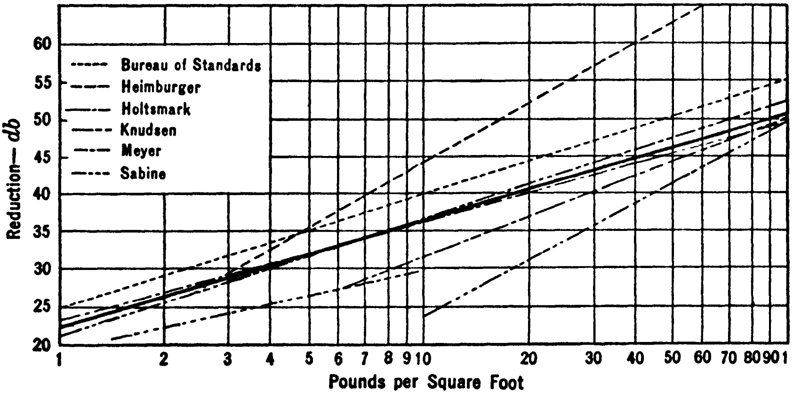


FIG. 139. Reduction factors obtained by different laboratories plotted in terms of the logarithm of the weight in pounds per square foot of the panel.

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[1] In most cases the *reduction factor* corresponds closely to what has been defined in this book as the T.L., and is given in decibels.

[2] It will be noted that there are two straight lines for Sabine's data — one for heavy-weight partitions, such as plastered tile, brick, or wood stud partitions, and another for light-weight panels, such as windows and doors. The two curves give a more accurate representation of his data than could be obtained with a single curve. This may be accounted for, in part at least, by the relatively important role played by the stiffness and the size of the panels in the case of the light-weight panels. The wide separation between Sabine's curve for heavy-weight partitions and the *probable average* curve, especially for partitions having a weight of about 10 to 20 pounds per square foot, is difficult to explain. (See Knudsen, Jour. Acous. Soc., **2**, 129 [July, 1930], and Sabine, Jour. Acous. Soc., **2**, 506 [April, 1931].) It is probable that many of the rigid partitions in this weight range which were tested by Sabine possessed peculiar

and Knudsen give the average T.L.'s for the panels tested, and should be independent of the properties of the test room, and the methods of testing. This probably accounts for the relatively good agreement among the data from these four sources. The heavy, solid line gives what the author considers to be the most probable value of the T.L. (that is, $10 \log_{10} 1/\tau$) for rigid panels of different weights per square foot of wall section. By the use of this solid-line curve, in conjunction with the other dotted curves in Fig. 139, appropriate adjustments can be made for the data from different laboratories so that all data will be at least approximately comparable. For example, for rigid panels having weights of about 40 pounds per square foot it is necessary to add about 1.0 db to the data of Meyer, 2.5 db to the data of Holtsmark, and 6.0 db to the data of Sabine, and to subtract about 1.0 db from the data of Knudsen, 4.0 db from the data of the Bureau of Standards, and 15.5 db from the data of Heimburger, in order that the data from the different laboratories on such panels be comparable. Similar adjustments can be made for the data on rigid panels weighing between about 1 and 100 pounds per square foot, although the accuracy of the adjustments will be uncertain for panels or partitions weighing less than about 10 pounds per square foot, owing to the effects of stiffness, size of panels, and the nature of clamping around the edges, which will be pertinent for light-weight panels. Although the curves in Fig. 139 apply only to rigid panels, the curves are serviceable for adjusting the data from the different laboratories on other types of panels and partitions. Thus, a panel rated at 30 db by the Bureau of Standards should be diminished by about 3.0 db, and a panel rated by Sabine at 30 db should be increased about 7.0 db in order that the data for the two panels be comparable. In this way, it is possible to adjust the sound-insulation data from different laboratories, and thus obtain not only more comparable ratings for all panels and partitions which have been tested in the different laboratories but in many instances ratings which are certainly in better accord

characteristics which did not conform to the simple *mass reaction* which characterizes most heavy-weight partitions. For this reason, it is possible that the adjustments for Sabine's reduction factors in this range, as indicated by Fig. 139, are somewhat larger than they should be. It is possible therefore that some of the "Probable Average Values of T.L." given in the table for partitions tested by Sabine (particularly those partitions for which Sabine obtained an average reduction factor of 25 to 35 db) are 2 or 3 db higher than the facts would warrant. However, the data on sound-insulation from practically all sources seem to warrant approximately such adjustments as have been made in the tables, and certainly the probable average values given in the last two columns in the tables give a fairer rating to the insulative value of the different partitions than would be given by the average reduction factors reported by the different laboratories.

with the facts than are the ratings published by some laboratories. It is probable that sound-insulation data which have been adjusted by means of the curves in Fig. 139 are not in error by more than 2 or 3 db. The data on the " Probable Average Value of T.L." given in the next to the last column in all the tables have been obtained by applying these adjustments to the average *reduction factors* obtained by different laboratories or investigators.

The data given in the tables include (1) a brief description of the panel or partition; (2) the weight in pounds per square foot of the panel; (3) the *reduction factors* as obtained by the different laboratories, usually at frequencies of 128, 256, 512, 1024, and 2048 cycles; (4) the authority for the data; (5) the " Probable Average Value of T.L.," based upon corrections given by the curves in Fig. 139; and (6) the " Probable Average Value of τ," computed from the " Probable Average Value of T.L."[3] The *reduction factors* at the different frequencies are very useful since they describe how the insulation value of the panel depends upon the frequency or pitch. This is often an important matter in the selection of materials or partitions for sound-insulation. For example, partitions which have a relatively low insulation value in the frequency range of 500 to 1000 cycles would not be suitable for the insulation of most noises met in buildings, since most of such noises contain a relatively large amount of sound energy in this frequency range. For this reason, the panels which show the highest values of T.L. may not supply the greatest amount of sound-insulation for all types of noise. It is necessary, therefore, in determining the best type of partition for each problem which arises in sound-insulation, to give consideration to the insulation values at the different frequencies as well as to the average value of T.L. or τ.

It is unfortunate that the data from the different laboratories are not in better agreement so that they would be directly comparable without making the adjustments which have just been described. However, when it is remembered that the making of sound-insulation measurements is a relatively new branch of science, that different methods of measurement have been used at different laboratories, that different-sized panels have been used, and that there are unavoidable differences in composition and structure of the panels, it is obvious that some adjustment must be made if the data are to be comparable, and thus of the greatest use to the architect and engineer. In addition, there has been no uniform practice at the different laboratories in regard to the choice of frequencies of test tones. If an average value be based upon a relatively large number of measurements at high frequencies and a relatively

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[3] $10 \log_{10} 1/\tau = \text{T.L.}$

small number of measurements at low frequencies the average result will be higher than it would be if the average were based upon a large number of measurements at low frequencies and a small number of measurements at high frequencies. This is the case since nearly all panels have considerably more insulation against high-frequency sounds than they do against low-frequency sounds.

The curves in Fig. 139 do not contain the data of Davis and Littler from the National Physical Laboratory. The reason for this is that the data available from Davis and Littler on rigid panels were insufficient to construct a curve. However, their data on such materials as they have tested, which may be compared with materials that have been tested in other laboratories, show that their average values of T.L. are about 2 db higher than would be indicated by the probable average value curve given in Fig. 139. A likely reason for this is that their data are based upon measurements above 300 cycles, and consequently the average values of T.L. would be too high. Accordingly, the " Probable Average Value of T.L." for their data have been reduced 2 db.

In some instances only the *reduction factors* obtained by the various investigators have been entered in the tables. In these instances — usually for materials having a low insulation value — it was quite impossible to determine what, if any, adjustments should be made to the average reduction factors in order to convert them into probable average values of T.L.

Partitions which possess outstanding merit with regard to both insulation value and practicability have been designated by the use of bold type for the description of the partition.

104. Tabulated Data on the Insulative Properties of Different Building Materials and Different Types of Wall, Floor, and Ceiling Constructions.

TABLE XXV

POROUS–FLEXIBLE MATERIALS AND FIBRE BOARDS

Description of Panel	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Airplane fabric, doped and varnished	0 055		3 6	3 0	5 9	10 1	Bureau of Standards*		
Celotex, carpet lining, ½″	27	.	13 4	12 4	15 1	21 5	"	14	0 040
Celotex, like above, ½″	53		21 4	18 8	22 3	24 6	"	20	010
Celotex, standard, ½″	30		14 2	14 7	18 0	23 5	"	15	032
Celotex, like above, ½″	66	.	22 4	17 3	23 4	27 4	"	20	010
Insulite, ½″	39	.	16 2	15 2	19 7	25 2	"	16	025
Insulite, 7/16″............. .	43		19 5	17 1	20 7	26 1	"	18	016
Insulite, ½″............. .	75		22 2	20 2	24 1	20 9	"	19	013
Wrapping paper, heavy	016		1 4	1 5	1 7	3 3	"		
Cabot's Quilt, ½″, four layers			.	19 4†			P. E Sabine	22	0063
Flax-li-num, ½″, four layers.			... .	26 1†			"	30	001
Hair felt, 1″.......	75	4 9	4 6	6 0	7 1	6 7	"		
Hair felt, 2″............ ..	.			9 3†			"		
Hair felt, 3″............. ..	....			11 8†			"		..
Hair felt, 4″.................	....	7 5	12 5	15 3	19 7	19 4	"		..
Hair felt, 1″, three layers alternated with four layers building paper..			..	27 9†			"	32	00063
Hair and fibrous asbestos, mixed, ½″, covered with heavy paper, stitched at 16″ intervals	1 13	15 3	17 2	17 4	19 1	22 9	"	21	0080
Seaweed, ½″, covered with light paper stitched at 3″ intervals......	.298	10 0	8 5	8 5	7 3	7 4	"		
Vegetable fibre, coarse, woody, ½″, pressed into flexible boards.....	625	10 6	10 0	10 6	16 0	10 0	"	..	. .
Cartridge paper, 0.0088″.......	031		0 5	1 5	2 0		Davis and Littler‡	.	....
Compressed board, 0.19″.....	.61		13 8	16 0	25 3		"	16	025
Eelgrass Quilt, 0.5″. .	20			5 0		.	"		. ..
Fibre board, 0.5″ (No. 1) .	75	.	15 5	19 0	29 0	..	"	19	013
Fibre board, 0.46″ (No. 2)	66		14 0	19 0	27 0	..	"	18	016

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* Reduction factors from the Bureau of Standards, for the most part, are for the following frequency bands: 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. The data for the several frequency bands are recorded under the frequencies to which the frequency bands most nearly correspond.

† Average value from 128 to 2048 cycles.

‡ Davis and Littler's reduction factors are for frequencies of 300, 500, and 1000 cycles. Their values are recorded under 256, 512, and 1024 cycles, respectively.

TABLE XXV — (*Continued*)

POROUS–FLEXIBLE MATERIALS AND FIBRE BOARDS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Fibre board, 0.29" (No. 3)	0 46		10 5	16 5	24 5		Davis and Littler‡	15	0 032
Fibre board, 0.42" (No. 4) .	57			16 5	26 0		"	19	013
Fibre boards (Nos. 3 and 4), layer eelgrass quilt between			11 0	25 5			"	.	....
Fibre boards (Nos 2 and 4), insulated by air space 23" wide (one on outer side of each of two brick walls separated by 5" air space)			24 0	40 0	49 0		"	36	00025
Fibre boards (Nos. 3 and 4) as above				27 5	45 5	.	"		....
Fibre boards (Nos. 3 and 4) as above, with layer eelgrass quilt hung loosely in interspace				38 5	59 5		"		....
Fibre boards (Nos. 2 and 4) on 1½" wood framework, 62" ×46"×4½", built into aperture			28 0	29 0	39 0		"	30	001
Fibre boards (Nos. 2 and 4) as above, with interspace filled with cotton waste (1 3 lb. per square foot)			29 0	31 0	41 5		"	32	00063
Hair felt, 0.58" ..	58		6 2	6 1	6 3	. .	"		....
Hair felt, like above, two layers	1 16		9 6	10 5	11 7		"	9	13
Hair felt, like above, three layers . . .			12 7	13 9	17 3		"	13	.050
Hair felt, like above, four layers. . . .			14 7	18 8	23 0		"	17	020
Sailcloth, 0.037".	14		4 5	8 5	14 5		"		. ..
Sailcloth, 0.025" .	09		3 0	5 0	10 0		"		....
Sailcloth, 0.025".	07		1 0	4 0	9 0		"	.	....
Inso Board, 1/16"		17 0		20 2		21 3	V. O. Knudsen	19	013
Rock Wool blanket, ½", covered on both sides with heavy brown paper . .		15 5		17 8		18 4§	"	16	.025
Upson Blue Stripe Insulation		14 0	15 1	16 0	18 5	21 1	"	16	.025
Cork board, 2" .				37 4§	. .	.	E. Petsold	....	....

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‡ For frequencies of 300, 500, and 1000 cycles. See note on page 304.

§ Average value of reduction factor given by E. Petsold.

TABLE XXVI

THIN RIGID MATERIALS

Description of Panel	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Aluminum, 0.006″...........	0 075		3 7	5 6	7 7	12 6	Bureau of Standards*		
Aluminum, 0.025″ .	35		17 9	13 2	17 7	23 2	"	16	0 025
Duralumin, 0.020″ .	33		14 1	12 5	17 6	22 5	"	15	032
Iron, 0.03″ galvanized ..	1 2		25 3	20 5	28 8	35 0	"	25	0032
Lead, 1/16″	3 90		31 8	33 2	32 0	32 1	"	30	0010
Lead, ⅛″ . .	8 2		31 0	27 2	37 5	43 8	"	32	00063
Plywood, ⅛″, three-ply	52		19 0	17 5	22 0	26 7	"	19	013
Plywood, ¼″, three-ply	73		21 0	20 7	25 5	26 0	"	21	0080
Mahogany, 1.85″	4 9		26 0	27 0	36 0		Davis and Littler‡	28	0016
Matchboard, each strip 46″×5″×½″, on framework of 1½″ wood 62″×46″×4½″, built into aperture	1 31		20 5	22 0	33 0		"	23	0050
Matchboard, double, as above			32 5	27 5	43 5		"	33	00050
Plywood, 0.6″, mahogany faced	1 4		21 0	24 0	33 0		"	24	0040
Plaster board, ½″....		27 0		28 0		33 0	V. O. Knudsen	28	0016
Plywood, ⅛″	45	12	16	17	22	26	E. Meyer	17	020
Sheet Iron, 0.08″...	3 2			33 ‖			"	33	00050

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

‡ For frequencies of 300, 500, and 1000 cycles. See note on page 304.

‖ Average value from 100 to 3000 cycles.

Table XXVII
DOORS AND WINDOWS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Doors									
Birch veneer, light, four panel		13.0	16.1	20.4	22.8	22.0	P. E. Sabine	22	0.0063
"Cold storage" door, double wall, 4" .. .		16.4	20.8	27.1	29.4	28.9	"	29	0013
Fabricated, hollow, flush or sanitary door, 1¾"				22.7†			"	27	0020
Fabricated, like above, hung in usual manner				20.8†			"	24	0040
Maple veneer, paneled, two doors hung with 2" separation in single casement				25.0†			"	30	001
Oak, solid, 1¾", with cracks as ordinarily hung		11.5	15.1	20.4	22.0	16.2	"	20	01
Oak, like above, well seasoned and air tight		15.1	18.2	22.8	25.7	25.2	"	25	0032
Oak, solid, swollen with dampness .		20.0	19.0	22.8	25.7	26.1	"	26	0025
Refrigerator door, 5½" yellow pine filled with cork.				24.6†			"	29	0013
Steel, solid, ¼"		25.1	26.7	31.1	36.4	31.5	"	35	00032
Model door panel and jamb ¶									
Panel just making contact against jamb		30.6		30.4		44.0	V. O. Knudsen	34	00040
Force of panel against jamb, 400 lb.		34.1		34.8		48.0	"	38	00016
Force of panel against jamb, 800 lb. .		34.1		35.2		48.0	"	38	00016
Rubber strips removed from outer step of jamb. Panel just making contact against jamb.		29.7		27.3		35.2	"	30	0010
Force of panel against jamb, 267 lb. .	..	31.4		29.2		39.4	"	33	00050
Force of panel against jamb, 533 lb..		32.9		29.2		40.1	"	34	00040
Wood door, 1¾", six panels, ½"	3.7				33.6**		G. Heimburger	31	00080
Wood doors, like above, two, separated 4½" ...	..				55.7**		"	43	000050

† Average value from 128 to 2048 cycles.

¶ The tests on this door and jamb were conducted for the purpose of determining the effect of the type of " seal " on the insulation furnished by a door. The door and jamb both terminated in three right-angle steps, so that the door made contact against the jamb at three separate stops (see Fig. 272). The stops on the jamb were made of ¼-in. strips of live India rubber. On the door were three ½-in. wood half rounds which were forced against the rubber strips when the door was closed. The data listed in the table show the effect of changing the pressure against the door and also the effect of reducing the number of stops from three to two.

** Average value 600 to 1200 cycles. The high frequencies used by Heimburger are partially responsible for the relatively high reduction factors which he obtained. The nature of the source of sound he used —

TABLE XXVII — (*Continued*)

DOORS AND WINDOWS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Doors — Continued									
Wood doors like above; one, 1 3/16", with ⅛" felt compressed to 3/16" between the doors					47 6**		G. Heimburger	39	00013
Wood doors like above, tested over door crack					25 8**		"	...	..
Windows									
Glass, plate, ¼"	3 5		32 6	30 9	33 5	34 2	Bureau of Standards	30	0010
Glass, double strength	1 6		26 2	27 4	30 8	33 0	"	27	0020
Glass, ⅛", twelve panes	.	16 9	18 3	21 5	25 8	23 6	P. E. Sabine	25	0032
Glass, plate, 3/16", four panes		21 4	19 0	24 1	25 1	21 8	"	26	0025
Glass, 3/16", small leaded panes.		19 2	20 0	24 3	31 4	27 8	"	29	0013
Glass, plate, 3/16", two panes		17 2	15 9	19 7	24 6	22 6	"	23	0050
Glass, plate, 3/16", two panes, double glazed, set in felt		18 5	19 6	25 6	32 3	30 8	"	30	0010
Glass, as above, set in putty	.	18 0	19 6	25 1	27 3	21 8	"	27	0020
Glass, triplex, 3/16", four panes	....	17 5	13 6	22 6	24 5	22 0	"	23	0050
Glass, plate, ¼", single pane	. .	21 8	20 8	23 0	25 1	19 0	"	25	0032
Glass, plate, ¼", four panes.		23 2	20 8	26 4	27 5	22 8	"	29	0013
Glass, plate, ¼", double glazed, sashes in contact				29 3†	..	..	"	35	00032
Glass, plate, ¼", double glazed, 1½" separation ...		..		34 0†	....	... .	"	40	0001
Glass, plate, ¼", double glazed, 4½" separation	.	.	.	35 3†	....	. .	"	41	000080
Glass, plate, ¼", double glazed, 7½" separation		...	... .	38 9†	....	....	"	45	000032
Glass, plate, ¼", double glazed, 9½" separation ..	..	.	. .	40 7†	....	....	"	46	.000025
Glass, plate, ¼", double glazed, 13½" separation.		..		42 5†	....	....	"	47	000020
Glass, plate, ¼", double glazed, 16" separation..				43 0†	....	....	"	48	000016
Glass window, single, closed tight	.	.		32 8§	....	...	E. Petzold		..
Glass window, single, poorly closed	....			4 2§	....	....	"		... .
Glass window, double, closed tight	... .		.	52 0§	... .	... .	"	. .	...
Glass window, double, poorly closed . .	..			16 4§	. .	.	"	.	..

a loud speaker directed at and placed near the partition, and enclosed by a small shell — also would tend to give high reduction factors, especially for very heavy and rigid partitions. Since the reaction of a panel or partition to sound vibrations is largely a mass-reaction it is necessary that the incident sound radiate against the entire panel when making insulation measurements.

† Average value from 128 to 2048 cycles.

§ Average value of reduction factor given by E. Petzold.

TABLE XXVIII
RIGID PARTITIONS
(Tile, Brick, Concrete, etc.)

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db 128	256	512	1024	2048	Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		cycles per second							
Brick panel, Mississippi, 8"; plastered both sides gypsum brown coat, smooth white finish; good workmanship	87		50.2	47.6	55.5	63.5	Bureau of Standards*	50	0.000010
Brick panel, New Hampshire, 8"; plastered both sides gypsum brown coat, smooth white finish; poor workmanship .	92	. .	47.7	48.1	55.6	56.3	"	48	000016
Brick panel, as above, good workmanship	97	...	47.7	49.4	57.0	59.2	"	49	000013
Brick, New Hampshire, laid on edge, furring strips wired, gypsum plaster board, plastered both sides gypsum scratch and brown coats, smooth white finish .	36.5	..	52.1	47.4	56.5	53.9	"	48	000016
Brick, as above, except furring strips nailed .	38.2		46.8	44.3	54.4	61.3	"	48	000016
Brick, as above, except Insulite replaced gypsum plaster board .	33.3	. . .	48.8	50.5	59.8	55.8	"	50	000010
Brick, as above, except furring strips wired, plaster applied directly to brick surface .	31.6	...	40.0	36.9	48.7	59.1	"	43	000050
Tile, clay, three-cell, 3"×12" ×12", plastered both sides gypsum scratch coat, very thin smooth-finish coat..	. ..	....	39.1	...	35.7	59.3	"	41	000080
Tile, as above, except lime plaster	... .	....	38.5	...	39.2	46.8	"	38	00016
Tile, hollow clay partition, three cells, 3" × 12" × 12", plastered both sides gypsum brown coat, smooth white finish.........	28	....	41.2	38.7	43.5	50.4	"	40	.00010
Tile, hollow clay partition, three cells, 4" × 12" × 12", plastered both sides gypsum brown coat, smooth white finish	29	.	41.1	40.0	41.5	49.9	"	40	.00010

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

TABLE XXVIII — (*Continued*)

RIGID PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Tile, like above, laid so that no flues over 2′ in length, plastered as above .	29		42.0	36.7	42.3	50.6	Bureau of Standards*	40	0.00010
Tile, like above, wood furring strips, paper, metal lath, gypsum scratch and brown coats, smooth white finish	34		55.6	52.8	57.3	57.6	"	52	0000063
Tile, hollow clay load-bearing, six cells, 6″ × 12″ × 12″, plastered both sides gypsum brown coat, smooth white finish .	39		38.8	42.1	46.6	53.5	"	42	000063
Tile, hollow clay partition, three cells, 6″ × 12″ × 12″, medium burned, plastered both sides gypsum brown coat, smooth white finish	37		41.2	35.4	45.1	52.1	"	40	00010
Tile, hollow clay soft partition, three cells, 6″ × 12″ × 12″, plastered both sides gypsum brown coat, smooth white finish .	37	.	41.1	42.0	43.7	50.1	"	41	000080
Tile, hollow clay, six cells, 8″ × 12″ × 12″, plastered both sides gypsum brown coat, smooth white finish .	48		44.3	44.5	48.9	58.0	"	45	000032
Tile, hollow clay, two units, 3¾″ × 12″ × 12″ and 8″ × 12″ × 12″, end construction, plastered both sides gypsum brown coat, smooth white finish	65		49.4	40.1	37.0	55.2	"	42	.000063
Tile, hollow clay, two units, 3¾″ × 5″ × 12″, and 8″ × 5″ × 12″, side construction, plastered both sides gypsum brown coat, smooth white finish	66	..	49.4	46.3	48.7	53.3	"	46	.000025
Tile panel, hollow clay, constructed of Heath cubes, plastered both sides gypsum brown coat, smooth white finish	55	....	48.6	46.3	48.4	55.4	"	46	000025

* For frequency bands of 150 to 157, 250 to 285, 500 to 585, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

TABLE XXVIII — (*Continued*)

RIGID PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Tile, hollow clay partition, three cells, 4" × 12" × 12", wood furring strips, Insulite, gypsum brown coat, smooth white finish . ..	34		52.2	51.9	60.9	61.1	Bureau of Standards*	53	0.0000050
Tile, as above, except Masonite replaced Insulite	28		55.3	53.2	56.8	68.8	"	54	0000032
Tile, like above, pads, wood furring strips, Insulite, gypsum brown coat, smooth white finish ..	34		55.7	52.4	53.3	60.2	"	52	0000063
Tile, hollow clay, 4", unplastered .	17	24.5	24.1	26.1	35.5	29.8	P. E. Sabine	35	.00032
Tile, like above, ½" plaster	22	25.1	24.3	26.9	38.2	33.9	"	38	00016
Tile, like above, 1" plaster	27	27.3	26.9	30.3	39.8	39.8	"	40	00010
Tile, like above, 1½" plaster .	28.8	28.0	27.4	31.9	40.4	40.2	"	41	000080
Tile, hollow gypsum, 3", unplastered	11.1	19.2	18.7	20.8	28.5	30.0	"	31	00080
Tile, solid gypsum, 2", unplastered .	10.4	18.1	18.1	20.4	25.3	27.9	"	30	0010
Tile, like above, ½" plaster	15.0	21.9	21.0	24.6	30.8	33.7	"	34	00040
Tile, like above, 1" plaster	19.6	22.9	23.8	27.5	36.9	37.6	"	38	00016
Tile, like above, 1½" plaster .	21.4	22.9	24.2	27.6	37.6	38.2	"	38	00016
Tile, solid gypsum, 3", unplastered .	14.2	19.4	19.0	21.9	33.5	35.4	"	33	00050
Tile, like above, 1½" plaster	25.4	24.5	26.0	31.2	39.8	40.2	"	40	00010
Bricks, Fletton, and lime mortar, 4½", fine cracks visible . ..	41		. ..	.	58.0		Davis and Littler	.	. .
Brick wall, solid, 12", erected inside of brick kiln	98	46.2	.	56.4	.	60.0	V. O. Knudsen	52	.0000063
Brick wall, 12", with 4" air space filled with ground clay, erected as above	102	45.6	. .	55.7	..	62.1	"	52	0000063
Tile, porous clay, 2⅜", 1/16" lime plaster each side	25.6	...	....	...	57.0**	..	G. Heimburger	43	000050
Tile, porous clay, 6", ⅜" lime plaster each side..	45.0	..	. ..	..	63.7**	. ..	"	47	000020
Tile, cinder concrete, 2", without plaster	12.3	.	. .	. .	14.8**	.	"	16	025
Tile, like above, 1/16" lime plaster each side...	19.2	.			51.9**		"	40	00010

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

** Average value from 600 to 1200 cycles. See note on page 307.

TABLE XXVIII — (*Continued*)

RIGID PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of *r*
		128	256	512	1024	2048			
		cycles per second							
Tile, cinder concrete, 4″, without plaster	24.5				33.2**		G. Heimburger	32	0.00063
Tile, like above, $\frac{1}{16}$″ lime plaster each side	31.5				58.9**		"	44	.000040
Tile, porous concrete, 4″, $\frac{1}{16}$″ lime plaster each side	24.5		..	.	59.4**		"	44	.000040
Brick wall, 2½″, unplastered.	....			37.0††			Holtsmark	40	.00010
Brick wall, 2½″, plastered both sides . .	....			43.0††			"	45	.000032
Brick wall, 4″, unplastered.	....			40.0††			"	43	.000050
Brick wall, 4″, plastered both sides	.			46.0††			"	48	.000016
Brick wall, 2½″, plastered both sides	31			42‖	..		E. Meyer	43	.000050
Brick wall, 4″, plastered both sides . . .	46			43‖			"	44	.000040
Brick wall, 10″, plastered both sides	93	37	47	48	57	55	"	50	.000010
Concrete wall, plastered both sides . . .	26			41‖		.	"	42	.000063

** Average value from 600 to 1200 cycles. See note on page 307.

†† Average value from 200 to 3400 cycles.

‖ Average value from 100 to 3000 cycles.

TABLE XXIX
WOOD STUDS AND PLASTER, METAL CHANNEL IRON AND PLASTER, ETC.

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Steel channels, ¾", plastered both sides gypsum scratch coat, ½", and brown coat ...	.		37 0	.	41 2	47 0	Bureau of Standards*	38	0 00016
Steel channels, ¾", metal lath, plastered both sides gypsum scratch coat, ½", and brown coat . . .			42 1		44 5	49 1	"	42	000063
Steel channels, ¾", metal lath, plastered gypsum scratch coat, ½", brown coat, ⅝", very thin smooth finish coat, troweled . . •			35 8		39 3	46 0	"	37	00020
Wood studs, 2" × 4", 17" o.c., ⅜" × 1½" wood lath, ⅜" apart, gypsum scratch, lime brown, smooth finish	....	....	49 5	....	42 6	52 2	"	44	.000040
Wood studs, metal lath, scratch and brown coats gypsum wood-fibred plaster (no sand)	.		44 0	.	41 1	53 4	"	42	000063
Wood studs, metal lath, scratch and brown coats plaster (1 part sand to 1 part gypsum wood-fibred plaster) .	....		43 4	..	43 7	55 0	"	44	000040
Wood studs, metal lath, three-coat smooth finish gypsum wood-fibred plaster (no sand)	. ..	.	46 3		42 5	56 6	"	45	000032
Wood studs, metal lath, three-coat smooth finish plaster (1 part sand to 1 part gypsum wood-fibred plaster)... ..		..	47 0		42 3	54 6	"	44	000040
Wood studs, sheet metal, three-coat smooth finish gypsum plaster.. .. .	...	.	47 0		46 6	51 8	"	45	.000032
Wood studs, wood lath, gypsum scratch and brown coats, smooth white finish...	17 4	38 2	39 6	39 2	43 9	49 0	"	38	.00016
Wood studs, ½" Insulite both sides, joints filled......	5 10	28 5	28 6	24 0	35 6	47 5	"	30	.0010
Wood studs, two ½" sheets Insulite both sides, joints filled .	6 60	33 9	32 2	29 4	40 8	58 5	"	33	00050
Wood studs, ½" Insulite both sides, gypsum scratch and brown coats, smooth white finish.................... ..	13 3	46 2	39 5	47 2	57 0	56 3	"	45	000032

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

TABLE XXIX — (*Continued*)
WOOD STUDS AND PLASTER, METAL CHANNEL IRON AND PLASTER, ETC.

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Wood studs, two ½" sheets Insulite both sides, joints filled, gypsum scratch and brown coats, smooth white finish	14.2	50.2	52.2	43.9	57.9	61.0	Bureau of Standards*	49	0.000013
Wood studs, staggered, ½" Insulite both sides, joints filled	4.94	34.1	29.9	27.9	41.8	59.3	"	35	00032
Wood studs, staggered, ½" Insulite both sides, Ecol Fabric, gypsum scratch and brown coats, smooth white finish	16.1	52.2	52.6	47.4	53.7	58.2	"	49	000013
Wood studs, etc., as above, except no Ecol Fabric	13.1	50.1	52.2	49.4	59.6	60.1	"	50	000010
Wood studs, ½" Insulite one side, plastered and back-plastered. Other side metal lath with scratch, brown and finish coats	20.9	45.4	45.1	44.7	47.6	57.7	"	44	000040
Wood studs, ½" Insulite one side, plastered with brown coat and back-plastered; furring strips, ½" Insulite, gypsum scratch, brown and finish coats. Other side metal lath plastered with gypsum scratch, brown and finish coats	21.3	49.9	53.0	52.0	57.3	62.9	"	51	0000080
Wood studs, Sheet Rock nailed each side, No. 12 porous gypsum poured between studs	11.8	37.7	..	37.2	.	38.1	"	34	00040
Wood studs, etc., as above, except No. 30 porous gypsum replaced No. 12	19.6	42.1	.	44.1	..	48.2	"	41	000080
Wood studs, ½" Flax-li-num nailed each side, 1" × 2" furring strips, wood lath, plastered both sides gypsum scratch and brown coats, smooth white finish	14.7		42.4	38.2	44.7	54.1	"	41	.000080
Metal lath, 1½" plaster	13.9	23.1	21.5	23.1	23.5	31.3	P. E. Sabine	32	.00063
Metal lath, 2½" plaster	23.2	24.4	23.5	27.3	36.7	41.4	"	38	00016
Metal lath, 3½" plaster	32.5	27.3	25.8	26.9	41.8	44.2	"	40	.00010
Metal lath, 4½" plaster	41.8	30.0	30.0	36.7	45.0	45.7	"	43	000050
Wood studs, 2" × 4", metal lath, ½" gypsum plaster	17.4		...	29.2†	.		"	37	00020

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

† Average value from 128 to 2048 cycles

TABLE XXIX — (*Continued*)

WOOD STUDS AND PLASTER, METAL CHANNEL IRON AND PLASTER, ETC.

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Wood studs, etc., as above, filled with granulated slag	27 4		.	36 7†			P. E. Sabine	43	0 000050
Wood studs, metal lath, 3.1 lb. per square yard; ¼″ scratch coat, ¼″–⅜″ brown coat gypsum plaster ..	17 4	40 0	41 5	49 1	55 8	48 1	"	49	000013
Wood studs, 2″ × 4″, wood lath, ½″ gypsum plaster .	18 0			29 4†			"	37	.00020
Wood studs, 2″ × 4″, wood lath, ½″ lime plaster . .	17 4			38 1†			"	44	000040
Wood stud; wood lath, ¼″ × 1½″, spaced ⅜″; gypsum scratch coat, ¼″; brown coat ¼″–⅜″, finish coat . . .	18 6	24 4	25 6	29 1	32 2	35 7	"	37	00020
Wood studs, etc., as above, except lime plaster	18 0	27 5	28 8	38 1	46 6	42 9	"	43	000050
Wood studs, 2″ × 4″, ½″ Celotex, unplastered	3 0	9 0	15 0	23 9	30 6	32 0	"	29	0013
Wood studs, etc., as above, filled with sawdust	6 6	15 3	23 7	27 0	38 0	39 7	"	36	00025
Wood studs, 2″ × 4″, ½″ Celotex, gypsum plaster .	12 0	17 7	24 7	37 0	43 7	36 7	"	40	00010
Wood studs, etc., as above, filled with sawdust	15 6	16 3	30 0	39 0	44 5	39 7	"	42	000063
Wood studs, 2″ × 4″, ½″ Masonite, ⅝″ gypsum plaster .	16 0			38 0†			"	45	000032
Wood studs, 2″ × 4″, ½″ felt, ¾″ furring, metal lath, gypsum plaster.	18 0			40 0†	.	.	"	46	000025
Wood frame, 2″ × 4″, ⅜″ plaster board, ⅜″ sand and fibre plaster both sides, 4″ porous wall fill between studs		38 1	.	40 2	.	41 4	V. O. Knudsen	39	00013
Wood studs, 2″×4″, 16″o c., expanded metal lath, plastered both sides scratch and brown coats "Insultex" plaster; 5½″	..	32 9	37 7	39 8	40 3	39 0	"	38	00016
Wood studs, etc., as above, except stand'd hard wall plaster instead of "Insultex" plaster	.	30 8	35 0	36 2	37 0	38 2	"	35	00032
Wood studs, tarred paper, chicken wire, 1″ cement plaster	..	25 2	...	29 5		30 2	"	28	0016
Wood studs, 30″ o.c., 2½″ wood boards, tongued and grooved on one side	8 2			. .	42.9**	..	G. Heimburger	36	00025

† Average value from 128 to 2048 cycles.

** Average value from 600 to 1200 cycles. See note on page 307.

Table XXX
FLOOR AND CEILING PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Concrete flat slab floor construction, reenforced. Insulite furred out, applied as ceiling	54 4	50 9	54 8	58 7	56 5	53 2	Bureau of Standards*	51	0.0000080
Concrete flat slab floor construction, reenforced. Floating floor consisting of nailing strips, rough and finish flooring Insulite furred out and applied as ceiling .	58 1	58 9	57 0	55 4	67 6	65 2	"	57	0000020
Concrete, etc., as above, with ½" Insulite between concrete slab and floating floor	58 9	57 9	58 2	55 8	66 3	67 3	"	57	.0000020
Tile, 8", four cell, flat arch floor panel, gypsum brown coat, smooth white finish. Cinder concrete filled between 2" × 4" wood studs 16" o.c. fastened to top surface. Hardwood flooring . . .	76		46 3	46 8	47 8	54 5	"	45	000032
Tile, as above, except floor finished with 2" cinder concrete and 1" cement	85		46 7	47 1	47 4	50 5	"	44	.000040
Tile, three-cell partition, 4" × 12" × 12". Ceiling finished with furring strips, ½" Insulite plaster	69 8	56 5	56 6	55 8	57 7	58 8	"	53	.0000050
Tile, as above, with floating floor consisting of nailing strips, rough and finish flooring	73 5	62 7	63 1	61 0	65 9	73 7	"	61	.00000080
Tile, as above, with ½" Insulite between masonry slab and floating floor..	74 2	63 6	70 3	63 4	63 5	68 7	"	62	00000063
Tile, as above, except ceiling stripped off and suspended ceiling attached....... ..	72 3	68 0	67.9	65 8	72 1	...	"	64	.00000040
Tile, three-cell partition, 6" × 12" × 12". Ceiling finished gypsum brown coat, smooth white finish.	83	..	51 2	46.8	49.6	60 4	"	48	.000016
Tile, as above, except 2" cinder concrete and 1" cement added to upper surface .	109	.	52 4	48 0	49 9	54 6	"	47	000020

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

TABLE XXX — (*Continued*)
FLOOR AND CEILING PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Wood joists. Lower side plastered on wood lath; upper side, sub-flooring and ⅞"* finish flooring	..	47 9	46 8	40 7	50 1	48 8	Bureau of Standards*	43	0 000050
Wood joists, etc., as above, with ½" Insulite between rough and finished floors	....	47 7	48 3	40 6	50 3	48 9		44	000040
Wood joists, etc., as above, with floating floor consisting of nailing strips, rough and finish flooring	....	57 6	57 5	54 8	62 4	57 6	"	53	0000050
Wood joists, etc., as above, with ½" Insulite between rough and finished flooring of floating floor		57 9	60 1	53 5	62 7	55 7		53	0000050
Wood joists, suspended ceiling of ½" Insulite plastered. Rough and finish flooring	12 6	52 6	53 6	49 2	54 9	55 3	"	49	000010
Wood joists, etc , as above, with ½" Insulite between rough and finish floors, floating floor of nailing strips, rough and finish flooring	16 1	62 4	65 3	57 3	68 8	62 3	"	59	0000013
Joists, 4" × 12", 2′ o.c., 7" filling of cinder on 1" boards between joists; ¾" finished floor, 1" sub-floor; 1" wood board, lime plaster on lath for ceiling	. .				77.6**		G. Heimburger	58	0000016
Joists, 4" × 8½", 2′ o.c.; ½" finished floor, 1/16" cardboard, 1" wood sub-floor, one layer rag paper; ceiling, two layers rag paper, 1" wood boards, lime plaster on lath...................	...	.	.	. .	68.6**	.	"	51	0000080
Joists, 4" × 9", 2′ o.c., 6½" cinder fill, two layers rag paper, ¾" wood board between joists; floor, 1¾" T & G wood boards, one layer rag paper; ceiling, 1" wood boards, lime plaster on lath	....	...	....	....	70.5**	....	"	52	.0000063

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* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

** Average value from 600 to 1200 cycles. See note on page 307.

TABLE XXXI
COMPOSITION AND SPECIAL PARTITIONS

Description of Panel	Weight in Lb. per Square Foot	Reduction Factors in db cycles per second 128	256	512	1024	2048	Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
Tile, hollow clay, 3″ × 12″ × 12″, spaced 1¾″ between sides. 1″ Flax-li-num, butted tight, placed between tile. One side of partition carried on ½″ × 4″ Flax-li-num strips, sides, top and bottom	50		55 2	50 8	50 8	65 8	Bureau of Standards*	52	0 000063
Insulite, ½″, sufficient layers to make total thickness of 5″, gypsum wall board core		27 6	.	38 4	.	39 5	V. O. Knudsen	35	00032
Insulite, as above, except galvanized iron core		27 7	. .	37 5	...	36 9	"	34	00040
Wood studs, 2″ × 4″, 1″ Gunite on outside of studs		30 6		33 8	. .	35 6	"	33	00050
Wood studs, as above, with $\frac{7}{16}$″ fibre board on inside of studs		35 2	.	35 6		38 7	"	36	00025
Wood studs, as above, except ⅜″ fibre board replaced $\frac{7}{16}$″		37 4		36 7	..	41 0	"	38	00016
Wood studs, as above, except ½″ plaster board replaced fibre board		34 4	. . .	35 0		37 9	"	36	00025
Wood studs, as above, except ½″ quilted material replaced plaster board	.	35 2	...	35 3		38 8	"	36	00025
Wood studs, ½″ plaster board, 6″ fill rock wood covered with ½″ mesh hardware cloth	.	29 6	.	35 5		37 0	"	34	00040
Wood studs, two layers ½″ plaster board, 6″ fill rock wool covered with ½″ mesh hardware cloth	. . .	34 0	..	39 2		42 8	"	38	00016
Wood studs, tarred paper, chicken wire, 1″ cement plaster; 2′ air space; wood studs, ½″ plaster board, 6″ fill rock wool covered with ½″ mesh hardware cloth; no structural connections; separate foundations... .. .	.	53 2	....	60.4	. . .	63 8	"	57	0000020
Wood studs, 2″ × 4″, 1″ gypsum plaster on outside of studs, ½″ Alltite, Style O, pink paper on inside of studs		36 1	....	44 4		47 2	"	41	000040

* For frequency bands of 150 to 157, 250 to 285, 500 to 547, 1000 to 1070, and 2000 to 2175 cycles. See note on page 304.

TABLE XXXI — (*Continued*)
COMPOSITION AND SPECIAL PARTITIONS

Description of Panel	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Wood studs, etc., as above, except Alltite covered with heavy tarred waterproof paper		36 2	...	44 1	....	47 8	V. O. Knudsen	41	0 000080
Wood studs, 2″ × 8″; 1″ stucco on ½″ Sheet-rock on outside; 7/16″ Masonite, furring strips, 1½″ rock wool on inside of studs ..		38	....	50	.	63	"	49	000013
Sound Studio Wall Constructions									
Wood studs, 2″ × 6″; 1″ Gunite on outside; Zonolite fill between studs; 7/16″ Masonite on inside of studs		...	....	....	....	....	"	42	000063
Wood studs, 2″ × 6″; 1″ wood sheathing, 1″ Gunite on outside; Zonolite fill between studs; 7/16″ Masonite on inside of studs . .	.						"	45	000032
Wood studs, 2″ × 4″; two layers ½″ plaster board, ¾″ Gunite on outside; 5″ air space, ½″ plaster board, 2″ × 4″ wood studs with mineral wool fill between, outer and inner walls connected at floor and ceiling	...			....	....	....	"	55	0000032
Wood studs, 2″ × 4″; 1″ stucco on outside; 1½″ quilt, wood strips, ½″ felt, wood strips, 7/16″ Celotex, 2½″ rock wool on inside of studs	. .	..	...	....	.. .	....	"	53	0000050
Wood studs, 2″×6″, 1″ sheathing on outside; ½″ jute fibre, 7/16″ Celotex on inside of studs	....	...	....	.. .	..	....	"	39	00013
Wood studs, 2″ × 6″; 1″ stucco on outside; 7/16″ Masonite on inside of studs .	. ..	..	....	....	....	....	"	38	00016
Wood studs, 2″ × 6″; ½″ plaster board, 1″ stucco on outside; mineral wool fill between studs.......	.. .	...	....	....	....	....	"	47	000020

TABLE XXXI — *(Continued)*

COMPOSITION AND SPECIAL PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of *r*
		128	256	512	1024	2048			
		cycles per second							
Wood studs, 2" × 6"; ¾" stucco on outside; 12" air space; ½" plaster board, 2" × 4" wood studs with rock wool fill between; outer and inner walls connected at floor and ceiling	....	.	....	....	....	...	V. O. Knudsen	52	0 0000063
Tile, cinder concrete, 2¾", two layers in contact, ⅝" lime plaster both sides	44 0	..	....	...	62.3**	.	G. Heimburger	46	000025
Tile, cinder concrete, 2" layer and 2¾" layer separated by 2" air space, ⅝" lime plaster both sides	39 8	.	....	.	62.8**		"	47	000020
Tile, etc., as above, with air space filled with granulated cork	...	. .	...	. .	72.3**	. .	"	54	0000040
Tile, cinder concrete, 2" layer and 2¾" layer with ¾" cork board between, ⅝" lime plaster both sides	41 0	...	....	...	61.8**	..	"	46	000025
Tile, cinder concrete, 2" layer and 2¾" layer with ½" quilt material between, ⅝" lime plaster both sides	40 5	...	.	....	65.7**	...	"	49	000013
Wood boards, 2½"; 1/32" building paper, 1" wood boards, 1" lime plaster on outside; 1" wood boards, 1" lime plaster on lath on inside	28.7	....	....	....	77**	....	"	58	0000016
Wood boards, 2½"; 1/32" building paper, 1" wood boards, 1" lime plaster on outside; 1" air space, 1" wood lath 20" o.c., 1/32" building paper, 1" wood boards, 1" lime plaster on lath	29.7	...	....	....	82.3**	....	"	61	00000080
Wood boards, T & G, 2½", ⅝" quilt material, wood studs 30" o.c.	9.0	....	....	....	48.8**	....	"	38	.00016
Wood boards, T & G, 2½", 4½" air space, 1" wood boards, T & G, wood studs 30" o.c.	12 3	...	....	....	61**	....	"	45	.000032

** Average value from 600 to 1200 cycles. See note on page 307.

TABLE XXXI — (*Continued*)

COMPOSITION AND SPECIAL PARTITIONS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db cycles per second 128	256	512	1024	2048	Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
Wood boards, T & G, 2⅓", 4½" air space, ¹⁄₁₆" asphalt paper, 1" air space, 1" wood boards, T & G, wood studs 30" o.c.	12 9		....	...	61.2**	..	G. Heimburger	45	0 000032
Wood boards, T & G, 2⅓", 4½" air space, ⅜" quilt material, ¹¹⁄₁₆" air space, 1" wood boards, T & G, wood studs 30" o.c ..	12 7	..	. ..	.	66.9**	.	"	49	000013
Brick wall, 2⅓", 2" furring strips, Celotex Lath plastered both sides	....		.	57 0††		.	Holtsmark	58	.0000016
Brick wall, 2⅓"; 2" furring strips and Celotex Lath on one side; other side plastered directly on brick ...	. .	.	.	45 0††	.		"	47	000020
Brick wall, 2⅓", 2" furring strips and Celotex Lath, plastered, on one side; other side plastered directly on brick.....	...		..	50 0††	.	.	"	51	.0000080
Brick wall, 2⅓", 2" furring strips and Celotex Lath on both sides, unplastered....	.		..	48 0††		.	"	49	000013
Brick wall, 4", 2" furring strips and Celotex Lath, plastered, on one side; other side plastered directly on brick	. ..	....	....	53 0††	....	..	"	54	0000040
Brick wall, 4", 2" furring strips and Celotex Lath on sides, unplastered..........	....	....	....	48 0††	....	...	"	49	000013
Pressed straw, 3½", plastered both sides	14	....	....	38‖	...	. ..	E. Meyer	39	00013

** Average value from 600 to 1200 cycles. See note on page 307.

†† Average value from 200 to 3400 cycles.

‖ Average value from 100 to 3000 cycles.

Table XXXII
DOUBLE WALLS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of r
		128	256	512	1024	2048			
		cycles per second							
Metal lath, double, on 1½″ channels, ¾″ gypsum plaster; without cross bracing clips; 4″, connected at edges only	18 0			43 6†		.	P. E. Sabine	48	0 000016
Metal lath, etc., as above, with cross bracing clips ..	18 0			34 9†			"	41	000080
Steel studs, ¾″, Rock lath, ½″ gypsum plaster; batten plates between angles 7′ o.c.; 5¾″; connected at edges only	12 0	23 5	33 2	45 2	49 4	38 7	"	44	000040
Steel studs, etc , as above, with batten plates 2′ on centers	12 0	21 3	29 4	34 8	36 3	25 5	"	38	00016
Tile, double hollow gypsum, 3″, 3″ air space, unplastered; 9″; connected at edges only	22 0			37 5†			"	44	000040
Tile, etc., as above, except 2½″ air space and ½″ felt; 9″	22 6			40 4†	.		"	46	000025
Tile, etc., as above, with 1″ plaster; 10″ ..	31 8			42 2†			"	47	000020
Tile, etc., as above, with ½″ Celotex in 2″ air space .	32 0			42 1†			"	47	000020
Tile, double 2″ solid gypsum, unplastered, unbridged, 2″ separation; structurally separated . .	20 4	25 2	34 2	44 5	51 0	62 6	"	48	000016
Tile, etc., as above, except bridged at middle . . .	20 4	21 3	32 7	37 0	45 6	52 0	"	44	000040
Tile, etc., as above, filled with sawdust . .	23 0	21 6	28 1	39 3	47 0	54 0	"	44	000040
Tile, etc., as above, except filled with slag . . .	30 9			42 7†			"	47	000020
Tile, etc., as above, except filled with felt . . .	22 3	...	..	48 5†	...	...	"	51	0000080
Tile, . double 2″ solid gypsum, unplastered, unbridged, 4″ separation; structurally separated...	20 4	28 4	47 4	54 2	59 0	56 8	"	51	000080
Tile, etc., as above, bridged top and bottom.........	20 4	.	....	46 9†	.	....	"	49	000013
Tile, etc., as above, unbridged, inner faces lined with 1″ felt	22.3	...	....	57 3†	....	...	"	57	0000020
Wood studs, 2″ × 4″, staggered, metal lath, ½″ gypsum plaster; 7½″; connected at edges only.	19 8	....	....	39.1†	....	....	"	45	.000040

† Average value from 128 to 2048 cycles.

TABLE XXXII — (*Continued*)
DOUBLE WALLS

Description of Panel (Bold type signifies that the panel has practical merit)	Weight in Lb. per Square Foot	Reduction Factors in db					Authority	Probable Average Value of T.L. in db	Probable Average Value of τ
		128	256	512	1024	2048			
		cycles per second							
Wood studs, etc., as above, except ½″ Celotex replaced metal lath; connected at edges only.	13 0		...	36 6†	.	.	P. E. Sabine	43	0.000050
Wood studs, 2″ × 2″, set on 6″ plate; ½″ gypsum plaster on ½″ Celotex; ½″ Celotex stood loosely between studs; 8″; connected at edges only	12 2			40 0†			"	49	.000013
Brick wall, 8″, 1″ Gunite; 12″ air space; ½″ plaster board on 2″ × 6″ wood studs, ½″ plaster board, 2½″ mineral wool, ¾″ furring strips, 2″ Sprayo-Flake				..			V. O. Knudsen	73	.000000050
Concrete, 8″, 13″ air space, 2″ × 6″ wood studs, two layers ½″ plaster board, two layers Masonite separated by ¾″ wood bats, 1½″ balsam wool		60 4	...	71.7	.	78 5	"	69	00000013
Concrete, 8″, 13″ air space, 2″ × 6″ wood studs, two layers ½″ plaster board, Masonite, 2″ × 4″ wood studs with mineral wool fill between ..	...	61 0	...	72 5	.	81 0	"	71	000000080
Tile, 12″, 1″ Gunite on outside, ¾″ Gunite on inside; 12″ air space; ½″ plaster board on 2″ × 6″ wood studs, ½″ plaster board, 3″ mineral wool, ¾″ furring strips, 1½″ Sprayo-Flake	....	.	....	....	....	....	"	71	.000000080
Wood studs, ½″ plaster board, 6″ fill rock wool between studs, covered with ½″ mesh hardware cloth; 2′ air space; wood studs, tarred paper, chicken wire, 1″ cement plaster; no structural connections	....	53 2	...	60 4	....	63 8	"	58	.0000016
Brick walls, two, 2½″, separated by 2″ air space, both outside surfaces plastered....	....	. .	.. .	47 5††	...	....	Holtsmark	49	000013
Brick walls, etc., as above, with loose Celotex lath in air space	....	.	....	47 5††	....	....	"	49	000013

† Average value from 128 to 2048 cycles. †† Average value from 200 to 3400 cycles.

105. Comments on the Use of the Tables; General Conclusions. The data in the preceding tables should enable the architect to make satisfactory selections of materials and types of structure to meet the practical requirements of sound-insulation in buildings. It should be remembered in making such selections that, although the author has attempted to make the data from all laboratories comparable, there may be errors as large as 2 or 3 db in many instances, and therefore small differences should not be regarded as having much significance.

A consideration of the data suggests the following generalizations concerning the insulative properties of different building materials and partitions:

1. The insulation value of rigid masonry or monolithic partitions increases directly as the logarithm of the weight per square foot of wall section — so that the rate of increase of insulation with increased weight is relatively slow for partitions which are heavier than, say, 30 or 40 pounds per square foot. As a consequence, it is often in the interest of both insulation and economy to substitute two or more light-weight partitions, or specially composed partitions, for heavy masonry partitions. There are many occasions in building practice where this may be done with a gain in insulation, a reduction in the dead load of the building, and at a reduced cost. However, for thin partitions, where the dead load is not a serious problem, dense rigid panels such as plastered brick or solid tile provide a satisfactory means of obtaining a T.L. of about 40 to 45 db.

2. Lime plaster on wood lath and wood studs gives considerably better insulation than an equal thickness of gypsum plaster on wood lath and wood studs. Sabine obtains an advantage of about 9 db for lime plaster as compared with gypsum plaster, and the Bureau of Standards obtains an even greater difference. Wood stud and plaster partitions rate slightly higher than chanel iron and plaster.

3. Wood partitions, with T & G joints, provide more insulation than do masonry partitions of the same weight or thickness. (The development of cracks in wood partitions, however, will greatly reduce their insulation value.)

4. Double partitions seem to offer the most feasible means of obtaining high insulation at reasonable cost and reasonable dead load. The separate partitions should be as completely insulated from each other as is possible, as the introduction of structural ties between the separate partitions tends to convert the two partitions into a single rigid partition and thus greatly reduces the insulation. The suspension of a blanket or fibre board between double partitions or between

the wood studs or channel irons in staggered stud partitions is often an aid to insulation. The addition of any absorptive material in the air space between double partitions contributes considerably to sound-insulation unless the absorptive material makes a rigid or semi-rigid *bridge* between the two partitions, in which case it may be worse than nothing. Thus, the addition of cinders, pumice, or other rigid-porous materials between structurally separated partitions will sometimes reduce the over-all insulation.

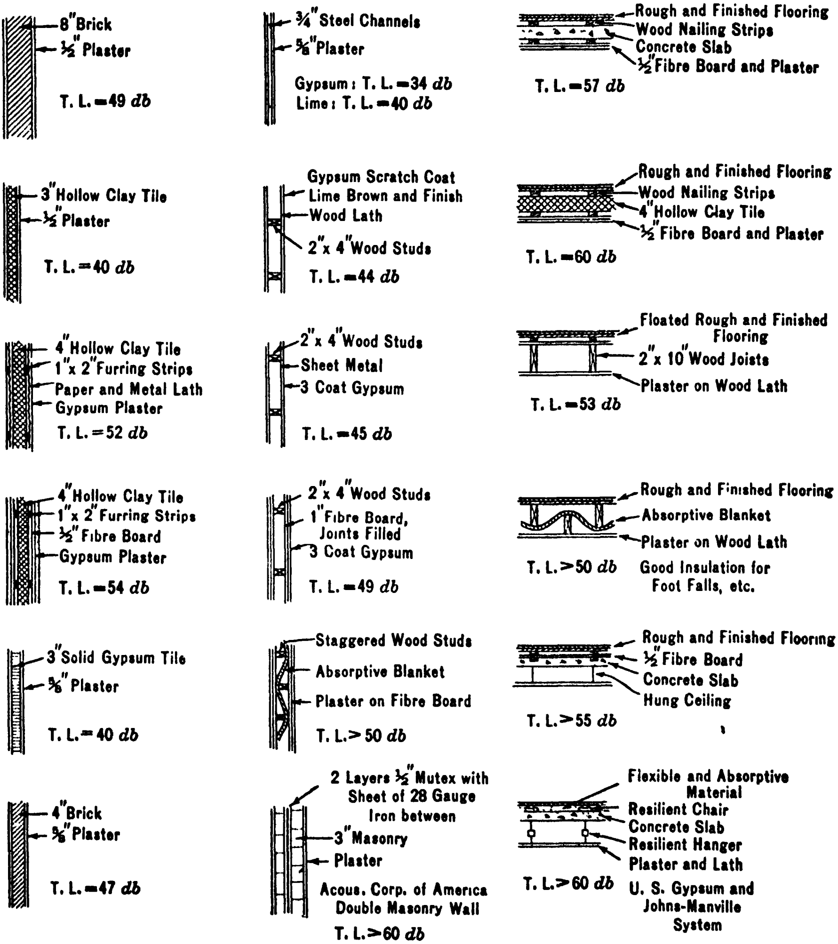

FIG. 140. Plan and sectional sketches of wall, floor, and ceiling partitions having a high degree of sound-insulation.

Many other characteristics of sound-insulation, and many practical suggestions for the selection of sound-insulating partitions, will be revealed from a study of the data given in the preceding tables. The reader should make a careful study of these tables, as frequent reference will be made to them in working out practical problems in sound-insulation.

In selecting a partition which will supply a specified amount of insulation, regard must be given not only to the insulative value of the partition but also to its structural value, its adaptability to the building, and its cost. As mentioned in Sec. 103, the names or descriptions of those partitions which, in the author's opinion, seem best adapted for building purposes have been designated with bold type.

A number of satisfactory types of construction for obtaining wall partitions having a T.L. greater than 40 db and floor and ceiling partitions having a T.L. greater than 50 db are indicated in Fig. 140. These methods of construction will meet most of the requirements for sound-insulation which will arise in connection with the design of buildings. The average T.L. is given for each partition.

CHAPTER XIII

THE INSULATION OF SOUND — CALCULATION IN BUILDINGS

106. Calculation of Insulation in Different Building Structures. By means of the average coefficients of transmission for different materials and types of partition, such as are given in the last column of the tables in the preceding chapter, it is possible to calculate the effective or overall insulation provided by the enclosing walls and ceiling of any room. Or, conversely, if a specified amount of insulation be required for a particular room or building, it is possible to determine the type of walls, ceiling, windows, and doors that will provide the required amount of sound-insulation. In making calculations of this nature, it is most convenient to determine the ratio of the intensity of the noise outside the room to the intensity of the noise which is transmitted into the room, and then this can be easily converted into the effective reduction in decibels. If I_1 be the intensity of the sound or noise outside the room,[1] and if I_2 be the intensity of the sound or noise which is transmitted into the room, then the ratio I_1/I_2 gives the number of times the intensity of the sound is reduced by means of the surrounding walls, floor, and ceiling of the room. The ratio I_1/I_2 can be calculated for a room by means of a simple application of Eq. (48). Rewriting Eq. (48),

$$I_2 = \frac{\tau A I_1}{a_2}, \tag{55}$$

which states that I_2, the intensity of the noise transmitted into the room, is equal to the rate of flow of sound into the room divided by the total absorption in the room. This equation applies to the case where sound is transmitted into the room only through the panel of area A. In general, all the boundaries of a room will allow sound to be transmitted into the room, so that the numerator of Eq. (55) should be replaced by $(\tau_1 A_1 + \tau_2 A_2 + \tau_3 A_3 + \cdots)I_1$ which gives the rate of flow of sound into the room through all the boundaries. Then Eq. (55) may be written in the form,

$$\frac{I_1}{I_2} = \frac{a}{\tau_1 A_1 + \tau_2 A_2 + \tau_3 A_3 + \cdots}, \tag{56}$$

---

[1] It is assumed in the following consideration that noise of this intensity surrounds all the boundaries of the room. When the *outside* intensity is different for different parts of the boundary, as is often the case, appropriate allowances must be made.

where τ_1, τ_2, and τ_3 are the coefficients of transmission of the different parts of the boundaries of the room, A_1, A_2, and A_3 are the corresponding areas, and a, written without the subscript, is the total absorption in the room. The total quantity in the denominator of Eq. (56), namely $\tau_1 A_1 + \tau_2 A_2 + \tau_3 A_3 + \cdots$, which will be designated by T, is the total **transmittance** for the boundaries of the room. Thus,

$$\frac{I_1}{I_2} = \frac{a}{T}; \tag{57}$$

and the effective insulation against outside noise, that is, the over-all reduction of the noise in decibels, is $10 \log_{10} I_1/I_2$, or $10 \log_{10} a/T$. This quantity will be called the **noise-reduction factor** for the room. Thus,

$$\text{Noise-Reduction Factor} = 10 \log_{10} \frac{a}{T}. \tag{58}$$

It gives the difference, in decibels, between the level of noise outside of a room and the level which that noise will attain inside the room. Eq. (57) or (58) shows quantitatively the amount of reduction owing to the insulative properties of the boundaries, and the amount owing to the absorptive material in the room. In problems of design, this often is a matter of considerable importance, since it will reveal whether it is better to increase the noise-reduction factor of a room by altering the structure or by adding absorption.

In order to illustrate the use of Eq. (58), a typical calculation will be made for determining the noise-reduction factor of a small lecture room.

Volume of room = 50,000 cubic feet.

Total absorption in room, including audience = 2400 sabines.

DESCRIPTION OF WALLS, CEILING, WINDOWS, AND DOORS; AND THE TRANSMITTANCE THROUGH THESE SURFACES

Material	Area, A, in Square Feet	τ	τA
4″ concrete slab ceiling plus ½″ acoustical plaster	2500	0.000025	0.0625
8″ brick walls plus ½″ acoustical plaster	4500	.0000080	.0360
$\frac{3}{16}$″ glass windows, closed	400	.00110	.440
1¾″ hardwood doors, good closure	100	.00031	.031
Total transmittance (T)			0.5695

Therefore $$\frac{a}{T} = \frac{I_1}{I_2} = \frac{2400}{0.5695} = 4210,$$

and $$10 \log_{10} \frac{I_1}{I_2} = 36.2 \text{ db.}$$

That is, the noise-reduction factor, or the effective insulation which the room provides against outside noise, is 36.2 db. Thus, if the lecture hall be located where the outside noise is at a level of 50 db, the level of the noise which reaches the lecture hall will be 50 − 36.2, or 13.8 db. This amount of noise is no louder than the unavoidable noise which is incidental to an audience, and will not produce a serious interference with speech or music. However, if the outside noise be at a level considerably higher than 50 db, the amount of noise transmitted into the room may be loud enough to constitute an annoyance, or even interfere with the hearing of speech or music.

The calculation of the transmittance of sound through the windows of the lecture hall indicates that the windows transmit more noise than any or all other portions of the boundaries. Thus, the total transmittance for the windows is 0.44, whereas the total transmission for the entire room is only 0.569. It is obvious therefore that but little would be gained by increasing the insulation value of the walls so long as the windows form a part of the walls. On the other hand, if the windows could be eliminated, so that all the walls would be 8-inch brick, it would be possible to reduce the total transmittance to 0.133, and the noise-reduction factor for the room would then be 42.6 db; that is, the gain in insulation would be 6.4 db.

In the design of buildings, it is advisable to determine first the probable amount of noise which will prevail in the immediate vicinity of the building. Then it is necessary to determine the amount of noise which can be tolerated inside the building. The difference between this amount and the amount of outside noise represents the insulation which should be provided by the boundaries of the room. The amount of noise existing in the neighborhood of the proposed site for a building can be determined approximately from existing data on noise surveys, or more accurately by making measurements of the noise in the vicinity of the site, such as were described in Chap. IX. The measurement of these outside noises should be confined to those noises which are likely to be persistent, such as traffic noise in a metropolitan neighborhood, or the noise of conversation or music in adjacent rooms. The building or room should then be designed to reduce this amount of persistent noise or sound to a level which can be tolerated in the room or building.

107. Noise Levels Which Can Be Tolerated Readily in Different Buildings. In nearly all public buildings a noise of 15 to 25 db will not be noticed because there are nearly always present internal noises of about that magnitude. In the following table there are listed the approximate magnitudes of noises which will be accepted without complaint in different types of rooms and buildings:

	db
Studios for the recording of sound, as talking-picture studios	6 to 8
Radio broadcasting studios	8 to 10
Hospitals	8 to 12
Music studios	10 to 15
Apartments, hotels and homes	10 to 20
Theatres, churches, auditoriums, classrooms, and libraries	12 to 24
Talking-picture theatres	15 to 25
Private offices	20 to 30
Public offices, banking rooms, et cetera	25 to 40

Special conditions or circumstances may alter these requirements or toleration limits, but for most purposes of design the limits given in the preceding table will be found to be highly satisfactory. In fact, there are but few existing buildings which are as quiet as is recommended in this table. The values given in the table therefore represent what the average man would regard as ideal. In order to illustrate the use of the data in this table, suppose it is desired to provide an adequate amount of insulation between the adjacent rooms in a hotel. The normal, expected level of conversation or noise in a hotel room is of the order of 60 to 65 db. The noise-reduction factor between adjacent rooms should therefore be about 45 to 50 db. In general, this will require that the windows in adjacent rooms be closed, or that special window mufflers be designed, otherwise the insulation between the two rooms may be limited to about 25 or 30 db irrespective of how good the insulation may be in the walls and ceiling. However, with closed windows and artificial ventilation it would be possible to select fairly standard types of construction which would give the desired amount of insulation, namely 45 to 50 db. It also would be necessary to use a double or special door if the two rooms are to be connected by a door.

By utilizing the simple method of calculation set forth in this chapter, and the data in Chaps. VIII and XII, the architect or engineer will be able to solve most of the problems which arise in connection with the insulation of sound in buildings. A number of examples, illustrating the practical application of these data and principles to the design of buildings, will be considered in Part III of this book.

CHAPTER XIV

THE AMPLIFICATION OF SOUND

108. Introductory. Measurements of the speech power of speakers in auditoriums and theatres indicate that one of the most serious limitations to good hearing in auditoriums is a consequence of the inadequate loudness of the average speaker's voice. If a room have a volume of 200,000 to 400,000 cubic feet, the average level of speech of the average speaker will not be more than about 50 db, whereas the level for the optimal hearing of speech is about 70 db. It is obvious therefore that there is dire need for some means of amplifying speech, especially in large auditoriums.

The type of auditorium which suffers most from this inadequate loudness of speech is of course the large open-air theatre, where there are relatively few surfaces for reflecting and reenforcing the sound generated by a speaker. If a person speaks out in the open with no reflecting surfaces around him, and with an absorptive covering on the ground, such as would be supplied by an audience, the intensity of the sound dies away almost inversely as the square of the distance away from the source. If a large plane reflecting surface be placed directly behind such a source of sound in the open the effect is nearly to double the intensity of the source of sound for listeners who are in front of the reflecting surface. This, however, does not double the sound level or loudness of the sound reaching the auditors, since the sound level increases approximately with the logarithm of the intensity. It will be recalled that a doubling of the intensity of the sound source increases the sound level only about 3 db. That is, if the intensity of a speaker's voice is at a level of 45 db without a reflecting surface behind the speaker, the addition of the reflecting surface will increase the level to about 48 db. Although this small increase of only 3 db may not seem to be of much value, it is sufficient to be a real aid to hearing when the sound level is as low as 45 db. By providing additional reflecting surfaces above and on both sides of the speaker, as is accomplished by the enclosed auditorium, the intensity of the sound reaching the auditors is somewhat further augmented, but even in completely enclosed auditoriums, larger than about 100,000 cubic feet, the loudness of the average speaker's voice is inadequate for ideal audition. In most auditoriums, it is probable that the average level of the sound reaching auditors not too near the source is as much as

8 or 10 db above the level which they would receive if they were listening to the same source of sound in the open. In respect to the loudness of sound, therefore, the enclosed auditorium has a distinct advantage over the open-air theatre, but the advantage is not sufficient to relieve the enclosed auditorium from the necessity of the amplification of sound. This fact should be clearly recognized in the design of all large auditoriums. The architect should be familiar therefore with the general principles underlying the amplification of sound.

One of the most common and satisfactory methods for amplifying sound is by means of a microphone, a vacuum-tube amplifier, and a loud speaker.

109. The Audio-Frequency Amplifier — Public Address Systems. An audio-frequency amplifier of the type used in every modern radio receiver, with a suitable microphone in the input and a suitable loud speaker in the output, are the essential elements of the so-called *public address system*, which is commonly used for the amplification of sound in large auditoriums. The sound waves impinge upon the diaphragm of the microphone, where they are converted from mechanical to electrical vibrations. The electrical vibrations are then amplified by the vacuum-tube amplifier, so that the electrical energy which is delivered to the loud speaker may be one hundred thousand or more times greater than the electrical energy generated by the microphone. The loud speaker then converts these amplified electrical vibrations into acoustical vibrations of a corresponding frequency. In general, the reproduced sound will be considerably louder than the original.

In order that the amplified and reproduced sound give an illusion of reality, the amplifying equipment must be free from distortion; it must be free from distracting or annoying noises; and it must reproduce the sound at a loudness level which is adequate for distinct and comfortable hearing — and at a level which is comparable with the loudness of sounds which we customarily hear. If the equipment possess these specified characteristics, the sound which is impressed upon the microphone will be reproduced by the loud speaker with a fidelity that will make it indistinguishable from the original sound. Unfortunately, the existing commercial equipment does not adequately possess these characteristics.

There are two types of distortion that are inherent in all commercial forms of amplifiers: the first is called **frequency distortion**, and results from the non-uniform amplification of all the frequency components which comprise the original sound; the second is called **non-linear distortion**, and results usually from overloading the electrical or acoustical elements of the circuit. The first type of distortion is most likely to occur in the loud speaker. The curve in Fig. 141 shows the response at different frequencies of one of the best of commercial loud speakers. The ideal loud speaker would exhibit a perfectly flat curve, instead of the irregular curve shown in Fig. 141. However, the loud speaker which has a characteristic like that shown in the figure gives fairly satisfactory quality, and it represents a vast improvement over the quality of loud speakers of only a few years ago which could reproduce only frequencies between about 300 and 2000 cycles, and which gave practically no response whatever to frequencies outside of this limited range. The second or non-linear type of distortion results whenever the acoustical output of the loud speaker is not directly proportional to the acoustical input to the microphone, in which case certain frequency components are introduced in the reproduced sound which were not present in the original sound. This type of distortion, which may be caused by the *non-linear* response of the microphone, vacuum tubes, transformers or loud speaker, becomes troublesome when the equipment is overloaded, which is most likely to occur in inexpensive equipment of low power rating.

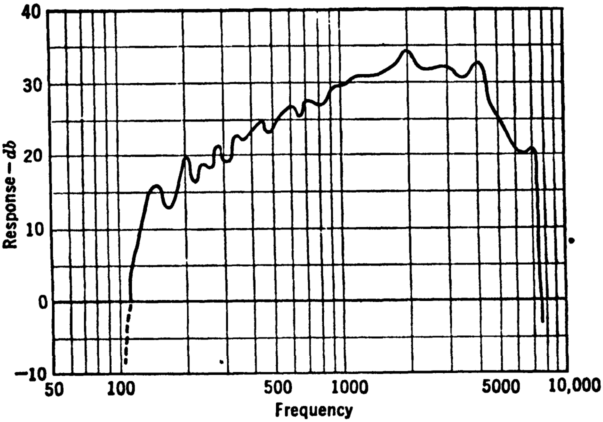

Fig. 141. Frequency response curve of a high-grade loud speaker.

A certain amount of noise is always present in amplifying equipment; there is residual noise in the room which is picked up by the microphone and amplified; and there is always a surface noise produced by the motion and mechanical vibration of the microphone, especially in the commonly used carbon button type of microphone. In addition, the vacuum tubes and their associated apparatus develop and pick up parasitic audio-frequency currents which produce the characteristic hissing, cracking, and booming sounds known to every radio owner. All these extraneous noises, which are inherent in every public address system, produce a masking effect upon the reproduced sound which is not only detrimental to good hearing but is often very annoying to the listeners. Owing to the unavoidable noise inherent in all amplifying equipment, it is necessary to amplify speech or music to a level well above the level of the noise; and it frequently happens that this level is somewhat too loud to be agreeable or natural to a person with normal hearing acuity.

In addition to distortion and noise, public address systems suffer from another defect which impairs the naturalness of reproduced sound. Ordinarily we listen to sound coming directly from its source to our two ears. A microphone responds to sound like a single ear, and monaural hearing is almost void of the power to localize or focus upon sounds; that is, a *monaural* microphone is unable to give depth or *perspective* to sounds which may originate at diverse positions in a room. In order to obtain a true *perspective* of reproduced sound, that is, to produce the effect of true binaural hearing, it would be necessary to use two microphones spaced apart like the ears, an amplifier for each microphone, and two head receivers for each listener — one for the right ear connected to the " right " microphone and amplifier, and one for the left ear connected to the " left " microphone and amplifier. Such elaborate equipment would seem to be prohibitively complicated and expensive for practical purposes, although it would contribute very appreciably to the naturalness and high quality of the reproduced sound.

Finally, the public address system possesses another inherent difficulty because the loud speaker must be located several — usually 25 or more — feet away from the microphone. This is necessary to prevent *feed back* or *howling* of the amplifying system. The sound may therefore seem to come from the loud speaker instead of from the actual source, thus detracting from the realism of the original sound. But in spite of these shortcomings inherent in public address systems they constitute a most important aid to good hearing in very large auditoriums.

In the following section there will be described a typical public address system which has been used very successfully for amplifying sound in auditoriums and in open-air gatherings.

110. The Western Electric Company's Public Address System.[1] The size and type of public address system required in any auditorium will depend upon the size and nature of the auditorium. The equipment which will be described in this section is suitable for auditoriums of moderate size, namely for auditoriums having volumes smaller than about 200,000 cubic feet. Larger auditoriums, and open-air installations, will generally require larger and specially designed equipment.

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[1] See Bulletin No. 423, "Information on New Apparatus Units for Program Pick-up and Public Address Systems," American Telephone and Telegraph Company.

It is advisable in all such cases to consult with the manufacturer's engineers with regard to the particular type of equipment required.

The principal parts of a typical Western Electric Company's Public Address System consist of the following: (1) transmitter, either of the carbon double button or condenser type; (2) transmitter filter; (3) transmitter mounting; (4) transmitter amplifier, in case it is of the condenser type; (5) mixing panel; (6) vacuum-tube voltage and power amplifiers; (7) volume indicator and gain control; and (8) loud speaker.

The transmitter is usually of the carbon double button, push-pull type, although some of the better installations now employ the condenser type of microphone.[2] The No. 387 double button transmitter has a fairly uniform transmission characteristic between 60 and 7000 cycles, the maximal variation amounting to about plus or minus 4 db. This transmitter is considered satisfactory for either distant or close pick-up purposes, although in very quiet rooms the noise produced by the carbon contacts may be objectionable. In the average auditorium there will be an amount of unavoidable noise sufficient to mask the noise produced by the carbon buttons, and therefore in most installations this noise will not be objectionable. The condenser microphone is more quiet, has a better transmission characteristic, and is much less likely to get out of order than the carbon type. The No. 394 condenser transmitter has an air-tight seal on the back of it, and the space between the

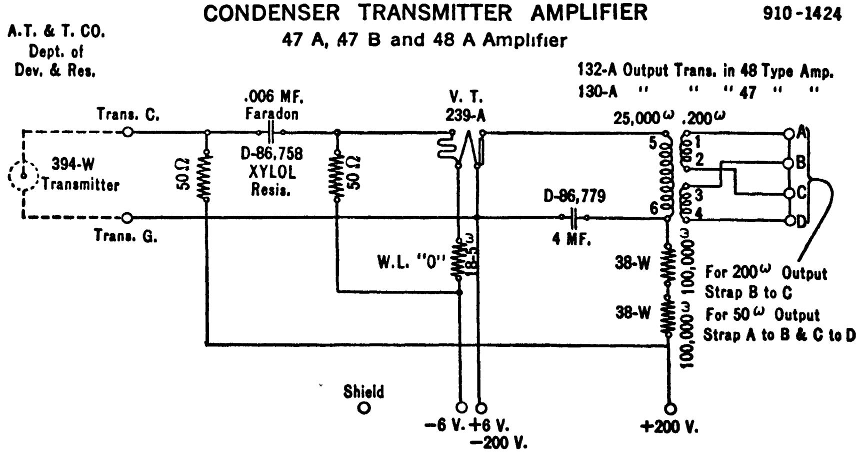

FIG. 142. Amplifier unit associated with 394-W condenser transmitter.

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[2] It is not improbable that the condenser type of microphone will soon be replaced by the electrodynamic type. (See Sec. 13.)

plates is filled with an inert gas. The nature of this seal, and the enclosed gas, require that the transmitter be used under pressure and temperature conditions corresponding to elevations between sea level and 3000 feet above sea level, and temperatures between 25 and 75 degrees Fahrenheit. Higher temperatures or lower pressures may damage the diaphragm or the protective rubber bellows. The condenser transmitter is not so sensitive as the carbon double button type, and thus requires an auxiliary transmitter amplifier. The condenser transmitter has remarkably good transmission characteristics — the over-all gain not varying more than plus or minus 3 db for frequencies between 40 and 7000 cycles. The transmitter requires a direct-current polarizing potential of about 200 volts. It is also necessary that the transmitter amplifier be connected with short wires to the transmitter, otherwise the capacitance of the connecting leads will greatly reduce the efficiency of the transmitter. The transmitter amplifier, usually a single-stage unit, is mounted integrally with the transmitter and is completely shielded by a metallic covering. In addition, all leads from the transmitter amplifier to the mixing panel and voltage amplifier are carefully shielded. The 47-A amplifier, which is usually used with the No.

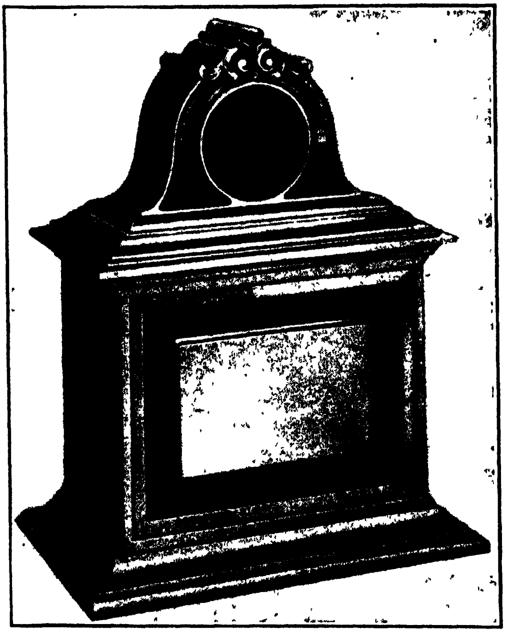
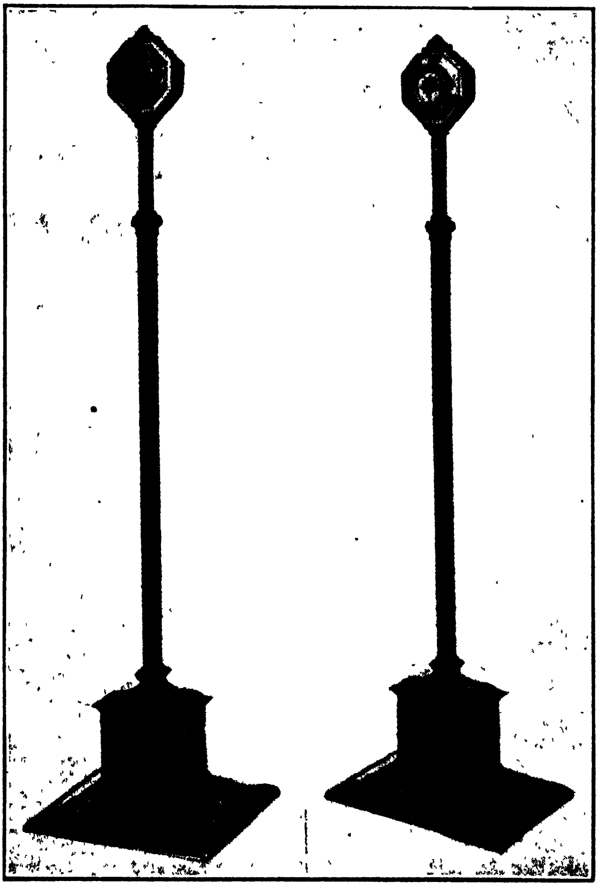


FIG. 143. Transmitter mounting for pulpit. (Front view.)

394 condenser transmitter, is shown in Fig. 142. The condenser transmitter together with its associated 47-A amplifier is about 4 inches in diameter, slightly more than 1 foot long, and weighs about 14 pounds. Fig. 143 shows a suitable mounting for the transmitter when it is to be used on a pulpit, and Fig. 144 shows a suitable mounting for more common use. Many other types of mountings and suspensions are used under different conditions.



Front Back

Fig. 144. Transmitter mounting for general use.

A mixing panel (Fig. 145) is used when two or more microphones are required to pick up a program, as for example when one microphone is used to record the singing of a chorus and another microphone is used to record the singing of a soloist. An operator at the mixing panel then combines the sound picked up by the two microphones in such proportion as will give the best effect.

The sound picked up by either one or more of the carbon or condenser transmitters, and *mixed* in the proper proportions at the mixing panel, is then amplified by means of a suitable amplifier, such as the 32-A type which is commonly associated with the 4-A public address system. A photograph of this amplifier mounted in a suitable cabinet is shown in Fig. 146. This amplifier consists of three stages of 231-D vacuum tubes followed by a power stage with a 205-D vacuum tube. The plate circuits of all tubes in this amplifier are supplied from a self-contained vacuum-tube rectifier, and the same rectifier supplies the filament current for the 205-D tube. The filaments of the three 231-D tubes require a 12-volt battery, usually of the lead storage type, although ten No. 6 dry cells will suffice for about 100 hours' service. This amplifier has a

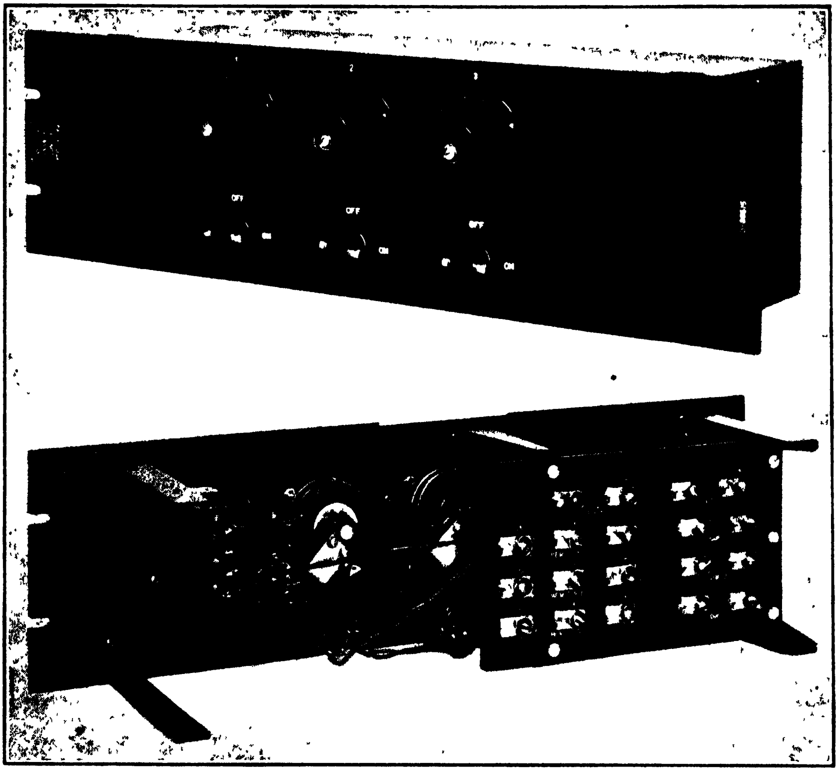


FIG. 145. Mixing panel for Western Electric Company's Public Address System. (Above — front view. Below — rear view, cover removed.)

gain of approximately 79 db, and the gain can be regulated in steps of 3 db throughout a range of 66 db. The amplifier has a good transmission characteristic between 50 and 5000 cycles, and will provide sufficient energy to operate one or even two 555 loud speakers, and these speakers will supply sufficient sound energy for all practical purposes in auditoriums not larger than about 200,000 cubic feet. The 555 receiver is of the electrodynamic type, and is used in conjunction with a large horn, such as is shown in Fig. 147. The horn shown in this figure has over-all dimensions of about 45 inches in width by 63 inches in height by 45 inches

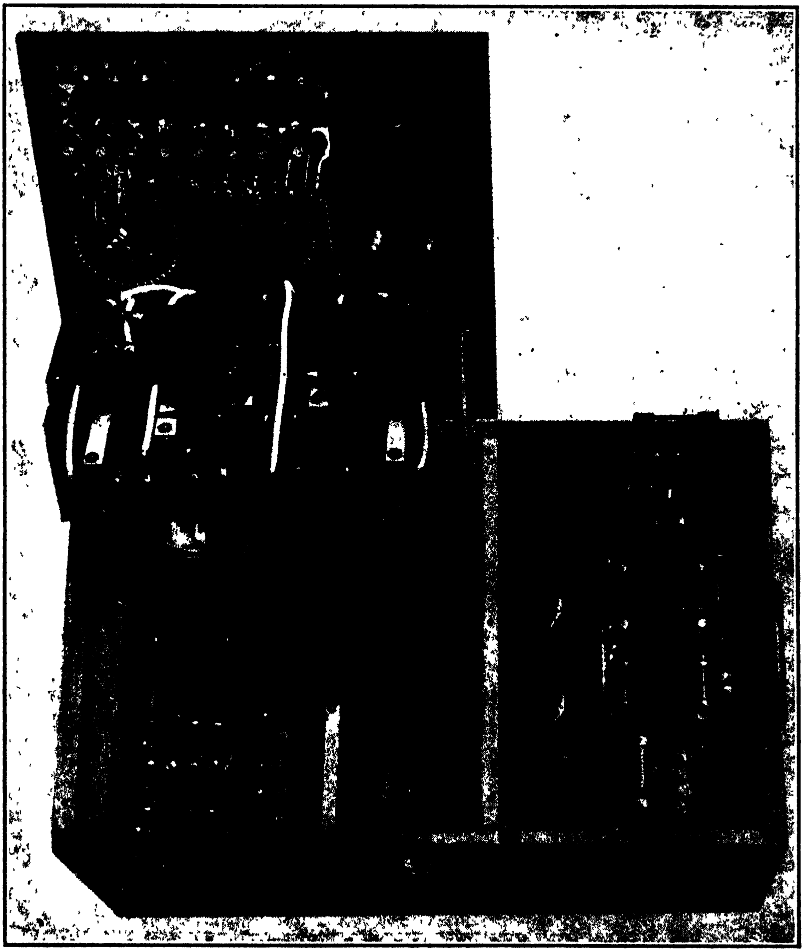


Fig. 146. Amplifier for Western Electric Company's 4-A Public Address System. (Inside view.)

in depth. The weight is approximately 165 pounds. Other horns of this type may employ two or more 555 receivers, thus radiating two or more times as much energy as a single one. Such large horns as these will reproduce satisfactorily the frequency range between about 100 and 6000 cycles. Smaller horns, as a rule, fail to reproduce frequencies in the lower-pitch range, and for this reason are not so satisfactory as the large horns. These large horns require special housing facilities in auditoriums, so that it often becomes necessary to make provision for them during the design or construction of auditoriums.

The horns have directional effects, that is, they tend to concentrate the sound, especially the high frequencies, along the axis of the horn. (See Figs. 242 and 243.) It is often necessary, therefore, in wide or large auditoriums, to use two or more horns, directed in such a manner as will give a fairly uniform distribution of sound in all parts of the auditorium. It is generally advisable to set aside a conveniently located small room which will house the amplifiers, mixing panel, and power supply. This room should have a floor space of about 8 feet by 10 feet for the equipment required in large auditoriums. The location of the horn or horns is an important matter which should be worked out in cooperation with an acoustical engineer. Reliable engineers are usually available through the manufacturer of the public address system. In general, the horns should be located so as to satisfy the following conditions: (1) supply

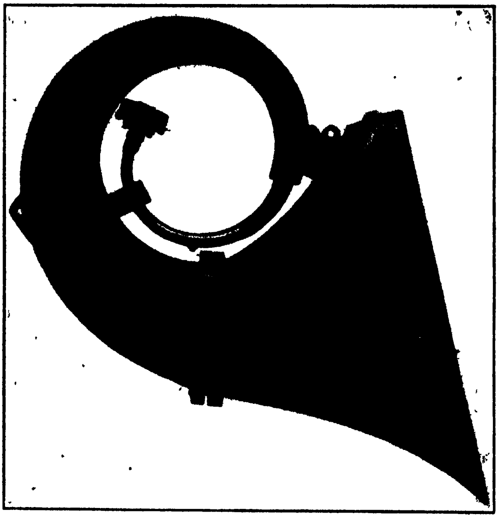


FIG. 147. Western Electric Company's 555 loud speaker and 12-A horn for 4-A Public Address System. (Side view.)

a nearly uniform and an adequate flow of sound energy to all auditors in the room; and (2) be near enough the speaker to give the illusion that the sound comes from the speaker, and yet be far enough away from the microphone to prevent regeneration or " howling " of the system. It is often possible to locate the horns so that they will correct or at least mitigate echoes or interfering reflections. Finally, the horns should be concealed, or artistically built into the decorations or appointments for the room.

111. Amplifiers for the Hard of Hearing. When an auditorium is wired for a public address system, it is advisable to provide a number of seats (about 2 or 3 per cent of the total number) with *hard-of-hearing* sets. These consist of telephone receivers, with suitable rheostats or volume controls, connected with the amplifier and microphone of the public address system. These sets are now used in many churches, but they are equally serviceable to the hard of hearing in lecture halls, civic auditoriums, and even many theatres.

FIG. 148. Section of seats in auditorium wired for deaf sets. Note the convenient location of the jack under the arm of the chair.

Even auditoriums which do not require a public address system are often equipped, and many others should be equipped, with special amplifiers for the hard of hearing. Fig. 148 illustrates a type of installation which has proved very satisfactory. A microphone located near the pulpit or the stage is connected with an amplifier. The output from the amplifier is distributed to a number of jacks which are located on the seats (as shown under the left arm of the seat in the figure). The persons with defective hearing are provided with telephone sets which they plug into the jacks. Each telephone set has a potentiometer which the listener holds in his hand, and by means of which he adjusts the loudness of the sound to his individual requirements. All persons having conductive deafness (and about one half of all the hard of hearing are in this class) and about one half of all persons having perceptive or nerve deafness will be able to hear very well with these deaf sets. It would be a very substantial accommodation to at least 3 per cent of the entire population — and probably 5 to 10 per cent of the adult population — if all large lecture halls and public auditoriums were equipped with suitable deaf sets. A small amplifier will supply sufficient energy for as many as thirty sets.

CHAPTER XV

ACOUSTICS OF AUDITORIUMS — GENERAL CONSIDERATIONS

112. Introductory. The preceding chapters have been concerned with those fundamental principles of sound which affect its control in buildings. In this and the following three chapters those fundamental principles will be used for the development of a working theory for determining the acoustical design of architectural interiors. This working theory should be developed in such a manner as will enable the architect to give to each room which he designs — whatever be its purpose — that rare utility and charm of perfect acoustical quality.

The theory should enable the architect not only to determine the particular design which will give to each and every room the best possible acoustical quality, but also to determine for every room, whether completed or on the drafting board, a quantitative rating which will uniquely represent the acoustical quality of that room. Obviously, both the principles of design and the methods of rating will be different for speech rooms from those for music rooms, although there are certain features that apply to both speech and music rooms.

In the design of rooms which are intended for speaking purposes the prime object is the realization of the conditions which will (1) promote **intelligibility**[1] and (2) preserve naturalness. Of greatest moment is the **intelligibility of speech** — a phrase which is used to signify how accurately and easily the separate and articulated sounds of speech are recognized. But good acoustics, even in speech rooms, requires more than good *intelligibility*. In the theatre, for example, the art of expression, to reach the highest level of esthetic perfection, demands that the naturalness and artistic beauty of speech be not only preserved but enhanced, so that the speech will " fall gently and sweetly " upon the ears of the audience. It will be shown presently that it is feasible to develop a working theory for rating the intelligibility of speech rooms. On the other hand, it is not simple to formulate a theory for rating the naturalness and artistic beauty of speech. However, if the room be designed in such a manner as to give the best possible intelligibility for speech, and if the room be free from all types of distortion, naturalness will be

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[1] This word, as used, is borrowed from telephone engineers.

preserved, and the artistic beauty of the speech at least will be unimpaired by the acoustical properties of the room.

113. Rating of Speech Rooms. It is a relatively simple matter to devise a method for making a quantitative rating of an auditorium that is intended for speaking purposes. The primary concern is how well we can hear the average speaker in the room. The method which telephone engineers have devised[2] for measuring the intelligibility of telephone, radio, and talking-picture equipment is also a very satisfactory method for measuring the intelligibility of auditoriums. In the telephone tests one person calls out lists of meaningless speech sounds into the transmitter, and another person listening at the receiver writes down, as accurately as possible, what he hears. By comparing the recorded lists with the called lists, a quantitative rating can be given to the intelligibility of the system. Such a test is called an **articulation test.** The **percentage articulation** signifies the percentage of typical speech sounds which are heard correctly. Thus, if a speaker calls out 1000 meaningless speech sounds into the transmitting end of the circuit, and an observer at the receiving end hears 750 of these speech sounds correctly, the *articulation* is rated at 75 per cent. When these tests are used for rating the acoustical merit of an auditorium, one person, located in the normal position for the speaker, calls out meaningless speech sounds, and several observers stationed in representative positions throughout the auditorium write down what they hear. The **percentage articulation of an auditorium** signifies the percentage of typical speech sounds which can be heard correctly by an average listener in the auditorium. The speech sounds, which are representative of all the vowels and consonants used in the English language, are made up of consonant-vowel, vowel-consonant, and consonant-vowel-consonant combinations, the separate sounds occurring on the average with about the same frequency that they occur in normal speech. The monosyllabic speech sounds are called out in groups of three at the rate of three syllables in one and one half to two seconds. Each group of three syllables is preceded by an announcement so that the effect of reverberation will be imposed upon the speech sounds. If, on the average, the listeners in the auditorium hear correctly four fifths of the total number of the called speech sounds, the articulation for the auditorium is rated at 80 per cent. These articulation tests thus afford a highly satisfactory means for rating the acoustical quality of an auditorium which is to be used primarily for speaking. A large series of tests seems to warrant the following conclusions: (1) If the articulation be 85 per cent or more, the hearing condition will be

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[2] H. Fletcher and J. C. Steinberg, "Articulation Testing Methods," Bell Syst. Tech. Jour. (October, 1929); also Jour. Acous. Soc. (Supplement to January, 1930).

very good. (2) If the articulation be 75 per cent, the hearing condition will be satisfactory, but attentive listening is required. (3) If the articulation be 65 per cent, the hearing condition is just barely acceptable, but the listening is very fatiguing. (4) If the articulation be less than 65 per cent, the hearing condition is unsatisfactory.

Fig. 149 shows a typical articulation list, such as has been used in determining the percentage articulation in many auditoriums. The speech sounds are all written in a phonetic alphabet, so that each symbol represents only one sound. The monosyllabic test syllables which are to be called out are written in the first column, and the key words which give the proper pronunciation of the test words are given in the second column, so that there is less likelihood of error in pronouncing

ARTICULATION TEST LIST — No. 19

No.	Test Syllable	Key Word	No.	Test Syllable	Key Word
1	za	z + (h)o(t)	26	touch	t + (c)ouch
2	wās	way + s	27	kī	ki(te)
3	chē	chee(se)	28	jod	jud(ge)
4	ăv	(h)ave	29	hib	h + (r)ib
5	mou	mou(se)	30	ug	(f)oo(t) + g
6	nĕp	nep(tune)	31	fou	fow(l)
7	rōk	(b)rok(e)	32	da	do(t)
8	shern	sh + earn	33	äch	ah + ch
9	īch	i(ce) + ch	34	berv	b + (n)erve
10	bov	(a)bove	35	ăb	(h)ab(it)
11	uz	(f)oo(t) + z	36	dāk	day + k
12	kō	co(ke)	37	fa	fa
13	tĕs	tes(t)	38	gäm	g + ah + m
14	thū	th + (s)oo(the)	39	hă	ha(s)
15	oush	ou(t) + sh	40	jouch	j + ouch
16	yig	y(et) + (d)ig	41	ik	(k)ick
17	wĕ	we(t)	42	la	la
18	at	(h)ot	43	zīv	z + (h)ive
19	thong	th + (s)ung	44	băm	bam(boo)
20	shă	sha(ll)	45	rĕn	ren(t)
21	si	si(n)	46	yōs	y + oh + s
22	ōr	ore	47	wong	w + (s)ung
23	pēsh	pea(ch) + sh	48	īt	(r)ight
24	nuf	noo(k) + f	49	thā	they
25	ōm	(h)ome	50	ash	(h)o(t) + sh

Fig. 149. List of meaningless speech sounds for conducting articulation tests in auditoriums.

the speech sounds. Fig. 150 shows a record sheet used by the listener. In the first column are recorded the syllables as heard by the observer. In the second column are recorded the test syllables which were called.

ARTICULATION TEST RECORDING SHEET

Title of Test: Articulation in Millspaugh Auditorium

Condition Tested: Empty, curtain raised; speaker at front, centre stage

List No. 6 Caller F. L. P.

Date 2—22—23 Observer V. O. K.

Syllable Articulation 82 per cent Observer's Seat AA9

No.	Observed	Called	Errors	No.	Observed	Called	Errors
1	gīj	gīj	✓	26	jăsh	jăsh	✓
2	chā	chā	✓	27	dan	don	o-a
3	hīz	hīz	✓	28	dat	da	t+
4	terv	ter	v+	29	tīj	tīj	✓
5	thuv	thuv	✓	30	zōr	zōr	✓
6	yăch	yăch	✓	31	mat	mat	✓
7	op	op	✓	32	yāsh	yāsh	✓
8	ming	ming	✓	33	houd	houd	✓
9	gersh	gersh	✓	34	bĕd	bĕd	✓
10	yăn	yăn	✓	35	houg	houg	✓
11	sert	sert	✓	36	vūs	vūs	✓
12	ris	ris	✓	37	kāng	kĕng	e–a
13	făng	făng	✓	38	vĕl	vĕl	✓
14	gab	gab	✓	39	mal	mal	✓
15	dosh	dosh	✓	40	kuz	kuz	✓
16	lūf	lūth	th–f	41	touf	touth	th–f
17	wer	wer	✓	42	dō	dō	✓
18	ūr	ūr	✓	43	yib	yib	✓
19	rūb	rūb	✓	44	pēs	pēs	✓
20	chom	chom	✓	45	vēt	vēf	f–t
21	păz	păz	✓	46	vōj	wōj	w–v
22	dāf	dāth	th–f	47	hon	hon	✓
23	kēng	kēng	✓	48	wēf	wēf	✓
24	rul	rul	✓	49	wo	wo	✓
25	chīk	chīk	✓	50	fōn	fōn	✓

FIG. 150. Record sheet used by listener in speech articulation tests.

The errors are recorded in the third column. The record sheet thus gives not only the number of errors made by each observer but the nature of the errors as well. Articulation tests of this type give pertinent information regarding the hearing properties of auditoriums. They require, however, that the observers be thoroughly trained in the use of such tests.

A much simpler method of articulation testing has been developed recently by Fletcher and Steinberg[3] which employs only well-known monosyllabic words, and which therefore reduces the training requirements of the observers. The words used in these tests are given in Table XXXIII.

Articulation lists are prepared from these monosyllabic words by writing the vowel list of words on one pack of cards and the consonant list on another pack of cards, and by shuffling each pack separately. The cards are then taken off in groups of three and articulation lists prepared. In the tests each group of three words should be preceded by an announcement, so as to introduce the normal interference of reverberation. Only the errors in vowels are counted in the vowel list, and only the errors in the indicated consonants are counted in the consonant list. With a little experience, assistants who have had no previous training can use these lists to determine the percentage articulation in an auditorium. The assistants should be thoroughly familiar with the words in each list, but these can be learned in about 20 minutes of study.[4] In using these simpler word lists the percentage syllable articulation can be correlated with the standard syllable lists by means of the equation:

$$S = 100\{1 - (1 - V_w C_w^2)^{0.9}\} \qquad (59)$$

S = percentage syllable articulation (for standard lists).
V_w = percentage vowel articulation (for word lists).
C_w = percentage consonant articulation (for word lists).

Thus, suppose the vowel articulation is 97 per cent and the consonant articulation 91 per cent, using the simple word lists. Then the *standard syllable articulation* is $100\{1 - (1 - 0.97 \times 0.91 \times 0.91)^{0.9}\} = 76.8$ per cent. That is, the syllable articulation, referred to the standard syllable tests, would be 81.6 per cent. The average percentage articulation for an auditorium is obtained from the results of listeners stationed in all representative positions in the auditorium, and with the speaker or caller located on the front central portion of the stage or platform. It is desirable to use as many as eight listeners or observers located in the following positions: front centre, front side, middle centre, middle side, rear centre, rear side, balcony centre, and balcony side. If each of the nine persons in the group acts as caller for a complete list of words or

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[3] *Loc. cit.*

[4] The results will be dependable after about four practice trials; i.e., after the beginner has listened to four complete vowel and consonant lists.

Table XXXIII

VOWEL WORD LIST

Sound to be Graded	English Words in the List	
a′	bat	back
ā	bait	bake
e	bet	beck
ē	beat	beak
i	bit	bit
ī	bite	bike
o	but	buck
o′	bought	balk
ō	boat	boat
u	book	book
ū	boot	boot

CONSONANT WORD LIST

Sound to be Graded	English Words in the List	
b	by	by
ch	which	which
d	die	die
f	fie	whiff
g	guy	wig
h	high	high
j		
k	wick	wick
l	lie	will
m	my	whim
n	nigh	win
ng	wing	wing
p	pie	whip
r	wry	wry
s	sigh	sigh
sh	shy	wish
th′	thy	with
th	thigh	thigh
t	tie	wit
v	vie	vie
w	why	why
y		
z	whiz	whiz
st	sty	whist

Note: The *h* following *w* is not pronounced in such words as *whim, whip,* etc.

syllables, the average of all the recorded lists will give a reliable figure of merit for the speech-hearing quality of the auditorium. In addition, the hearing qualities in different parts of the auditorium also are revealed. For example, Fig. 151 shows the percentage articulation in different parts of Millspaugh Auditorium (Los Angeles Junior College), which was tested in this manner, first with an audience of 240 (reverberation time at 512 cycles = 3.9 seconds) and then with an audience of 950 (reverberation time at 512 cycles = 2.1 seconds). The effects of location and the size of the audience upon intelligibility are clearly revealed.

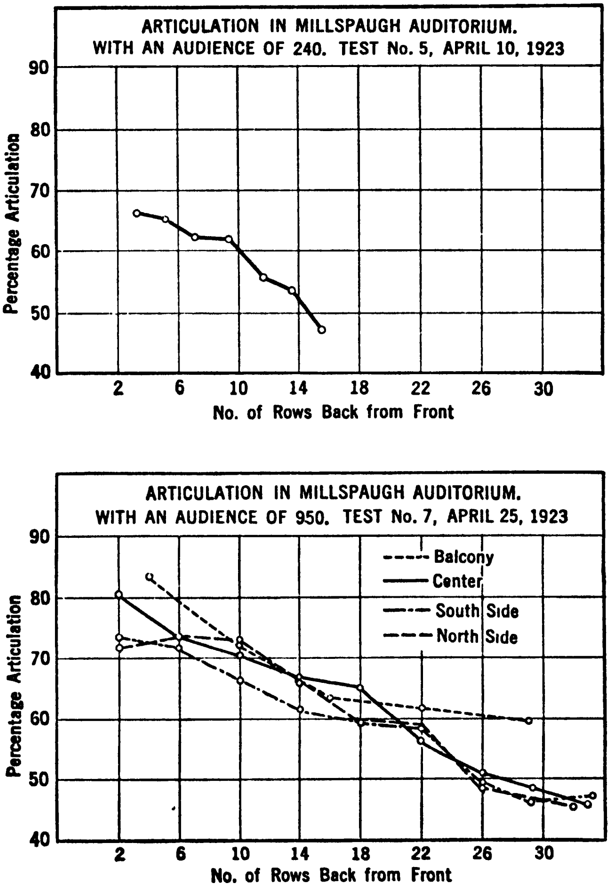

FIG. 151. Percentage articulation in different parts of an auditorium having a seating capacity of 1600.

114. Factors Affecting the Hearing of Speech in Auditoriums. There are four principal factors which affect the hearing of speech in auditoriums; namely, the shape of the room,[5] the loudness of the speech which reaches the listener, the reverberation characteristics of the room, and the amount of noise in the room. The quantitative influence of each of these factors will be considered in some detail. In general, the shape of the room should be designed so that there will be a uniform flow of sound to all listeners; the speech must be loud enough to be heard distinctly in all parts of the auditorium; the reverberation must be reduced so that there will be no detrimental overlapping of the separate sounds of speech; and the noise must be reduced to such a level that it will not mask even the feebler sounds of speech such as the unvoiced consonants. Each of these factors enters into the problem of hearing in auditoriums in such a way as to affect markedly the intelligibility of the speech. Thus, the unamplified speech of the average speaker in large auditoriums is rarely if ever loud enough for optimal hearing conditions; the time of reverberation is always long enough to produce some overlapping of the separate syllables; there is always a certain amount of noise, either avoidable or unavoidable; and no matter what shape an auditorium may have there will be some destructive interference between the direct and reflected sound. It will be the problem of the following sections in this chapter and of the two following chapters to determine the quantitative influence of each of these factors, so that the over-all hearing conditions in any auditorium can be appraised.

Consider first of all the hearing conditions in an ideal space, such as is afforded in the open air away from all possible sources of noise. In such a space, if the speaker be not more than two or three feet away from the listener, the intensity level of the speech at the ears of the listener will be about 70 db, which is the optimal level for distinct and comfortable hearing; there will be utterly no reverberation; there will be no disturbance from noise; and there will be no interfering effect from reflection, the reflected component from the ground uniting almost in phase with the direct sound. Articulation tests conducted in such an ideal space give an articulation of 96 per cent. (See Sec. 130.) It may seem to some that the articulation should be more nearly 100 per cent under these ideal conditions, but a few errors are unavoidable, such as the confusion of *th* (as in *thin*) and *f*, *n*, and *ng*, or possible errors of pronunciation or of perception or even remembering. Tests have shown that an

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[5] It will be assumed later in formulating a quantitative basis for rating speech rooms that such unwarranted defects as echoes, long-delayed reflections, and troublesome concentrations of sound have been eradicated. See Chap. XVI, which considers the problem of shape.

articulation of 96 per cent is actually greater than can be attained in any room, even though the acoustical properties of the room be made as nearly perfect as is possible.

If we consider now the quantitative factors which affect the hearing conditions in a room, it is clear that it is necessary to introduce reduction or distortion factors owing to (1) the shape of the room, (2) inadequate loudness, (3) excessive reverberation,[6] and (4) extraneous noise. Following this suggestion, it is possible to represent the percentage articulation in any room by the equation[7]:

$$\text{Percentage articulation} = 96k_sk_lk_rk_n. \tag{60}$$

k_s = the reduction factor owing to the shape of the room.

k_l = the reduction factor owing to the inadequate loudness of speech.

k_r = the reduction factor owing to the excess of reverberation in the room.

k_n = the reduction factor owing to the extraneous noise in the room.

In the ideal quiet space, each of these factors, k_s, k_l, k_r, and k_n, will be equal to unity, so that the percentage articulation under these conditions would be 96 per cent, that is, the value found by experiment in a quiet open space.

Experimental data have been obtained by means of which it is possible to determine the appropriate values of k_s, k_l, k_r, and k_n for any auditorium. When these factors are determined for a certain auditorium and substituted in Eq. (60), the resulting product gives the probable percentage articulation in that auditorium.

It is admittedly only an approximation to represent these factors by single numbers. For example, the reverberation is described not by a single number but by a curve giving the times of reverberation at different frequencies. However, if one takes the time of reverberation for a tone of 512 cycles, one will have a fairly reliable index for representing the condition of reverberation in a room,[8] and the use of such a single

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[6] Excessive reverberation, as here used, is intended to include any unbalance of reverberation, as an excessive reverberation for the low frequencies even when the reverberation time at 512 cycles is ideal.

[7] This equation applies only to the average speaker. Various speakers differ widely not only in the matter of the loudness of their speaking voices but also in such significant matters as enunciation, pronunciation, and emphasis — factors which affect profoundly the resulting articulation.

[8] There would be exceptions to this rule when the reverberation times at other frequencies showed extreme departures from the optimal reverberation characteristic, but these exceptions are rare if reasonable care has been used in the selection of absorbent materials.

index is very valuable for rating the acoustical quality of auditoriums. In problems of design, on the other hand, consideration should be given to the reverberation throughout the important pitch range, for example, at 128, 512, and 2048 cycles.

Similarly, the shape of the room is a rather involved factor, and cannot be represented rigorously by a single number. However, the matter of shape in the conventional, rectangular auditorium is not a potent factor in determining the articulation, and it therefore is not only admissible to use a single factor to represent the effect of shape on articulation, but the factor k_s in most cases will not deviate appreciably from unity. In more unusual cases, in which the shape departs widely from conventional types, and in rooms which are burdened with echoes, delayed reflections, or focusing effects, the factor k_s may be appreciably less than unity. Although insufficient data are as yet available for making a quantitative evaluation of the factor k_s for auditoriums of different shape, it is possible to determine shapes which will approach very closely the ideal, and which will provide satisfactory solutions to most of the practical problems which arise in connection with the acoustical design of architectural interiors. The problem of the shape of auditoriums in relation to acoustical design is a matter of prime importance and therefore will be considered in the following chapter.

CHAPTER XVI

THE ACOUSTICS OF AUDITORIUMS — SHAPE[1]

115. Fundamental Principles. Before the present century the problem of the acoustics of a room was regarded almost wholly as a problem of the shape, proportions, and size of the room. Many empirical rules and practices had been handed down from past generations, and in nearly all the treatises on architectural acoustics which were written before 1900 the paramount consideration was given to an analytical study of the rays of sound in enclosures. Architectural acoustics was largely an applied branch of geometrical acoustics. As was shown in Chap. I, there were a few students of acoustics before the present century who recognized the importance of reverberation in room acoustics, but the indefatigable work of W. C. Sabine on reverberation, which began in 1895, was so successful in accounting for the acoustics of rooms that it shifted the principal consideration in acoustics from the problem of shape to the problem of materials. As a result, there has developed, especially in the United States, a tendency to regard reverberation as the dominant and almost determining factor in room acoustics, and at the same time to give too little regard to the important aspects of shape and size of auditoriums. As has been stated repeatedly, good acoustical design must be based upon a proper understanding of all the factors which affect the generation, transmission, and hearing of sound. Each of the named factors is important, and the neglect of any one factor may ruin an otherwise ideal design.

In the present chapter, special consideration will be given to the problem of the shape of auditoriums. The problems of noise, loudness, and reverberation will be considered in the following two chapters.

In the design of an auditorium it is not only necessary to avoid shapes which will produce acoustical defects, such as echoes and interfering reflections, but it is of prime importance to design shapes which will facilitate the most advantageous flow of sound energy to all auditors in the room, and at the same time preserve or even enhance the natural beauty of speech and music. Of course, the acoustical requirements of an auditorium do not alone assume such importance as to dictate shape and size,

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[1] The problem of shape in the design of auditoriums is treated very effectively in Bagenal and Wood's "Planning for Good Acoustics," Methuen (1931). See especially Chap. III.

but there are certain fundamental principles and requirements with respect to acoustics which should contribute potently to the determination of the shape and size of an auditorium.

In the first place, it is necessary to recognize those forms which should be avoided. There are two outstanding forms which should never be tolerated: (1) those which will produce a pronounced focusing of sound, thus giving an excessive concentration of sound in some places and a scarcity of sound in other places; and (2) those which will produce excessive delays between the sound which reaches the auditors by a direct path from the source and that which reaches the auditors by reflection from the ceiling or walls. The sound which comes by the reflected paths always has to travel a greater distance than the sound which comes by the direct path, and if the difference in these path lengths is as great as 65 feet the reflected sound will be delayed to the extent that it is heard as a separate sound; that is, the delayed sound produces an echo. (See Sec. 18.) Even when the reflected sound is delayed as much as 50 feet it unites with the direct sound sufficiently out of phase to produce a masking or *blurring* interference. Delayed reflections are most damaging when they are concentrated or focused by means of a concave surface. Figs. 152 and 153 exhibit conspicuous defects both from the standpoint of excessive focusing of sound and also from excessive delays of the reflected sound. Fig. 152 shows the transverse section of an auditorium with a barreled ceiling having a centre of curvature near the level of the floor. In a room of this shape, sound originating at *O* is reflected by the ceiling in such a manner as to be brought to a sharp focus at *O′*. As a result, there will be an excessive concentration of sound in the vicin-

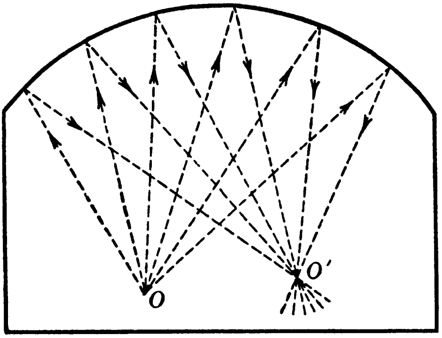

FIG. 152. Reflection of sound from a barreled ceiling which has a radius of curvature equal to the height of the room.

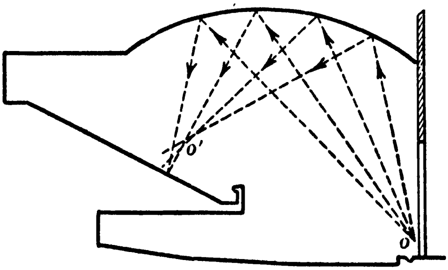

FIG. 153. Reflection of sound from a domed ceiling.

ity of O', and an inadequate amount of sound at other positions in the room, which receive practically no reflected sound, and thus become *dead spots.* Furthermore, if the distance from the source O to the ceiling and back to an auditor at O' exceeds the direct path distance between O and O' by 65 or more feet, the auditor at O' will hear a distinct echo. Such concentrations, dead spots, and echoes as result from barreled ceilings of the type shown in Fig. 152 are ruinous to the acoustics of a room. On the other hand, if the radius of curvature of the ceiling in Fig. 152 were increased to about twice the ceiling height, the ceiling would be a most beneficial reflector for sound originating near the floor on the longitudinal axis, since there would be no divergence or convergence of the reflected sound. Such a ceiling, if not too high, would be very satisfactory for a lecture hall.

Fig. 153, which also exhibits a defective shape, is a longitudinal section of an auditorium with a domed ceiling. In an auditorium of this type, the sound which originates at the front part of the stage is brought to a focus in the front portion of the balcony. Again, if the path length of the reflected sound exceeds the path length of the direct sound (from O to O') by 65 or more feet, the auditors in this part of the balcony will be bothered by echoes. Or if the difference of paths amounts to as much as 50 feet — although there will be no echo — there will be a confusing interference in this locality, resulting from the union of the direct and reflected sound. It is clear then that shapes of this type should be avoided.

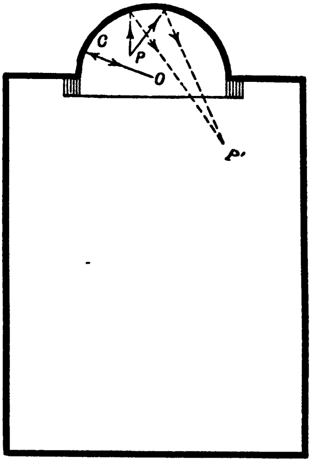

Fig. 154. Reflection of sound from cylindrical wall behind a speaker.

Fig. 154 exhibits another shape, in plan, which should be avoided. In this auditorium, the normal position for the speaker is at O, which is the centre of curvature of the rear wall behind the speaker's platform. Much of the sound originating at O is reflected back to O, such as the ray OC, and consequently a speaker located in this position gets an exaggerated estimate of the loudness of his own voice and thus tends to speak with inadequate loudness. At the same time he is very much annoyed by the incessant bombardment of his own voice against his ears. This same shape would mar the acoustical quality of musical ensembles. Thus, a player or singer located at O would hear his own instrument or voice too loudly and therefore would not generate an adequate amount of sound energy to balance with other sources on other parts of the stage. In addition to the defect just mentioned there would be many others owing to secondary foci in the seated area corresponding to different positions on the stage. For many positions on the platform or stage between *O* and the curved wall, there will be conjugate foci in the seated area. Thus, sound originating at *P* would be brought to a focus at *P′*.

The design of an auditorium should not only avoid such objectionable forms as have just been described but it should possess reflecting surfaces so spaced and shaped as to provide a uniform distribution of sound energy to all parts of the room, and the reflected sound should arrive nearly in phase with the direct sound. In general, if the difference in path between the direct and the reflected sound does not exceed 45 or 50 feet the addition of the reflected component will augment the loudness and often enrich the quality of the sound reaching the auditor. Fig. 155 shows a longitudinal section of an auditorium which is not only remarkably free from concentrations, dead spots, and echoes, but is so shaped as to give a nearly uniform distribution of reflected sound to all parts of the auditorium, with a slight preference for the more remote parts. Further, by keeping the ceiling low, the difference in path between the direct and the reflected sound is not excessive. The low, gently sloping ceiling directs the reflected sound to those portions of the auditorium which most need such reenforcement, as under the balcony and in the rear part of the balcony; and there are no reflected components delayed long enough to produce either a destructive interference or an echo. The sloping ceiling under the balcony, in like manner, provides a beneficial reenforcement for the last rows on the orchestra floor and at the same time increases the height of the opening so that more energy is available for reaching those auditors under the balcony who would otherwise receive an inadequate amount of sound energy. The shape indicated in Fig. 155 is only typical of what is desired acoustically, and such a design could be modified to better suit the architectural style of the auditorium without sacrificing acoustical merit.

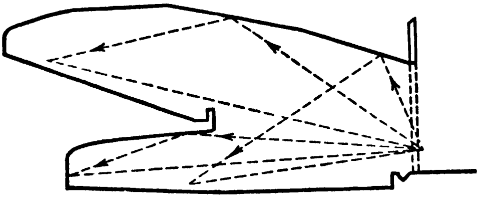

Fig. 155. Longitudinal section of an auditorium designed to give a helpful reflection of sound to all parts of the auditorium.

In very large auditoriums it may be difficult, or even impossible, to avoid large and therefore troublesome differences of path between the direct and reflected sound. In such instances it is advisable to break up the surfaces producing these delayed reflections by introducing coffers, beams, pilasters, or other irregularities in contour, all of which tend to diffract and diffuse the sound in all directions and thus prevent interfering reflections or echoes. In such very large auditoriums where it is necessary to sacrifice the benefit of the reflections from the walls and ceiling it may be necessary to design special reflecting surfaces which are near the stage or source of sound, or in certain cases it may be necessary to install special equipment for the amplification of sound, such as public address systems. In such cases, the loud speakers or horns which project the sound often can be located sufficiently close to the reflecting surfaces, and directed in such a manner, as to obviate interfering reflections.

An interesting scheme for designing the shape of an auditorium has been proposed by Professor H. L. Cook,[2] who has shown that it is possible to determine mathematically the shape of the ceiling of an auditorium which will give a uniform intensity of sound energy in practically all parts of the auditorium. Although he does not describe the exact form of the ceiling which will accomplish this end, he states that it is not in serious conflict with feasible types of architectural design. The ceiling would have a somewhat complicated curvature, which probably would require careful study before constructing it.

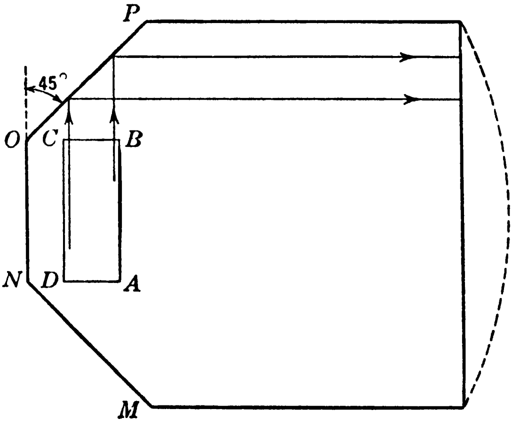

Fig. 156. Simple rectangular plan with splayed side walls.

116. Floor Plan. Designing for good acoustics naturally begins with the design of the floor plan. The design should be based upon (1) the arrangement of the seating area in such a manner as will bring the audience as near as possible to the stage or speakers' platform; and (2) the utilization of the walls and stage setting in such a manner as will give the most beneficial reenforcement to the direct sound. Thus a relatively wide and shallow auditorium will be a better shape than a narrow and long one; and an auditorium with plane reflecting walls near the

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[2] H. L. Cook, "Acoustic Control in Theatre Design," Jour. Frank. Inst., **208**, 319 (1929).

speaker will have a better shape than will an auditorium with concave walls far removed from both speaker and audience.

A number of pertinent characteristics with regard to the design of floor plans are revealed in Figs. 156 to 161. Fig. 156 shows a simple rectangular plan, relatively wide and shallow, with splayed walls near the stage or platform. The surfaces *MNOP* are favorably situated to reenforce sound originating within the rectangle *ABCD* — the most probable locations of the speaker. The rear wall should be straight (or well broken) and treated with absorptive material so that it will not reflect an echo back to the stage or the front seats. A concave rear wall, such as is indicated by the dotted line, should be avoided in all designs, as it is almost certain to produce an echo in the front part of the auditorium, and especially on the stage.

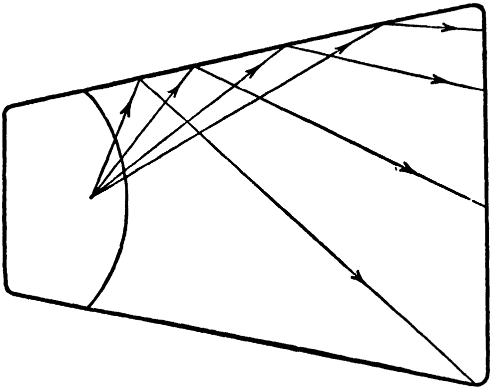

FIG. 157. Fan-shaped plan, showing beneficial reflections from side walls.

Fig. 157 shows a fan-shape design which provides beneficial reflections for the entire seated area. In this design the audience is located near the stage, the stage is surrounded by near-by reflecting surfaces, there is no possibility of multiple reflections between parallel side walls, and incidentally a large seating area is available for a balcony. Fig. 158 shows a slight modification of the fan shape which possesses considerable merit. (See Bagenal and Wood, p. 191.)

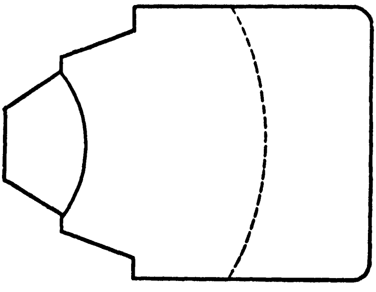

FIG. 158. Modified fan shape with well-designed reflecting splays.

Figs. 159 and 161 show circular and elliptical shapes which nearly always give difficulties from focusing effects, echoes, and non-uniform distribution of sound. Two outstanding defects are shown in the circular plan in Fig. 159. First, sound originating at *O* and directed at nearly grazing incidence to the walls, as in the direction *OA*, is successively reflected along the path *OABC*, that is, it tends to creep along the sides of the wall.[3] Second, sound re-

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[3] See Sec. 19 on whispering galleries.

flected from the rear portion of the cylindrical walls, as rays *OM*, *ON*, *OP*, and *OQ*, are brought to a focus at approximately *O′*. The outstanding defect of the elliptical plan is shown in Fig. 161. Sound originating at one focus *O* of the ellipse is concentrated at the other focus *O′*. Fig. 160 shows a modified circular form in which the circle is divided into a number of convex surfaces.[4] This shape overcomes the inherent difficulties in the circular plan. A similar modification can be made of the elliptical plan.

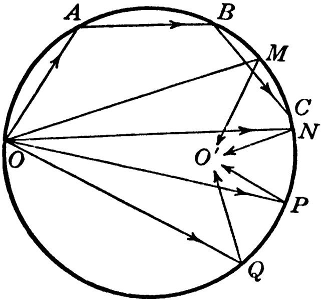

FIG. 159. Circular plan showing the tendency for sound to creep around the walls (shown by ray *OABC*), and also the focusing of sound which is reflected from rear part of the circular wall.

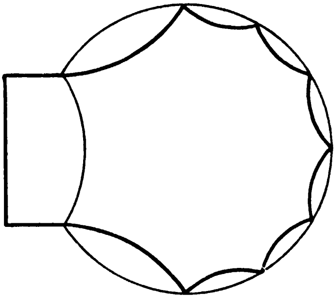

FIG. 160. Modified circular form which is free from the defects shown in Fig. 159.

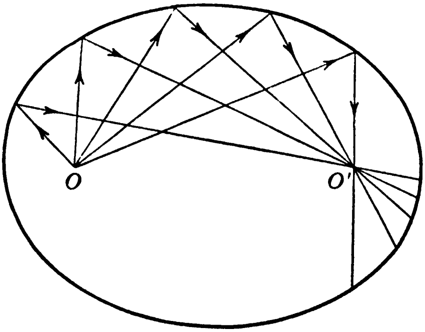

FIG. 161. Elliptical plan showing pronounced focusing effect.

117. Elevation of Seats. It is good design, not only from the standpoint of seeing but also from the standpoint of hearing, to elevate the rear seats in an auditorium, especially in larger auditoriums. The acoustical aspect of this problem has been investigated by E. Petzold,[5]

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[4] Bagenal and Wood remark that Sir Herbert Baker utilized this principle in the design of the Ninth Church of Christ Scientist, Westminster.

[5] E. Petzold, "Raumakustische Überhöhung," Deutsche Bauhütte, **32**, 30 (January 11, 1928).

who bases his recommendations on the requirement that each listener shall be elevated with respect to the person immediately in front of him so that the listener's head is about 12 centimeters (4.7 inches) above the ray of sound which would just pass over the head of the person in front of him. The seating elevation required to satisfy this condition is shown in Fig. 162. By a simple consideration of the geometry of the rays of sound which will satisfy this condition, Petzold submits the following equation for determining the required elevations of the different rows of seats:

$$h_n = h_{n-1} + h - \frac{r(H - h_{n-1})}{s + (n - 1)r}. \tag{61}$$

H is the elevation of the source, r is the horizontal distance between rows of seats, h is the distance which each listener is to be elevated into

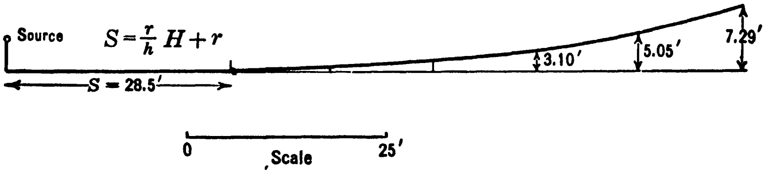

FIG. 162. Elevation of floor for satisfactory hearing in an auditorium.

the sound stream, which Petzold specifies as 12 centimeters, or 4.7 inches, s is the horizontal distance from the source to the last row which does not require elevation,[6] $h_1, h_2, \cdots h_n$, are the elevations of the first, second, $\cdots$ nth rows behind the row which is the distance s from the source. In the case illustrated in Fig. 162, $H = 3.9$ feet, $h = 4.7$ inches (0.39 foot), $r = 2.6$ feet, and s becomes 28.5 feet. Then, according to Eq. (61), $h_1 = 0.04$ foot, $h_5 = 0.49$ foot, $h_{10} = 1.59$ feet, $h_{15} = 3.17$ feet, $h_{20} = 5.11$ feet, and $h_{25} = 7.37$ feet.

If it be assumed that each listener should be elevated a fixed angle above the person immediately in front of him instead of a fixed elevation into the sound stream, a somewhat different formula would result, and the rear seats would have to be elevated relatively more. This would probably provide a slightly better condition for hearing, but the advantage gained would in most cases be too small to warrant the necessary extension of the height of the room. However, the elevations of the seats given by Eq. (61) should be regarded as fixing approximately the minimal elevations consistent with good design. Slightly greater elevations are desirable if they can be obtained at a reasonable cost and without disturbing the general design of the room or building.

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[6] As Petzold shows, $s = \frac{r}{h}H + r$.

118. Ceiling Design. The ceiling of a properly designed auditorium is the most potent of all surfaces for reenforcing sound by reflection. Wherever it is possible the ceiling should serve as a sounding board. It is large enough to give regular reflections, and it can be located in such a manner as to direct a useful flow of sound energy to those parts of an auditorium which are in greatest need of increased intensity.

An effective overhead reflecting surface or ceiling splay may be designed by means of a simple geometrical method proposed by Petzold.[7] This method is illustrated in Fig. 163, which shows a part of a longitudinal section of an auditorium with a balcony. It is required to determine the slope and extent of ceiling surfaces, above a speaker located at *O*, which will reflect sound within the angle limited by *a*, the uppermost auditor, and *b*, the nearest auditor who needs the benefit of reflected sound. The point *P* is fixed, or chosen arbitrarily, as the point of intersection between the splayed surface and the main part of the ceiling. The reflecting surfaces *PQ* and *QR* are determined as follows: Connect *a* and *P* with a straight line, and continue the line to *P′* so that *PP′* = *PO*. Draw *P′O* and bisect it at *S*. Now draw *PS* and *bP′*, which intersect at *Q*. The line *PQ* then specifies the slope and extent of a surface which will reflect sound originating at *O* to all listeners located between *a* and *b*. The surface *QR* is determined in a similar manner. The surface *NP* is designed to reflect sound only to balcony seats. If the speaker may occupy several positions, the constructions should be determined for the extreme positions of the speaker, and a compromise made which will best suit the most probable position.

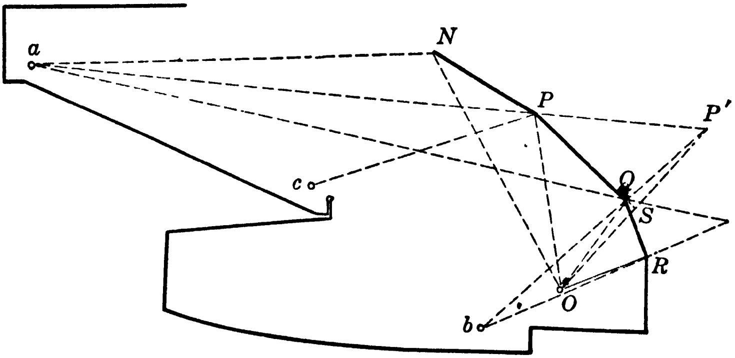

FIG. 163. The design of ceiling splays.

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[7] E. Petzold, "Akustik der Rednerkanzel," Zentralblatt der Bauverwaltung, p. 332 (June 10, 1931).

The upper sketch in Fig. 164 shows a defective type of reflection which occurs when a level ceiling is joined at right angles to a vertical rear wall. Sound rays striking the ceiling near the rear wall, as at *P*, will be reflected first to the rear wall, as at *Q*, and then to the first few rows of seats, as at *R*. This may produce an echo in the front part of the auditorium. Again, sound rays striking the rear wall, as at *N*, will be reflected first to the ceiling, as at *M*, and then to the back part of the stage, as at *L*. These harmful reflections can be converted into beneficial ones by introducing a ceiling splay between the level part of the ceiling and the rear wall, as shown in the lower sketch in Fig. 164. Here the rays *O′P′* and *O′N′* will be reflected to the rear seats, adding 1 or 2 db to the intensity level of the sound in that part of the room where increased intensity is most needed. Properly designed concave coves instead of plane splays will be as effective as the splays, and often will be better adapted to the general design of the room. The use of coves or splays between the ceiling and side walls also has merit in preventing echoes and long-delayed reflections, and in directing advantageous reflections upon the audience.

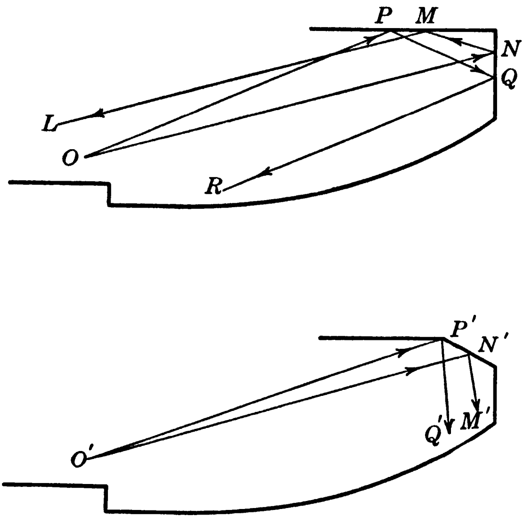

Fig. 164. A suitable ceiling splay (or cove) connecting the ceiling to the rear wall prevents echoes in the front part of the auditorium and reenforces the sound reaching the rear rows of seats.

119. Design of Balcony Recess. As a rule, good design of the balcony recess requires a shallow depth and a high opening. This permits a ready flow of sound into the space under the balcony; and the intensity level in this space then approximates the average intensity level in other parts of the auditorium; which means that the balcony recess is an integral part of the main body of the auditorium and is not a separate space coupled to the main part by means of a small opening. On the other hand, if the balcony recess be relatively deep and the opening relatively low, the intensity level under the balcony will be considerably below the level in the main part of the auditorium, that is, the balcony recess is a separate space which receives sound energy only by means of the opening which couples the small recess to the large auditorium. That the seats under the balcony of the conventional auditorium are in dire need of a greater supply of sound energy is evident from the complaints which come from auditors who sit under the balcony, and is clearly revealed in Fig. 151, which shows that the speech articulation is poorer under the balcony than it is in any other part of the room.

The features which should characterize the shape of a balcony recess are shown in Fig. 155. In general, the depth of the recess should not exceed twice the height of the balcony opening; the front part of the balcony soffit should be designed to reflect sound which comes directly from the source to the auditors under the balcony; and the rear part of the balcony soffit should be coved so as to direct the incident sound upon the rear seats rather than upon the rear wall and then back to the front part of the auditorium. Either a part of the overhead proscenium splay or a ceiling splay above the proscenium arch should be designed to reflect sound under the balcony.

120. Side Walls. The general location of the side walls of an auditorium was considered in connection with the design of floor plans (Sec. 116). The splayed surfaces which form the diverging walls of the proscenium, and those portions of the side walls which are designed to act as reflectors, should be large, smooth, unbroken surfaces. They should not be penetrated by doors, windows, arches, or boxes, and they should not be made ineffective by ornamental plaster or any other ornamentation in high relief. Such penetrations and relief work as may be required should be located where they will not hamper the reflective action of those parts of the wall which are designed to function primarily as reflectors. Fig. 158 shows an arrangement of side walls which gives beneficial reenforcements to sound. There are no doors or boxes on the proscenium splays, and the wall surfaces are free from other surface irregularities which would interfere with the primary function of reflection.

As a rule, only the wall surfaces near the floor levels are useful for reflecting sound upon the audience, and consequently the upper portions of the walls may be treated in relief for decorative purposes or they may be treated with absoprtive materials for the control of reverberation.

A slight inward inclination of the side walls, as was designed for the Salle Pleyel in Paris (see Fig. 253), is an effective means of directing advantageous reflections upon the audience. The inclination of the side walls also prevents multiple reflections between parallel walls. It is a measure worthy of adoption in the design of large auditoriums where every possible contribution to increased loudness is a prime necessity, but it is scarcely warranted in small auditoriums.

121. Sounding Boards. It has been shown in the preceding sections of this chapter that it is advantageous, especially in large auditoriums, to have large reflecting surfaces behind, above, below, and on both sides of the stage or speakers' platform. These reflecting surfaces, when properly designed, will add at least 5 or 6 db to the sound level of the direct sound waves reaching the audience — an addition that is greatly needed in large auditoriums. In many monumental buildings these beneficial reflectors do not exist, and consequently many attempts have been made to design sounding boards for the purpose of reenforcing the voice of a speaker or of other sources of sound. The effect of a large reflecting sheet-iron surface, 10 feet by 12 feet, placed directly behind a speaker, has been tested by the author and found to offer some benefit for the hearing of speech in large auditoriums. Thus, speech articulation tests conducted in a large, empty auditorium, with and without the reflecting surface behind the speaker, who stood near the middle of the stage floor, showed that the articulation was 62 per cent when the reflector was used and 59 per cent when it was not used. The observed difference in the articulation of only 3 per cent is not great, but it is greater than the experimental error in making the tests and is consistent with what would be expected on the basis of the increased loudness, which would amount to about 2 db. A similar improvement in articulation has been observed with the speaker on the front of the stage when the asbestos curtain was lowered so as to serve as a reflecting surface directly behind the speaker.

F. P. Whitman[8] tested the effect of a circular sounding board in a reverberant chapel 134 feet long and 30 feet wide. The sounding board was supported horizontally above the pulpit. It was 6 feet in diameter and was surrounded by a vertical rim which extended 6 inches below the plane of the horizontal reflecting surface. Words were called out from a spelling book, and listeners in different parts of the chapel recorded the words which they heard. Tests with and without the sounding board showed a slight preference (only 1 to 2 per cent) with the sounding board, for listeners in the front seats of the chapel. No improvement could be attributed to the sounding board for listeners in the more remote parts of the chapel. If the reverberation in the chapel had been reduced to a suitable degree it is probable that the sounding board would have given slightly better results.

A sounding board may sometimes serve specific purposes, such as preventing the progress of sound to remote surfaces which would give rise to echoes. This is most likely to occur in auditoriums with very

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[8] F. P. Whitman, "On the Acoustic Efficiency of a Sounding Board," Science, N.S., **38,** 707 (November 14, 1913).

high ceilings, and especially in churches where the ceiling may be as high as 100 feet or even higher.

In order to derive any real benefit from a sounding board it should be large in comparison with the wave length of the sound it is to reflect. Since practically all the useful energy in speech is contained in frequencies above 500 cycles, the sounding board should be large in comparison with the wave length of sound of this frequency, which is slightly more than 2 feet. The sounding board therefore should have dimensions of the order of at least 8 or 10 feet each way.

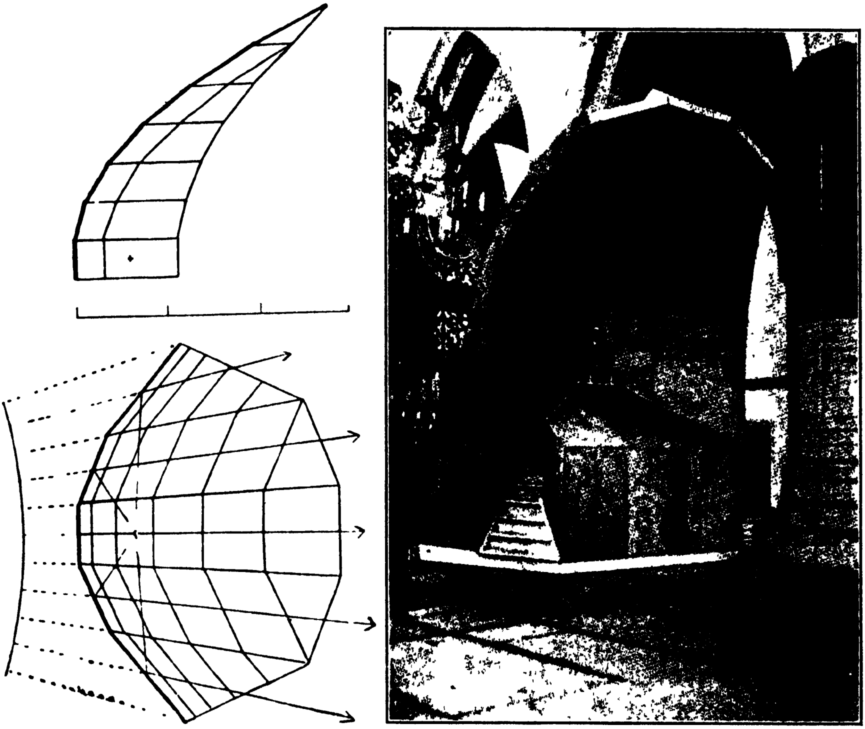

Fig. 165. Large sounding board of modern design. (*J. P. Fokker.*)

In one of the earliest treatises on architectural acoustics, T. Roger Smith[9] reports an account of the installation of a parabolic sounding board in a church in London as early as 1829. The reflector was large, having a diameter of nearly 12 feet and a depth of about 4 feet. The reflective action of this sounding board directed the sound to the end

[9] T. Roger Smith, "The Acoustics of Public Buildings," 62 (1861). See also Davis and Kaye, "Acoustics of Buildings."

and rear galleries in such a manner that persons claimed they heard better in these galleries than they did when seated near the pulpit. Many other sounding boards similar to this design were introduced in other churches, but although they met with varying degrees of success, they were not free from objectionable features. One of the chief objections to such reflectors is in connection with their action as a sound collector. Thus, in the case of a parabolic sounding board, all sounds coming from remote positions in the auditorium are brought to a focus near the head of the speaker, who is thus annoyed or even embarrassed by this accumulation and concentration of sounds which originate in the audience.

122. Effect of Shape on Speech Articulation. Although no conclusive data have been obtained to show just how the hearing of speech in an auditorium depends upon shape, it is quite certain that the shape should conform with the general principles which have been recommended in the preceding sections. In a series of speech-articulation tests conducted in fifteen auditoriums in Los Angeles there seemed to be a slight preference for auditoriums which were wide and short rather than those which were narrow and long[10]; that is, those shapes which bring the audience near the stage seem to provide better hearing conditions than those which require many listeners to sit a great distance from the source. More data are required before definite conclusions can be made with regard to the improvement which results from the use of properly designed ceilings, splays, coves, and walls, but the benefits which result from a systematic and careful design of the shape of an auditorium cannot be denied.

In the auditorium of conventional rectangular shape it is probable that the factor k_s which was included in Eq. (60) does not differ appreciably from 1.0. In very large auditoriums, especially with curved surfaces, it is probable that k_s may be reduced to a value as low as 0.95 or even 0.90. It also is probable that in small rooms or in auditoriums with properly designed reflecting surfaces k_s may reach a value as high as 1.06. Such a small increase may not seem to be worthy of great effort, or to warrant changes from the conventional types of auditorium, but even a small increase in the value of k_s may increase the articulation in a large auditorium from say 70 to 75 per cent; and such an increase in articulation is a practical improvement of real value.

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[10] This preference is further supported by some tests of hearing in the open. See Sec. 174.

CHAPTER XVII

ACOUSTICS OF SPEECH HALLS — NOISE, LOUDNESS AND REVERBERATION

A. NOISE

123. Introductory. The nature of the auditory masking of one tone by another suggests that either tones or noise would interfere with the hearing of speech. This is of course borne out by experience. For example, it is almost impossible to carry on a conversation in a noisy place, such as in a subway train or in a noisy boiler factory. It is of interest to know how much noise, if any, can be tolerated without interfering with the hearing of speech. It is also of considerable interest to know whether any particular frequencies produce a greater interference than other frequencies.

The interfering effect of tones and noise upon the hearing of speech in rooms has been determined quantitatively by conducting speech-articulation tests in the presence of either disturbing tones or a disturbing noise. These tests were conducted in a room having a volume of 15,000 cubic feet and a time of reverberation at 512 cycles of 1.20 seconds. The interfering tone or noise was generated by appropriate electro-acoustic circuits and was conducted to the observer's ears by means of a pair of telephone receivers, so adjusted on the head band that each receiver was held at a fixed distance of slightly less than 1 inch from the ear to which it was attached. In this manner the speech sounds, which were produced in the room, had ready access to the ears of the observer through the openings between the receivers and the ears; and at the same time the electrically produced interfering tones or noises could be communicated to the ears of the observer. The speaker or *caller* could not hear the interfering tone or noise and therefore did not raise his voice in an effort to speak above the noise. The speaker spoke in an easy, natural, conversational voice, at a distance of 6 feet from the listener. Measurements of the level of the speech in the neighborhood of the listener indicated an average level of approximately 47 db above a slight residual noise (about 10 db) in the room. This loudness of speech is comparable with the loudness of the average conversational voice in an auditorium.

124. Interfering Effect of Musical Tones upon the Hearing of Speech in a Room. A series of speech articulation tests has been conducted in the presence of each of the following tones: C_2 (128 cycles), C_3 (256 cycles), C_4 (512 cycles), C_5 (1024 cycles), C_6 (2048 cycles), and C_7 (4096 cycles). Each interfering tone was maintained at each of four or five different sound levels between 20 db and 80 db. The results of these tests are shown in Fig. 166. It will be noted that so long as the sound level of the interfering tone is not too high, that is, so long as it is below about 50 db, the interfering effect is nearly the same for tones of all frequencies up to 2048. However, if the interfering tone is fairly intense — above a level of about 50 db — the low-frequency tones produce a much greater interference than do the high-frequency ones. This

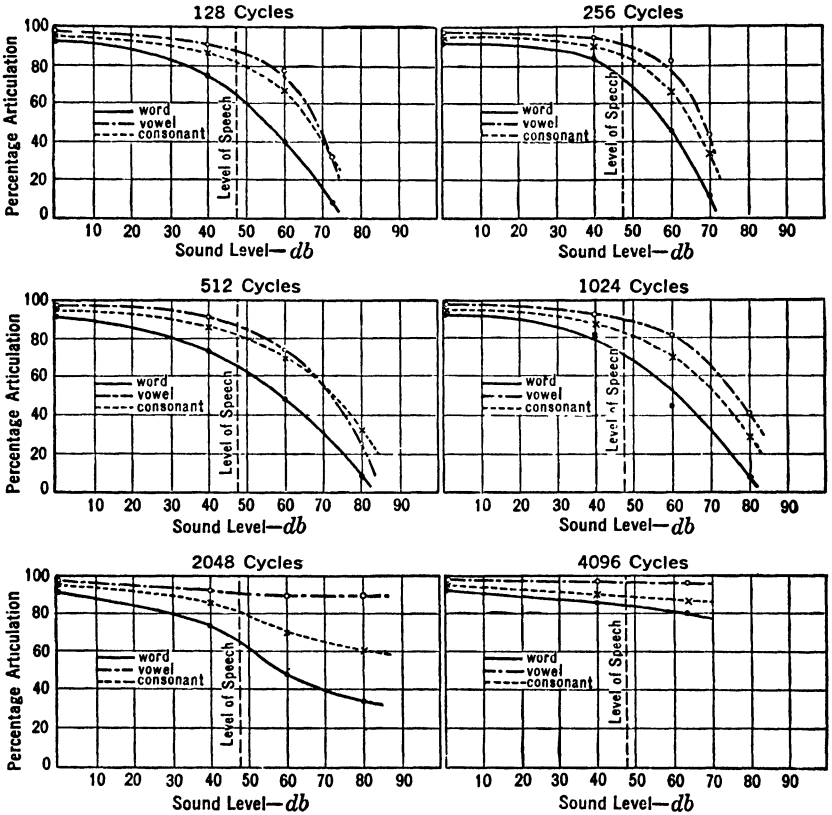

FIG. 166. Curves showing the interfering effect of tones upon the hearing of speech. The "word" (or "syllable"), "vowel," and "consonant" articulations are plotted separately.

is represented more clearly in Fig. 167, where the percentage articulation has been plotted as a function of the frequency of the interfering tone at two different levels, namely at 47 db (which was comparable with the loudness of the speech) and at 70 db. It will be seen that interfering tones at a level of 47 db produce an interference which is almost independent of the frequency; whereas when the interfering tones are at a level of 70 db the low frequencies effect a much greater interference than do the high frequencies. This result is borne out by the experimental findings concerning the auditory masking of one tone by another. Very intense tones are known to *overload* the ear to the extent that non-linear distortions are introduced by the hearing mechanism, and these distortions produce a whole series of subjective tones. When the interfering tone is both intense and of a low frequency, the series of subjective tones will activate a relatively wide frequency range of the receptive mechanism within the cochlea. Thus, nearly the entire mechanism which is used for the recognition of the sounds of speech is disturbed by the low-frequency tone and its subjective overtones, and as a consequence the hearing of speech is made difficult or even impossible. On the other hand, high frequencies, especially above 2048, do not produce an appreciable interference because the subjective tones which may be caused by *overloading* the hearing mechanism would consist of frequencies above about 4096, and consequently the interference would disturb a relatively unimportant portion of the hearing mechanism — thus interfering with only a few of the fricative consonants. It is found that interfering tones disturb the hearing of the consonants very much more than they do the

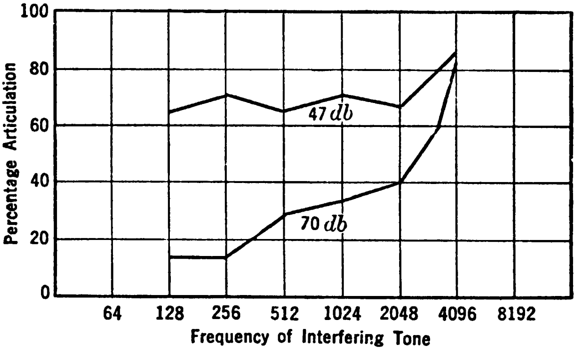

FIG. 167. Curves showing the percentage articulation of speech in the presence of interfering tones of different pitch. The upper curve is for interfering tones having a sound level of 47 db, and the lower curve is for interfering tones having a sound level of 70 db.

hearing of the vowels. This is what one would expect, since the consonants contain such relatively small amounts of energy.

125. Interfering Effect of Noise upon the Hearing of Speech in a Room. Similar articulation tests have been conducted in the presence of a disturbing noise. The noise in these tests was produced by a buzzer type of audiometer which generated a wide range of frequencies similar to that shown in Fig. 10. The results of these tests are shown in Fig. 168, where the word or syllable articulation is plotted as a function of the sound level of the interfering noise.

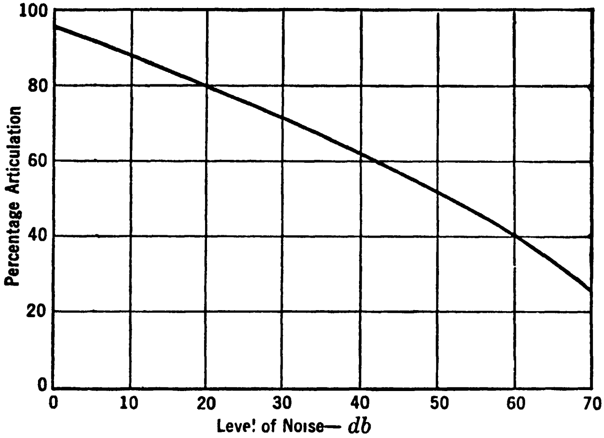

FIG. 168. Curve showing the percentage articulation of speech in the presence of a typical noise of various sound levels.

The data on the interfering effect of tones and noise lead to certain conclusions which have a significant bearing upon the problem of the hearing of speech in rooms, as follows:

1. The interfering effect increases with increasing intensity of either tones or noise. For tones with a sound level which is lower than that of the speech, the effect is almost independent of the frequency; but if the interfering tone become louder than the speech, tones of low pitch produce a greater interference than do tones of high pitch.
2. The interfering effect of either tones or noises is of such a nature as to disturb the hearing of consonants more than the hearing of vowels.
3. A noise produces a greater interfering effect than does an equally loud tone of any pitch. Thus, a typical noise, having a sound level equal to that of the speech, reduces the syllable articulation to about 50 per cent, whereas any tone below 2048 cycles, and of the same sound

level, reduces the syllable articulation to about 70 per cent. This is to be expected, since the noise, which is made up of a wide band of frequencies, interferes with the hearing of nearly all the frequency components of speech.

4. An inspection of the curve in Fig. 168 will show that even a very slight noise impairs the hearing of speech appreciably. It may be concluded that the speech must be at least 30 or 40 db above the level of the noise if the noise is not to produce a harmful interference. This emphasizes the necessity for extreme care in eliminating noises from auditoriums, especially in large auditoriums where the energy of the speech is of necessity very much diluted.

126. The Noise-Reduction Factor k_n. The curve given in Fig. 168, which shows the manner in which the hearing of speech depends upon the intensity of an interfering noise, makes it possible to determine the value of the noise-reduction factor k_n, as used in Eq. (60). The dotted curve in Fig. 169 has been derived from the data in Fig. 168. It gives the values of k_n for different levels of the noise. In this curve the abscissa is the ratio of the level of the noise, in decibels, to that of the speech, also in decibels. Thus, when the noise is at the same level as the speech, the abscissa in Fig. 169 is 1.0. The value of k_n for no noise is taken as unity, and all other values of k_n, as shown by the dotted curve,

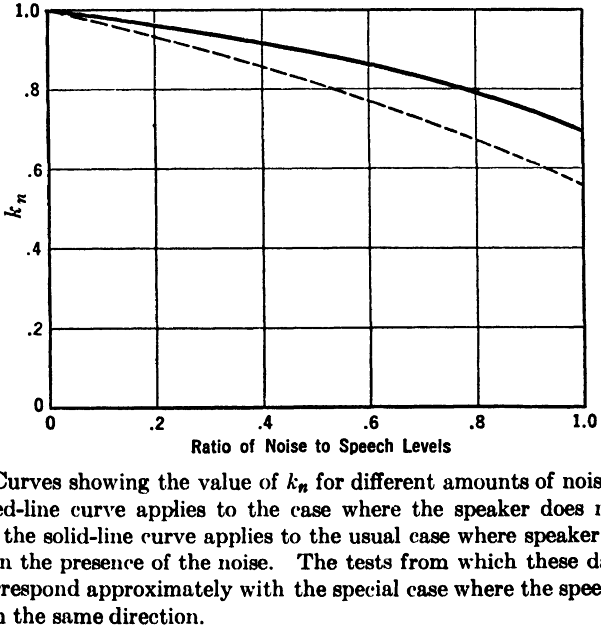

FIG. 169. Curves showing the value of k_n for different amounts of noise in a room. The dotted-line curve applies to the case where the speaker does not hear the noise and the solid-line curve applies to the usual case where speaker and listener are both in the presence of the noise. The tests from which these data were obtained correspond approximately with the special case where the speech and noise come from the same direction.

are obtained by taking the ratios of the ordinates in Fig. 168 to the ordinate for zero noise level. This method for determining k_n is only an approximation, and gives more nearly the lower limit to the noise-reduction factor, which would apply only when the noise disturbs the listeners and not the speaker. But in general the noise bothers the speaker as well as the listener, and consequently the speaker will raise his voice in an attempt to speak above the noise. Experience has indicated that the solid-line curve in Fig. 169 is in better accord with the conditions which ordinarily prevail in an auditorium, and this curve should be used for determining the value of k_n in auditoriums. The manner of using this curve in practical problems is as follows: First determine, by measurement if necessary, the average noise level in the room under consideration. Take the ratio of this noise level (in decibels) to the probable level (also in decibels) of the speech in the room; and read off from the solid-line curve in Fig. 169 the appropriate value of k_n. For example, if it is found that the average noise level in an auditorium is 20 db and the average speech is 50 db, the ratio of the noise level to the speech level is 0.4, and therefore the value of k_n would be 0.93. This condition of noise is comparable with that found in auditoriums in which a reasonable degree of care has been exercised to eliminate all disturbing noise. The average noise prevalent in many auditoriums is considerably more than this and may often be as high as 30 to 40 db. Under such conditions of noise it is almost impossible to recognize speech of normal loudness.

B. LOUDNESS

127. Introductory. It is obvious that there is an upper limit to the size of an auditorium in which unamplified speech can be heard satisfactorily, simply because the sound energy is diluted to the extent that some of the feebler sounds of speech, especially the unvoiced consonants, become unrecognizable or even inaudible. In the design of auditoriums it is necessary therefore to know how the loudness of speech is affected by the size of the auditorium, and also how the intelligibility of speech is affected by the loudness of the speech reaching the listeners. We hear better in the front rows of an auditorium than we do in the rear rows primarily because the sound is louder in the front rows, but secondarily because the sound which we hear in the front rows is largely direct sound, and only a small portion of it is reflected or reverberant sound. On the other hand, the sound which reaches the rear rows of an auditorium is not only reduced in intensity but is made up largely of reflected and interfering components of sound; that is, a large portion of the sound reaching the rear part of the auditorium is reflected or reverberant sound.

These two factors, namely loudness and reverberation, largely determine the intelligibility of speech in a quiet auditorium, and both factors will now be considered. Loudness will be considered first.

128. Effect of Loudness upon the Recognition of Speech in an Auditorium. The work of Fletcher and Steinberg[1] has shown how the loudness of speech affects its recognition. In their experiments, the loudness of the speech was controlled by means of a resistance attenuator in a high-quality telephone and amplifier circuit. The gain or amplification of the amplifier was adjustable, so that the level of the speech could be given any value between zero and 120 db. Articulation tests obtained at different levels gave the data which are shown by the dotted curve in Fig. 170.[2] It will be seen from this curve that the optimal loudness of speech appears to be about 70 db, which corresponds to an intensity ten million times that which would be just barely audible. This is somewhat louder than the normal level of speech in auditoriums, which is usually of the order of 50 to 60 db, or even less in very large auditoriums. The data represented by Fig. 170 indicate that if the loudness of undistorted speech be between 50 and 100 db, the articulation is above 90 per cent, which is wholly satisfactory. Below 50 db the articulation drops off rapidly as the level is further diminished. Thus, at 30 db the articulation is 66 per cent and at 20 db it is only 40 per cent.

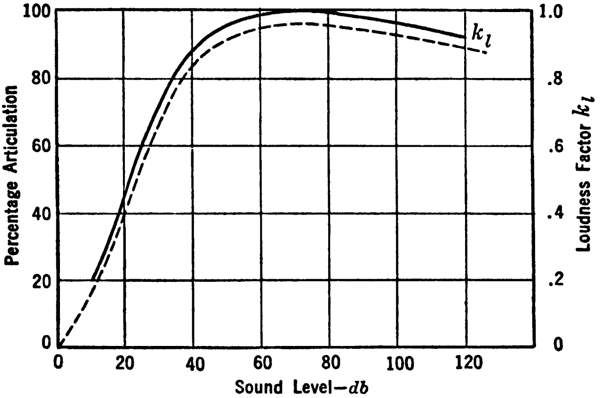

FIG. 170. Curves showing percentage speech articulation at different levels of speech (dotted-line curve), and the corresponding loudness reduction factor k_l (solid-line curve).

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[1] H. Fletcher, "Speech and Hearing."

[2] More recent work by J. C. Steinberg has modified slightly the shape of this curve, but the difference is not great enough to alter appreciably the results here deduced. See Jour. Acous. Soc., **1**, 120 (October, 1929).

The solid-line curve shown in Fig. 170 has been derived from the broken-line curve. The solid-line curve gives the value of the loudness-reduction factor k_l for different speech levels between zero and 120 db. The value of k_l at 70 db, the optimal level, is taken as unity, and the value of k_l at all other levels is the ratio of the percentage articulation at that level to the percentage articulation at 70 db. The solid-line curve in Fig. 170 is useful in connection with Eq. (60), provided the average loudness level of a speaker's voice in an auditorium be known.

129. Average Acoustical Power of Speakers in Auditoriums. The data on the effect of loudness upon speech articulation indicate that it would be desirable to maintain the intensity of speech in auditoriums at a level of not lower than 50 db, and preferably at a level between 60 and 70 db. It has been mentioned previously that the average speaker in a large auditorium does not maintain a level as high as 50 db. It will be seen presently that he does reach or even surpass this level in small rooms, but in large, non-reverberant auditoriums it requires considerable effort on the part of the speaker to maintain an average level of 50 db, and in very large auditoriums it will be impossible to maintain this level without the aid of amplifiers.

The approximate level of speech in an auditorium can be determined from simple calculations based upon some numerical constants of speech and hearing obtained by Bell Telephone engineers.[3] The data of Sacia and Sivian at Bell Laboratories indicate that the average speech power generated by an average speaker in normal conversation is about 10 microwatts. The actual power output of different speakers, and even of the same speaker, varies widely from this average value. For example, they found that the peak power may sometimes rise to 2000 microwatts.

Every public speaker is fully aware that he must raise the intensity of his voice above the ordinary conversational level in order to be heard in a large auditorium. It is evident therefore that his energy output, particularly in very large auditoriums, will be considerably above the average conversational level of 10 microwatts. In order to determine the approximate power of the average speaker's voice in an auditorium, the author has obtained some measurements on the loudness of speakers' voices in a small and also in a moderately large auditorium. The measurements were made with the help of a microphone (suspended near the middle of the auditorium), an amplifier with an attenuation circuit and a head-set in its output, and a high-quality electric phonograph. The electric phonograph, with a calibrated volume control, was first used

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[3] H. Fletcher, "Useful Numerical Constants of Speech and Hearing," Bell Syst. Tech. Jour., 4, 375 (July, 1925).

for a source of speech in the auditorium. The loudness of the reproduced speech was maintained at different measured levels, and at each level the attenuation circuit associated with the amplifier (which was located in a remote room) was adjusted until the speech, as heard in the head-set, was reduced to the minimal threshold of audibility. A similar adjustment of the attenuation circuit, when someone was speaking in the auditorium, gave a measure of the sound level of his voice. The method is essentially a substitution method in which the average level of the speaker's voice is compared with a measurable level from the electric phonograph. The results obtained from six male speakers (instructors in the University) in the small auditorium are given in Table XXXIV. In every case the speaker was unaware that his voice was under observation until after the measurements were obtained.

The average level of the speaker's voice, measured near the middle of the auditorium, depends principally upon the energy output of the speaker and the total absorption of the room and its contents. It has been shown that the average steady state volume density of diffuse sound energy ρ_0 in a room is proportional to the rate of emission of sound energy E and inversely proportional to the total absorption a in the room. The value of ρ_0 is given by

$$\rho_0 = \frac{4E}{ca}. \tag{20}$$

In Eq. (20) E represents, for the present consideration, the average energy output of the speaker, and ρ_0 represents the average measured volume density of the speaker's voice as *detected* by the microphone and amplifier. In order to evaluate E in microwatts it is only necessary to evaluate ρ_0 and a in the proper units, and then solve (20) for E. The absorption a should be expressed in square centimeters of a perfectly absorbing surface, as an open window, and ρ_0 should be expressed as an energy density, as microjoules per cubic centimeter. The determination of ρ_0 is based upon the data of Fletcher and Wegel on the sensitivity of the normal ear. According to their data, barely audible speech in a quiet room would have approximately an intensity of 9×10^{-10} microwatt per square centimeter. The average volume density, assuming a uniform distribution of sound energy throughout the room, would be therefore, at minimal audibility, $9 \times 10^{-10}/c$, or 2.6×10^{-14} microjoule. If, then, the actual level of the speech in the room has been measured in decibels, it is possible to evaluate ρ_0 in microjoules per cubic centimeter by the familiar relation db $= 10 \log_{10} \rho_0/\rho_m$, where ρ_m is the volume density at the minimal threshold, that is, 2.6×10^{-14} microjoule per cubic centimeter. With ρ_0 and a known, and evaluated in these appropriate units, Eq. (20) can be solved for E. The result will give, in microwatts, the average power output of a speaker. The values of the average power of speakers' voices given in the last columns of Tables XXXIV and XXXV were determined in this manner.

TABLE XXXIV

Volume of room = 27,200 cubic feet (770 cubic meters).
Absorption of auditorium (empty) = 472 square feet (43.9 square meters).

Speaker	Observed Average Sound Level* in decibels	Total Absorption in Room in square meters	Average Power of Speaker's Voice in microwatts
1 (man)	51.2	108.9	32.5
2 "	56.2	70.6	66.2
3 "	50.9	82.8	23.0
4 "	48.3	54.9	8.5
5 "	44.7	67.9	4.5
6 "	53.0	66.5	30.0
Average	50.7	....	27.4

* The average level of each speaker was based upon many observations taken during the course of an hour's lecture.

It will be noticed that the speech power of the six different speakers listed in Table XXXIV varies between rather wide limits, namely, from 4.5 to 66.2 microwatts. Even the same speaker exhibited a wide variation, for in some instances the power would momentarily surge to a peak value of 1000 or 2000 microwatts, and at other times would drop to 1 microwatt or even less. The average power for the six speakers is 27.4 microwatts. It is admittedly impossible to obtain an accurate determination of the mean power of the average speaker in an auditorium from so few as six speakers. However, the average value obtained from these measurements is certainly a good approximation, and is sufficiently representative of the normal value to serve a useful purpose. On the basis of these few measurements, it appears that in a small auditorium (27,200 cubic feet) the average speaker increases the power of his voice about 170 per cent above the power level of ordinary conversation in a small room, which telephone engineers have found to be about 10 microwatts.

A similar series of measurements on the power of speakers' voices in a larger auditorium gave the results in Table XXXV.

Again, it will be noticed that the different speakers vary considerably in their speech power, from 23.4 to 142.0 microwatts. As would be

TABLE XXXV

Volume of room = 240,000 cubic feet (6790 cubic meters).
Absorption of auditorium (empty) = 3600 square feet (335 square meters).

Speaker	Observed Average Sound Level in decibels	Total Absorption in Room in square meters	Average Power of Speaker's Voice in microwatts
1 (man)	49.4	335	65.5
2 "	45.6	335	27.5
3 "	46.1	413	37.8
4 (woman)	43.0	632	28.4
5 (man)	43.5	531	26.8
6 "	51.0	502	142.0
7 "	42.7	560	23.4
8 (woman)	44.3	629	38.2
Average	45.7		48.9

expected, the average person speaks with greater energy in a large auditorium than he does in a small one. Thus, the average power of the speaker's voice in the large auditorium is 48.9 microwatts compared with 27.4 microwatts in the small auditorium. However, the increase in the average power of a speaker's voice in the large auditorium is not sufficient to compensate for the diminution of loudness owing to the greater amount of absorption in the larger room. Thus, the observed average sound level of six speakers in the small auditorium was 50.7 db, whereas the average level for eight (other) speakers in the large auditorium was only 45.7 db. It will be noticed, by referring to Fig. 170, that a level of only 45.7 db is approaching a dangerously low point. A slight disturbance from noise or reverberation, or a slight " fading " of the voice, will result in unsatisfactory hearing — a phenomenon which is observed all too frequently in auditóriums.

C. REVERBERATION

130. Effect of Reverberation upon the Hearing of Speech in a Small Room. In order to describe the reverberatory properties of a room it is necessary, as has been mentioned previously, to specify the time of reverberation for tones of different pitch, for example, throughout the range of pitch between 128 and 4096 cycles. For many purposes, however, it is sufficient to consider the time of reverberation for a single tone of 512 cycles. This is done very widely in practice, and is a safe expedient provided the absorptive materials in the room do not exhibit marked selectivity in their absorptive properties. Whenever the term *time of reverberation* is used, without specification of frequency, it refers to the time required for a tone of 512 cycles to decay 60 db. It should be remembered, however, that it is important to give consideration to the times of reverberation for tones throughout the entire audible range, and that, for the control of reverberation in rooms, materials should be selected which will provide the optimal reverberation characteristics for tones of all pitch. Many materials, especially thin, porous materials, exhibit high absorption for high frequencies but relatively low absorption for low frequencies. Thus, in rooms treated with selectively absorptive materials, as thin felts or thin acoustical plasters, the time of reverberation may be as long as 5.0 seconds at 128 cycles and only 1.0 second at 2048 cycles. Obviously, it would be hazardous to describe the reverberation of such rooms in terms of the time of reverberation at a single frequency. In most rooms, however, and particularly in rooms in which an audience is present, the time of reverberation at 128 cycles is not more than about two times the time of reverberation at 512, and for frequencies above 512 the reverberation is nearly uniform. Under such conditions, and these are most frequently encountered in practice, the time of reverberation at 512 cycles gives a fairly reliable index of the general condition of reverberation in the room, and it serves as a simple and single quantity for describing the reverberatory characteristics of a room.[4]

In order to determine the quantitative effects of reverberation upon the recognition of speech in a small room (4096 cubic feet), articulation tests have been conducted in such a room in which the time of reverberation was controlled by bringing into the room different amounts of 1-inch hair felt. In this way it was possible to reduce the time of reverberation in the room from 5.01 seconds to 0.50 second. During the tests the listener had his back turned to the *caller* so that there was no chance for the listener to see the lips and face of the caller.

The results of the speech tests conducted in this room are shown in Fig. 171. It will be noted that the percentage articulation improved continuously as the time of reverberation in the room was reduced. The articulation was only 62 per cent when the time of reverberation was 5.0 seconds, but it increased to 94 per cent when the reverberation was reduced to 0.50 second. These tests indicate that the optimal time of reverberation is certainly not more than 0.50 second, and is probably less. This is to be expected in a small room since there would be an

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[4] It should be mentioned again that, in calculating for reverberation, separate computations should be made for frequencies of at least 128, 512, and 2048 cycles. This will insure the selection of materials which will give a proper balance to the reverberation.

abundance of speech energy even when the time of reverberation is reduced to a small fraction of a second. It was not possible, with the materials then available, to reduce the time of reverberation in the room below 0.50 second, but the effect of an even shorter time of reverberation was determined by conducting similar speech-articulation tests in the quiet out-of-doors where the reverberation was practically nil. With the caller and listener occupying the same relative positions as they did in the small room, the syllable or word articulation was 95.7 per cent. This indicates that even a very short time of reverberation in a small room — 0.50 second — produces a slight interfering effect, since the highest word articulation obtained in the room, at 0.50 second, was 94 per cent. However, the difference between 94 per cent and 95.7 per cent is very small, and an articulation of 94 per cent provides unusually good hearing conditions. The results show very decisively the advantage of short reverberation times for all small rooms in which speaking is an important factor.

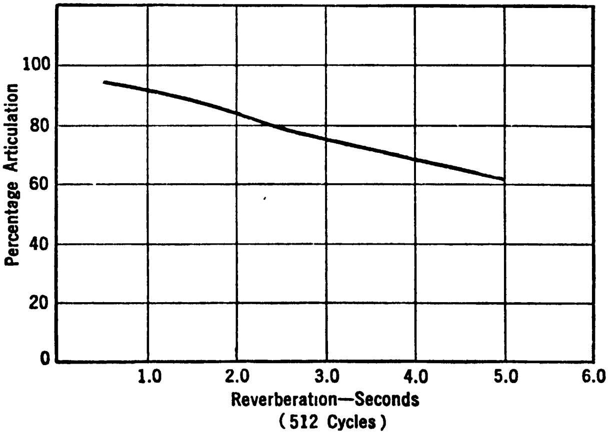

FIG. 171. Curve showing the percentage speech articulation for different reverberation times in a small room.

131. Effect of Reverberation upon the Hearing of Speech in Large Auditoriums. A further study of the effect of reverberation upon the hearing of speech has been conducted in a series of large auditoriums, all having approximately the same shape (rectangular with balcony) and the same volume (200,000 to 300,000 cubic feet) but different times of reverberation, varying from 8.5 seconds down to 0.85 second. The results of these tests are shown by the small circles in Fig. 172. The lower curve is drawn to represent the most probable fit with the observed data. The results of these tests are similar to those obtained in a small room. It will be noted that the articulation decreases approximately 6 per cent for each additional second of reverberation. It is evident therefore that a deviation of one or two tenths of a second from the optimal reverberation time can be readily tolerated — such a deviation resulting in loss of articulation of only 1 per cent or less.

The lower curve in Fig. 172, which represents the mean result of the experimental determinations, was not obtained for a constant level of speech, because the intensity is dependent upon the amount of absorption in the room, which varied from about 1500 sabines in the most reverberant to more than 9000 sabines in the least reverberant auditorium. Assuming the average power of the speakers' voices to remain constant, the resulting intensity of the speech in each auditorium would be almost inversely proportional to the total amount of absorption in that auditorium. On the basis of the average power of the speakers' voices used in these tests, which was determined experimentally (see Sec. 129), and the amount of absorptive material in each auditorium, it was possible to calculate the average level of the speech in each auditorium. From these data, and the articulation data given in Fig. 170, it is possible to apply a correction to the lower curve in Fig. 172 which will give the percentage articulation which would have been obtained if the average level of the speech had been maintained at 70 db, that is, at about the optimal level for the hearing of speech. The upper curve in Fig. 172 shows the result of applying such a correction. The dotted portion of the curve has been extrapolated, but such an extrapolation seems justified by the articulation tests which were conducted in the

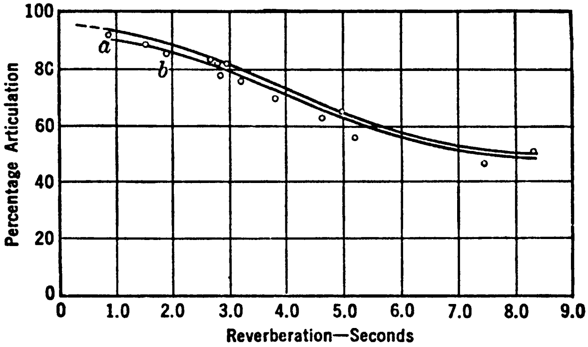

FIG. 172. Curves showing the interfering effect of reverberation upon the hearing of speech. The lower curve represents the most probable fit with the observed data. The upper curve represents what the percentage articulation would have been if the level of the speech had been 70 db.

smaller room, in which the time of reverberation was reduced to 0.50 second.

By means of the upper curve in Fig. 172 it is possible to determine the value of k_r, the reduction factor corresponding to different times of reverberation. This is useful in connection with Eq. (60) for calculating the probable articulation in an auditorium. The value of k_r is arbitrarily taken as unity for a time of reverberation of 0.50 second. Then the value of k_r for any other time of reverberation is the ratio of the percentage articulation at that time of reverberation to the percentage articulation for a time of 0.50 second. The curve in Fig. 173 gives the value of k_r obtained in this manner for times of reverberation between 0.50 second and 8.5 seconds. It will be seen that k_r decreases almost uniformly as the time of reverberation increases from 1.0 to 6.0 seconds. Above 6.0 seconds the rate of decrease of k_r appears to be less rapid.

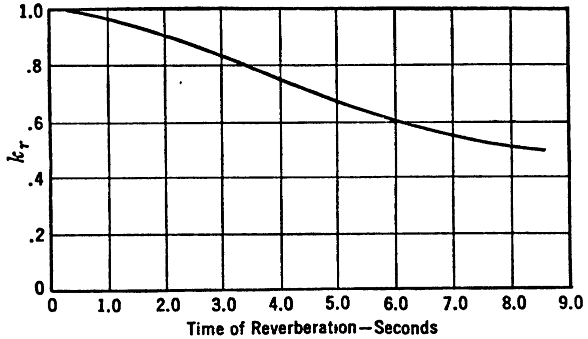

FIG. 173. Curve giving the reverberation reduction factor k_r for different times of reverberation.

The articulation data obtained in these tests show quantitatively the importance of reducing the time of reverberation in large speech rooms. If the loudness of speech in large rooms were adequate it would be advantageous to reduce the time of reverberation to zero, but since the average level of speech in large auditoriums is considerably below the optimal level of 70 db, any reduction of reverberation produces a corresponding decrease in the average intensity of the speech which will be detrimental to good hearing. Therefore, as will be shown in Part D of this chapter, the combined effects of loudness and reverberation conspire to make a particular time of reverberation the most advantageous one for an auditorium of a certain size. Before taking up this problem, however, further consideration will be given to the effect of the variation of reverberation time with frequency.

132. Variation of Reverberation with Frequency and Its Relation to the Quality of Speech. It has been mentioned repeatedly that the reverberation characteristics of a room cannot be precisely represented by a single quantity, as for example by the time of reverberation at 512 cycles, although such a single-frequency representation is very useful for purposes of calculation or comparison, and is warranted if used with an understanding of how the reverberation time depends upon the frequency. It is necessary therefore to give careful consideration to the times of reverberation for different frequencies throughout the speech and music range, or to know the shape of the *characteristic reverberation curve*, that is, the time of reverberation plotted as a function of frequency. There are certain tolerable variations of reverberation with frequency, and there is perhaps a most suitable or an optimal type of reverberation for both the generation and reception of speech. A casual consideration of the subject indicates that a very wide variation in reverberation time with frequency is not desirable, since those frequency components for which the reverberation time is long would be over-emphasized and excessively prolonged, whereas those frequency components for which the reverberation time is short would be under-emphasized, or completely masked, and would die away to inaudibility all too soon. Just such a condition as this exists in a room which is treated with thin porous materials which are highly absorptive for high frequencies and poorly absorptive for low frequencies. Such materials may give to a room a reverberation characteristic similar to that shown in Fig. 174; that is, the reverberation time is 4 or 5 seconds for frequencies below 128, and

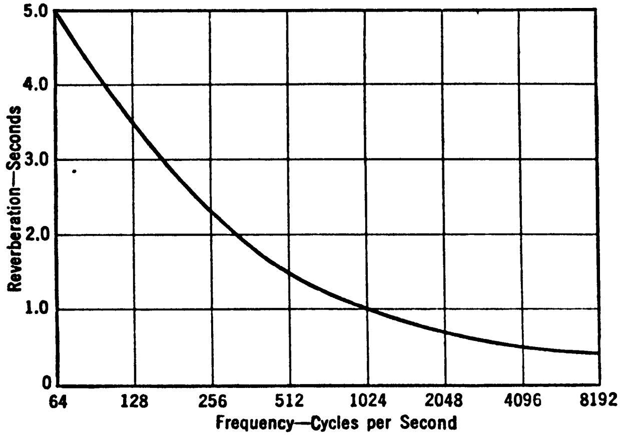

FIG. 174. Reverberation characteristic of a room treated with a thin, porous material that is selectively absorptive at high frequencies.

only 1 second or less for frequencies above 1024. On the basis of the reverberation time for 512 cycles, this room might be considered to possess the optimal time of reverberation for speech, and yet it is obvious that such a room would not have ideal reverberatory properties. The low frequencies would " boom " loud and long, and the high frequencies — which contribute so fundamentally to the consonantal sounds of speech — would be damped and masked almost beyond recognition.

The question arises, then, what type of reverberation characteristic is most desirable? Should it be a uniform or flat characteristic, that is, one in which the time of reverberation is the same for all audible frequencies; or should it be a characteristic which increases with the frequency; or one which decreases with the frequency? The best type of characteristic would be one which would allow all the frequency components of speech to build up and die away at such rates that during the growth and decay, as well as during the steady states, all the frequency components would be maintained at such sound levels as would provide the most natural and pleasing quality of speech. In order to provide this condition, it would seem that during the decay, for example, all frequency components should reach the threshold of audibility at the same time. If all the frequency components of speech in a room were of such intensities as to be the same number of decibels above the minimal threshold during the steady state, then during the decay of the speech all components would reach the threshold of audibility at the same time provided the reverberation time were constant for all frequencies. But it is well known that, on the average, the very low frequencies and the very high frequencies in speech are at lower levels than the level of the intermediate frequencies. Thus, the curves in Fig. 51, which give relative values of the average speech level per octave, indicate that the level for both men's and women's voices has a maximum at about 600 cycles, and that it drops off gradually for both lower and higher frequencies. Obviously, then, the reverberation time in a speech room should be shorter at about 600 cycles than at lower or at higher frequencies, and in order that all frequency components reach the minimal threshold at the same instant, the time of reverberation at each frequency should be inversely proportional to the level in decibels at that frequency, that is

$$tS = \text{constant}, \tag{62}$$

where S is the level of the speech (in decibels) at a particular frequency and t is the required time of reverberation at that frequency. Thus, if the speech level be 46 db at 512 cycles and only 23 db at 64 cycles, then the time of reverberation at 64 should be twice as long as the time of reverberation at 512. Thus, if the optimal time at 512 be 1.3 seconds, then the optimal time at 64 should be 2.6 seconds. For frequencies above about 1000, the optimal time should be greater than the optimal time at 512. By means of Eq. (62) and the data contained in Fig. 51, it is possible to construct the *characteristic reverberation curve* which should be best adapted for average speech conditions. Such a curve is shown in Fig. 175 for a room in which the optimal time of reverberation at 512 cycles is 1.3 seconds.

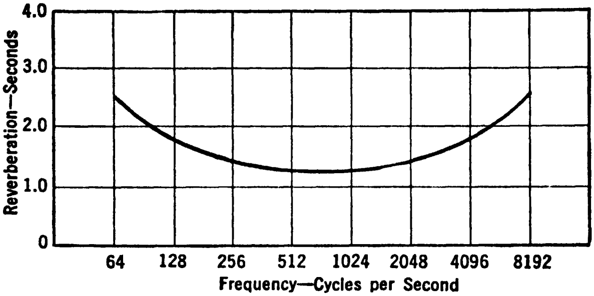

FIG. 175. Reverberation characteristic for a speech room. With such a characteristic the different frequency components of average speech will die away at such rates that all components will reach inaudibility at about the same instant.

Since the time of reverberation is nearly inversely proportional to the amount of absorption in a room, the absorptive characteristic of the average boundaries and contents of the room, in order to give a reverberation characteristic similar to that shown in Fig. 175, should be similar in form to Fig. 176. That is, the absorptive material in the room should have the highest absorption at a frequency of about 600 cycles, and then should diminish for frequencies both below and above that frequency. At 128 and at 4096 cycles the coefficient should be about

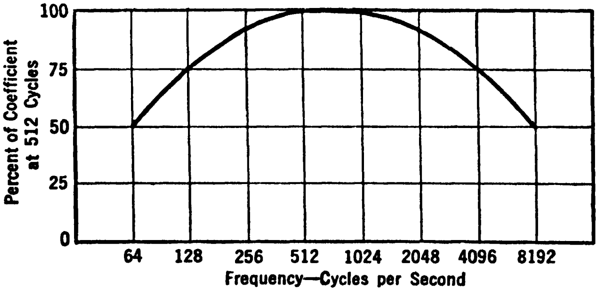

FIG. 176. Absorption characteristic of the boundaries of a room required to give a reverberation characteristic similar to that shown in Fig. 175.

75 per cent of the coefficient at 512 cycles. This would call for absorptive materials somewhat similar to thick hair felt, that is, for materials which are both porous and flexible, so that there would be a rather broad but selective absorption in the frequency range around 512 to 1024 cycles.

MacNair[5] arrives at a somewhat similar result for the optimal reverberation characteristic for a room by proposing the criterion that the loudness of all frequency components should decay at the same rate. In order to recognize the significance of this criterion it is necessary to refer again to Fig. 44, which shows the relation between the loudness and the sound level of pure tones of different pitch. Thus, a tone of 150 cycles which has a sound level of 30 db is judged to be as loud as a tone of 1000 cycles which has a sound level of 50 db. Because of this relation between sound level and loudness, it is necessary that low-frequency components (below 700 cycles) die away more slowly than do high-frequency components if all frequency components of complex sounds are to maintain the same rate of change of loudness during the growth or decay of complex sounds. In order to satisfy this requirement, the absorptive characteristic of the boundaries and contents of a room should be similar to that shown in Fig. 177. That is, the absorptive material in the room (including the audience) should have an increasing coefficient of absorption between 64 and 700 cycles — increasing approximately two fold through this range of frequencies; it should have a constant coefficient for all frequencies between about 700 and 4000; and it should decrease slightly for frequencies above 4000. Such an absorption characteristic is approximately supplied by an audience, and

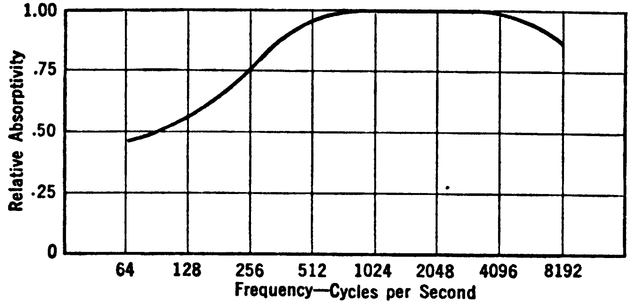

FIG. 177. Absorption characteristic of the boundaries of a room required to give a constant rate of growth or decay of loudness for all frequency components of speech or music.

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[5] W. A. MacNair, "Optimum Reverberation Time for Auditoriums," Jour. Acous. Soc., 1, 242 (January, 1930).

it is a significant fact that an audience of sufficient size provides a highly satisfactory means of reducing the reverberation in rooms which are reputed to possess good acoustics.

This suggests another possible criterion which must not be overlooked in determining the most satisfactory type of reverberation characteristic for a room: namely, that man possesses an inherent preference for the type of reverberation to which he is accustomed, that is, he has become adapted to types of reverberation which have been characteristic of existing rooms. For many generations man has lived in rooms which are finished and furnished with materials which are, as a rule, more absorptive for the high frequencies than for the low frequencies, and consequently he has become accustomed to hearing speech under these conditions — a circumstance which undoubtedly has developed in man an unconscious preference or prejudice in favor of absorptive materials which are more absorptive for the high than for the low frequencies.

All three of the criteria just considered — the frequency distribution of the sound level of speech, the relation between loudness and sound level, and man's adaptation to the acoustical properties of furnished rooms — certainly have a bearing upon the type of absorptive characteristic a material should have in order to give the most satisfactory acoustical properties to a room. All three of these factors suggest that the coefficient of sound-absorption of acoustical materials for speech rooms should increase with the frequency up to about 700 cycles. The first two criteria suggest that the coefficient should increase almost uniformly from 64 to 700 cycles — and the total increase in this range should amount to approximately 100 per cent. That is, if a material have a coefficient of 0.50 at 700 cycles, it should have a coefficient of 0.25 at 64 cycles. For frequencies above about 700, the first criterion (Fig. 176) would suggest the desirability of a decreasing coefficient of sound-absorption, whereas the second criterion (Fig. 177) suggests a preference for a constant coefficient between 700 and 4000 cycles, and a slightly decreasing coefficient above 4000 cycles. A decreasing coefficient for the higher frequencies (above about 1000 cycles) is further indicated by reason of (1) the masking effect which low frequencies have upon high frequencies, (2) the importance which high frequencies possess in preserving the intelligibility and naturalness of speech, and (3) the high absorption in the air of the higher frequencies. A consideration of all the factors which have a bearing upon the type of reverberation characteristic which will be best adapted for the control of reverberation in speech rooms seems to point to a characteristic similar to that shown in Fig. 176. Until further quantitative data are obtained it would seem that materials having an absorptive characteristic similar to that exhibited by Fig. 176 would be the most satisfactory for the acoustical treatment of speech rooms. This characteristic does not differ appreciably from the one proposed by MacNair (Fig. 177) for frequencies below 700 cycles, and the high absorption in the air at high frequencies certainly calls for a decreasing coefficient for frequencies above about 1000 cycles.

Experience indicates that fairly large departures from the reverberation characteristic exhibited in Fig. 176 are admissible without serious impairment of the acoustical quality of speech rooms. For example, speech-articulation tests conducted in two different auditoriums which differed widely in their reverberation characteristics indicate that the type of reverberation characteristic does not have so pronounced an effect upon speech articulation as one might anticipate. Thus, the small circles in Fig. 172 designated by *a* and *b* do not depart appreciably from the smooth curve, which gives the percentage articulation for auditoriums having different times of reverberation at 512 cycles, although the articulation represented by *a* is for an auditorium which showed a nearly uniform absorption characteristic for all frequencies and the articulation represented by *b* is for an auditorium in which the reverberation time is very much longer for low frequencies than for high frequencies. Thus, for the auditorium indicated by *a* in Fig. 172 the time of reverberation was 1.05 seconds at 128 cycles and 0.85 second at 512 cycles. On the other hand, the time of reverberation for the auditorium marked *b* was nearly 5.0 seconds at 128 cycles and 1.9 seconds at 512 cycles. It is true that the articulation in the auditorium marked *a* is slightly better than is indicated by the smooth curve, and the articulation in the auditorium marked *b* is slightly poorer than is indicated by the smooth curve, although the differences are not much greater than the experimental error in obtaining the data. It is thus probable that the departures of the points *a* and *b* from the smooth curve in Fig. 172 are attributable to the manner in which the reverberation varies with pitch; but it should be remembered that since these departures are small it is not probable that those absorptive materials which conform precisely to the *preferred* type of characteristic, such as is represented by Fig. 176, will prove far superior to absorptive materials which are commonly used for acoustical treatment of rooms. However, it seems advisable to give a preference to materials which have absorptive characteristics comparable with the one indicated by Fig. 176, and manufacturers of acoustical materials should attempt to develop ones which will at least approximate the characteristic here proposed. The use of such materials seems desirable for the preservation of naturalness in the quality of speech, even though it may not contribute much to the articulation or intelligibility of speech. Architectural acoustics attains its highest aim in the design of speech rooms only when it imparts to those rooms qualities which give both the optimal conditions for the recognition of speech and also the most favorable conditions for the preservation of the beauty of speech; and the use of materials having the most favorable absorptivity at all frequencies is one expedient for this aim.

D. COMBINED EFFECTS OF LOUDNESS AND REVERBERATION — CALCULATION OF PERCENTAGE ARTICULATION

133. Loudness and Reverberation. In the earlier sections of this chapter the effects of loudness and reverberation upon the hearing of speech in auditoriums have been considered separately. It is obviously necessary to consider the joint effects of these two factors as they are encountered in auditoriums. Thus, it is apparent that as the time of reverberation in an auditorium is reduced the average loudness of speech, assuming the speaker to maintain a constant rate of speech power, will be reduced correspondingly. Since in general the average power of unamplified speech in an auditorium is considerably below the loudness for the optimal articulation, there should be a particular time of reverberation which will give the best choice between reverberation and loudness. That is, the effects of reverberation and loudness, acting jointly, determine the optimal time of reverberation for the recognition of speech in any auditorium. This optimal time of reverberation is attained when a further reduction in the reverberation will concurrently reduce the loudness of the speech to the extent that the impairment produced by the diminished loudness will just compensate for the improvement

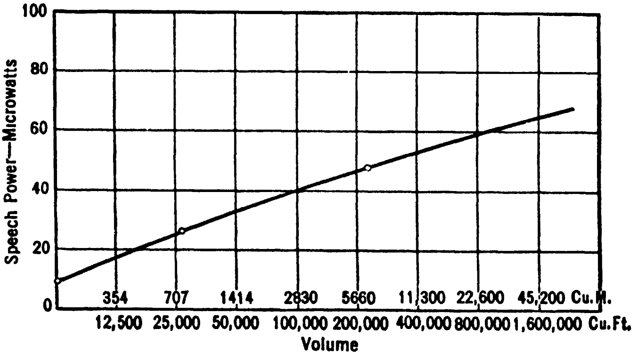

Fig. 178. Curve showing the probable speech power in auditoriums of different sizes.

occasioned by the reduction of the reverberation. The manner in which this occurs is indicated by the data given in Table XXXVI, which applies to an auditorium having a volume of 400,000 cubic feet. In the first column is given the time of reverberation in the room at a frequency of 512. The average speech intensity, expressed in terms of the minimal audible intensity of speech, is given in the second column. The data in the table are based upon the assumption that the average speaker will maintain an average speech power output of 54 microwatts, which is the value obtained from the curve in Fig. 178. It will be noted that the average speech intensity has been taken as proportional to the time of reverberation in the room, that is, inversely proportional to the total amount of absorption in the room. (This assumes that the steady state has been reached, which is approximately the case. It also assumes the Sabine reverberation formula, which is sufficiently accurate for these calculations.) The third column in Table XXXVI gives the average level of speech in the auditorium, expressed in decibels. The value of the loudness-reduction factor is given in the fourth column (obtained from Fig. 170), and the value of the reverberation-reduction factor (obtained from Fig. 173) is given in the fifth column. In the last column is given the product k_lk_r. The percentage articulation in the room, according to Eq. (60) which includes the factor k_lk_r, is therefore proportional to the values given in this last column.

TABLE XXXVI

Volume of auditorium = 400,000 cubic feet (11,330 cubic meters).
Average speech power = 54 microwatts.

Time of Reverberation in seconds	Average Speech Intensity*	Average Speech Level in decibels	k_l	k_r	k_lk_r
0.50	0.665×10^4	38.2	0.850	1.00	0.850
0.75	1.00	40.0	.874	.993	.868
1.00	1.33	41.2	.885	.982	.870
1.25	1.66	42.2	.894	.967	.865
1.50	2.00	43.0	.900	.953	.858
2.00	2.66	44.3	.910	.924	.840
3.00	4.0	46.0	.925	.837	.775
4.00	5.3	47.3	.936	.752	.704
6.00	8.0	49.0	.950	.600	.570
8.00	10.6	50.3	.959	.510	.489

* The speech intensity is given in terms of the minimal audible speech intensity.

It will be noted that the product $k_l k_r$ has a maximum for a time of reverberation of 1.00 second; that the product decreases only slightly for times of reverberation below 1.00 second; and that it decreases appreciably for times of reverberation above 1.00 second. However, the product does not vary appreciably for times of reverberation between about 0.75 and 2.00 seconds, indicating that throughout this range the benefit derived from reducing the reverberation is approximately nullified by the concomitant reduction in loudness. It is possible to obtain data similar to those given in Table XXXVI for an auditorium of any size and any time of reverberation. The procedure would be as follows: First determine from Fig. 178 the probable speech power of the average speech in the room, and, assuming that the speaker maintains this power output for different times of reverberation, calculate the resulting level of speech in an auditorium of this size for different times of reverberation. The values of k_l and k_r can be determined directly from the curves in Figs. 170 and 173, respectively. The optimal time of reverberation is then the time for which the product $k_l k_r$ is a maximum.

134. Hearing of Speech in Auditoriums — Calculation of Percentage Articulation. It was found in the preceding section that loudness and reverberation influence speech in such a way that there is an optimal time of reverberation for the hearing of speech in an auditorium of a certain size. It is to be anticipated that more reverberation will be tolerated in large auditoriums than in small ones simply because the increased reverberation promotes loudness. For auditoriums of conventional shape, that is, of the rectangular type, so that there are no outstanding defects, such as sound foci, echoes, or long-delayed reflections, the value of k_s will be approximately 1.0. Further, if it be assumed that the noise in auditoriums has been reduced to a relatively low level (about 13 db), so that the intensity level of residual noise is only one fourth of the intensity level of the speech, the value of k_n will be 0.96. Then Eq. (60) becomes[6]

$$\text{P.A.} = 92.2 k_r k_l \qquad (60')$$

By means of this equation, it is possible to calculate the probable P.A. in auditoriums of different sizes. The curves in Fig. 179 have been determined by means of this equation and a series of tables similar to Table XXXVI. The curves in Fig. 179 indicate the probable values of P.A. in auditoriums of different sizes and with different times of reverberation. Thus, curve (*a*) is for an auditorium having a volume of 25,000 cubic feet, and times of reverberation from 0.5 second up to 8.0 seconds. In like manner, curves (*b*), (*c*), (*d*), and (*e*) give the probable values of

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[6] The abbreviation P.A. will be used for percentage articulation.

P.A. in auditoriums having volumes of 100,000 cubic feet, 400,000 cubic feet, 800,000 cubic feet, and 1,600,000 cubic feet, respectively. If an articulation of 75 per cent be regarded as the minimal admissible articulation for satisfactory hearing in an auditorium, and such a limit seems to be pretty well established by experience, it is apparent that the average speaker will not be heard satisfactorily in an auditorium larger than about 1,000,000 cubic feet, no matter what condition of reverberation has been provided for the auditorium.[7] In an auditorium as large as 800,000 cubic feet, the reverberation should not exceed about 1.95 seconds if the P.A. is to be above the critical value of 75 per cent. Similarly, in order that the P.A. be not less than 75 per cent in an auditorium having a volume of 400,000 cubic feet, the time of reverberation should not exceed 2.35 seconds; and in an auditorium having a volume of 100,000 cubic feet the time of reverberation should not exceed 2.70 seconds. In general, the times of reverberation just specified are the longest which can be tolerated, that is, they indicate the longest admissible times of reverberation (with the smallest audience present) for satisfactory hearing. All these conclusions are based upon the assumption that noise has been reduced to a relatively low level, and that there are

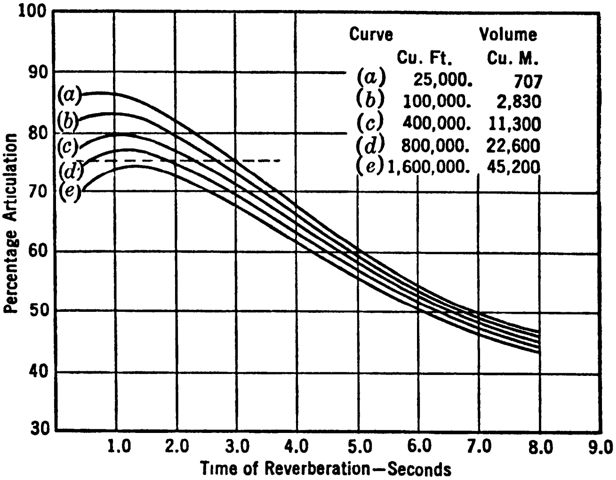

Fig. 179. Percentage articulation curves in auditoriums of different sizes and with different times of reverberation. These curves indicate that there is an optimal time of reverberation for the hearing of speech in an auditorium of a certain size.

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[7] With absolute quiet in the room and with a speaker with a loud and distinct voice it may be possible to hear satisfactorily in an auditorium as large as 1,000,000 cubic feet, but under the conditions ordinarily met in practice the hearing of unamplified speech will be unsatisfactory in auditoriums of this size.

no defects from shape, such as echoes or interfering reflections. In the presence of greater noise, or other defects, it may be advisable to reduce the upper limits of reverberation times somewhat below those indicated in the foregoing discussion.

It should be borne in mind that the curves in Fig. 179 apply to the average speaker, and that speakers with weak voices will not be heard so well as is indicated by the curves. The curves in Fig. 180 have been calculated for different speakers in the same auditorium — one having a volume of 400,000 cubic feet. These curves apply to a group of fourteen instructors in the University of California at Los Angeles. Curve (*f*) is for the speaker with the weakest voice in the group of fourteen. It will be seen that the articulation for such a speaker, even under the most favorable listening conditions in this auditorium, does not exceed 70 per cent. It is to be expected therefore that such a speaker would not be heard satisfactorily in an auditorium of 400,000 cubic feet, and in this particular case experience confirms the expectation. On the other hand, the curve marked (*b*) is for the loudest speaker in this group of fourteen, who should be, and is, readily heard in an auditorium of 400,000 cubic feet. The curve marked (*e*) is for the average of the four weakest, and that marked (*c*) for the average of the four loudest, speakers tested. The curve marked (*d*) is for the average of all speakers. It will be noted that the louder speakers are heard very much better than the

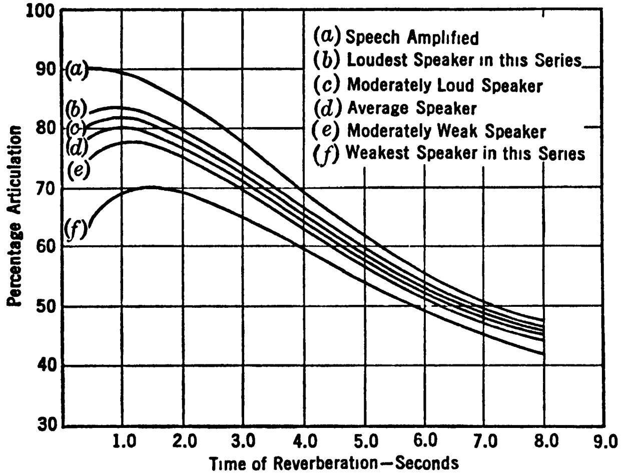

FIG. 180. Group of curves showing how the loudness of a speaker's voice affects the hearing of speech in auditoriums. These curves are for a rectangular auditorium having a volume of 400,000 cubic feet. The loudness of a speaker's voice is seen to be an important factor.

weaker ones — the highest articulation for the loudest speaker is 84 per cent as compared with 70 per cent for the weakest speaker. This difference is quite significant, inasmuch as an articulation of 75 per cent is required for satisfactory hearing. It explains quantitatively why some speakers are heard very nuch more satisfactorily than others. It also will be noted, by referring to the curves in Fig. 180, that the optimal time of reverberation is different for different speakers even in the same auditorium, varying from about 0.85 second for the loudest speaker to 1.50 seconds for the weakest. However, a time of reverberation of about 1.0 to 1.25 seconds will quite satisfactorily approximate the optimal hearing conditions for all speakers.

Curve (*a*) in Fig. 180 has been calculated upon the assumption that the speech has been amplified, without distortion, to a level of 60 db, with a background of noise of only 15 db, and with a time of reverberation of 1.0 second. The advantage of such distortionless amplification of speech is clearly indicated. Thus, when the time of reverberation is less than 1.0 second the articulation is 90 per cent, which can be regarded as practically perfect for the hearing of speech. This curve shows that suitable amplifiers, such as public address systems, provided they are free from distortion and noise, are of great value in large auditoriums. At times, such amplifiers are also beneficial in smaller auditoriums, especially if the auditorium is beset with disturbing noise, or if some of the speakers who use the auditorium have weak voices.

135. Optimal Time of Reverberation for Speech Rooms. In the design of auditoriums it is of the utmost importance to know to just what extent the reverberation should be reduced in order to secure the most nearly ideal acoustical properties. In rooms which are intended for speech, the chief consideration is to provide the condition which will enable the listeners to hear speech with the greatest ease and accuracy. There is, of course, the other factor which should receive consideration, namely, the naturalness or the euphony of the speech. This would apply particularly to rooms which are intended for dramatic purposes, where it is necessary to secure a certain dramatic effect or an atmosphere of reality; if a room be either over-treated or under-treated it may lose some of these characteristics of naturalness or reality. However, it is a prime essential that the speech be heard clearly and easily, and if the room be adjusted to provide the highest possible P.A., it is not likely that the room will be so dead as to be *oppressive* — a complaint which is sometimes made against rooms which are highly damped, as radio broadcast or talking-picture studios.[8]

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[8] The experience of the author indicates that these *complaints* are made by people who are accustomed to fairly *live* rooms, and that even those who at first register

It will be noted that the curves in Fig. 179, which give the probable values of the P.A. for the average speaker in auditoriums of different sizes, all have well-defined maxima. These maxima occur at reverberation times which depend upon the size of the auditorium — varying from somewhat less than 1 second for small auditoriums to about 1.5 seconds for rather large auditoriums. Obviously, these maxima give the optimal times of reverberation that a room should have if the sole consideration is that of providing conditions which will enable the listeners to hear speech with the least effort and with the highest intelligibility. The curve in Fig. 181 was obtained by plotting the times for the maxima in Fig. 179 as a function of the size of the auditorium, and therefore this curve gives the time of reverberation which an auditorium should have in order that unamplified speech be recognized with the greatest ease and accuracy. Class rooms, lecture rooms, court rooms, dictation rooms, and all rooms where it is important that speech be heard with the fewest possible errors, should be designed to have times of reverberation approximately equal to those given by the curve in Fig. 181. In theatres, churches, school auditoriums, or other rooms which are used for both speech and music, the optimal time of reverberation is about 25 to 50 per cent greater than the time given by the curve in Fig. 181. It should be remembered that this curve gives the optimal time of reverberation for a tone of 512 cycles, and the times of reverberation at other frequencies should have approximately such values that the reverberation characteristic for the room will be similar to that indicated in Fig. 175.

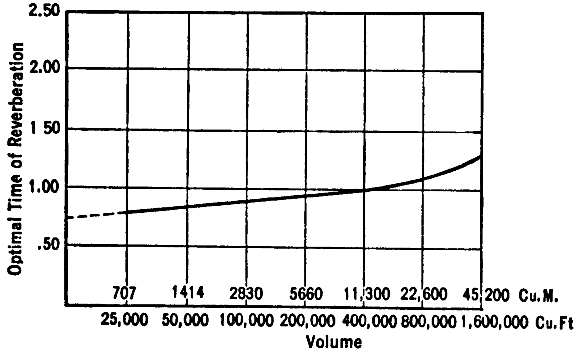

FIG. 181. Curve giving the optimal time of reverberation (at 512 cycles) for the hearing of speech in auditoriums of different sizes.

complaints soon not only become adapted to *dead* rooms but find them very much to their liking. The author also has observed that it is only about rooms treated with thin, porous materials, that is, with materials which are selectively absorptive for high frequencies, that complaints concerning the *oppressive* feeling are made.

Finally, the low periods of reverberation based upon the theory and experiments described in this chapter should be obtained by the use of absorptive materials located on surfaces near the audience, and the surfaces near the speaker should be finished with reflective materials. Rooms treated in this manner meet the highest requirements for both speaker and listener.

136. Nature of the Errors in the Recognition of Speech in a Large and Reverberant Room. In the preceding sections of this chapter the errors in the recognition of speech were not classified with respect to the nature of the errors; that is, *all* the errors were simply counted in determining the percentage articulation. However, it is of interest to know something about the *nature* of the errors as well as the number of errors which are made when one listens to the average speaker.

The errors in the recognition of speech in an auditorium which has a time of reverberation of about 5.0 seconds and a volume of 225,000 cubic feet are classified in Table XXXVII. In this particular auditorium the total number of monosyllabic speech sounds which were used in the tests numbered 2200. Of this total number of called speech sounds, 1213, or 51.5 per cent, were recognized correctly. The total number of consonants in these 2200 speech sounds was 4048, of which 3093, or 76.4 per cent, were recognized correctly. Similarly, of the total 2200 vowel sounds, 2052, or 93.3 per cent, were recognized correctly. The total number of consonant errors was 955. Of these, 529 were final consonants, 224 were initial consonants, 117 were omissions of the called consonants, and 85 were additions which were not called. The preponderance of the errors among final consonants is noteworthy, and is probably the result of the masking produced by the reverberation of the preceding vowel.

A complete tabulation of the consonant errors which occurred in the tests in this one auditorium is given in the table. The first column gives the consonant called; the second gives the number of times it was called. The next 24 columns give the classification of errors — " Omission " meaning that it was erroneously omitted, and " Addition " that it was erroneously added. For example, *ng* was heard as *m* 21 times, as *n* 41 times, was omitted 14 times, but was never added (in error), or heard as *ch*, *f*, or *h*. The last two columns give the total number of errors and the percentage of errors for each consonant. It will be seen that *ng* was mistaken more frequently than any other sound — 94 times out of 176, or 53.4 per cent of the total number of times it was called. Similarly, *d* was mistaken 42.7 per cent, and *v* 39.2 per cent, of the total number of times they were called. On the other hand, such consonants as *r*, *s*, *w*, and *y* were rarely mistaken. Thus, *y* was mistaken only 5.1

per cent, and *w* only 6.2 per cent, of the total number of times they were called.

TABLE XXXVII

Sounds Called	No. of Times Called	Classification of Errors																								Total No. of Errors	Per cent Errors
		b	ch	d	f	g	h	j	k	l	m	n	ng	p	r	s	sh	th	t	v	w	y	z	Omission	Addition		
b	220		1	6	1	6	2		2	1	5			1		1	2			12	2			5	5	52	23 6
ch	176								5								3	1	4						1	14	8 0
d	220	14			1	22	1	1	1	1	1	4	2		2				4	9				19	12	94	42 7
f	176	10					2		6		1	1		4		1		13	7	11				8	4	68	38 6
g	176	8	1	11				2		3	1	2	5		3			1		4		1	1	14	5	62	35 2
h	176	1			1				4					2					2					14	4	28	15 9
j	176		7	4		17										4	1		1	1		6	3	1		45	25 3
k	176		3		2	2	10											1	10					1	13	42	23 9
l	176			1		3														1			1	7	4	17	9 7
m	176	15		2		3	3			1		11	6		1					2		1		3	1	49	27 9
n	176	1		4	1					1	18		5					2						2	6	40	22 7
ng	176	1		1		9				5	21	41								2				14		94	53 4
p	176	4			6	1	16		7									1	5					2		42	23 9
r	220	4		1		1				6											1			1	2	16	7 28
s	176				1	2												3	3				5		1	15	8 5
sh	176		11	1				1						1		2		1	2					1		20	11 4
th	176	4		6	19	2			10	1			1	1		3			10				2	7	2	68	38 6
t	220	1	1		2		13	1	16					3		1	1			1				5	18	63	28 6
v	176	33		5		8	1			1	1	1			1			2						9	7	69	39 2
w	176	1									4									3		2		1		11	6 25
y	176					6	1	1				1														9	5 1
z	176			5						1		2				9		3	2	11		1		3		37	21 1
	4048	97	24	47	34	82	49	6	51	21	52	63	19	12	7	21	7	28	50	57	3	11	12	117	85	955	23 6

Public speakers, and instructors in oral expression, could make a substantial contribution to the problem of hearing in auditoriums if they would utilize this information in the training of the speaking voice. If speakers are aware of the nature of the errors of speech which occur in auditoriums, they will make a conscious effort to place appropriate emphasis upon those sounds of speech which give the greatest difficulty, and especially upon such consonant endings as *ng*, *d*, *v*, *f*, and *th*, which are responsible for a large portion of the complaints concerning poor acoustics in speech halls.

137. Hearing of Speech in Auditoriums — Summary. By means of the data and curves which have been described in the preceding sections it is possible to ascertain how well speech will be heard in any auditorium; or to assess, in advance of construction, the acoustical merits of rooms which are intended primarily for speaking purposes. Thus, it is possible to determine quantitatively the effects of size, reverberation, and noise in all speech rooms, and to specify the requirements and limitations for these rooms in order that they shall attain a specified degree of acoustical excellence. For example, suppose it is desired to design a lecture hall without a balcony which will seat 600 persons, and which will have an average speech articulation of not less than 80 per cent with 200 or more persons in the hall — a specification which will provide very satisfactory conditions for the hearing of speech. From the curves in Fig. 179, it would seem necessary, or at least desirable, to design a room having a volume of not more than 100,000 cubic feet. If 7 square feet be allowed for each person, the floor plan should have an area of 4200 square feet. This would allow a ceiling height of about 24 feet, which would provide a room having a volume of 100,800 cubic feet. Referring again to Fig. 179, it will be seen that for an auditorium having a volume of 100,000 cubic feet, the time of reverberation must not exceed 1.85 seconds in order to keep the speech articulation in excess of 80 per cent. This time should be provided for the smallest possible audience the room is to accommodate. It is also necessary to take such measures for the insulation and prevention of noise as will reduce the residual noise in the hall to about 10 to 15 db. If the lecture hall be designed within the limits just specified, the hearing conditions in the room will meet the preassigned requirements.

A consideration of the effects of shape, size, reverberation, and noise upon the hearing of speech in auditoriums indicates that ideal or perfect acoustics is only a relative condition, and that no matter what may be done for the improvement of the hearing conditions in an auditorium the speech articulation will not attain a degree of perfection higher than that indicated by Eq. (60). Those who expect to hear perfectly the unamplified speech of the average speaker in very large auditoriums expect the impossible. For example, it would seem that the best condition for the hearing of speech in a room having a volume of 400,000 cubic feet would be attained when the reverberation time was reduced to 1.0 second, and that the articulation would then be about 80 per cent.[9]

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[9] It should be remembered that the articulation data in this chapter apply to the conventional rectangular auditorium which does not possess the advantages of the special or auditory shapes advocated in Chap. XVI. If the shape of the auditorium be designed so as to utilize the full benefits of reflected sound it may be possible to

If better hearing conditions are required, provision should be made for the artificial amplification of speech.

By means of Eq. (60), and the curves for evaluating k_l, k_r, and k_n, it is possible to determine whether any proposed design for a speech room will be feasible, and if feasible to specify the requirements for the room in order that the percentage articulation will attain a prescribed degree of excellence. The problem of the acoustical design of speech rooms is therefore removed from the realm of uncertainty and placed upon a secure basis of quantitative calculation. Many examples of the usefulness of the theory and facts discussed in this chapter, and typical methods of calculation in the design of buildings will be given in Part III of this book, which deals with practical problems of design.

secure a speech articulation 3 or 4 per cent greater than is indicated by the curves in Fig. 179.

CHAPTER XVIII

THE ACOUSTICS OF MUSIC ROOMS — FUNDAMENTAL PRINCIPLES AND CONSIDERATIONS

138. Introductory. In the three preceding chapters it was shown that the acoustical properties of speech rooms could be determined quantitatively from a consideration of such factors as size, shape, reverberation, and noise. Obviously these same factors are largely determinative of the acoustical properties of music rooms, but their influence is not amenable to precise evaluation. Nearly everyone has certain notions about the acoustics of music rooms, and the most casual inquiries will reveal that these notions are not always in accord with each other. For example, some people declare their preference for music as heard in the open air, whereas others, especially the critics of music, avow a definite preference for music as heard in a concert hall. This is to be expected in an art which is so extensive and so diversified as music, since there are certain parts of musical compositions — sweet, melodious, and of a rippling character — that will sound better in the absence of reverberation, whereas there are other parts of musical compositions — harsh, discordant, or of a sustained character — that will sound better in a reverberant room. However, there is a general unanimity of opinion with regard to a number of fundamental principles, and these principles should guide the design of music rooms in such a manner as will provide the optimal conditions for (1) the preservation of the naturalness of musical sounds, and (2) the enrichment of the tonal quality and tonal blending of musical sounds.

A properly designed music room is more than a work of science; it is as well a work of art. It should provide not only the proper conditions for listening to music so that the auditors obtain the best possible musical effect, but also the best possible conditions for the generation of music. It is necessary therefore that the acoustical conditions of a music room be adjusted to satisfy the requirements both of the performers and of the listeners — requirements which are not in general identical. Every one must have noticed that certain rooms are acclaimed by performers who state that it is easy to play or sing in those rooms, whereas auditors will complain of the acoustical conditions in the same rooms. It appears that the performer desires a more reverberant space than does the listener. The performer wishes to feel the reenforcement, the resonance, and the support which are provided by highly reflective surfaces in fairly close proximity to him. The listener, on the other hand, is interested primarily in the quality of the sound which reaches him. He wishes all the frequency components of music to be properly preserved and blended. Both performers and listeners desire a certain amount of reverberation in music rooms. Whereas the chief function of reverberation in speech halls is the promotion of loudness, it appears that reverberation has a more important role in the acoustics of music rooms — it adds fullness, roundness, color, and harmony to music, and for this reason reverberation of the proper type and amount is an indispensable property in all music rooms.

139. Rating of Music Rooms. It was found in Chap. XV that the percentage speech articulation afforded a fairly satisfactory manner for giving a quantitative rating to speech rooms. It is not so simple a matter to give a quantitative rating to music rooms, since so much depends upon the musical taste and disposition of the listeners. The rating of music rooms is not a purely physical problem which can be solved by the physicist alone. Its complete solution will require the cooperation of physicists and musicians, and it may be necessary to seek the help of psychologists and estheticians.

But the solution of the problem, however complicated, is not without hope. It is true that the acoustical design of music rooms will have to depend upon the dictates of musical taste — a criterion which may not admit of accurate definition, or even be the same for different individuals. But such experiments as have been performed indicate that the musical tastes of different listeners are in fairly good agreement, at least in their choice of the optimal time of reverberation for a specific type of music. For example, in the tests of W. C. Sabine in the New England Conservatory of Music, a committee of six competent music instructors were in remarkably good agreement in determining the optimal time of reverberation for piano music in small music rooms. The tests in five different rooms, which varied in volume from 2600 cubic feet (74 cubic meters) to 7400 cubic feet (210 cubic meters), indicated that in order to secure the best effect for piano music the reverberation time at 512 cycles should be approximately 1.08 seconds. The shortest approved time of reverberation was 0.95 second, and the longest approved time was 1.16 seconds. The maximal departure from the mean was therefore 0.13 second, and the average departure from the mean was only 0.05 second. Later investigations by Watson,[1] Lifschitz,[2] P. E. Sabine,[3] and others have

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[1] F. R. Watson, "Acoustics of Buildings," second edition, 34 (John Wiley & Sons, 1930).

[2] Samuel Lifschitz, Phys. Rev., **27**, 618 (1926).

[3] P. E. Sabine, Trans. of S. M. P. E., **12**, 35 (1928).

confirmed this finding of W. C. Sabine, and have found that as the volume of the room increases the optimal time of reverberation increases, reaching a value of slightly more than 2.0 seconds for very large rooms.

140. Requisites for Ideal Acoustics in Music Rooms. Since the acoustical requirements for the performer in a music room are not necessarily the same as those for the listener, the requisites for the production of music and for the listening to music will be considered separately, although it is obvious that many of these requisites are common to both the generation and the reception of music. The ideal conditions for the artistic production of music may be classified as follows:

1. The performers should not be distracted by noise, whether of inside or outside origin.
2. The spaces for the orchestra, soloists, chorus, organ (if there be one), and audience should be arranged and articulated *acoustically.*
3. Provision should be made for the reenforcement of sound by reflection and resonance from suitably designed boundaries in the proximity of the stage or platform, thus giving support to the generation of music, and making it easy to sing or play. This will also allow each musician to hear his own music blended with the composite music from the ensemble.
4. Proper reverberation and resonance should be provided, so that each note will persist long enough to enable the artist to determine precisely the true pitch of the following tone; and so that all the frequency components of music will be sufficiently emphasized and prolonged to give a true and natural balance between bass and treble without undue effort on the part of the artist.
5. There should be no conjugate foci in the orchestra or stage space, and no echoes or interfering reflections from the rear wall, ceiling or elsewhere.
6. The acoustical properties of the room should be independent of the size of the audience; that is, the acoustical quality of the room should be approximately the same for rehearsing as it is with partial or capacity audiences.

The ideal conditions for listening to music may be classified as follows:

1. The audience should not be disturbed by noise.
2. Provision should be made for proper loudness. This involves the size of the room and the amount of absorptive material used in it.
3. Provision should be made for the reenforcement of sound by reflection from suitably designed boundaries in the proximity of the audience, thus giving a nearly uniform distribution of sound in all parts of the room.

4. Proper reverberation and resonance should be provided, so that all the frequency components of music will be sufficiently emphasized and prolonged to satisfy the highest standards of competent listeners. Reverberation must be prominent enough to sustain harmony and enrich tonal articulation, but not so prominent as to impair the individual character and beauty of each tone or chord in rapidly moving music.

5. There should be no echoes, interfering reflections, or sound foci in any part of the auditorium.

6. The acoustical properties of the room should be independent of the size of the audience in the room.

A number of these conditions are so obviously essential that it is almost banal to mention them, and yet experience too frequently demonstrates that even the most obviously essential conditions have been completely ignored or violated in the design of music rooms.

For the sake of clarity in analysis, the conditions for the generating of music and for the listening to music have been mentioned separately. Now, for the sake of unity and economy, many of these conditions will be considered from the standpoint of both generating and listening.

141. Freedom from Noise. It often happens that the problem of noise insulation in music rooms is overlooked, or is approached in a purely empirical manner. In the ideal music room, noise either of outside or inside origin should be reduced to a level of not more than 10 to 15 db, which is about as quiet as it is possible to maintain a room with an audience, owing to such unavoidable noises as breathing, rustling of clothing, and moving in seats. Measurements in many existing concert halls and other music rooms reveal that noise from outside traffic, from the ventilating equipment, from the organ blowers, or from other apparatus in the building often reaches a level of 30 db or more. Such noises are disturbing to both performers and listeners, and mask many of the more delicate tonal components which impart the finest quality to music. It is possible and feasible to make measurements of the noise level in the neighborhood of the proposed site for any music room, and then design the boundaries of the room so as to reduce these noises to the required level.[4] All equipment in the building, and especially the ventilating machinery, the organ blowers, and the elevators, should be installed in such a manner as to reduce the noise they produce to a level of 10 db or less. These problems of noise reduction can be placed upon an engineering basis, and by suitable caution in designing the building

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[4] For a method of calculating the amount of insulation supplied by various types of structure, involving doors and windows, see Sec. 106.

and selecting the equipment it is possible to provide rooms which will be free from noise — a condition of prime importance in all music rooms.

142. Arrangement of Spaces for Orchestra, Soloists, Chorus, Organ, and Audience. The arrangement of the several spaces in a music room allotted to orchestra, soloists, chorus, organ, and audience is largely an individual problem which must be worked out for each room, or at least for each type of room. As specific arrangements for different types of music rooms will be recommended in Chap. XXIV, only a few general principles will be mentioned in this section. The several spaces in any one room should be properly articulated, and should be adapted to function acoustically in the best possible manner. For example, the orchestra, stage, and audience, in the usual theatre type of auditorium, should be so arranged that the orchestra will be heard on the stage with sufficient loudness and will not be heard by the audience so loudly as to mask the singing on the stage. This defect is often encountered in the conventional opera and musical comedy houses: the singers on the stage will complain that they cannot hear the orchestra, and at the same time the audience will complain that they hear nothing but the orchestra. The deep orchestra pits, partly extending under the stage, as found in Wagner's opera house at Bayreuth, in the National Theatre at Oslo, Norway, in the Royal Opera House at Vienna, and in the Royal Hungarian Opera House at Budapest, are certainly desirable at least from the standpoint of the audience — the singing from the stages of these opera houses is not masked by the orchestra, as is so commonly the case in opera houses with shallow orchestra pits. Further, when the brass instruments are located in the rear and bottom of the pit (as in the Wagner opera houses) there are no complaints about the " brass being too loud." The use of a glass screen of adjustable height between the orchestra pit and the audience will help to give a proper division of orchestral sound between the stage and the audience. Additional sound can be obtained on the stage, if needed, by providing an adjustable grille or opening between the stage and the orchestra pit.

The audience should not be located too near the orchestra or stage; otherwise some seats are likely to receive an undue amount of energy from near-by instruments in comparison with the energy which they receive from more remote ones. An auditorium with diverging walls, with the orchestra and stage located at the narrow end of the room, and with a separation of at least 20 feet between the first row of seats and the orchestra, will help to overcome this defect. If for economical reasons the audience must be seated nearer to the orchestra than about 20 feet, as in the theatre type of music room, the deep orchestra pit with a fairly high partition between orchestra and audience will effectively accomplish the desired separation. In rooms for oratorio the orchestra and the chorus should occupy a compact and carefully articulated space. Each person in the orchestra or chorus should be located within about 65 feet from every other member, otherwise there will be a noticeable lack of synchronism.

The best location for the organ is behind the chorus and the orchestra, and the organ should face the audience, so that it speaks directly into the main part of the room. This is usually possible in concert halls, but difficulties are often encountered in church and theatre buildings. In many churches, however, the organ may be located behind and just slightly above the altar. If concealed with a suitable grille, it will not interfere with the beauty and the favored location of the altar. In the theatre, the division of the organ on the two sides of the proscenium opening is probably the best location, although such a location is not based upon the sole interests of the organ but becomes a necessity in order to leave the stage opening free for other purposes. For this reason, as well as certain other reasons which will be discussed later, organ music does not sound so good in a theatre as it does in a properly designed church or in a concert hall.

143. Proper Loudness — Size and Absorption of Room. Experience with different kinds of music in small rooms indicates that the preferred or most favorable loudness level of music is at an average of about 68 db. In order to maintain this loudness level in a room having a volume of 3500 cubic feet (100 cubic meters) and a reverberation time of 1.0 second at 512 cycles, the source should have a power of approximately 200 microwatts. This corresponds approximately with the power output of two average singers or two average musical instruments, although the power output from either singers or instruments may at times exceed this value a hundred fold, and at other times they may attain only one one-hundredth of this power. If a sound level of 68 db provide an acceptable average loudness effect, and if each singer or instrument generate on the average an acoustical power of 100 microwatts, it would be a simple matter to determine the acceptable size of a room which is to accommodate, as a rule, a specified number of singers or instruments. Thus, if 68 db be considered the optimal sound level, and 1.0 second the optimal reverberation time, a room having a volume of 1,060,000 cubic feet (30,000 cubic meters) would require about 500 instruments or singers; or an orchestra of 100 would have to be crowded into a room of about 200,000 cubic feet (5700 cubic meters). But experience seems to favor a time of reverberation in excess of 1.0 second in very large rooms — partly because we are accustomed to reverberant rooms and partly because the longer reverberation time seems to compensate for the diminished loudness. For practical reasons it is not feasible to have an orchestra as large as 500, nor is it customary to have large rooms with a reverberation time as short as 1.0 second. Some sort of compromise must be made, and the one recommended by F. R. Watson,[5] namely, that the energy of the source of sound should vary as the two-thirds power of the volume of the room, that is approximately as the floor area of the room, seems to offer a satisfactory guide in determining the most favorable size of room for a certain number of instruments. On this basis, a room having a volume of about 1,000,000 cubic feet would require a source of sound having a power of about 9400 microwatts, or an orchestra of about 94 pieces. The question of the optimal size of a music room, however, should be subjected to further experimentation before a final answer is given. But there is no urgent necessity for modifying the present practice, which conforms pretty closely to the conditions proposed above. It should be remembered that a two or three fold variation in the size of a room involves an intensity change of only 3 to 5 db in about 65 db. Further, the difference between a single instrument, as may be used in solo work, and 100 instruments, as in a symphony orchestra, is a difference of not more than 20 db, and usually is much less than this because a soloist always attempts to generate an adequate amount of energy for the room in which he is performing, and on the average his power output is in excess of 100 microwatts. Thus, an average power output of 500 to 1000 microwatts is a more probable value for a soloist or a single instrument in a very large hall. For these reasons, it is apparent that there is considerable latitude in choosing the most favorable size of music rooms. Experience has shown that if a small studio have a volume of about 3500 to 18,000 cubic feet, if a recital hall have a volume of about 18,000 to 100,000 cubic feet, and if a concert hall have a volume of about 180,000 to 1,000,000 cubic feet, entirely acceptable conditions will prevail from the standpoint of volume or loudness of sound, provided of course that the reverberation has been properly adjusted. As would be expected, oratorio, with combined orchestra and organ, requires a very large room, probably of the order of 500,000 to 2,000,000 cubic feet. The most sublime effects of oratorio can be obtained only in spacious rooms.[6]

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[5] F. R. Watson, "Acoustics of Buildings," 37 (John Wiley & Sons, 1930).

[6] Some observations and quotations of J. B. Upham (Amer. Jour. Science, **65**, 358 [1853]) are of interest in this connection. He quotes the following significant remark of Gardiner: "Who has not observed the peculiar lustre imparted to a musical performance in a spacious church, which heard in other situations would give the ear no pleasure?" Dr. Upham (a physician in Boston) possessed some remarkably advanced and accurate notions concerning the acoustics of music rooms, especially with respect to reverberation and resonance. (See Sec. 5.)

144. Proper Reverberation Characteristics. Many musicians, especially those who do not have an absolute sense of true pitch, depend upon reverberation to sustain one tone long enough to determine the true pitch of the following tone. (This of course applies primarily to instruments of the violin or the trombone type which have no fixed keys or frets, but it also applies to the brass and wood-wind instruments where the pitch can be slightly altered by the nature of blowing.) Further, the reverberation in the generating end of the room should be sufficient to give support and balance to the generation of music, to enable each performer to hear his own music as well as that from all his associates, and to impart to the music that life and brilliance which can come only with a proper amount of reverberation. Finally, the reverberation should have such a frequency characteristic as will give a natural balance between bass and treble notes, without a strained effort on the part of the performers.

The problem of the optimal time of reverberation from the standpoint of the listeners has attracted the attention of many investigators. Many attempts have been made to determine the optimal time of reverberation for rooms of different size, and some attempts[7] have been made to determine the most favorable relation between reverberation time and frequency.

145. Variation of Reverberation Time with Frequency. The variation of reverberation time with frequency will be considered first. This problem is similar to the one already discussed in Sec. 132 in connection with speech rooms. A number of questions arise, similar to those already considered in that section. What criteria should be adopted in determining the most favorable reverberation characteristic for a music room? Should the reverberation time be the same for all frequencies? Should the reverberation characteristic be what we are accustomed to — a composite made up of the absorption characteristics of the audience and the boundaries of the room? Should it be based upon the frequency distribution of sound energy in music, so that all components of music, on the average, will die away to inaudibility in the same length of time? (This was essentially the criterion recommended for speech rooms.) Should it be based upon the physiological relation between loudness, intensity, and frequency, so that the rate of growth or decay of loudness will be the same for all frequency components, as proposed by MacNair? Or should the reverberation time increase as the frequency increases, as suggested by Wente?[8] The second, third, and fourth criteria mentioned are all quite opposed to the first and the fifth criteria

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[7] W. A. MacNair, *loc. cit.*

[8] E. C. Wente, Amer. Arch. (August 20, 1928).

— that of a uniform reverberation time for all frequencies, and that of a reverberation time which increases with the frequency. There seems to be good reason to rule out both these criteria, since they would overemphasize many of the higher partials or overtones. Fortunately, the other three criteria lead to conclusions which are not widely divergent. This has already been shown for speech rooms, and if the frequency distribution of sound energy in music is, on the average, comparable with the distribution in speech, we should expect the optimal reverberation characteristic for music to be comparable with that which has been proposed for speech. It remains then to determine the frequency distribution of sound energy in average music, from which it is possible to determine the type of reverberation characteristic which would be required by the third criterion, that is, the characteristic which would make all frequency components in music, on the average, decay at such rates that they would reach inaudibility at the same instant. From the curve in Fig. 71, which gives the approximate distribution of the average sound level of typical compositions as played by piano or orchestra, it is possible to determine, as was done in Sec. 132, the required reverberation characteristic. This characteristic is given in Fig. 182, which applies to a music room in which the optimal time of reverberation at 512 cycles is 1.3 seconds. It will be seen that the reverberation time is nearly constant from 512 to 4096 cycles, that it increases to about 3.0 seconds at 128 cycles, and that it increases to 2.0 seconds in the octave between 4096 and 8192 cycles. In general, it will be seen, by comparing this curve with the curve for speech rooms in Fig. 175, that the reverberation characteristic for music rooms is flatter than the one for speech rooms. The reason for this is that music embraces a wider frequency range than does

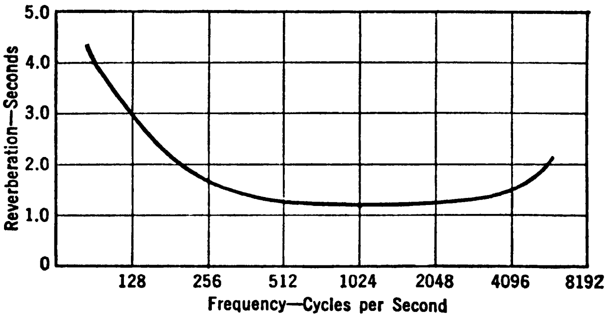

Fig. 182. Curve showing the type of reverberation characteristic a music room should have in order that, on the average, all frequency components will decay to inaudibility at the same instant. This curve applies to a room in which the optimal time of reverberation at 512 cycles is 1.3 seconds.

speech. The reverberation characteristic represented by Fig. 182 is in fairly good agreement with the characteristic based upon the criterion of MacNair, namely, that the rate of change of loudness for all frequency components be the same. It is possible that the reverberation characteristic for music rooms should be even flatter than the curve in Fig. 182 indicates, since the distribution curve in Fig. 71 is based upon the frequency of occurrence of the different pitch components as well as the " spectral " distribution in a typical composition. That is, the curve in Fig. 71 drops off at low frequencies not only because there is a lower level in the low frequencies but also because the low frequencies occur less frequently than do the components in the medial range. However, the distribution curve in Fig. 71 gives a fair approximation to the actual intensity distribution in a typical composition, and consequently the curve in Fig. 182 is a satisfactory guide for the control of reverberation in music rooms.

146. Optimal Time of Reverberation. Turning attention to the optimal time of reverberation (for a frequency of 512), experience indicates that the time of reverberation in a room should increase with the size of the room. The chief reason for this, as has been stated earlier, is no doubt attributable to the fact that the increase in reverberation tends to compensate for the diminished intensity of sound in large rooms.[9] Lifschitz, in 1926, and MacNair, in 1929, proposed a simple relation between the average level of sound in a room (in decibels) and the time required for that sound to die away to inaudibility. This relation may be written in the form

$$tS = \text{constant}, \tag{62}$$

where S is the initial level of the sound in a room and t is the time required for that sound to die away to inaudibility. MacNair expressed this relation in the form of a definite integral of the loudness taken throughout the time of decay of the sound to inaudibility. According to MacNair, this " implies that one's brain is a ballistic instrument which is concerned with not only the maximum value of loudness but also with the effect of loudness integrated throughout a considerable interval of time." This is a plausible notion provided the individual values of S and t do not depart far from the values to which we are accustomed. But certainly a feeble tone dying away slowly cannot be ex-

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[9] Schuster and Waetzmann (see note 3, Chap. V) have published some interesting comments on optimal reverberation time. In general, they are of the opinion that reverberation time should not increase with the size of an auditorium as much as is indicated by the curves of Watson and Lifschitz. See also an important paper by G. v. Békésy which deals with this subject (Ann. d. Physik, 5. Folge, Bd. 8, Nr. 7, 851–873 [1931]).

pected to give the same sensation as, or even a comparable sensation with, that of an intense tone dying away quickly, especially in slowly moving music, even if the product of S and t be constant for both the feeble and the intense tone. However, the results which are obtained on the basis of Eq. (62) are in such good agreement with the optimal times of reverberation recommended by Watson, Lifschitz, P. E. Sabine, and others — all of which are based upon the times of reverberation in rooms which are acclaimed by competent critics — that considerable confidence has developed in the correctness of some such relation as is expressed in Eq. (62). In using this equation, certain assumptions have to be made with regard to the value of S, to the reverberation equation, and to an accepted time of reverberation for a room of specified size. In arriving at the value of S, both Lifschitz and MacNair assumed a constant rate of emission from the sound source in rooms of all sizes. Both assumed the Sabine reverberation formula. Lifschitz assumed that the optimal time of reverberation in a room having a volume of 9200 cubic feet (260 cubic meters) or less is 1.06 seconds, and MacNair assumed an optimal time of reverberation of 2.0 seconds in a room having a volume of 1,000,000 cubic feet (28,000 cubic meters). MacNair's choice was based upon the good agreement of the findings of Watson, Lifschitz, and P. E. Sabine, in a room having a volume of about 1,000,000 cubic feet. Perhaps the most questionable assumption made by both Lifschitz and MacNair is that the rate of emission of the source is the same in all rooms. It is true that this assumption leads to results which are in good accord with the generally accepted values of the optimal time of reverberation for rooms of different size; but it must be remembered that most accepted optimal times have been based upon the Sabine reverberation formula (Eq. [23]) and that the recent and more accurate reverberation formula (Eq. [26]) will lower these optimal times about 15 to 25 per cent. It seems advisable therefore to base the optimal times of reverberation upon Eq. (26), that is, upon the more accurate reverberation formula, and upon the assumption that the rate of emission of the source is not constant, but increases with the size of the room, for example, as the two-thirds power of the volume of the room. It will be assumed also that the optimal value of the average power of the source in a room having a volume of 3500 cubic feet (100 cubic meters) and a time of reverberation of 1.0 second is of the order of 200 microwatts; that is, the source is made up of two units each generating 100 microwatts of acoustical energy. The average acoustical power of probable sound sources in rooms of different size will then be given by the equation

$$E = 100n = kV^{2/3}, \qquad (63)$$

where E is the power of the source in microwatts, n is the number of musical instruments or singers in the room, V is the volume of the room in cubic meters, and k is a constant. The approximate value of k can be determined by substituting the values of $n = 2$ and $V = 100$ for a small room having a volume of 100 cubic meters. This gives $k = 9.3$, and the probable average power of sound sources in music rooms of different sizes therefore is given by

$$E = 9.3V^{2/3} \text{ microwatts.} \tag{64}$$

Therefore, the volume density ρ, in microjoules per cubic meter, in a room of volume V, will be

$$\rho = \frac{4E}{ca} = \frac{4 \times 9.3V^{2/3}}{ca}, \tag{65}$$

where c is the velocity of sound in meters per second and a is the total absorption in the room in square meters of perfectly absorbing surface.

At minimal audibility the volume density ρ_0 is about 2.6×10^{-8} microjoule per cubic meter. Hence

$$\frac{\rho}{\rho_0} = 14.2\frac{V^{2/3}}{ca} \times 10^8. \tag{66}$$

Therefore the probable sound level of music in a room of volume V is, in decibels above the minimal threshold,

$$S = 10 \log_{10}\left(14.2\frac{V^{2/3}}{ca} \times 10^8\right)\cdot \tag{67}$$

Let τ be the optimal time of reverberation, that is, the optimal time required for a decay of 60 db. Then

$$t = \frac{S}{60}\tau. \tag{68}$$

Substituting in (62) the values of S and t given by (67) and (68),

$$\frac{\tau}{60}\left[10 \log_{10}\left(14.2\frac{V^{2/3}}{ca} \times 10^8\right)\right]^2 = \text{constant.} \tag{69}$$

Introducing the values of $\tau = 1.0$ second, $V = 100$ cubic meters, $c = 344$ meters per second, and $a = 15.5$ square meters, the value of the constant becomes 76.2.

Now introducing in (69) the reverberation formula, namely $\tau = 0.161 V/-S \log_e (1 - \alpha)$, where S is the exposed interior surface of the room and α is the average value of the absorption coefficient of the surface S, there results

$$\frac{.161V}{-60S \log_e (1 - \alpha)}\left[10 \log_{10}\left(14.2\frac{V^{2/3}}{ca S} \times 10^8\right)\right]^2 = 76.2. \tag{70}$$

When V = 30,000 cubic meters and S = 6400 square meters, α becomes 0.47, and the optimal time of reverberation τ becomes 1.2 seconds. Hence, if the intensity of a sound source in a music room increases in proportion with the two-thirds power of the volume of the room (as is approximately the case for orchestra halls), and if the time of reverberation in a room should increase with the size of the room in such a manner as to satisfy Eq. (62), it would seem that the optimal time of reverberation in a large room having a volume of 30,000 cubic meters should be about 1.2 seconds. This is not in good agreement with generally accepted values of the optimal time of reverberation for a large music room of this size, namely about 2.0 seconds. However, it has already been mentioned that most of the data which Watson, Lifschitz, and P. E. Sabine used in arriving at optimal times of reverberation were based upon the Sabine reverberation formula, and that if the more exact formula had been used the time for a music room having a volume of 30,000 cubic meters would be about 1.6 seconds instead of 2.0 seconds. Further, since large music rooms are often used with only a single instrument or singer as the sound source — under which condition the assumption of Lifschitz and MacNair regarding the strength of the sound source is more nearly applicable — a time of reverberation of about 1.6 seconds would be required to satisfy the condition tS = constant. If the arithmetical mean between 1.2 and 1.60, that is 1.4 seconds, be taken as the optimal time for the large music room (1,060,000 cubic feet), such a compromise would provide a condition which would approximately satisfy tS = constant, for either ensembles or soloists. The optimal time of reverberation for music rooms, according to this criterion, would vary from 1.0 second in small rooms up to about 1.4 seconds in large concert halls. In rooms for oratorios, organs, and for special types of music a reverberation time as long as 2.0 seconds, or even longer, may be desired.

It should be remembered in connection with these low periods of reverberation that musical taste is profoundly influenced by the past. Music not only has been heard almost exclusively in reverberant rooms, but much of the music of the past has been composed for reverberant or moderately reverberant rooms. Every room is a part of the musical instruments played in that room, and this fact has been in the mind of the composer, consciously or unconsciously, as he composed great masterpieces. Bagenal has given convincing evidence that much of Bach's music was composed for St. Thomaskirche at Leipzig, a church that is somewhat more reverberant than our modern acoustically treated churches, but much less reverberant than the orthodox cathedrals of Europe. The rapid movement of the fugues and toccatas of Bach was no doubt encouraged by the acoustics of St. Thomaskirche. It is not improbable therefore that the present trend toward non-reverberant rooms will influence contemporary and future composition, and it must be admitted that rooms with short periods of reverberation will allow a clarity of musical rendition that can never be attained in rooms with long periods of reverberation.

There is another important factor regarding the optimal reverberation time in music rooms; namely, that instead of only one, probably there are many optimal times of reverberation for the same room — a particular time and character of reverberation for each type of music. The optimal time of reverberation for the slow and sustained harmony of oratorio and nearly all church music probably is much longer than the optimal time for the quickly moving music of opera or orchestra. Even the different compositions of the same composer, or the different parts of the same composition, require different amounts and types of reverberation. The eventual solution of the reverberation problem in music rooms therefore may call for adjustable absorption so that the reverberation may be controlled to meet the requirements for different types of music.[10] Optical effects are often used to influence musical rendition. In a similar manner, acoustical effects, such as the control of reverberation, may be expected to add considerably to the beauty and artistry of music. The organ, for example, would enjoy an even greater versatility than it now does if the organist could control the reverberation in the room to suit the type of music he is playing — a long reverberation period for the full sustained chords of the diapasons, and a short period for the rapidly moving fugues on the strings and wood winds.

The chart in Fig. 183 shows the approximate range of optimal reverberation times (at 512 cycles) for different types of music rooms and for different kinds of music. The chart is based not only on the theoretical considerations in this chapter but upon measurements or calculations of reverberation in music rooms throughout Europe and the United States. Some of these rooms will be considered in Chap. XXIV. It will be noted that the optimal time of reverberation is not represented in this chart by a line but by a broad band. Roughly this band indicates the different times of reverberation required to give the best effects for different types of music in rooms of different size. The optimal time will

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[10] This is already done in many radio broadcast and sound-picture studios. The reverberation time in the municipal broadcast studio in Budapest, for example, can be varied from about 0.5 second to more than 4.0 seconds. C. Moeller, in a paper presented before the XII International Congress of Architects in Budapest, September, 1930, recommended adjustable reverberation for auditoriums, and referred to the Assembly Hall of the Workmen's Club at Ózd, Hungary, for which he had designed a series of rolling curtains which could be let down from the ceiling to such heights as would provide the most satisfactory condition of reverberation.

generally depend upon the character of the music which is to be rendered in the room. Organ or oratorio music will require a fairly large reverberant room; solo or chamber music will sound better in a fairly small non-reverberant room; and opera or orchestra music will require considerably shorter times of reverberation than will organ or oratorio music. Further, much of the dramatic music of Wagner, for example, probably will require a longer time of reverberation than will the lighter and more melodious music of Verdi or Mozart. This is roughly indicated on the curve. It would seem desirable therefore to be able in some rooms to vary the reverberation time to meet the conditions which will be most

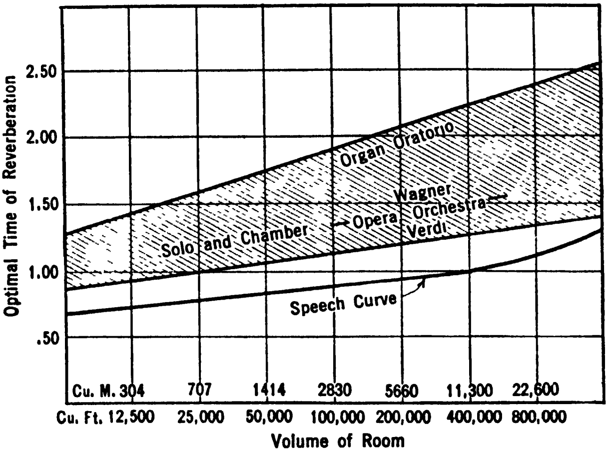

FIG. 183. Chart showing optimal times of reverberation for music rooms.

satisfactory for each type of music which is to be rendered in the room. In some rooms it may be feasible to have hangings on the wall which can be exposed or concealed as conditions require. In still other rooms it may be possible to use suitable shutters in the ceiling with an absorptive material behind the shutters. Such a control would furnish a quick and convenient means of adjusting the reverberation time throughout rather wide limits, and it would offer interesting possibilities for producing new and artistic effects in music. It seems entirely feasible therefore that at least some music rooms of the future will have provisions for adjusting the reverberation time to give the best possible effect to the rendition of different types of music. For example, it would be a simple matter to equip the organ room in a broadcasting studio with facilities for controlling the reverberation, and the *control board* could be located at the organ console.

With the aid of the chart in Fig. 183 it is possible to ascertain the approximate optimal time of reverberation (at 512 cycles) for a room of specified size and purpose. The reverberation times at other frequencies can be determined by means of the curve in Fig. 182. Thus, the time of reverberation at 128 cycles should be about 2.3 times as long as the optimal time for 512 cycles, and for frequencies above 512 cycles the reverberation time should be about the same as it is for 512 cycles. More specific recommendations with regard to the optimal reverberation for different types of music rooms will be found in Chap. XXIV.

147. Resonance. The resonant properties of a room are affected by the size of the room, by alcoves, recesses, or objects in the room, and by the forced vibration of the boundaries of the room. Wood flooring, thin wood paneling, and certain types of plaster on lath, for example, are readily set into forced vibration, either by the direct mechanical coupling of such instruments as the cello, bass viol, or piano, which are in contact with the floor, or by the aerial waves which impinge upon the boundaries of the room. The forced vibration of these resonant surfaces is of course influenced by the free or natural modes of vibration of the resonant surfaces, so that the re-emitted sound from these surfaces has a frequency distribution which is different from that of the incident sound. The amount of this re-emitted sound, especially for tones of low pitch, is not inconsiderable. For example, when a low-pitched sonorous tone is produced in a room, the vibration of thin wood paneling in the room can be felt with the finger tips or measured with seismic devices. No adequate measurements of this *resonant* sound have been made as yet, and it is therefore premature to speculate concerning its quantitative effects on music, but there seems to be an unquestioned preference among both musicians and music lovers for rooms which contain large surfaces of resonant materials, and until more quantitative data on the effects of resonance are obtained it would seem advisable to be guided empirically by this preference, and include certain areas of resonant materials, as thin wood paneling and plaster on lath, in the design of new music rooms.[11]

[11] The author has in progress a series of experiments on panel and volume resonance in rooms. The data obtained to date indicate that the resonant vibrations of thin wood panels may exert an appreciable influence upon room acoustics, but that the amount of energy re-radiated by plaster on lath or by wood sheathing is so small as to have but little influence upon the acoustics of rooms. Such materials, however, possess high merit for providing the proper balance of reverberation throughout the pitch range. Wood paneling and plaster on lath have relatively high absorption for the low frequencies, and relatively low absorption for the high frequencies, and hence compensate for porous materials which usually have very low absorption for low frequencies and very high absorption for high frequencies. Highly waxed and polished wood surfaces are especially desirable in this respect. The author's experiments on volume resonance show that all the natural frequencies predicted by the classical theory of the vibration of the air in a room are not only present, but are so prominent as to affect profoundly the quality of sound in small rooms.

148. Echoes, Interfering Reflections, and Sound Foci. The phenomena of echoes, interfering reflections, and sound foci have been considered in connection with the acoustics of speech rooms, but they are responsible for so many serious defects in existing music rooms that it seems desirable to mention them again in connection with music rooms. Chronologically, at least, they should receive consideration before all other problems in design. The rules for avoiding their troublesome defects are simple, and the designer of every music room should be thoroughly familiar at least with the following general rules:

1. Avoid shapes and dimensions which will result in large differences of path between the direct sound rays from the source to the listener and the reflected sound rays from the source to the boundaries of the room and thence to the listener. A path difference of about 65 feet is required to produce an echo, but a difference as great as 55 feet will produce an interference, especially in rapidly moving music. If the size of the building requires dimensions which involve path differences in excess of 55 feet, the surfaces which give rise to these delayed reflections should be well broken, or treated with a highly absorptive material or with a perforated grille backed with an absorptive air space, so that the incident sound will be diffusely reflected or absorbed, rather than regularly reflected.
2. Concave surfaces nearly always are likely to converge the reflected sound in such a manner as will produce sound foci. Such surfaces should be avoided as much as possible, and where used the radius of curvature should be either very small or very large in comparison with the lineal dimensions of the room. A cylindrical rear wall, with centre of curvature near the stage, or a cylindrical or spherical ceiling, with the centre near the floor, are two of the most common sources of sound foci in auditoriums, and often the differences of path are great enough to introduce either echoes or interfering reflections.
3. The design of a room should be guided by the basic principles mentioned in (1) and (2); if any question arises with regard to shape, a study of the propagation of waves should be made in model sections, either by means of the ripple tank, by spark photography, or by optical methods.

149. Variation of the Acoustical Properties of a Room with the Size of the Audience. The acoustics of every room should be as nearly independent of the size of the audience as possible. The most satisfactory method of providing this condition is to equip the room with heavily upholstered chairs. There are now available several types of upholstered opera or theatre chairs which have approximately three fourths as much absorption as a person. If a room be equipped with such chairs, the reverberation in the room will be nearly the same whether empty or occupied by a partial or a capacity audience. If cost or other factors prohibit the use of upholstered seats, the floor, especially between and under the seats, should be carpeted, and additional absorption should be used in the room so that the reverberation time will not vary between wide limits when the room is used for rehearsal purposes or when it is used with either small or large audiences.

PART III

APPLICATIONS TO BUILDING DESIGN

CHAPTER XIX

SCHOOL BUILDINGS

150. Introductory. The fundamental principles of architectural acoustics, in their present state of development, have been presented in Part II. The application of these principles to problems of design is the chief concern of the architect or builder, and therefore, in Part III, specific problems of design which are likely to arise in representative types of building will be worked out in considerable detail.

In the present chapter the usual problems which arise in the acoustical design of school buildings will be considered. There can be no question about the prime importance of good acoustics in school buildings. The chief function of the school is instruction, and, in spite of modern developments in methods of teaching, instruction comes, and likely will continue to come, largely by word of mouth and listening. It probably is not over-rating the importance of the acoustics of school buildings to state that good acoustics is even more important than good illumination, and most people will agree that it is at least equally as important as heating and ventilating. Yet in many instances the illuminating, heating, and ventilating of school buildings are planned and executed in accordance with the best obtainable scientific and engineering knowledge, as of course they should be, and the matter of acoustics is left to luck or guesswork, ignoring some of the most fundamental principles which were set forth in Part II. The idea, still shared by some architects, builders, and school authorities, that the acoustical outcome of a school building cannot be determined until the building is completed is an untenable one and can no longer be used as an excuse for poor acoustics. The acoustical outcome of a school building, or any other building, is a problem in good designing and good engineering, and if the fundamental principles of architectural acoustics are incorporated in the design of the building there need be no uncertainty as to the acoustical outcome of that building — the acoustics will be good. If these principles are not incorporated, or if they are violated, there likewise need be no uncertainty — the acoustics will be bad, bad to the degree that the principles have been ignored or violated.

In planning for the acoustics of a building it is advisable first of all to survey the general problems involved. In the design of a school building the following problems should be considered: (1) the selection of the site, (2) a survey of noise in the vicinity of the site, (3) the location of the buildings and the playgrounds, (4) the general problems of sound-insulation, (5) the determination of rooms which will require special acoustical designing, and (6) the execution of the acoustical designs for these rooms. The general plan of handling these problems will be discussed in the following sections in this chapter. Obviously, all the building requirements for the school plant must share in determining the most feasible design, but consideration of acoustics should not be postponed until after the other features of design have been determined, as is so often done at present. The problem of acoustics begins, as indicated above, with the selection of the site.

151. Choice of Site. It is not often that the architect or builder, and less often that the acoustical engineer, is consulted in the matter of the selection of a school site. There are, however, important acoustical considerations with regard to the selection of the site, and the architect or acoustical engineer should give his services and advice to school boards and others in the selection of sites for school buildings. Proximity to the homes of the students and transportation facilities are of course the most important considerations in the selection of a site, but it often happens that transportation facilities alone will fix the location of a site near the intersection of main traffic arteries — often at the intersection of trolley lines. Such a location is convenient, but it nearly always involves an incommensurate compromise in the problem of acoustics. It is advisable to make a compromise between the matter of proximity to transportation lines and freedom from excessive noise. Such a compromise can be made by locating the site approximately one block away from noisy traffic arteries. Many existing sites are wholly unadapted for school buildings, simply because the required economy in construction cannot provide adequate insulation against the outside noise. In many instances, the noise is not only distracting to scholarly thinking, but it interferes with audition to the extent that the hearing of speech is rendered difficult or even impossible. It is true that adequate insulation can be provided against almost any amount of noise which is likely to be encountered in metropolitan neighborhoods, but the cost of providing such an amount of insulation will often be prohibitive. In such instances, it is more feasible to select a site in a quiet environment.

152. Noise Survey. Every school site, whether in a quiet or noisy location, should be given a noise survey preliminary to the designing of the school buildings. If the site be a quiet one, no extraordinary precautions need be taken for the insulation of outside noise. On the other hand, if there be considerable noise in the vicinity of the site, as is likely to be the case in urban communities, the noise survey should be made for the purpose of ascertaining the amount of insulation which will be required in the buildings in order to exclude the outside noise, or at least to reduce it to such a level that it will not constitute a disturbance. In most instances the noise survey can be made with sufficient accuracy by the tuning-fork method described in Sec. 87. For example, if such a noise survey should show that the amount of noise at a certain site is of the order of 60 db, and if a noise level of 20 db is the limit of noise that can be tolerated in the building, then it is apparent that the building should be designed in such a manner as to provide an insulation against outside noise of at least 40 db.

153. General Problems of Sound-Insulation. From the data obtained in the noise survey it is possible to determine the amount of insulation which will be required to meet any specified condition of quiet within the school building. It often happens that the problem of sound-insulation will be greatly facilitated by the proper arrangement of the buildings on the school site. For example, the auditorium should be located in a particularly quiet part of the site. It should be set back at least 100 feet from a quiet side street and at least 300 feet from a busy boulevard or trolley line. If the auditorium is a part of another building it should be thoroughly insulated from surrounding corridors and adjacent rooms. The athletic field and playground, the gymnasium, and the music rooms should be far removed from the site of the auditorium. The location of the different rooms within each building often can be arranged in such a manner as to avoid noise interference between different rooms. It would not be advisable, for example, to have the music room adjacent to the oral English room, or to have either of these rooms near the gymnasium. It is obvious therefore that careful planning in regard to the location of the buildings on the site, and the location of the rooms within the buildings, will help materially in the solution of the sound-insulation problem. After the noise survey has been made and the best possible arrangement of buildings and rooms has been determined, it is possible, by means of the tables on sound-insulation given in Chap. XII and the process of calculation outlined in Sec. 106, to determine the general type of wall construction and the types of doors and windows required to provide the necessary amount of sound-insulation.

154. Rooms in School Buildings which Require Acoustical Designing. There are few if any rooms in a school building which will not be made better by proper acoustical designing, and the improvement usually will warrant the expense. In general, the following rooms should be given the principal consideration: auditorium; class rooms and lecture halls, including especially oral English rooms, foreign language rooms and music rooms; gymnasium; cafeteria; typewriting rooms; administration rooms; and corridors. Each room, or each type of room, should be studied individually, although it may be possible to adopt a uniform acoustical material and a nearly uniform type of treatment in all the rooms.

155. Recitation Rooms. There are no severe restrictions about the shape and size of recitation rooms, although long narrow rooms or excessively large rooms should be avoided. Rooms having dimensions of 25 feet in width by 30 feet in length by 12 feet in height will be found very satisfactory for classes of not more than 50 pupils. Approximately the same proportion of width to length is desirable for either smaller or larger recitation rooms. The effective insulation between adjacent rooms should not be less than 40 to 45 db, and where extreme insulation is needed the effective insulation should be as high as 50 db. The amount of absorptive material which should be added to these rooms in order to provide the optimal condition of reverberation will depend upon the size, and therefore the age, of the pupils who are to occupy the room. Thus, if the room is to be used by children under six years of age, the amount of absorption supplied by the audience will be relatively small and it will be necessary to use a correspondingly greater amount of absorptive material for the walls and ceiling of the room than would be required in a room for adults.

The manner of working out the acoustical design of a typical recitation room is suggested in the following example which will be worked out in detail. Suppose a recitation room 25 feet by 30 feet by 12 feet is to accommodate a class of 25 junior high school pupils. The absorption per child is 3.5 sabines. There are to be 25 wood desks each having an absorption of 0.4 sabine. The floor is to be covered with a material like battleship linoleum, having a coefficient of 0.04. (All coefficients will be referred to a frequency of 512.) First, choose from the tables on sound-insulation the type of wall construction which will provide an average T.L. of not less than 40 db, as lath and lime plaster with the plaster applied to a thickness of at least ½ inch on both sides, or porous clay tile plastered on both sides. If forced ventilation is provided for the recitation rooms the windows should fit tightly in their frames so as to eliminate the transmission of sound from room to room by way of the windows. If no ventilation is provided for the rooms, and the windows are likely to be open, there is no occasion for providing a high degree of insulation through the walls since the limiting factor in the transmission from room to room will be by way of the windows.

The most important single factor in the acoustics of the recitation room is the control of reverberation. Although the optimal time of reverberation in a small recitation room is not in excess of 0.75 second, there is very little to be gained in using a shorter time of reverberation than 1.0 second, and consequently it will be entirely satisfactory to adjust the time of reverberation in the room to a period of 1.0 second with 25 pupils in the room. The reduction of the reverberation time below 1 second might add considerably to the cost of treating the room, and the benefit derived would scarcely warrant this added expense, except perhaps in important lecture halls. The amount of absorptive material required to provide a time of reverberation of 1.0 second can be readily determined by means of Eq. (30). The volume of the room is 9000 cubic feet, and the interior surface is 2820 square feet. Since the room is a typical rectangular room the value of k in Eq. (30) is 0.05.[1]

$$1.0 = \frac{0.05 \times 9000}{-2820 \log_e (1 - \alpha)},$$

or

$$\log_e (1 - \alpha) = -\frac{450}{2820} = -0.159.$$

Or, from Appendix III, $\alpha = 0.147$,

which is the average coefficient of absorption the entire boundaries of the room should have in order to give a time of reverberation of 1.0 second. (Strictly, the reverberation formula holds only for rooms in which all boundaries have the same absorptivity; but if the absorptive material be distributed fairly uniformly over the entire boundaries of the room, the formula will give sufficiently accurate results for all practical purposes.) The total amount of absorption required in the room is therefore the product of this average coefficient times the interior surface of the room, that is, 0.147 × 2820, or 415 sabines. Next, determine the amount of absorption in the room which is supplied by those objects and surfaces which must of necessity be in the room, as the 25 pupils and desks and the 750 square feet of floor area. The absorption supplied by the 25 pupils and 25 desks is $25(3.5 + 0.4) = 97.5$ sabines, and the absorption supplied by the floor is $750 \times 0.04 = 30.0$ sabines. Therefore the walls and ceiling of the room should supply $415 - (97.5 + 30)$, or 287.5 sabines. The area of the walls is 1320 square feet, but as a rule not more than one half of the wall area, or 660 square feet (on the upper walls), will be available for acoustical treatment. The ceiling area is 750 square feet, all of which is suitable for acoustical treat-

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[1] The value of k is more precisely 0.049 for conventional rooms of rectangular shape, but the approximate value of 0.05 is sufficiently accurate for all practical purposes. This approximate value is used by most authorities in this country, and consequently it will be used throughout this book for conventional rooms of rectangular shape.

ment. Thus a total of 1410 square feet is available for treatment. There are several methods of treatment for providing the required 287.5 sabines of absorption. The lower portion of the walls, including doors, windows, and blackboards, will provide a certain amount of absorption. This can be calculated by taking the sum of the products of areas times coefficients for the different materials which comprise the lower portion of the walls, but it usually can be estimated with sufficient accuracy by assigning an average coefficient for the entire surface and multiplying by the area. Thus the hard plaster, doors, and windows which comprise the lower surface of the walls will have an average coefficient of about 0.03. Therefore the absorption supplied by the 660 square feet of the lower walls will be 660 × 0.03, or 19.8 sabines. The entire ceiling and upper walls, aggregating 1410 square feet, may be treated with an acoustical plaster having a coefficient of 0.19, which will give 268 sabines. This amount of absorption added to the absorption supplied by the lower walls, the floor, and the 25 pupils and desks will closely approximate the total amount of absorption required in the room to give a time of reverberation of 1.0 second. Obviously, the same amount of absorption can be obtained by choosing a more absorptive material for the ceiling (a material having a coefficient of about 0.33) and treating the entire walls with hard plaster; or the upper 660 square feet of walls can be treated with a material having a coefficient of about 0.37, and the remainder of the walls and the entire ceiling finished with hard plaster. The total absorption required in the room is not a critical amount — a variation of 10 or even 20 per cent will not appreciably alter the acoustical quality of the room — and therefore some latitude may be exercised in the selection of the absorptive treatment for the room. There is a slight preference for the wall rather than the ceiling treatment. If the treatment were limited to the ceiling the vertical components of sound would be absorbed very quickly, whereas the horizontal components would persist too long. With the treatment on the walls the reverberant sound will die away more uniformly in all directions.

There are usually many recitation rooms in a building, and not all of them may be uniform in size, but it is nearly always possible to select some standard form of treatment which will give highly satisfactory acoustics in all the rooms. Reverberation times between 0.80 and 1.20 seconds will be entirely acceptable in all recitation rooms.

The percentage articulation in the recitation room just considered, assuming reasonably quiet conditions, will be, according to Eq. (60′) in Sec. 134, 92 $k_l k_r$. In a small recitation room k_l will be about 0.98 (see Appendix IV), and k_r for a reverberation time of 1.0 second will be

0.98 (see Fig. 173). Therefore the probable P.A. (percentage articulation) in this room will be about 89 per cent, which represents an exceptionally fine condition for the hearing of speech.

The selection of the particular type of acoustical material for the treatment of the recitation rooms must be guided by a number of factors. (See Chap. VIII and especially Table XX.) First, the material should have a reasonably good absorption characteristic, similar to that shown in Fig. 176 for speech rooms; or, at least, it should not be excessively absorptive for high frequencies and relatively non-absorptive for low frequencies. If the coefficients for frequencies near and above 512 be not more than two or three times the coefficient for 128 the material will be satisfactory from the acoustical standpoint. Second, the questions of cost and maintenance often will limit the choice to three or four materials. From these, the ultimate selection will depend upon the adaptability of the material to the general architectural requirements of the room, and especially to such requirements as structural strength, combustibility, texture, and decorative potentialities. If the architect be familiar with the acoustical, structural, and decorative properties of absorptive materials he will be able to choose the material and type of installation which will best suit the requirements of the room.

If the entire walls and ceiling of the class room to which we have referred had been finished with hard plaster, the total absorption in the room with an audience of 25 pupils would approximate 190 sabines, and the time of reverberation would be about 2.25 seconds. With this reverberation time, the P.A. would be 92 × 0.99 × 0.90, or about 82 per cent. Although this would provide tolerable hearing conditions, it would be much less satisfactory than a room with a P.A. of 89 per cent. Further, with the occasional small class of, say, only 10 pupils, the reverberation time would be 3.2 seconds and the P.A. would be only 74 per cent, which is not satisfactory for recitation purposes. Further, a reverberation time of 3.2 seconds or even 2.25 seconds in a small room is very annoying both to speakers and listeners, even though it is possible to understand speech in the room. With such excessive times of reverberation, the room would sound empty, all extraneous noise would be exaggerated, and both speaking and listening would be accompanied by an unnecessary nervous strain. The exclusion of noise and the reduction of reverberation are indispensable in adapting recitation rooms to the function of oral instruction.

156. Oral English Rooms. The oral English room is a special type of class room in which the acoustical properties for the hearing of speech should be as nearly perfect as possible. The room should be located in a quiet part of the building, and every reasonable precaution should be taken to insulate it against outside or contiguous noise. If the walls have a T.L. of 40 to 45 db, and if the windows and doors close tightly in their frames, there should be no difficulty from noise except in very noisy locations, where special measures for insulation are necessary.

In Fig. 184 is shown a suggestive design of an oral English room which will provide very good acoustical conditions. The room is 38 feet by 25 feet by 14 feet, and will seat 75 to 100 persons. The platform is elevated 2 feet above the floor level, and the rear rows of seats are appropriately elevated, thus providing good *sound* lines and good *sight* lines to all auditors in the room. A portable screen, which should be made of fairly reflective material, as wood veneer, can be used on the platform to give certain stage effects, when required, and also to give added reenforcement to the voices of the speakers. The floor can be either wood or concrete, but if concrete it should be covered with linoleum or some similar material.

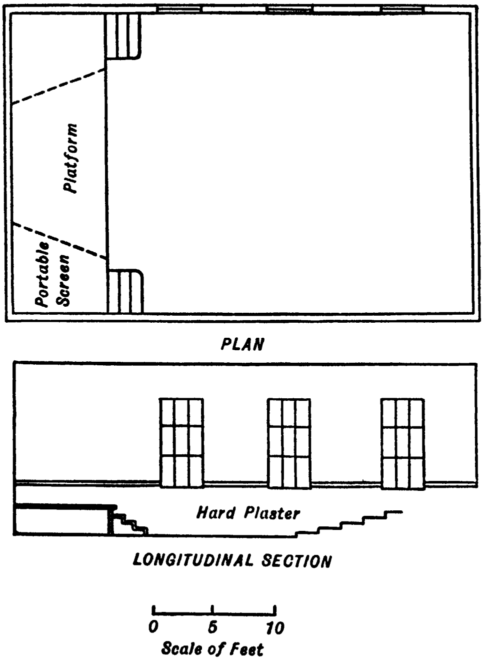

FIG. 184. Acoustical study of an oral English room.

The optimal time of reverberation for an oral English room can be determined from the curve for speech in Fig. 181. For the room shown in Fig. 184, the volume is 38 feet by 25 feet by 13 feet (13 feet is the average height), or 12,400 cubic feet, and the interior surface is 3638 square feet. The optimal time, according to Fig. 181, is 0.75 second. However, as can be seen from Fig. 171, which shows how the P.A. varies with the time of reverberation, but little is to be gained in speech articulation by reducing the reverberation below 1.0 second, and many individuals do not like the *acoustical effect* of a room having a reverberation time as short as 0.75 second. A speaker feels that a very dead room fails to give support to his voice, and some listeners feel that the speech is unnecessarily muffled and that it is lacking in resonance and vitality. For purely esthetic purposes the optimal reverberation time is about 1.10 seconds. A reverberation time of 1.0 second provides a satisfactory compromise in the room we are considering, and if this time be planned for an audience of 50 persons (each having an absorption of 4.0 sabines), the reverberatory properties of the room will be highly satisfactory for all purposes. The manner of determining the best type of acoustical treatment for this room is as follows:

The reverberation constant k for this room is very nearly 0.05. Therefore

$$\log_e (1 - \alpha) = -\frac{0.05V}{S} = -\frac{0.05 \times 12{,}400}{3638} = -0.170.$$

Hence, from Appendix III, $\alpha = 0.156$. Hence, the total absorption required in the room is $0.156 \times 3638 = 568$ sabines.

		Sabines
Absorption of O.P. wood floor (including platform and risers)	= 1050 × 0.06 =	63.0
Absorption of hard plaster wainscot, three windows and two doors	= 500 × 0.03 =	15.0
Absorption of 50 persons (4.0 units each) and 50 wood seats (.2 each)	= 50 × 4.2	= 210.0
Therefore the total absorption supplied by floor, wainscot, windows, doors and audience	=	288.0
And therefore the upper walls (1136 square feet) and ceiling (950 square feet) should supply	568 − 288	= 280.0

This required amount of absorptive material can be supplied by treating the walls, above the wainscot, with an acoustical plaster having a coefficient of 0.23 at 512 cycles and finishing the ceiling with hard plaster; or by treating the ceiling with a material having a coefficient of 0.28 at 512 cycles and finishing the entire walls with hard plaster. The choice of the absorptive material should be guided by the considerations mentioned in the preceding section on recitation rooms. (See also Sec. 83 and Table XX.) The wall treatment is preferable to the ceiling treatment since it will facilitate a more uniform growth and decay of sound in the room.

The probable P.A. in this oral English room, assuming a reasonably quiet condition and an audience of 50 persons, will be 92 $k_l k_r$. From Appendix IV, $k_l = 0.97$, and from Fig. 173, $k_r = 0.98$. Therefore P.A. $= 92 \times 0.97 \times 0.98 = 88$ per cent. With no audience in the room, the reverberation time will be about 1.56 seconds, and the probable P.A. will be $92 \times 0.98 \times 0.95 = 86$ per cent. Consequently, the room will be nearly as satisfactory for rehearsals or for small classes as it will be for a class of 50. With an audience of 75 persons, the reverberation time will be 0.84 second, and the probable P.A. will be 89 per cent.

If this same oral English room were finished with hard-plaster walls and ceiling, the reverberation time with no class in the room would be 3.9 seconds, and the P.A. would be only 69 per cent. The room would be very unsatisfactory for rehearsal purposes, or even with small classes. With a class of 50 pupils in the room the reverberation time would be 1.6 seconds and the P.A. would be 85 per cent. Although this would provide an acceptable condition for many purposes, it would be far from ideal. Speech would be readily recognized under such a condition of reverberation, but the separate sounds of speech would overlap and confuse; and the room would be regarded as a *difficult* room for either speaking or listening. On the other hand, when the reverberation time has been reduced to about 1.0 second, and when adequate insulation has been provided against outside noise, the room will be regarded as an *easy* room in which to speak, and listeners will hear clearly the most delicate modulations of the voice.

157. Music Rooms. The general specifications for the shape and size of a music room will follow rather closely the specifications already given for an oral English room (see Fig. 184). It is perhaps not so important to elevate the rear seats in a music room as it is in an oral English room, but it is desirable if it does not interfere with the other uses of the room. The elevation of the rear seats not only assures a better flow of sound energy to those seats, but it helps to prevent the multiple reflection of sound waves between the ceiling and the floor.[2]

The optimal reverberation time for music rooms is slightly longer than the optimal time for speech rooms. For a room 38 feet by 25 feet by 13 feet, similar to the one shown in Fig. 184, the optimal time of reverberation is about 1.10 seconds, which should be attained with the most probable number of pupils in the room. If the room is to be used at times for rehearsal purposes, that is, with only a few persons in the room, it may be desirable to install a velour or monks-cloth hanging which can be drawn across the room, about half way between the platform and the rear of the room. The acoustics of the room as used for rehearsals will then resemble the acoustics with an audience in the room.

The distribution of the absorptive material in a music room requires considerate care. The walls and ceiling near the platform should be finished with hard, reflective materials, whereas the side and rear walls of the seated area should be fairly absorptive. This distribution of

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[2] In a study of room acoustics by W. Linck (Ann. d. Phys., 4, 1017, [1930]) it is shown that a sloping floor is much better than a level one.

absorptive material in a music room is found to satisfy the requirements of the performers, who wish a fairly reverberant space, and the listeners, who wish only a moderate amount of reverberation. The use of an appropriate acoustical plaster for the rear and side walls, or an acoustical tile or fibre board in the ceiling, usually will provide the optimal condition of reverberation in the room. The exact amount and location of the absorptive material can be determined by going through the routine calculations similar to those given for the oral English room.

The use of velour or other absorptive hangings on the platform should be avoided, as such absorptive material will impair the reverberant and resonant properties of the *generating* end of the room. If a portable reflecting screen be used on the platform, similar to the one shown in Fig. 184, it should be made of wood veneer, heavily painted canvas, or other reflective and resonant material.

Large areas of resonant material, as wood paneling and wood flooring, are found to be beneficial in music rooms. It is therefore desirable to use wood floors and a wood wainscot, especially in the vicinity of the platform. These resonant materials give *life* and sustenance to music without producing the harmful effects of reverberation. They also provide relatively high absorption for the low-frequency components of music.

The insulation of sound deserves special attention in the design of music rooms. It is not only necessary to exclude extraneous noise from the music room, but it is equally necessary to confine the music within its own room so that other near-by rooms will not be disturbed. This can be accomplished satisfactorily by designing the wall, floor, and ceiling boundaries for the room in such a manner that they will have a T.L. of not less than 45 db, and by installing doors and windows which will have a T.L. of not less than about 30 db. This implies that the windows of the room should be kept closed, and therefore that artificial ventilation should be provided for the room. Where it is impracticable to provide artificial ventilation, the room should be located in a separate wing and the windows should open upon a part of the campus which is well removed from assembly or class rooms.

158. Lecture Halls. The requirements which were specified for recitation and oral English rooms are of the greatest importance in the design of lecture halls. The hearing of speech is the chief function of a lecture hall, and therefore every means should be utilized to give to the room the best possible acoustical properties for the hearing of the speech. The volume of the room should be kept as small as feasible, the auditors should be seated near the lecture table, the seats should be elevated appropriately, and the walls and ceiling should be designed so as to give beneficial reflections of sound toward the auditors. If the room is to seat more than about 500 persons, it will be desirable to introduce a balcony so that the auditors will be brought nearer the speaker.

There are many possible designs which will prove satisfactory, but the plan and longitudinal section shown in Fig. 185 exhibit the more salient features which should be incorporated in the design of lecture halls. This room has a length of 60 feet, a width of 50 feet, and an average height of 18 feet. The ratio of length to width may deviate somewhat from the design shown in the figure. Thus, the room may be wider than the one indicated, but there should not be any appreciable extension of length. Long, narrow rooms are not so satisfactory as short, wide rooms. In the lecture hall shown in Fig. 185, the seats are elevated not only sufficiently to give good *audition lines* to all seats but also to give an unobstructed view of the top of the lecture table from all seats in the room — a feature which is of considerable value if the room is to be used for demonstrated lectures. The slope of the seated area was determined by *sight line* requirements and is steeper than would be required for satisfactory hearing. The slope could be reduced to about one half of that shown in Fig. 185 and still be satisfactory for hearing.

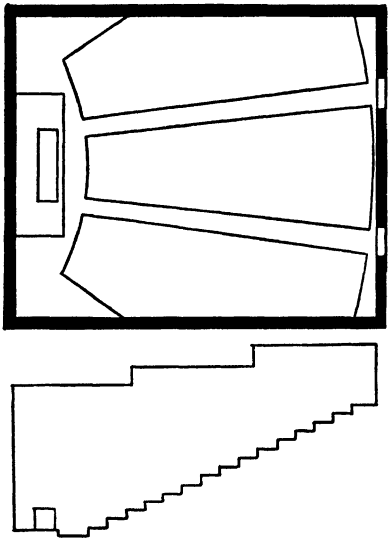

FIG. 185. Lecture hall designed for good seeing and hearing.

After the size and shape of the lecture hall have been determined, consideration should be given to the insulation of noise. The amount of insulation required for the walls, floor, and ceiling will depend upon the location of the lecture hall, that is, upon the amount of noise in the immediate vicinity of the room, both within the building and outside. If the site for the lecture hall be a noisy one, a survey should be made to determine the magnitude of the noise which must be insulated from the room. Suppose that such a survey has revealed a probable noise level of about 60 db in the vicinity of the proposed room — which corresponds to a moderately noisy location. If an amount of insulation be planned for the room which will reduce this noise to 15 db inside of the room, an entirely satisfactory condition will be obtained. Thus, the residue of 15 db will be no louder than the unavoidable noises which will always be in the room when an audience is present. The room therefore should be designed to provide a noise reduction of 60 − 15 or 45 db. The type of wall and ceiling construction required to give this amount of insulation can be calculated in the following manner. From Eq. (58) the noise-reduction factor in decibels is given by

$$\text{Noise-reduction factor} = 10 \log_{10} \frac{a}{T}, \tag{58}$$

where T is the total transmission through the boundaries of the room and a is the total amount of absorption in the room. The volume of the room is 50 feet × 60 feet × 18 feet = 54,000 cubic feet, the interior surface 10,800 square feet, and the optimal time of reverberation about 1.0 second. The total absorption in the room is therefore given by the reverberation equation, $t = 0.05\, V/-S \log_e (1 - \alpha)$. Hence, $\log_e (1 - \alpha) = -0.25$, or $\alpha = 0.221$, and $a = \alpha S = 0.221 \times 10{,}800 = 2387$ units. Substituting in (58), $45 = 10 \log_{10} 2387/T$, or $4.5 = \log_{10} 2387 - \log_{10} T$. Whence, $T = 0.0755$. In order to reduce T to this value, it probably is necessary to dispense with windows, or to use two sets of windows in each opening, separated by an air space of at least 6 inches. Suppose that there are no windows, and that there are two sets of doors, each 5 feet by 7 feet, and that the coefficient of transmission for the doors is 0.0005 (which requires at least $1\frac{3}{8}$-inch solid wood doors with rubber strips around the edges, so that all threshold cracks are closed). The transmission through the doors will then be $0.0005 \times 70 = 0.0350$ unit. The transmission through the walls and ceiling (assuming that transmission through the floor will be negligible) must not exceed 0.0755 − 0.0350 or 0.0405 unit. Since the area of the walls and ceiling (less the area of the doors) is 6890 square feet, $6890 \times \tau$ must not exceed 0.0405, where τ is the coefficient of transmission of the walls and ceiling. That is, τ must not exceed 0.0000059, or the T.L. for the walls and ceiling must be as high as 52.3 db. Hence the walls and ceiling should have an insulation equivalent to that of a 10-inch brick wall. (See, for example, Tables XXX and XXXI.)

The absence of windows implies that artificial ventilation will be provided for the room. It is necessary therefore to install an adequate amount of attenuation in the ventilating ducts to reduce to not more than 15 db the level of the noise transmitted through the ducts. The heating and ventilating contractor should be required to guarantee that the fan and motor noise reaching the room from the duct openings, or from other sources, will not exceed the specified level of 15 db.

The reverberation time in the lecture hall shown in Fig. 185 should not exceed 1.0 second with the average-sized audience the room is designed accommodate. The optimal time is as short as 0.80 second, but there is not much to be gained by reducing the reverberation time below 1.0 second, since the further reduction results also in a reduction in the intensity of speech, and the benefit which might be anticipated from the reduced reverberation is nearly nullified by the resulting reduction in the intensity of the speech. However, the reverberation time should not be permitted to be much in excess of 1.0 second, as the percentage articulation drops off quite rapidly for times of reverberation above that point. If the room have a seating capacity of 300, it would be advisable to provide the optimal time of reverberation for two thirds of capacity audience, that is, 200 persons. The choice of absorptive material, the amount required, and its location in the room should be guided by the principles and calculations which were set forth in the sections on recitation rooms and oral English rooms. (See Secs. 155 and 156.) As a general rule, it is preferable to apply the absorptive material to the side and (especially) rear walls rather than to the ceiling. This will minimize multiple reflections between parallel walls, and will provide a more uniform rate of decay of sound in all directions in the room. In addition, it will leave the wall behind the speaker, and the ceiling, in hard reflective materials, and thus increase the amount of once-reflected sound reaching the auditors. If approximately 2200 square feet of the side and rear walls be treated with an acoustical material having coefficients of sound-absorption of 0.25 to 0.30 at 128 cycles and 0.58 to 0.63 at 512 cycles, the optimal time of reverberation of 1.0 second will be very closely approximated with a class of 200 students in the room. This will provide a P.A. of not less than 85 per cent. Even with an occasional small attendance of only 50 to 100 the reverberation time will be shorter than 1.5 seconds, and the P.A. will be in excess of 82 per cent, so that the lecture hall will have good acoustical quality under all possible conditions of use.

159. Auditorium. Because of the diversity of uses of the school auditorium, it should possess as nearly as possible the acoustical properties which are required in lecture halls, in music rooms, and in theatres. Since the acoustical requirements for speech and music rooms are not the same, it is advisable to make a compromise so that the auditorium will best serve its diverse uses. Fortunately, the requirements for speech and music are not so divergent as to place any real obstacle in the way of making this compromise, so that, if the acoustical properties are adjusted to the mean requirements for speech and music, the auditorium will be satisfactory for both speech and music.

The general specifications for the shape and size of the auditorium were described in Chap. XVI. The principal features of shape which should guide the acoustical design of a school auditorium are illustrated in Fig. 186. The floor plan, the elevation of the seats, the proscenium splays, the ceiling design, the high opening under the balcony, the removable apron over the orchestra pit, and the portable wood veneer set all contribute to good acoustics. There are of course many admissible deviations from this shape, but in all cases the shape should be designed so as to favor an approximately uniform flow of sound energy to all seats, and the once-reflected sound should arrive at the listeners not later than about one twentieth of a second (or 55 feet) behind the direct sound. The advantages of such a shape as that shown in Fig. 186 are manifest from a consideration of the paths of reflected sound, shown by the broken lines. For example, the overhead splay of the proscenium is designed to reflect sound to auditors located between *a* and *b*, that is, to auditors who are most in need of reflected sound.

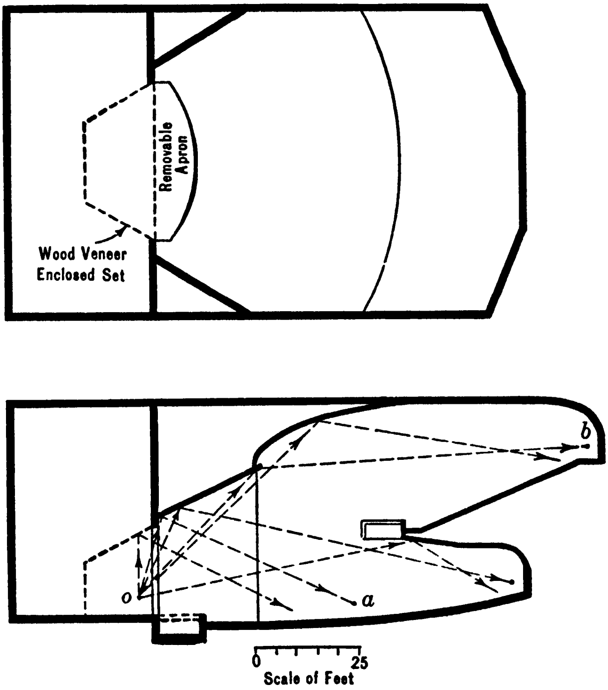

FIG. 186. Acoustical study of a school auditorium.

The size of the auditorium should be kept as small as possible. Large auditoriums — larger than about 200,000 cubic feet — are nearly always unsatisfactory for the school auditorium. Thus, speakers with weak voices — and many pupils are in this class — are rarely heard satisfactorily in auditoriums larger than about 100,000 cubic feet. Auditoriums for elementary schools (where the children are not older than 11 or 12 years) should not be larger than about 50,000 to 75,000 cubic feet. In the junior high school the size should not exceed about 100,000 cubic feet; in the senior high school it may be as large as about 150,000 cubic feet; and in colleges and universities 200,000 cubic feet should be regarded as the upper limit of size. (These volumes include the volume of the recess under the balcony but not the volume of the stage recess.) It often is possible to hear satisfactorily in larger auditoriums, but as a rule the limits of size just specified represent the upper safe limits, and a great deal of dissatisfaction and inefficiency will be eliminated by avoiding the design of larger auditoriums for school purposes. If for any reason it becomes necessary to design larger auditoriums, provision should be made for the installation of a suitable public address system. This will prove very beneficial for assemblies and other gatherings where speaking within close range of the microphone is possible, but it will be of little, if any, benefit for theatrical productions where the speakers are often far away from the microphone.

The problem of noise insulation should be worked out in the manner outlined in the preceding section. (See also Chap. XIII.) The auditorium should be located in a quiet section of the campus, and if it forms a part of another building it should be thoroughly insulated from the remainder of the building. There should be two sets of tightly fitting doors between the auditorium and the corridor or outside. If a high degree of insulation be required, as in the case of the lecture hall of the preceding section, it will be very helpful to dispense with windows, or to design special windows of high insulating value. Any noise from the ventilating or other mechanical equipment should be adequately insulated; the floor should be covered with linoleum or some other soft covering; and the chairs should be of a rigid, substantial construction, and securely fastened to the floor, so that there will be no creaking or squeaking.

The exact calculation of reverberation involves a three-space problem — the stage recess, the main part of the auditorium, and the recess under the balcony — but if the stage have an enclosed set and if the balcony recess be not too deep the calculation of reverberation reduces to a one-space problem. However, in order to make this simplification, it is assumed that an adequate amount of absorption will be added to each of these three spaces so that there will be a uniform rate of growth or decay of sound in all parts of the auditorium. The complete set of hangings required for the stage setting ordinarily will supply a sufficient amount of absorption for the stage recess. In fact, a full set of stage hangings will make the stage too *dead* for musical settings, and for this reason it is advisable to provide a wood veneer or heavily painted canvas set for musical programs, such as is shown by the dotted lines in Fig. 186. If the soffit of the balcony, or the side and rear walls under the balcony, be treated with an absorptive material having a coefficient of 0.25 to 0.30 at 512 cycles, the recess under the balcony ordinarily will have a suitable reverberation time. It remains then to provide the optimal time of reverberation throughout the entire auditorium, including the set-enclosed space on the stage and the recess under the balcony. This obviates the uncertain task of assigning coefficients of absorption to the stage opening and also to the opening under the balcony.

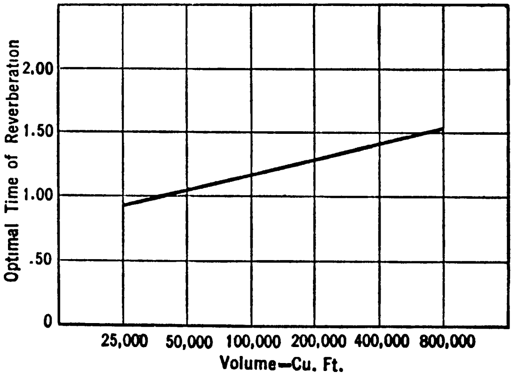

FIG. 187. Optimal reverberation time (512 cycles) for school auditoriums.

As mentioned previously, the optimal time of reverberation for a school auditorium involves a compromise between the optimal times for speech and music. The curve shown in Fig. 187 represents a compromise which is well adapted to average requirements. Thus, an auditorium having a volume of 100,000 cubic feet should have a time of reverberation of 1.18 seconds. It is customary to provide this time for two thirds of capacity audience. Suppose that we wish to determine the amount of absorptive material required for an auditorium having the following characteristics: volume $V = 100{,}000$ cubic feet; interior surface $S = 16{,}700$ square feet; seating capacity = 750 junior high school children (3.6 units each); concrete floor covered with linoleum (coefficient = 0.04) = 6000 square feet. The total amount of absorption required for the auditorium is obtained from the reverberation equation, $t = 0.05\, V/-S \log_e (1 - \alpha)$. Hence,

$$\log_e (1 - \alpha) = - \frac{0.05 \times 100{,}000}{16{,}700 \times 1.18} = -0.254, \quad \text{or} \quad \alpha = 0.224;$$

and the total absorption required for the auditorium is 0.224 × 16,700, or 3740 sabines. The absorption supplied by the audience and the floor is 500 × 3.6 + 6000 × 0.04 = 2040 sabines. Therefore the walls and ceiling of the auditorium, including the stage set and the walls and ceiling under the balcony, should supply 3740 − 2040, or 1700 sabines of absorption. The installation of a suitable type of acoustical plaster on the side and rear walls, including the side and rear walls under the balcony, and the installation of a hard plaster wainscot and a hard plaster ceiling, will provide the required amount of absorption in a very satisfactory manner. The choice of acoustical plaster will be guided by the area of the surface available for treatment, by the coefficients of available plasters, and by the suitability of the plaster for the architectural treatment of the auditorium. The proposed treatment for this auditorium, assuming wood chairs, will provide the times of reverberation and the probable P.A.'s given in the following table.

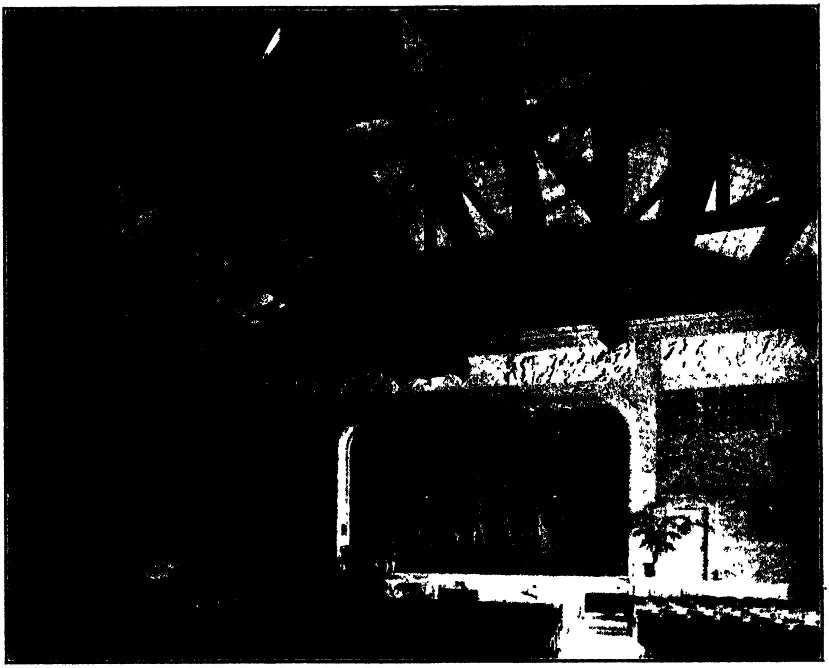

Fig. 188. Le Conte Junior High School Auditorium, Los Angeles, showing "Trutone Acoustical Tile" in ceiling and loud speaker horns for the amplification of speech.

It will be seen that with an audience of 250 or more, the P.A. will be in excess of 80 per cent, which will provide entirely satisfactory hearing conditions for speech. The reverberation times also will be entirely acceptable for music. With fewer than 250 persons in the auditorium, the reverberation will be slightly excessive, although tolerable, for either

Size of Audience	Approximate Time of Reverberation in Seconds	Percentage Articulation (P.A.)
No audience	2.50	77
250	1.55	82
500	1.18	84
750	1.00	84

speech or music. If better acoustical quality is desired for audiences smaller than 250, it can be secured by installing upholstered seats.

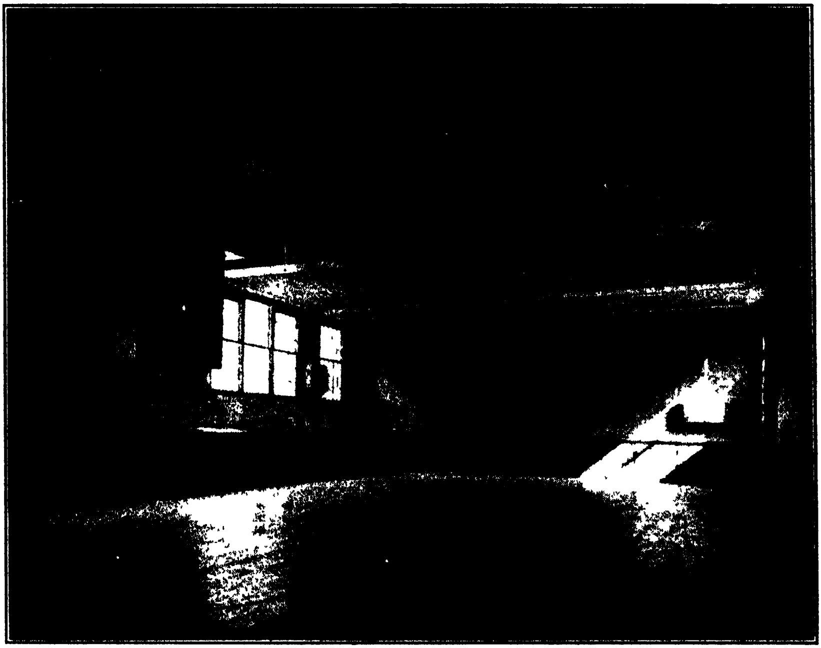

FIG. 189. Gymnasium of Beehive School, Warrensville, Ohio, showing "Acousti-Celotex" ceiling and brick walls. (*Fulton and Taylor, Architects.*)

Although upholstered seats are not necessary in auditoriums having a volume as small as 100,000 cubic feet, they are very beneficial in larger auditoriums since they tend to keep the reverberation more nearly constant for either small or capacity audiences. It is good practice to recommend them for all large auditoriums, especially when the audi-

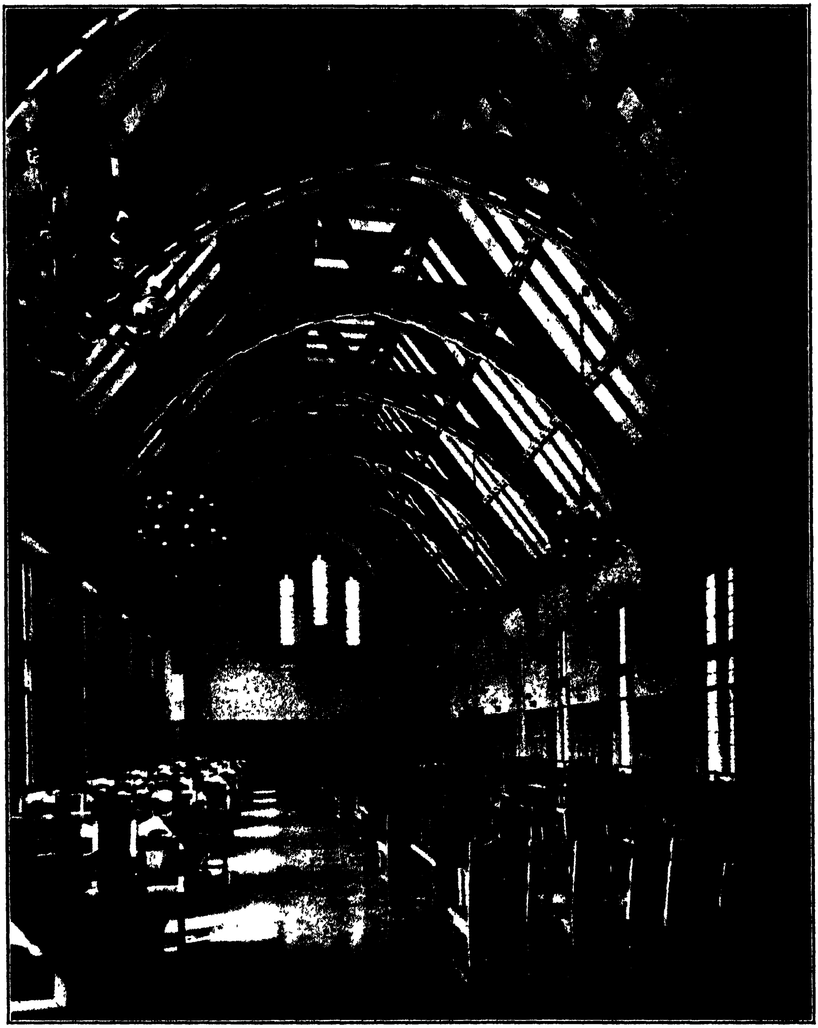

FIG. 190. Dining room in men's Residence Hall, University of Chicago. The ceiling is in two colors of "U.S.G. Acoustone," and the walls are in "Sabinite Acoustical Plaster." (*Zantzinger-Borie and Medary, Architects.*)

torium is to be used for small as well as large audiences. Upholstered seats are particularly helpful in auditoriums during either dramatic or musical rehearsals, since the acoustical properties of the room are nearly the same with and without an audience.

160. Gymnasium, Cafeteria, and Miscellaneous Rooms. The gymnasium and cafeteria do not present any unusual acoustical problems. The question of noise-insulation is important only in so far as the noise generated in these rooms may constitute an interference to near-by rooms. Whenever possible it is advisable to locate the gymnasium and cafeteria at considerable distances from the auditorium, lecture halls, and class rooms. If it is necessary to crowd all buildings and rooms into a small space, the walls and ceiling of both the gymnasium and the cafeteria should be designed to have a high degree of sound-insulation. The suitable reduction of reverberation is the outstanding acoustical requirement for both the gymnasium and the cafeteria. If the reverberation time in the empty gymnasium be reduced to not more than 1.75 seconds, and the reverberation time in the empty cafeteria to not more than 1.50 seconds, the acoustical properties of these rooms will be satisfactory. It is advisable to select a very durable acoustical material for the gymnasium, such as fibre board or mineral wool covered with hardware cloth, and apply it only to the ceiling and upper walls. The selection of the acoustical material for the cafeteria should be guided by such factors as sanitation, decoration, maintenance, and cost. The absorptive material should be installed in the ceiling, because in that position it will be most effective in reducing reverberation and noise. (See p. 139.)

Other rooms in school buildings which require acoustical treatment include laboratories, typewriter rooms, recreation rooms, and offices. A material having a coefficient of sound-absorption of 0.25 to 0.50 applied to the ceilings will provide satisfactory acoustical conditions in these rooms. Finally, the ceilings or the ceilings and upper walls of all corridors, lobbies, hallways, and stairways should be treated with an acoustical material having a coefficient of sound-absorption of not less than 0.20. This will not only make these concourses more quiet, but also will help to reduce noises which otherwise would be transmitted through doors into class rooms.

CHAPTER XX

PUBLIC AND COMMERCIAL BUILDINGS

161. Introductory. The types of building which will be considered in this chapter include municipal auditoriums, parliamentary buildings, museums and libraries, office, bank, and industrial buildings, and hospitals. In most of these buildings, with the exception of the municipal auditorium, the principal acoustical problem consists of the adequate insulation of outside noise and the control and absorption of inside noise. There is an increasing public demand for quiet in all public and commercial buildings, and it is now generally recognized by building authorities that noise in buildings will be an outstanding factor in contributing to obsolescence.

162. Municipal Auditoriums. From the standpoint of acoustics, the municipal auditorium is the most important of all public buildings. Since it is used for such a wide variety of functions, many aspects of acoustics must be considered in determining the design of the building. First of all, it must be satisfactory as a speech hall. But it also is frequently used as a concert hall for all sorts of musical productions. And on rather frequent occasions it is used for conventions in which speech may originate not only on the stage, but in any part of the hall. The general principles of design are similar to those which already have been described for speech and music rooms. However, the municipal auditorium is usually very large, and therefore problems of echoes, delayed reflections, and adequate loudness in all parts of the auditorium are much more important than they are in the smaller auditoriums. The selection of the site, the insulation against noise, the design of the shape, and the control of reverberation should be worked out along the lines already suggested for school auditoriums. If the municipal auditorium is to be a very large one, or if it departs from conventional shapes which experience has found to be satisfactory, it is advisable to construct models of the proposed design, and to make studies of the reflection and the distribution of sound to all parts of the auditorium. At the same time, measurements in a model similar to those described in Chap. V will enable the architect or engineer to determine the mean free path for the auditorium, and thus determine the proper value of *k* which should be used in the reverberation formula.

The optimal time of reverberation in a municipal auditorium is based upon a compromise between the requirements for speech and music; the times given by the curve in Fig. 187 will provide a satisfactory guide. The variation of reverberation time with pitch should conform approximately to the curve shown in Fig. 175, or to the curve shown in Fig. 182. This will provide a balanced reverberation for all the frequency components of speech and music. In order to attain this type of variation of reverberation time the absorptive characteristic of the boundary materials should conform approximately to the curve shown in Fig. 176. For frequencies between 256 and 2048 a deviation of ±5 per cent will not be objectionable, and for lower or higher frequencies a deviation of ±10 per cent can be tolerated.

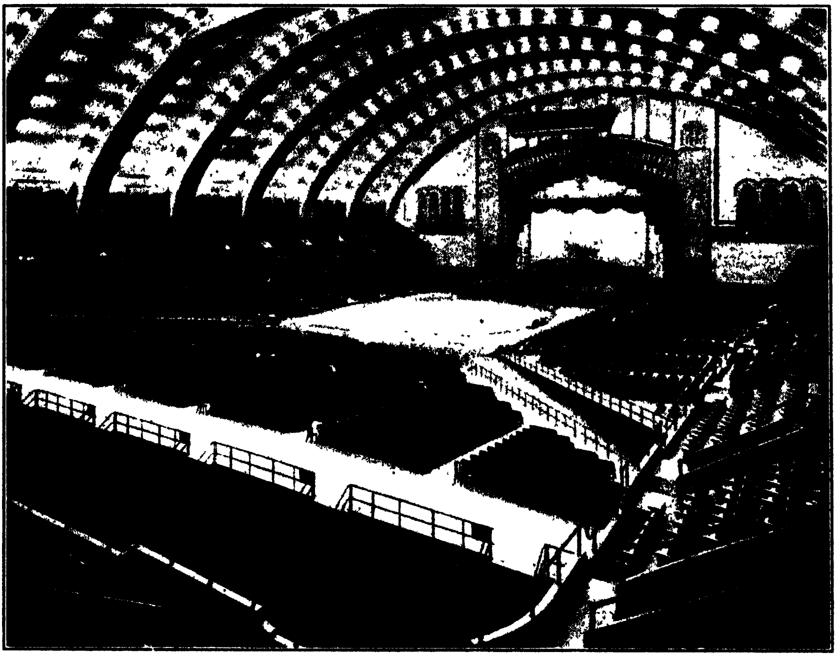

FIG. 191. Convention Hall, Atlantic City, New Jersey. The largest auditorium in the world. Entire ceiling covered with "Acousti-Celotex." Although 675 feet long and 135 feet high, it is possible, with the aid of the public address system, to hear speech satisfactorily in all parts of the auditorium.

The municipal auditorium usually consists of a number of connected spaces, as the stage recess, the main part of the auditorium, and the space under the balcony. A sufficient amount of absorptive material should be used in each of these spaces to provide approximately uniform rates of decay of sound in all parts of the auditorium. Since it is often necessary to provide a level floor in a municipal auditorium, the stage should be elevated somewhat more than in the conventional design of auditoriums. This will provide better *hearing* and better *seeing,* especially for the rear seats. The stage should be equipped with an enclosed set similar to the one indicated for the school auditorium shown in Fig. 186. In general, wood veneer will be the best material for this enclosed set, but heavily painted canvas will provide a fairly satisfactory substitute. If the stage of the auditorium be converted into a setting for musical concerts by means of the customary velour hangings, an excessive amount of the sound is absorbed and lost in the stage recess. This not only makes for a deficiency of sound energy out in the auditorium, but it makes it hard for musicians to play together, since they experience greater difficulty in hearing one another. The use of a properly designed set made of reflective material will overcome both these defects. All seats which are permanently installed in the auditorium should be heavily upholstered and covered with a porous fabric, so that the reverberation time will not depend too much upon the size of the audience which is present. Finally, a public address system is quite indispensable in auditoriums seating more than about 2000 persons. Provision for the installation of this equipment should be made in the original design of the building, and suitable housing units should be provided for the electrical equipment, as well as for the sound projectors. If the auditorium is to be used extensively for conventions in which speaking may originate from any position on the floor, a portable microphone should be made available for such speakers. For further information concerning the design of municipal auditoriums the reader should consult Sec. 181 dealing with the design of theatres, and Sec. 186 dealing with the design of concert halls. The problem of the acoustical design of a municipal auditorium is a difficult and an important one which requires special study, beginning with the initial sketches on the shape and size of the auditorium and ending with the testing of the completed auditorium.

163. Parliamentary Buildings. Parliamentary buildings, as discussed in this section, will include all types of legislative, administrative, or judicial buildings. In general, there are two types of room in parliamentary buildings which require acoustical consideration: (1) Assembly rooms, including council chambers, legislative chambers, court rooms, committee rooms, and all rooms where meetings or conferences may be held. These rooms are, above everything else, speech rooms, and therefore everything possible should be done to provide them with the best possible conditions for the hearing of speech. (2) Work rooms, including public and private offices, printing rooms, reference rooms, and filing rooms. The acoustical conditions in these rooms should be of such a nature as will facilitate both the speed and ease of work, that is, the rooms should be quiet and free from reverberation.

Since parliamentary buildings are usually located in a busy and therefore a noisy part of the city, it is necessary that the buildings be designed so as to insulate these noises to a tolerable level. Thus, it is certain that a court room, a council chamber, or an assembly room in an urban locality cannot be maintained quiet enough for speech if it is necessary to have the windows open for purposes of ventilation. It is necessary therefore that all assembly rooms in noisy localities be provided with artificial ventilation, so that all windows can be closed. (There may be exceptions to this requirement where the windows open onto a relatively quiet court.) In all cases the windows should be of heavy glass, and in extreme cases double windows separated by a wide air space should be provided. Since the assembly rooms are used exclusively for speech, the time of reverberation provided should be in close agreement with the optimal time for speech rooms. (See Fig.

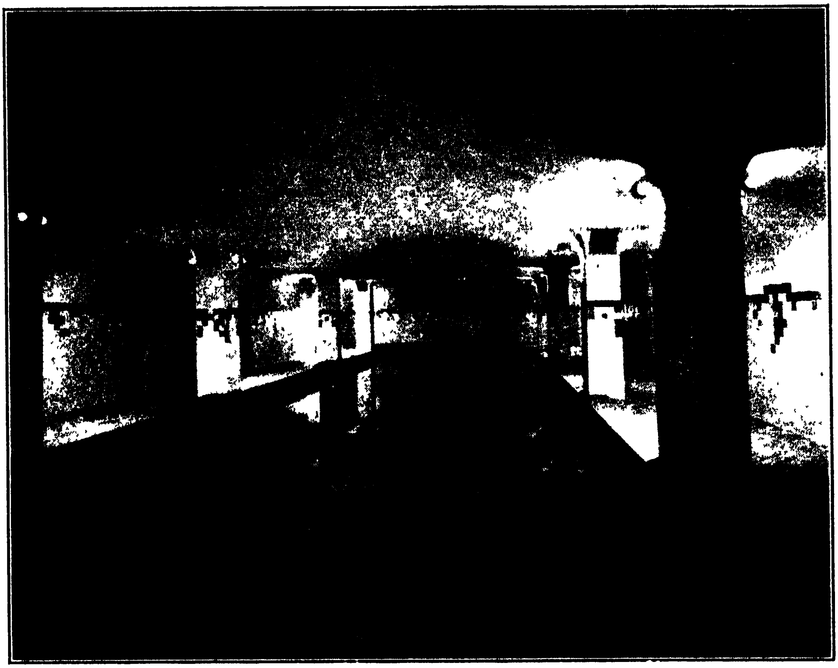

Fig. 192. Swimming pool with ceiling and upper walls treated with "Macoustic Plaster."

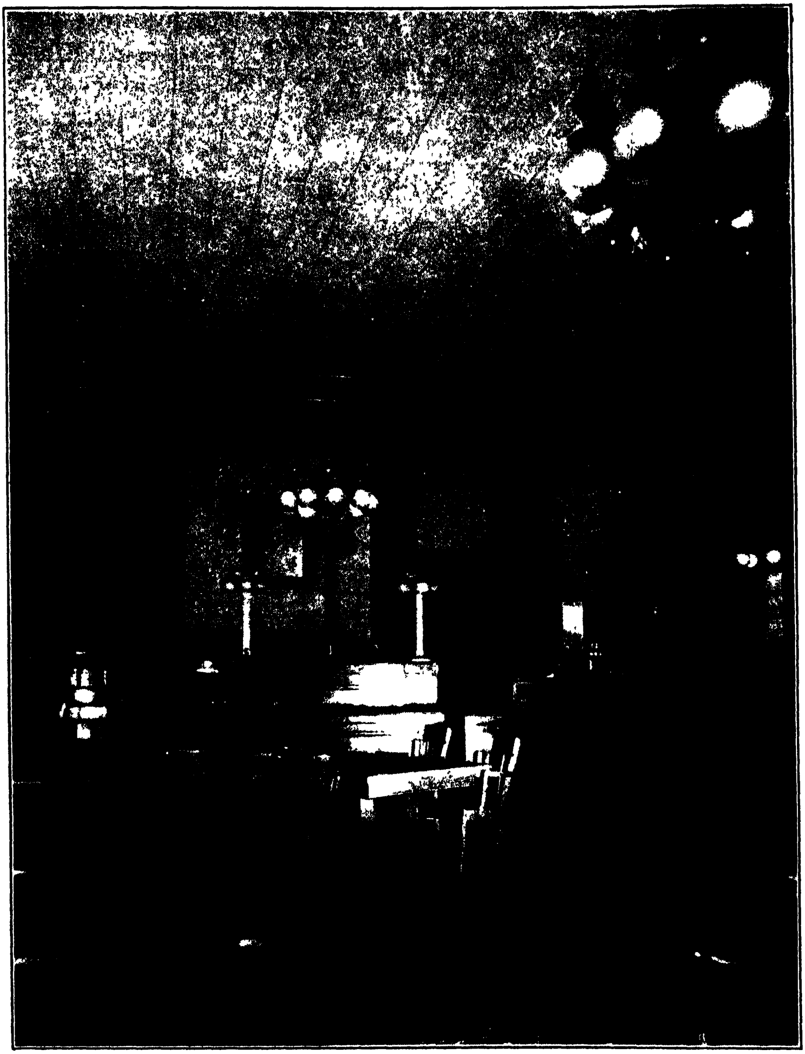

FIG. 193. Court room in Cook County Courthouse. Ceiling and walls are treated with highly absorptive tile.

181.) It is particularly important that good acoustical conditions be provided in council chambers and court rooms, where both spectators and participants should be able to hear easily and perfectly. To this end, high ceilings and unnecessarily large rooms should be avoided. A flat ceiling, 14 to 20 feet high, of hard plaster or other highly reflective material, is desirable provided the walls and floor can be treated so as to give a suitably low period of reverberation.

Typical examples of calculations of insulation and reverberation for rooms of this type are worked out in the chapter on school buildings. Noise from the outside should be reduced to not more than 15 db in the room. If this degree of quiet has been attained, and if the reverberation time has been reduced to the optimal time for speech rooms, no difficulties will be encountered in rooms smaller than about 100,000 cubic feet. In larger rooms it is advisable to design the shape and to arrange the various parts of the room so as to favor the flow of sound from speakers to listeners. In addition, it may be necessary to install a suitable public address system, especially in very large and noisy rooms.

164. Museums and Libraries. There is a growing insistence on the part of the public that all museums and libraries be treated acoustically. In general, all exhibit or reading rooms, and corridors and stairways, in museums and libraries should be treated with suitably absorptive material. If the reverberation time be reduced to about 1 second in the smaller rooms, and to about 1.5 to 2.0 seconds in the larger rooms, the rooms will be found to be entirely satisfactory. If there are lecture halls in these buildings, special attention should be given to the acoustical properties of these rooms, so that the optimal conditions will be obtained for the hearing of speech. (See Sec. 158 for the design of lecture halls.) Some architects are of the opinion that the reference and reading rooms in libraries are not in need of acoustical treatment, since they are not used for speaking purposes. However, in untreated rooms, especially in large reading or reference rooms with hard-plaster walls and ceilings, it is likely that the closing of a door, the dropping of a book, or other noises incidental to the conduct of routine business in the room will generate such noises as will constitute a real annoyance to the occupants of the room. It is axiomatic that quiet is desirable for study or reading, and every reasonable effort should be made to secure this environment in museums and libraries.

The Museum of History, Science and Art, Los Angeles, designed by the Allied Architects, and the Pasadena Public Library, Myron Hunt, architect, were studied in advance of construction for the purpose of determining the required extent and type of acoustical treatment. As a result the ceilings, and in some instances the walls, of all rooms or corridors used by the public were treated with an acoustical plaster having a coefficient of absorption of about 0.18 to 0.20 at 512 cycles. The outcome in both buildings was highly satisfactory. One need only visit such buildings as these and compare them with others which have not been treated acoustically to be convinced that the acoustical treatment of museums and libraries is a prime necessity.

165. Office, Bank, and Industrial Buildings. The value of quiet in office buildings, bank buildings, and in all buildings where people work has been amply demonstrated in recent years. Workers in quiet surroundings can do more and better work than they can in noisy surroundings. Noise is especially irksome and destructive of efficiency among individuals who do mental or creative work. In a quiet and non-reverberant office one has no difficulty in hearing or in being heard over the telephone; dictation is easy and free from errors in the recognition of the sounds of speech which are so frequent and annoying in noisy rooms; formal conferences or informal conversations proceed without the participants failing to hear what is said; and the entire nervous system of the worker is relieved from the incessant bombardment of irritating

FIG. 194. Press Room, Chicago Daily News. Ceiling, including beams and ventilating ducts, finished in Johns-Manville "Sanacoustic Tile."

noises. Those who work in a quiet environment are therefore better adapted to meet and solve the problems of the day, and are not so fatigued at the end of the day as are those who are obliged to work in the presence of noise.

The value of quiet in offices has been fully demonstrated by extensive studies on the effect of office quieting upon the efficiency of workers. Thus, the acoustical treatment in a certain large office cost $6000. It was estimated that if this cost were prorated over ten years, including interest at 6 per cent, the cost would be two cents a day for each employee. It would require an increase in the efficiency of the employees of only one half of 1 per cent to cover the cost of the acoustical treatment. Tests by many companies have shown that the increase in the efficiency of clerical workers, for example, has amounted to several per cent. Thus, the application of sound-absorptive material to the ceiling of an insurance office was accompanied by an increase of 12 per cent in the output of the office. In another life insurance office, tests conducted in three different departments showed that the acoustical treatment of the ceilings produced an increase in working efficiency of 8.8 per cent. This was more than eight times the increase in efficiency required to justify the cost of the installation. Similar treatment of the telephone receiving room of a telegraph office produced a decrease of 42 per cent in the number of errors and a decrease of 3 per cent in the cost per message.

Some recent tests by Donald A. Laird of Colgate University have revealed some interesting facts concerning the effects of noise on working efficiency.[1] Tests were conducted on four typists who were required to do routine typing in the presence of a noise, first when the hard-plaster walls and ceiling of the room were exposed, and then when the walls were partially covered with panels of perforated fibre board. Noise was generated by means of a " noise machine " which produced the sounds of an electric motor, ball bearings rotated in a hexagonal sheet-iron drum, an auto siren, and a telephone bell. Tests were made of (1) the energy consumption of the typists (by measuring the metabolic rate from samples of exhaled air), (2) the speed of typists (by determining the number of strokes per minute and the time for removing a completed letter and inserting a new sheet), and (3) the number of errors made in typing. The results of the tests indicated that on the average the typists expended 19 per cent more energy in doing the same work in the untreated room than they did in the treated room. A gain in speed of 4.3 per cent was noted when the noise was reduced by means

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[1] Donald A. Laird, "Measurements of the Effect of Noise on Working Efficiency," The Journal of Industrial Hygiene, 9, 10 (October, 1927).

of the absorptive panels in the room. In this connection it was noted that the speedier workers were more affected by noise than were the slower workers. In fact, the slowest worker was not affected at all by the noise, whereas the fastest worker was affected the most. The number of errors made in typing was not greatly affected by noise, although the two fastest typists made fewer errors in the treated room than they did in the untreated room. No tests were made to determine the effect of noise upon the number of errors made in taking dictation, but other tests which have been made to determine the effect of reverberation and noise upon the number of errors made in the recognition of speech would indicate that the number of errors in dictation in the untreated room would have been at least twice as numerous as the errors in the treated room. It may be stated therefore that quiet working conditions will reduce very appreciably the consumption of body energy for doing a given amount of work, will increase the speed of work, will reduce the number of errors made in many types of work, and will eliminate nearly all errors in the recognition of speech.

FIG. 195. Office, Second Floor, Northern States Power Company, St. Paul, Minnesota. Entire ceiling treated with "Insulite Acoustile."

The necessity for quiet in doctors' offices is perhaps even greater than that for other commercial offices. The amount of noise encountered in the average physician's office is so great that it is impossible by the usual tests to detect an impairment of hearing unless the patient has less than 80 per cent of normal hearing. In other words, the amount of noise present in the average physician's office is sufficient to produce a masking effect equivalent to a deafness of 20 per cent. It is as important that the otologist's office be quiet for making tests of hearing as it is that the optometrist's or ophthalmologist's office be dark for the making of certain tests of seeing. It is likewise important that the general physician's office be quiet for tests with the stethoscope or for tests by auscultation. Diagnoses based upon such tests cannot attain the highest possible accuracy or fidelity if made in noisy offices.

FIG. 196. Switchboard room, Pennsylvania Hotel, New York. Entire ceiling treated with Johns-Manville "Sanacoustic Tile."

Modern developments in the design of office buildings indicate very clearly that future buildings will be both quiet and air conditioned. In fact it is almost impossible to provide adequate quiet in office buildings if open windows be depended upon for the ventilation of the rooms. Quiet rooms, especially in office buildings which are located in metropolitan centres, can be realized only with closed windows, and conse-

FIG. 197. Edison Building, Los Angeles, (*Allison and Allison, Architects*). More than 20,000 square yards of "Kalite" plaster used in ceilings of all offices.

quently the future development of quiet in office buildings is likely to be associated with the future development of air conditioning. It was shown in Chap. XIII that a typical room with windows closed provided an insulation of 36.2 db. If 20 square feet of the windows in this same room be open, the over-all insulation will be reduced to 11.0 db. Since open windows transmit much more sound into a room than do the rest of the boundaries of the room, it is futile to attempt to improve the insulation through the walls and ceiling of a room so long as the windows are open.

FIG. 198. Interior of Exhibition Room in Edison Building. "Kalite" plaster, 1¼ inches, applied directly to metal lath in ceiling.

The Southern California Edison Building, Los Angeles, Allison and Allison, architects, is an example of a recently constructed building which is both air conditioned and acoustically treated. All windows in the building are permanently and tightly closed, and are opened only in cases of emergency. Every office and work room in the building has been treated acoustically: (1) the ceilings of most work rooms with an acoustical plaster having a coefficient of sound-absorption of about 0.30 at 512 cycles, and (2) the ceilings of public offices and other special rooms with an acoustical plaster having a coefficient of about 0.50 at 512 cycles.

The average level of the noise in private offices in this building (located in downtown Los Angeles) is from 15 to 26 db, depending upon location, and the average noise level in larger offices and work rooms is from 34 to 48 db, depending upon the number of people and the type of work in each room. If the windows are opened the noise level increases 25 to 30 db in the private offices, and 10 to 20 db in the larger rooms. The windows are always closed during working hours, and under this condition the acoustical properties of all office and work rooms in the building are very good.

As a rule, it is not feasible to prescribe optimal times of reverberation in connection with the acoustical treatment of office, bank, and industrial buildings. The addition of absorptive material in such rooms reduces the level of noise in the room, improves the conditions of the room for the hearing of speech, and tends to prevent the spread of noise from its source to remote parts of the room. The reduction of noise in the room occasioned by the introduction of the absorptive material in the ceiling or in the ceiling and on the walls will depend upon the total amount of absorption added to the room. Thus, if an untreated room has a total of 200 sabines of absorption, and if 1800 sabines of absorptive material be added to the ceiling and walls of the room, the total absorption in the room will then be 2000 sabines. Since the intensity of sound in a room is, to a first approximation, inversely proportional to the amount of absorption in the room, the average intensity of the noise and all other sounds in the treated room will be only one tenth as great as they would be in the untreated room. That is, the addition of the 1800 units of absorption to the room will result in a 10-db reduction in the level of all noise in the room, whether the noise is of inside or outside origin. Thus, if in the untreated room the average level of the noise be 50 db, the level of this same noise in the treated room would be 40 db. A reduction from 50 db to 40 db may not seem to be a very appreciable one to those who are not familiar with the relation between intensity, sound level, and loudness. But when it is remembered that a reduction of 8 or 9 db will be judged by the average person as a reduction in loudness to one half of the original loudness,[2] it will be readily appreciated that the average worker in a room will regard a reduction of 10 db as equivalent to more than a 50 per cent reduction in the loudness of the noise; and when noise, as judged by the average person, is reduced to less than one half, the reduction is genuinely appreciated, and may represent the difference between acceptable and intolerable conditions.

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[2] John S. Parkinson, "Experimental Judgments of Relative Loudness by a Number of Observers as Related to the Decibel Scale" (Abstract), Jour. Acous. Soc., 3, 7 (July, 1931).

Further, such a reduction in the reverberation as is occasioned by the addition of this amount of absorptive material will make a marked improvement in the acoustical properties of the room for the recognition of the sounds of speech, and this factor will contribute greatly to the individual's satisfaction with the room. Also, the effect which absorption has in localizing noises in a room is a factor which contributes to the personal comfort of the worker. Thus, a noise which originates in a remote part of an acoustically treated room is not only reduced in intensity, but the noise seems to originate at a relatively great distance from the listener. The absence of reverberation in a room enables the individual to localize the source of the sound, whereas in a reverberant room the multiplicity of reflections bombarding the ears from all directions places the individual in a state of confusion regarding the origin of these noises.

The absorptive treatment of offices is nearly always accomplished by treating the ceiling with a highly absorptive material, as tile or felt, although in recent years there is a growing tendency to treat both the ceiling and the walls with a less absorptive material, as acoustical plaster. It is not feasible to set forth any definite rules for selecting the most feasible type of acoustical material for a certain room. In general, however, if the entire ceiling of offices 10 to 15 feet in height be treated with an acoustical material having an average coefficient of sound-absorption of 0.30 to 0.50,[3] the results will be satisfactory. If the ceiling height of the room be greater than 15 feet a material having an average coefficient of 0.50 to 0.80 should be used. If the ceiling be very high, say in excess of 30 feet, it is often desirable to apply acoustical treatment to the walls as well as to the ceiling. In large offices which are relatively low, treatment of the ceilings will be more effective than treatment of the walls. (See Sec. 55.) And in small offices with highly reflective and parallel walls the absorptive treatment should be applied to the walls as well as the ceiling. This will prevent multiple reflections between parallel walls,

The choice of material and type of treatment must be determined by a number of factors in addition to the coefficients of absorption, such as appearance, ease of decoration, maintenance, combustibility, and cost. (See Sec. 83 and Table XX.) A difference of 10 per cent in the absorption coefficients of two materials will at most make a difference of only 1 db in the average level of noise in the room. It would be a mistake therefore to choose one particular material merely because it was 10 per cent more absorptive than another if the choice of this more absorptive material entailed any appreciable sacrifice in

[3] The arithmetical mean of the coefficients at 128, 512, and 2048 cycles.

structural quality, appearance, or cost. Finally, consideration should be given to the absorptive characteristic of the material which is selected for office quieting. In general, the types of vibration which make up the noise in an office, such as the impact noises of typewriters and business machines, the ringing of bells, the conversations of other occupants of the room, and traffic noises which come in through partially open windows, are made up of an almost continuous band of frequencies from the lowest to the highest audible sounds. It is therefore necessary that the absorptive material have a uniformly high absorption coefficient from about 100 to 4000 cycles. But since most noises are preponderantly comprised of frequencies between about 200 and 2000 cycles, as judged by the ear, the acoustical materials should be highly absorptive in this range. In most cases of office treatment it is sufficient to rate materials in terms of their coefficients at 512 cycles, since the coefficient at this frequency is quite representative of the coefficients throughout the frequency range from 200 to 2000 cycles, but it is somewhat better to use an average coefficient based upon the mean of 128, 512, and 2048 cycles, and to give preference to materials which possess a good absorption characteristic. Materials which have a coefficient at 128 cycles of about one third to one half of the coefficient at 512, and which are about as absorptive for all frequencies above 512 as they are at 512,

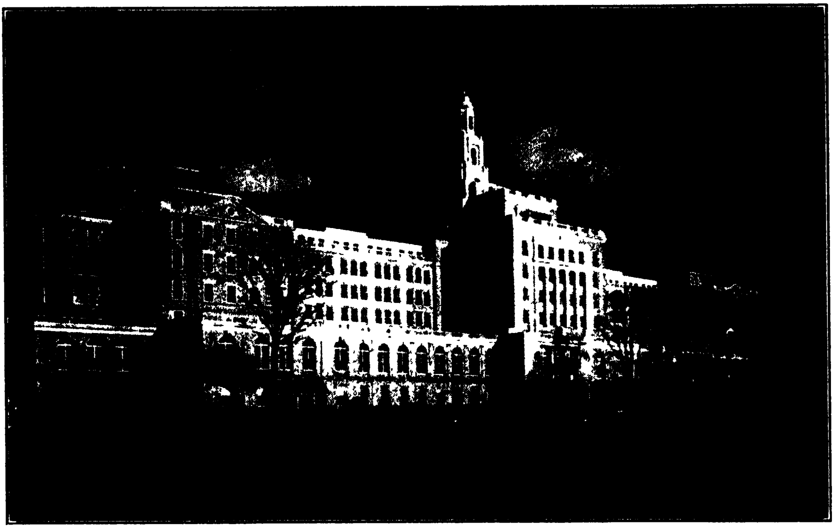

FIG. 199. Aetna Life Insurance Building. More than 300,000 square feet of "Acousti-Celotex," Type BB, used for acoustical treatment.

will have a satisfactory absorption characteristic for office-quieting purposes.

166. Hospitals. Nearly always the first order of the doctor for the patient confined in a hospital is " the patient must have quiet." The hospital is usually located in a busy part of the city where the noise level is 60 db or more. The windows must be open for ventilation, and therefore the insulation provided by the room may not be more than 10 to 20 db. The " quiet " therefore which is ordered for the patient must be realized in the presence of a din of 40 to 50 db of traffic noise, not to mention the noises which may originate inside the building — such as the crying of infants, the groaning or screaming of suffering adults, and the inexcusable noises of attendants, utility wagons, and building equipment. Such is the situation in the modern hospital where no real effort has been made to secure quiet. Modern monolithic structures with hard-plaster walls and ceiling, with long unbroken corridors (efficient speaking tubes connecting all parts of the building), with no absorptive carpets or hangings in the patients' rooms, with open windows and poorly fitting doors, with inadequate isolation and insulation for nurseries, labor rooms, and acute patients' rooms — these present an array of acoustical problems which are in the direst need of solution. It will be the purpose of the present section to outline the general nature of these problems and to suggest practical methods of solution.

Although the amount of noise that patients can tolerate without being disturbed varies greatly for different individuals, a level of about 15 db will be tolerated by nearly all, and this is about as low a level as can be attained without going to extreme types of structure involving prohibitive costs. Furthermore, if the noise level in a room be reduced below 15 db, the patient may hear his own heart beat, or may hear other internal noises which may be a source of annoyance or even worry to him. However, there is little danger of attaining this degree of quiet under the existing conditions associated with hospitals and the construction of buildings. On the other hand, if the architect and engineer design a building in which the noise level in the patients' rooms is calculated not to exceed 15 or 20 db, and if the construction be properly supervised, the required degree of quiet can be attained without adding more than 3 to 5 per cent to the cost of the building. In order to attain this end it will be necessary to choose a location in which the average outside noise level is not greater than 35 to 40 db (where open windows are depended upon for the ventilating of the rooms) or, if the noise level be greater than 50 db, to design the building with permanently closed windows, in which case air conditioning must be provided for all rooms.

Completely air-conditioned hospitals, with permanently closed windows, not only will provide a solution to the most difficult aspect of providing quiet, but they also will provide the benefits of properly regulated temperature and humidity, washed and dust-free air, and will exclude the possibility of drafts of air from open windows. Permanently closed windows for buildings located in noisy sites is the first and the most important expedient in providing quiet in hospitals. This expedient alone will provide a reduction of all outside noise of at least 20 db. It is of course possible to mitigate noises by absorptive treatment, and by paying attention to many other details in construction, — possibly a reduction of 10 to 15 db can be attained by such measures — but it should be clearly recognized that the adequate exclusion of traffic noises in metropolitan centres cannot be accomplished unless the windows are kept permanently closed.

FIG. 200. Auditorium in Orthopedic Hospital, Los Angeles. "Trutone Acoustical Tile" in all ceiling panels.

The acoustical design of a hospital can be worked out along the following lines. The first step consists in making a noise survey in the vicinity of the proposed site for the hospital. This survey should be made during representative portions of the day and the night, and should extend to all parts of the proposed site. Assuming that this noise survey has determined the probable magnitude of the noise level in the vicinity of the proposed building, it is possible to design the walls and windows for the building to provide the required amount of insulation, namely the difference between the level of the outside noise and the 15 or 20 db which can be tolerated in the patients' rooms. Thus, if the probable level of the outside noise is found to be 60 db the walls and windows of the hospital should provide an insulation of 40 to 45 db. An inspection of the tables giving the coefficients of transmission for different materials and types of wall structure (Chap. XII) will enable the architect to select a type of wall construction which will provide the required amount of insulation. The manner of making the calculations on sound-insulation has been indicated in the typical problem worked out in detail in Chap. XIII, Sec. 106. (See also Sec. 158.) If the site be a particularly noisy one, and if a high degree of quiet be planned for the hospital, it may be necessary to use double windows in each opening, the two windows being separated by an air space of 6 to 12 inches.

If the cost of construction prohibits the installation of air-conditioning equipment for patients' rooms, it is of course necessary to provide ventilation by means of the windows, in which case it probably will be impossible, in metropolitan localities, to reduce the noise in the rooms to as low a level as 15 or even 20 db. The use of suitable window mufflers placed outside of the window openings will provide an effective insulation of as much as 6 to 10 db. In many instances this amount of insulation contributes materially to the quiet in the room, although it should be borne in mind that existing types of window muffler are by no means equal in value to closed windows.

The problem of noise isolation should be given careful consideration in laying out the general plan of the hospital. The building should be located away from busy traffic arteries, electric trams, or other sources of noise. The building should be set back from the streets, and should be surrounded by tall trees and other planting. The approaches for ambulances, doctors' automobiles, and delivery trucks should be far removed and thoroughly shielded from the patients' rooms. The heating and ventilating equipment room, the X-ray room, the kitchen, utility rooms and employees' dining room, the administration offices, and the elevators should be thoroughly insulated from the patients' rooms. Special isolation and sound-insulation should be provided for the maternity and nursery rooms. Equally good insulation should be provided for the rooms of acute sufferers who are likely to be noisy. It is often possible to segregate rooms for such patients in separate wings of the building. The cries of a patient in pain often will reach a sound level of 80 db. It therefore requires an insulation of 60 to 65 db between these rooms and the rooms which are to be shielded from such disturbing noises. In general, this amount of insulation cannot be attained by a single wall, much less by a single door or window. It is necessary therefore to use at least two separate doors between units which require such large amounts of sound-insulation.

The floors of all corridors and utility rooms should be covered with a resilient floor covering, as rubber tile or battleship linoleum. Such coverings not only help to take up the noise of footfalls and utility wagons, but they also contribute to the absorption of sound.

All wards, private patients' rooms, labor and delivery rooms, nurseries, operating rooms, clinic or class rooms, dining and utility rooms, every corridor and nearly every other room in the hospital should be treated with sound-absorptive material. The modern hospital often has many rooms which are used for instruction purposes, for clinics, for conferences, and for technical or administrative meetings. These rooms should be treated in such a manner as to provide the optimal acoustical condition for the hearing of speech. (See chapter on school buildings.) The use of absorptive material in all other rooms is for the purpose of suppressing noise. If the ceilings of all these rooms and of all the corridors be treated with an acoustical material having coefficients of not less than 0.15 at 128 cycles and not less than 0.40 at 512 cycles, the control of reverberation will be satisfactory. If a less-absorptive material be used, as acoustical plaster, the entire ceiling and at least the upper half of the walls should be treated with a material having coefficients of sound-absorption of not less than 0.10 at 128 cycles and not less than 0.20 at 512 cycles.

The choice of acoustical materials for the treatment of hospitals should receive the most careful consideration. First of all, the material must not interfere with the sanitary requirements of the hospital. This requires a hard, clean surface which can be decorated, or a surface which has a permanent glaze. The surface must be of such a nature as will withstand washing and scrubbing every two or three months, and redecorating every year or so, without disintegrating or without losing an appreciable amount of its absorptive value. This subject has received careful attention by C. S. Neergaard,[4] who has collected some useful data on the merits and on the relative costs of installing and maintaining different acoustical materials in hospitals. The materials were tested for the absorption of water during scrubbing and following soaking, and for the content of water after drying for 72 hours. The plasters

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[4] C. S. Neergaard, "How to Achieve Quiet Surroundings," The Modern Hospital, 32 (March, 1929).

tested showed that the better grades of acoustical plaster gained weight in the amount of 6 to 11 per cent after scrubbing, and 14 to 20 per cent after soaking. After a period of 72 hours of normal drying all the absorbed water had evaporated.[5] Perforated and painted fibre board, and a special felt covered with a perforated oilcloth, absorbed greater contents of water after scrubbing than did the acoustical plasters, and the fibre boards and felts contained 20 per cent (by weight) of water after normal drying for 72 hours. Neergaard's tests indicate that the most suitable materials for the acoustical treatment of hospitals are felted materials (mineral wools are now available) which can be covered with a painted and washable membrane, perforated fibre boards which can

FIG. 201. Kitchen in Michael Reese Hospital. (*Schmidt, Garden and Erickson, Architects.*) Ceiling treated with painted "Acousti-Celotex."

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[5] In some tests conducted by the author in connection with the acoustical treatment for the Los Angeles County General Hospital, Acute Unit, it was found that two types of acoustical plaster (both having coefficients of absorption in excess of 0.20 at 512 cycles) would withstand repeated washings. These plasters gained weight in the amount of 36 per cent after soaking. Twenty-five per cent of the absorbed water remained in the plaster after drying for 24 hours, and 5 per cent after drying for 72 hours.

be painted many times without loss of absorptive value, and acoustical plasters which can be washed and redecorated without appreciable loss of absorptive value.

Recently, a number of tiles and plasters have been developed which possess all the merits required of acoustical materials for the treatment of hospitals. The specifications for the new Los Angeles County General Hospital, Edwin Bergstrom and associates, architects, called for an acoustical plaster having coefficients of absorption of not less than 0.10 at 128 cycles, 0.20 at 512 cycles, and 0.26 at 2048 cycles. In addition, the specifications called for a plaster of high tensile and compressive strength, which can be washed with soap and water and cleaned with a vacuum cleaner operating under a nozzle pressure of 3 inches, which will not dust, rub or fall off from the walls or ceiling, and which can be integrally colored to a uniform light buff. The selection of the acoustical plaster for this building was based upon cleaning, washing, and sound-absorptive tests of many competitive plasters which were applied to the walls and ceilings of several test rooms provided at the building. As a result of these tests a plaster has been developed which meets all the acoustical and structural requirements set forth in the architects' specifications.

Many people are of the opinion that the pores in acoustical materials provide ideal nests for the proliferation of bacteria. This point also has been tested by Neergaard,[6] who collected a number of typical materials, including felts, fibre boards, and acoustical plasters, and applied cultures of *B. prodigiosus,* by means of brushing and spraying, to five typical acoustical materials. The materials later were tested for the presence of these bacteria at different depths in the materials. All the tests revealed the presence of bacteria up to the eighth day following the infusion, but on the twelfth day the tests were negative on all the materials. The results were about the same for both the organic and the inorganic materials, and indicated that in general acoustical materials do not possess any better germ-breeding nests than do hard plaster, wood, and other materials which are used for the interior walls and ceilings of hospital rooms. On this point Neergaard states, " Certainly there is no evidence of bacterial proliferation, even with the saprophytic *B. prodigiosus,* and there is every reason to believe that the materials composing the samples would provide an even less satisfactory source of food supply to organisms accustomed to a more highly developed parasitic existence." It would appear therefore that such acoustical materials as are commonly used for the treatment of hospitals do not increase the hazard of germ propagation.

[6] C. F. Neergaard, Jour. Acous. Soc., **2**, 106 (July, 1930).

The advantages to be gained in making the hospital quiet are manifold. Materials and types of construction are available, which, if used in accordance with the established principles of architectural acoustics, will provide a much-needed quiet — and at a price which will be amply warranted.

CHAPTER XXI

CHURCH BUILDINGS

167. Introductory. In one of the best and most widely read American books on church architecture, written at the beginning of this century, the only specific proposal for securing good acoustics is a suggestion that long and narrow naves possess better acoustical properties than do short and wide naves. Although, as a general rule, this suggestion may contain an element of fact — since long and narrow naves would have a shorter reverberation time than would relatively short and wide naves, owing to the shorter mean free path between successive reflections — it is, of course, only a relatively inconsequential factor in determining the acoustical properties of a church building. There are ample architectural reasons for the long, narrow, and high nave, but solely from the standpoint of acoustics the short, wide, and low nave is superior, especially for the spoken part of the church service. But religious tradition, architectural beauty, and the high purpose of the church should not be detrimentally compromised even for good acoustics. Fortunately, the requirements for good acoustics are of such a nature that they do not call for any pernicious changes in the structural composition of either classical or modern church architecture. But it must be remembered that the proper vehicle for speech and music is as truly an artistic and spiritual expression of the church as are proportions in form, durability in materials, and simple elegance in furnishings. The sermon in the modern church, and especially in the Protestant church, has become a most important part of the church service, and although the congregation assembles principally for the purpose of worship, the present-day worshipers will be greatly dissatisfied if they cannot hear the sermon. It can hardly be disputed that church architecture reaches its most sublime beauty only when it conveys to its disciples, both through the eye and through the ear, that which is the finest and the most enduring of our civilization. It is the purpose of the present chapter to outline some of the practical methods by which this high objective — in its acoustical aspects — can be attained.

The interior shapes of churches are often very complicated, consisting of numerous connected spaces; but nearly all existing forms have evolved from two primitive ones — the oblong and the circle — into variations of the Greek or Latin cross. In the more complicated forms, the acoustical problem is one of coupled spaces, in which it is necessary to give careful consideration to the resulting acoustical properties in the sanctuary and in the chancel, in the organ chamber and the choir loft, in the nave and the transcepts, and in the aisles and the adjacent chapels. We shall begin with the simplest forms of country churches, where the acoustical problem is concerned with a single rectangular room. Then, following the order adopted by Ralph Adams Cram in his admirable book, " Church Building," we shall consider successively the increasingly more complex forms of village churches, city churches, and cathedrals.

It is necessary at the same time to recognize the general nature of the acoustical requirements for churches of different denominations. Music is an important function in all churches. The sermon is a more important function in the Protestant church than it is in the Roman Catholic church.[1] In the Christian Science church, the acoustical requirements involve good audition for speaking, reading, and singing from the platform, and in addition good audition for speaking which may originate from any seat in the auditorium. The synagogue, as a rule, is circular or octagonal in plan, and the ceiling is high and domed. It therefore must be studied very carefully from the standpoint of echoes, sound foci, delayed reflections, and excessive reverberation. The Gothic cathedral, on the other hand, is not so likely to suffer from echoes, sound foci, and delayed reflections; but because of its extreme length the audience is not near the source of sound, and therefore provision should be made to project the sound to even the most remote auditors. In all churches the necessity for complete insulation against outside noises cannot be too strongly emphasized. Of all places, the church should provide a quiet refuge from the outside world of noise and turmoil. This is impossible in a church where one is disturbed by the honking of automobiles, the clanging of trolley cars, and the grinding and clashing of the gears of motor busses and trucks. These and many other varied problems in acoustics which arise in the design of church buildings will be discussed in the following sections.

168. Country Churches. The country church is usually a long rectangular room with the sanctuary and chancel at one end and the nave at the other end. Fig. 202 shows an arrangement of organ, choir, pulpit, and lectern which conforms to good acoustical design. The organ speaks directly into the chancel and the nave, and is behind the choir, where it can support rather than submerge the singers. The pulpit and lectern are both near the audience. If the importance of the altar precludes the feasibility of locating the organ behind and above it, the

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[1] The Reformation brought a change in church architecture which places the major emphasis on the pulpit rather than on the altar.

organ can be located in a chamber behind the altar, and concealed from the audience by a suitable grille which, at the same time, will not impede the flow of sound from the organ to the chancel and nave. This location of the organ is far better than the one so frequently assigned to it in modern design, namely, on either side of the chancel.

Reasonable precaution should be taken in insulating the church against outside noise, or against noise which may originate in adjacent rooms. If the building is located on a quiet country road it is not probable that any special measures need be taken, but if it is located on a busy highway, or if there are other sources of noise in the vicinity of the church, the walls, ceiling, doors, and windows should be designed to provide adequate insulation against all existing or probable future noises. The manner of making the calculations and choosing the proper types of construction for any required amount of insulation is worked out in Chap. XIII. (See also Sec. 158.) If the walls are of stone or brick, and if the ceiling has a comparable degree of insulation, it is likely that the problem of sound-insulation will consist only of providing sufficiently heavy, and tightly fitting, doors and windows.

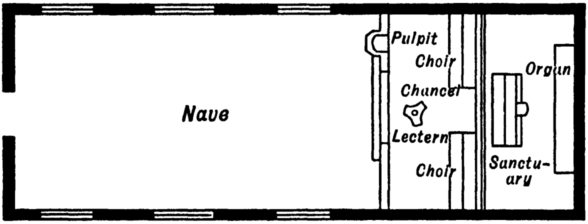

FIG. 202. Suggestive plan for country church, showing location of organ, choir, pulpit, and lectern for good acoustical properties.

The prime consideration in the acoustical design of the country church, as in all speech and music rooms, is the proper control of reverberation. In general, the walls, floor, and ceiling of the chancel and sanctuary should be finished with fairly reflective and resonant materials, as wood or lime plaster on lath; and the walls and ceiling of the nave should be finished with fairly absorptive materials, as acoustical plaster or tile. The optimal time of reverberation (at 512 cycles), which should be provided for two thirds of capacity audience, will depend upon the size and the denomination of the church, and can be determined from the chart given in Fig. 203. This chart is based upon the requirements for both speech and music and upon the nature of the services conducted by different denominations. Observations and measurements in many churches which have highly acclaimed acoustics show that these churches have times of reverberation comparable with those shown in the chart. The lower part of the band should be used for Christian Science churches because of the predominant importance of the spoken service. The upper part of the band should be used for cathedrals and Roman Catholic churches, where music is a relatively important part of the service. And the medial part of the band should be used for Protestant and Jewish churches, where speech and music are equally important.

Thus, suppose the church (Protestant) shown in Fig. 202 has a length of 90 feet, a width of 30 feet, and an average height of 35 feet. The church will accommodate 210 persons, so that the optimal time of reverberation should be provided for 140 persons. Suppose that the entire floor is of pine, and that 1100 square feet of the floor — the aisle, the chancel, and the sanctuary — be covered with carpet strips over ½-inch felt padding. With the carpet on the floor of the chancel and sanctuary, no other absorptive material should be used for the walls and ceiling of the chancel and sanctuary. Suppose therefore that the walls of the chancel and sanctuary are of lime plaster and the ceiling of wood.

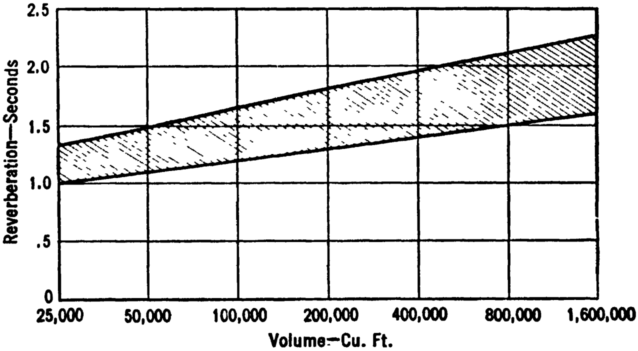

Fig. 203. Optimal reverberation times for church auditoriums. The lower part of the band should be used for Christian Science churches, the medial part for Protestant and Jewish churches, and the upper part for cathedrals and Roman Catholic churches.

The volume of the church is 94,500 cubic feet, and the interior surface is 13,400 square feet. The optimal time of reverberation is 1.30 seconds. In order to determine the materials to use for the walls and ceiling of the nave which will provide this time of reverberation it is necessary to go through the routine calculation, as follows:

The reverberation constant[2] k is 0.049. Therefore

$$\log_e(1-\alpha) = \frac{0.049V}{-St} = \frac{0.049 \times 94{,}500}{-13{,}400 \times 1.30} = 0.266.$$

Or $$\alpha = 0.234,$$

and $$\alpha S = 3140 \text{ sabines.}$$

The absorption supplied by the audience, wood floor, carpet, and the walls and ceiling of the chancel and sanctuary is tabulated as follows:

		Sabines
140 persons . . .	at 4.2 =	588
1600 square feet wood floor	at 0.06 =	96
1100 " " carpet . .	at 0.40 =	440
2500 " " lime plaster	at 0.05 =	125
1200 " " wood. .	at 0.06 =	72
Total . . .	=	1321

It is necessary therefore that the walls and ceiling of the nave supply 3140 − 1321 or 1819 sabines of absorption. This can be accomplished by treating all available wall and ceiling areas of the nave with an acoustical plaster having a coefficient (at 512 cycles) of about 0.27 to 0.30, or by treating the ceiling and the upper part of the walls with a more absorptive material and the lower part of the walls with ordinary plaster. The characteristic of the absorptive material should be such as to give the room a balanced reverberation for all frequencies. This condition will be satisfactorily approximated if the absorptive material have a coefficient at 128 cycles equal to about 40 to 60 per cent of the coefficient at 512, and a coefficient for frequencies above 512 of not more than 20 to 30 per cent in excess of the coefficient at 512.

If the acoustical design of a small country church conform to the principles and recommendations set forth in this section the church should be entirely satisfactory for both speech and music. The speech articulation will be in excess of 80 per cent in all parts of the nave, and music will have the required reverberation to balance the separate tonal components and to sustain and blend the harmony.

169. Village Churches. The acoustical problem of the church in the village, or small city, differs from that of the church in the country in two respects. The principal difference is in regard to the size and shape

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[2] This is the value given in Table III for a long, narrow church. The value $k = 0.05$ would be sufficiently accurate for practical purposes. However, it is obvious that the mean free path in a long narrow room will be somewhat shorter than the theoretical value $4V/S$, and therefore the value of 0.049 or even 0.048 would be appropriate for a church of the type here considered.

of the church. The acoustical problem becomes more important and more difficult as the size of the auditorium increases and as its shape becomes more and more complex. The second point of difference is in regard to the insulation of outside noise. There are likely to be more traffic noises, or more disturbances from near-by industrial plants, in the village or small city than there are in the country; and wherever such noises abound, the walls and ceiling, including the doors and windows, of the church should provide sufficient insulation to shut out completely these disturbances of the outside world.

In plan, the village church will differ from the plan of the country church shown in Fig. 202 in two essentials: (1) both the length and the width will be increased; and (2) it is likely that transepts and a porch (or narthex) will be added to the nave. These extensions and additions do not affect the arrangement of the chancel, choir, sanctuary, or organ chamber, and the arrangement of these spaces shown in Fig. 202 for the country church should be followed as closely as possible in the village or small city church. The addition of transepts to the nave will alter the distribution of sound in the auditorium, will alter slightly the mean free path or average distance between reflections, and therefore will modify the reverberation constant k which must be used for calculating the reverberation time in the church. Thus, suppose the church is cruciform in plan, similar to the model described in Sec. 55. Then the value of k will be 0.053, instead of 0.049, which holds only for simple rectangular rooms. If the church does not approximate the shape of any of the models described in Sec. 55, it may be advisable to construct a small model and ascertain the value of k from an experimental determination of the mean free path. Such a model also will be useful for investigating the possibility of echoes from ceiling or wall reflections.

In general, it will be necessary to use a certain amount of absorptive material on the walls and ceilings of the nave and transepts to obtain the optimal condition of reverberation. The absorptive material should be distributed fairly uniformly in the nave and transepts so that there will be the same rate of growth and decay of sound in all directions and in all parts of the auditorium. This will be accomplished satisfactorily if the walls and ceilings of the transepts be treated with the same materials — and in about the same proportion of areas — as the walls and ceiling of the nave. As in the country church, the chancel and sanctuary should not be *over-treated* with absorptive material. If as much as 50 per cent of the floor area of the chancel and sanctuary be covered with carpet, the walls and ceiling should be finished with materials having an absorptivity comparable with wood or lime plaster. If no carpet for these areas be contemplated, then a portion of the upper walls, or the ceiling, should be treated with a suitable absorptive material, but in no case should the chancel and sanctuary contain large amounts of absorptive material. The calculations for the proper control of reverberation will be similar to those outlined for the country church. In most cases, it will be found that many materials will be sufficiently absorptive, if applied to areas which are suitable for treatment, to provide the optimal time of reverberation, and therefore the choice will be broad enough to make possible the selection of materials which will be in keeping with the requirements of permanence, simple elegance and the entire plan of the architectural treatment of the interior. From the standpoint of acoustics only, it generally will be preferable to apply absorptive material to the walls rather than the ceiling, as the treatment of the walls with absorptive material will prevent multiple reflections between parallel surfaces, and help to provide a more uniform rate of growth and decay of sound in the entire enclosure.

The problem of sound-insulation can be worked out along the lines already discussed in connection with the country church. The addition of the porch or narthex to the nave provides a means of securing two sets of doors between the nave and outside, and provision should be made to keep both sets of doors — the ones between the nave and the porch, and the ones between the porch and outside — closed during services. The use of carpets on the aisles not only contributes to the amount of absorption required for the optimal condition of reverberation, but also reduces the noise of footfalls of those who leave or enter the church during services.

With heavy, rigid walls and ceiling, with heavy and tightly fitting doors and windows, and with a proper amount and distribution of absorptive material within the nave, transepts, and chancel, the village church of conventional size and shape will have ideal acoustics — speech will be heard satisfactorily in all parts of the auditorium; and music, both vocal and instrumental, will be free from distortion and from the disturbing effects of noise and excessive reverberation, and its quality will be enriched and sustained by the proper amounts of reverberation and resonance.

In the modern church for the village or small city there may be, in addition to the church auditorium, a Sunday School assembly room, a social room, and smaller class rooms, all of which require proper acoustical treatment. These rooms are not essentially different from the rooms to be found in school buildings, and their acoustical design should be worked out along the lines described in Chap. XIX.

170. City Churches. The city church presents acoustical problems which are as varied as its architectural style and treatment, and therefore each structure should be studied as a new and particular problem in acoustics. There are, however, many aspects that are common to the acoustical design of all city churches, such as insulation of noise, control of reverberation, and the arrangement of chancel, choir, organ, pulpit, and lectern. These features have been discussed in the preceding sections of this chapter, and are at least as important in the design of city churches as they are in the design of country or village churches. The city church differs from the country or village church principally with regard to shape and size. It may be of the conventional Gothic type with high, vaulted nave, narrow aisles, fluted columns, long and narrow chancel and sanctuary, and adjacent transepts; it may be of octagonal or circular plan with a high and domed ceiling, with or without a balcony; or it may be of simple rectangular form, as wide as it is long, and with a relatively low ceiling.

Since the city church is nearly always of large dimensions, the problem of supplying an adequate amount of sound energy to all auditors is likely to present a real difficulty. The pulpit and lectern should be well elevated and near the audience, and if possible there should be large and near-by reflecting surfaces either above or behind both the pulpit and the lectern. In extreme cases carefully designed sounding boards may be desirable. Although the sounding board may contribute only slightly to better hearing, the contribution, however small, is both necessary and worthy of the effort.

The shape of each church design should be studied with regard to echoes, interfering reflections, sound foci, and the distribution of sound to all auditors. This often can be done satisfactorily by a study of pencil sketches with the ray or image methods, but in case the shape is complicated it can be best accomplished by studies in three-dimensional models, by the ripple tank method, the spark photography method, or by the optical method described in Sec. 55. Studies by the optical method will not only reveal outstanding defects of shape and suggest alterations which will overcome the defects, but will provide a means for determining the mean free path and thus the parameter k for the reverberation formula.

The modern church in the city is much more than the traditional place of worship in which the formal services of the church are conducted. It is a religious and social centre which provides a Sunday School assembly room, social hall, dining room, class rooms, and rooms for many other activities. Good acoustical design in the modern city church requires that careful consideration be given to the treatment of all these rooms. In general, where the rooms are of conventional rectangular form with ceiling heights less than 30 feet, it is sufficient to treat the walls

Fig. 204. St. Joseph's Episcopal Church, Detroit. Ceiling treated with Type B "Acousti-Celotex." (*Nettleton and Weaver, Architects.*)

or ceilings, or both walls and ceilings, of the several rooms with materials of suitable absorptivity, and to provide an adequate amount of insulation to prevent noise interference between adjacent or near-by rooms which are to be used at the same time.

The nature of the acoustical problems which arise in city churches and practical methods which have proved satisfactory for solving these problems will be considered by outlining what has been done in four typical churches: a Protestant, a Roman Catholic, and a Christian Science church, and a Jewish synagogue.

(*a*) *The Protestant Church. St. Joseph's Episcopal Church, Detroit.* This church, designed by Nettleton and Weaver, is reputed to have excellent acoustics for both speech and music. An interior view is shown in Fig. 204. The church seats 700 persons and has a volume of approximately 200,000 cubic feet. The pulpit is well elevated and located near the audience, so that no special reflecting surfaces are needed to supply all listeners with an adequate amount of speech energy. No special measures were adopted for sound-insulation, but the finished church is free from disturbing outside noise. The shape and size of the auditorium did not present any difficulties from the standpoint of sound foci, echoes, or interfering reflections. It remained only to provide a suitable time of reverberation, and to use a type of absorptive material which would permit an elaborate decoration in the ceiling. Type B Acousti-Celotex afforded both the absorptive and decorative properties required for the ceiling treatment. A decorated ceiling bay is shown in Fig. 205. Calculations of the reverberation time in advance of construction indicated that this material applied to the entire ceiling would reduce the period of reverberation in the empty auditorium to 2.6 seconds. Measurements in the finished auditorium revealed a reverberation time of 2.4 seconds. With an audience of 500 the reverberation time is just over 1.5 seconds, and with an audience of 700 the reverberation is just under 1.4 seconds. It will be seen that these times are in good agreement with those specified as optimal in Fig. 203, and that the reverberation time does not vary greatly with the size of the audience.

The church organist, Mr. William I. Green, acclaims the acoustics to be exceptionally good for music. Owing to the nearly uniform reverberation, with or without an audience, the organist is able to produce the same acoustical effects in the empty auditorium as he is when an audience is present. This is an important advantage for organ players since it is not necessary to use one type of playing when rehearsing in the empty auditorium and another type when performing before an audience.

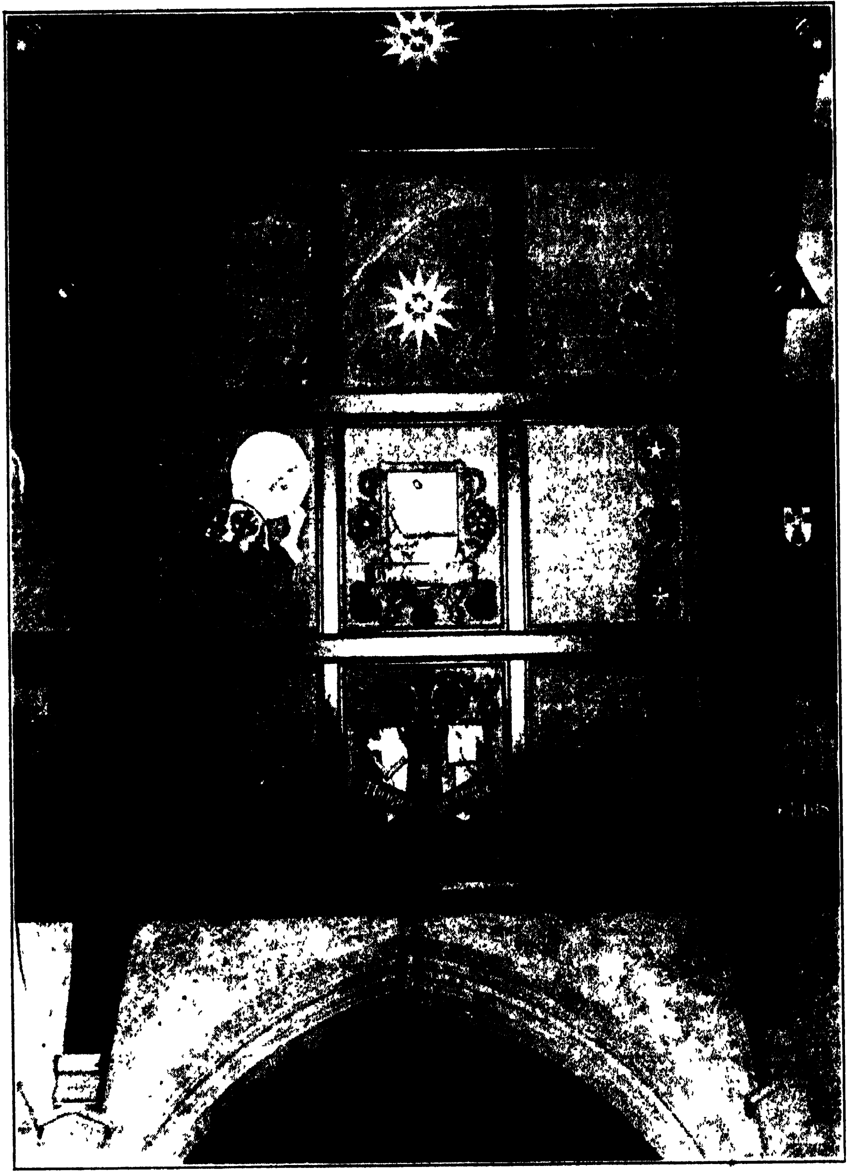

FIG. 205. Ceiling bay in St. Joseph's Episcopal Church, Detroit, showing the heavy decoration applied to the acoustical treatment.

(*b*) *The Roman Catholic Church. St. Vincent's Roman Catholic Church, Los Angeles.* Although this church cannot be cited as one having ideal acoustics, it does have better than average acoustics; and it is of particular interest in connection with the acoustical problems in church design which we are considering in this chapter. The volume of the auditorium is 650,000 cubic feet and the seating capacity is about 1500. At the time the church was originally designed by Albert C. Martin, architect, good acoustics was regarded as a problem of the proper control of reverberation. All smooth surfaces in the ceiling of the auditorium, with the exception of the ceiling over the organ (about 6500 square feet in all), were treated with a ½-inch acoustical felt, and the entire walls of the sanctuary, nave, transepts, and aisles were finished with a carbide process travertine which, according to laboratory tests, had some, although slight, acoustical merit.

The acoustical outcome was much better than in most Roman Catholic churches of comparable size in which no special acoustical materials had been used, but, as standards of good acoustics were elevated, it became apparent that the acoustics could be improved. Accordingly, when certain alterations and redecorations were undertaken in 1929, under the direction of Cram and Ferguson, and Samuel E. Lunden, architects, it was decided to improve the acoustics of the main auditorium. Reverberation tests conducted in September, 1929, showed the following times of reverberation in the empty auditorium:

128 cycles	4.72 seconds
512 "	3.94 "
2048 "	2.63 "

These tests indicated that more absorptive material was needed in the church in order to reduce the reverberation to a suitable value.

At the same time, speech articulation tests were conducted in the auditorium both with and without the aid of a public address system, which had been used at times in the church. Without the public address system, the P.A. (percentage articulation) was 52 per cent in the front pews and diminished to 26 per cent in the rear pews. With the help of the public address system hearing conditions were even worse, especially in the front part of the auditorium. The P.A. was about 27 per cent in all parts of the auditorium.

Tests conducted at this time also indicated the necessity of increasing the insulation against outside noise — the noise in the church at times reached a level of 35 db.

The ceiling treatment was replaced by a more absorptive acoustical tile, and additional acoustical tile was applied to the ceilings of all aisles. Although it was realized at the time that this amount of absorptive material would not be sufficient to reduce the reverberation to the optimal time, it was deemed inadvisable to alter the architectural beauty of the walls or to carpet the floor or add cushions in the pews. The measured reverberation times in the empty auditorium after all alterations and decorations had been completed were as follows:

128 cycles	3.18 seconds
512 "	2.85 "
2048 "	2.40 "

With an average audience in the church the reverberation time at 512 cycles is reduced to about 2.2 seconds, whereas the optimal time is slightly less than 2.0 seconds (see Fig. 203).

Speech-articulation tests were conducted in the auditorium to ascertain the effectiveness of the acoustical treatment and also to determine the benefit derived from the use of an improved public address system which replaced the older one. The tests showed an average P.A. in the empty auditorium of 68 per cent, with the public address system operating at the normal level, and an average P.A. of 54 per cent with the public address system turned off. If these P.A.'s be compared with those obtained before the alterations were commenced it will be noted that the hearing conditions were very much improved. With a capacity audience in the auditorium, and with the public address system operating properly, the hearing is quite satisfactory in all parts of the auditorium. Music is rendered without the aid of the public address system and is regarded as very good.

There is still considerable noise inside the church from outside traffic. This noise could be reduced by installing another set of doors between the auditorium and the narthex, and by keeping all doors and windows closed during church services.

(*c*) *Christian Science Church. Thirteenth Church of Christ Scientist, Hollywood, California.* The plan of the auditorium in this church, designed by Allison and Allison, architects, is shown in Fig. 208, and an interior view is shown in Fig. 209. It is a church of moderate size (about 300,000 cubic feet), seating 1248 persons. The wall behind the readers' platform gives a good reenforcement to the readers' voices, and the relatively low ceiling provides a beneficial reflection to speech originating at any seat in the auditorium. The platform is well elevated, as are also the rear seats in the auditorium, thus providing all auditors with good *audition* lines as well as good *sight* lines.

All the usual precautions were taken to free the auditorium from disturbing noises. The church is located on a rather quiet side street where

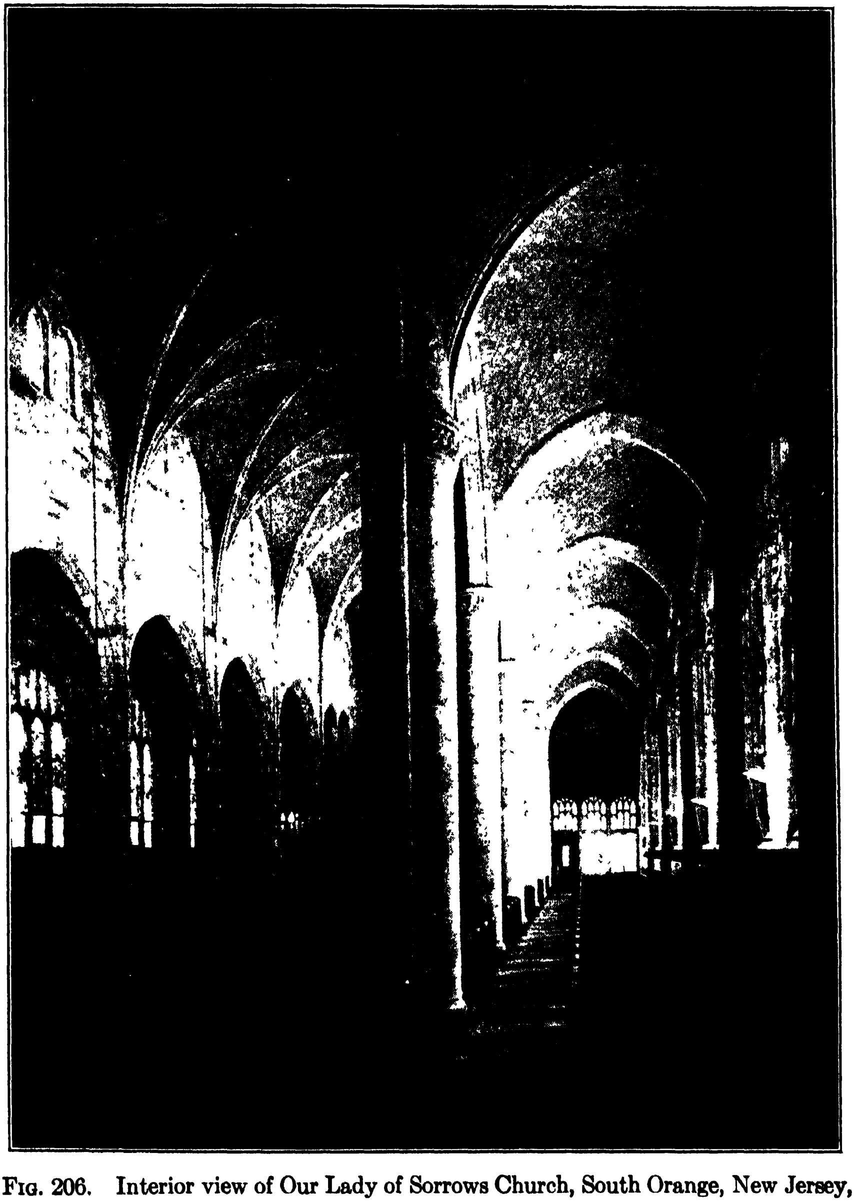

FIG. 206. Interior view of Our Lady of Sorrows Church, South Orange, New Jersey, showing the location of the organ above the rear balcony, and the acoustical tile in the ceiling.

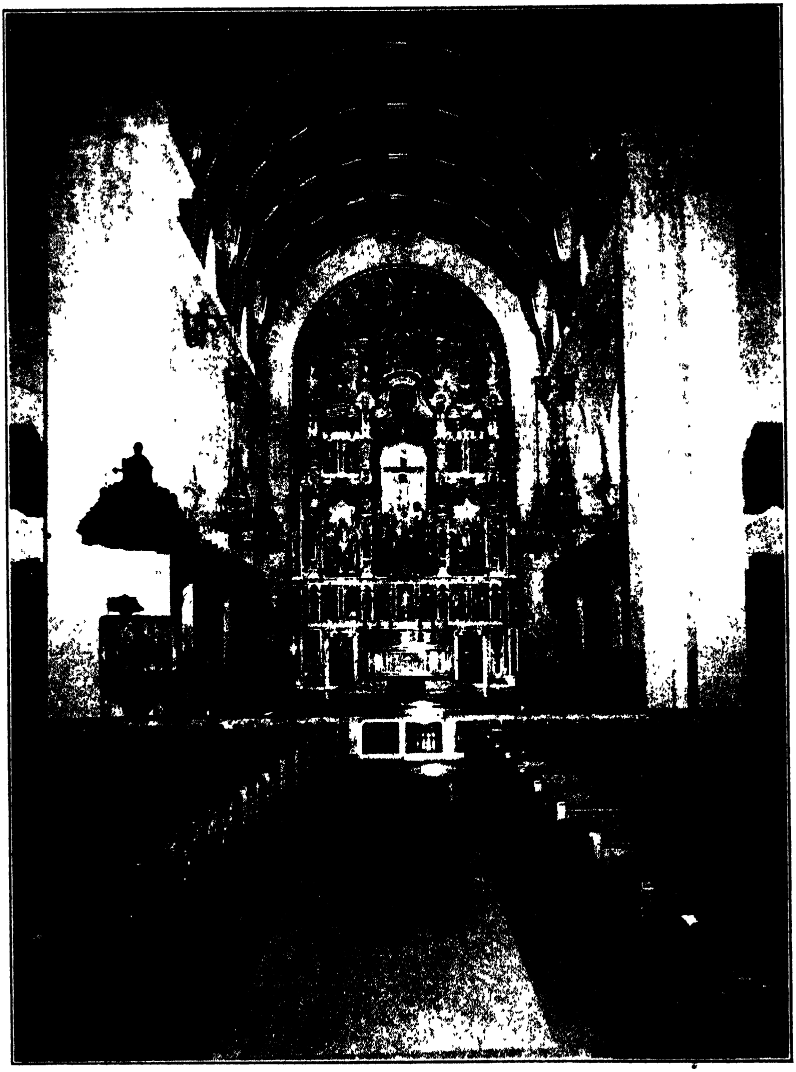

FIG. 207. Interior of St. Vincent's Roman Catholic Church, Los Angeles, California.

the noise level is rarely above 40 db. However, the insulation was made good enough to give quiet inside the auditorium even with an outside noise of 50 db. All doors and windows were of heavy, rugged construction and were fitted carefully into their frames so that all threshold cracks were closed. The entire floor of the foyer was carpeted over a felt carpet lining. This helped to absorb outside noise before it reached the main auditorium, and also prevented any possible noise from the footfalls of late comers.

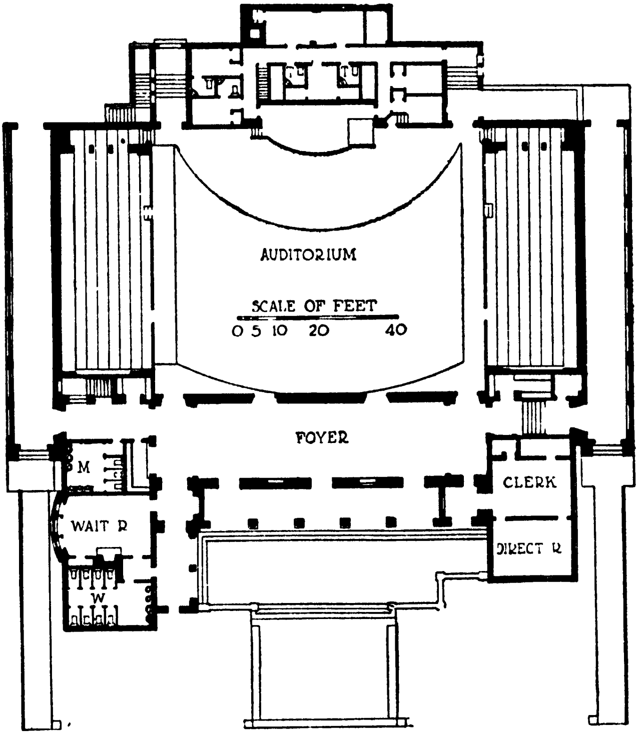

FIG. 208. Plan of Thirteenth Church of Christ, Scientist, Hollywood. (*Allison and Allison, Architects.*)

The reverberation time was reduced to 1.5 seconds at 512 cycles for two thirds of capacity audience, and to 1.3 seconds with a capacity audience. This was accomplished by (1) treating the upper walls of the auditorium with an acoustical plaster having a coefficient of 0.18 at 512 cycles (the lower walls were left in hard plaster to give helpful reflections and to prevent possible rubbing or dusting off of the acoustical plaster), (2) covering the entire floor with carpet strips over ½-inch felt lining, and (3) installing upholstered seats throughout the auditorium.

Speech-articulation tests conducted in the finished auditorium revealed that the acoustical properties were very satisfactory. The articulation was 85 per cent in the front and 82 per cent in the rear part of the auditorium. A speaker at any position in the seated area could be heard very well in all other parts of the auditorium.

(*d*) *Jewish Synagogue. B'Nai B'Rith Temple, Los Angeles.* The recently completed B'Nai B'Rith Temple, in Los Angeles, A. M. Edelman, architect, and Allison and Allison, consulting architects, furnishes a good example of acoustical designing both in advance of and during construction. The architect and the consultant on acoustics worked in close cooperation from the beginning of the rough sketches for the Temple, in 1925, until the building was completely furnished, in 1929. The general design of the Temple called for an octagon in plan and a high, domed ceiling. The required height of the dome and ceiling to give good proportions in design made it necessary to sacrifice the benefit of ceiling

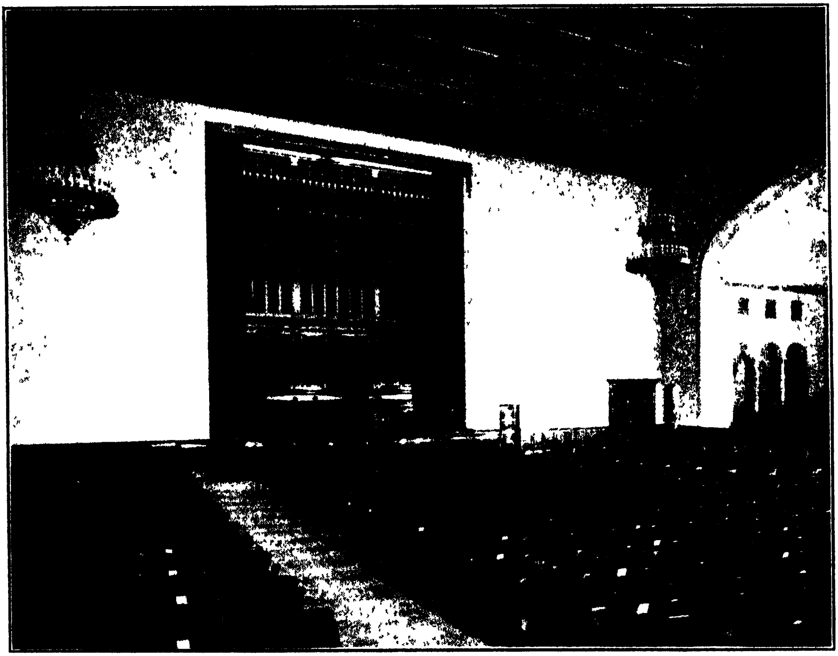

FIG. 209. Interior view of auditorium in the Thirteenth Church of Christ, Scientist, Hollywood, California.

reflections, except for a portion of the groined ceiling above the choir loft. During the early stages of the design, acoustical studies were made by means of small sectional models and the ripple tank. (See Sec. 29.) These studies indicated the presence of two troublesome reflections: (1) from the ceiling surface above the choir loft, and (2) from the rear half of the dome. The first reflection was converted into a beneficial one by elevating slightly the choir loft. The second reflection, which would have produced a distinct echo in the front central part of the main floor, was overcome by penetrating the soffit of the dome with deep coffers — 12 to 16 inches deep — and treating the panels of the coffers with highly absorptive tile.

Fig. 210 shows an outline of the plan of the adopted design for the main auditorium, and Figs. 211 and 212 show respectively an interior and an exterior view of the completed Temple. The auditorium is 100 feet wide, 100 feet deep, and the ceiling height to the soffit of the dome is slightly over 100 feet. It will be seen that the shape, in plan, is based upon correct acoustical principles. The audience is located near the speakers' platform, and receives advantageous reflections from wood paneling directly behind the platform and from the diverging side walls (also of wood paneling up to a height of about 16 feet from the floor).

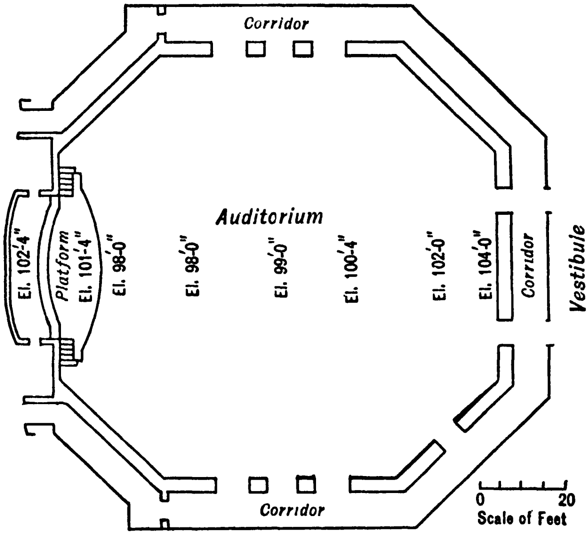

FIG. 210. Plan of the B'Nai B'Rith Temple, Los Angeles. (*A. M. Edelman, Architect; Allison and Allison,' Consulting Architects.*)

The platform is elevated 4 feet above the main floor, and the rear seats are elevated sufficiently to allow all auditors on the main floor an abun-

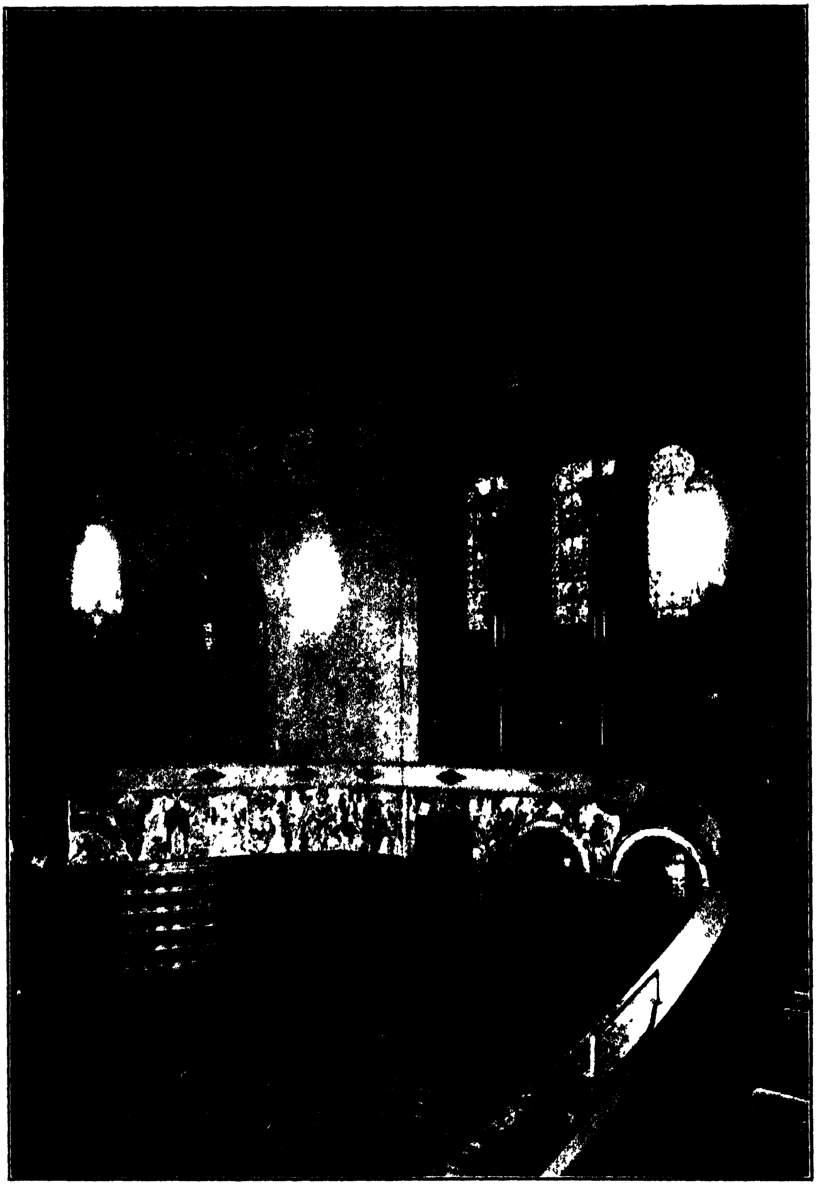

FIG. 211. Interior view of B'Nai B'Rith Temple.

dant supply of direct and once-reflected sound. (See elevations marked on Fig. 210.) The choir loft is elevated 14 feet, 6 inches above the speakers' platform, has a wood floor, and is backed by wood paneling. The organ is located above and behind the choir loft, and speaks directly into the main part of the auditorium.

The Temple is located on a busy thoroughfare (Wilshire Boulevard), where the average noise level is 50 to 55 db, but it is adequately insulated against this outside noise. The walls are of heavy reenforced concrete; there are two sets of heavy and tightly fitting doors between the outside and the inner auditorium; there is an additional wall between the auditorium and the surrounding corridor; the corridor and the vestibule are treated with absorptive material; and the windows are of heavy, leaded glass, are permanently closed, and the ratio of the window area to the total wall area is low, so that the amount of noise transmitted through the windows is relatively small. Owing to the large amount of absorptive material in the auditorium, the residual noise is reduced to a level which can be readily tolerated. In fact, the noise reduction provided by the combined effects of insulation and absorption amounts to slightly more

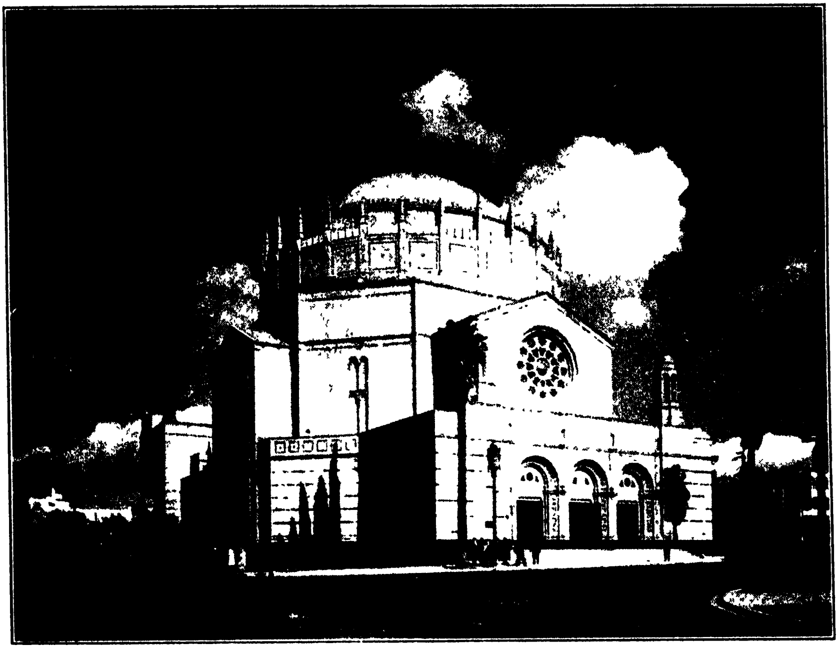

FIG. 212. Exterior view of B'Nai B'Rith Temple.

than 40 db, so that the residual noise from the outside does not exceed 15 db, which is no greater than the unavoidable noise of a quiet audience. The ventilating equipment room is well removed and insulated from the auditorium. The fans and motors are of the slow-speed type, so that the noise reaching the auditorium from this source is negligible.

The remaining and most important part of the acoustical design consisted of securing for the large auditorium (800,000 cubic feet) the proper condition of reverberation. The initially planned times of reverberation (at 512 cycles) were as follows:

No audience present	2.20 seconds
600 persons "	2.01 "
1200 " "	1.85 "
1800 " "	1.75 "

In order to secure these rather low times of reverberation it was necessary to use large areas of highly absorptive materials for nearly the entire inner boundaries of the auditorium. In fact, all surfaces except the wood wainscot and the frescoed frieze above the wainscot are acoustical materials. The panels in the coffers of the dome are a highly absorptive acoustical tile (0.30 at 128 cycles and 0.65 at 512 cycles); the ribs of the coffered dome are of cast acoustical plaster; the walls above the frescoed frieze are of acoustical plaster (0.12 at 128 cycles and 0.19 at 512 cycles); the walls of the aisle are of acoustical tile; the main and balcony floors are completely carpeted over "ozite"; and all pews are made up of heavily upholstered chairs with both backs and seats padded and covered with porous fabric.

Unusual care was exercised in the selection of the acoustical plaster. Nine small Sunday School rooms were plastered with nine different types of acoustical plaster, and absorptive tests were conducted in all rooms in order to determine the absorptivity of the different plasters at frequencies of 128, 512, and 2048. The final selection of the acoustical plaster was based upon the results of these tests and upon the other physical properties of the plasters, such as tensile strength, texture, color, and ease of maintenance. After the selection was made, the plastering contractor was required to duplicate the approved plaster in the test room, with respect to thickness, texture, color, and porosity. Porosity tests with the apparatus described in Sec. 72 were made during the application of the plaster.

After the auditorium was plastered, but before it was furnished with carpet and upholstered seats, absorptive tests were conducted in the auditorium to determine the grade and amount of carpet required to give the optimal condition of reverberation. The times of reverberation in the unfurnished auditorium were as follows:

128 cycles	4.08 seconds
512 "	3.39 "
2048 "	2.62 "

These tests indicated that in order to secure the optimal condition of reverberation[3] it would be necessary to carpet all aisles on the main floor and in the balcony with a heavy grade of carpet strips over ¾-inch "ozite"; to carpet the remainder of the floor space, both on the main floor and in the balcony, with carpet strips over ½-inch "ozite"; and to use heavily upholstered chairs throughout the auditorium. The resulting times of reverberation in the completely furnished auditorium were as follows:

	128 cycles	512 cycles	2048 cycles
No audience present	3.20 seconds	2.03 seconds	1.75 seconds
600 persons "	3.04 "	1.90 "	1.64 "
1200 " "	2.90 "	1.77 "	1.53 "
1800 " "	2.78 "	1.67 "	1.43 "

Although these times of reverberation are slightly shorter than those originally planned, they provide highly satisfactory conditions for either small or capacity audiences and for either the spoken or musical service. Speech-articulation tests in the finished auditorium gave a speech articulation varying from 88 per cent in the front part of the main floor to 77 per cent in the rear of the balcony. These findings are confirmed qualitatively by reports from members of the congregation who state that they can hear very well in all parts of the auditorium. In fact, the hearing of speech in this auditorium is better than would be anticipated on the basis of Eq. (60) and the theory presented in Chap. XVII. The reason for this is probably attributable to the seating arrangement, which places all seats relatively near the pulpit, and to the beneficial reflections from the wall directly behind the speaker and from the diverging walls on both sides of the speaker.

The auditorium is not only acclaimed for its good acoustics as a speech room, but is likewise acclaimed as a good music room. Both choral and organ music are heard to good advantage in all parts of the auditorium.

The Assembly Room, volume 113,000 cubic feet, has its walls and ceiling treated with the same type of acoustical plaster as was used in the main auditorium. The resulting reverberation time with two thirds of capacity audience is 1.30 seconds. The acoustics are very satisfactory for both speech and music. In like manner, the Banquet Room and all the larger Sunday School rooms are treated with acoustical plaster.

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[3] At the time these tests were made it was decided to provide slightly shorter times of reverberation than had been initially planned two years earlier.

171. The Cathedral. Since, as was shown in the preceding section, the city church presents acoustical problems which must be considered individually, it is apparent that it is impossible to set forth specific recommendations for dealing with the acoustical problems in the cathedral. It is equally apparent, however, that the same general principles that determine good acoustics in smaller churches must apply to the cathedral. But the cathedral, more than all other church buildings, is a transcendental work of art, and as such, beauty to the eye and to the soul should not be sacrificed to obtain excellence in acoustics.

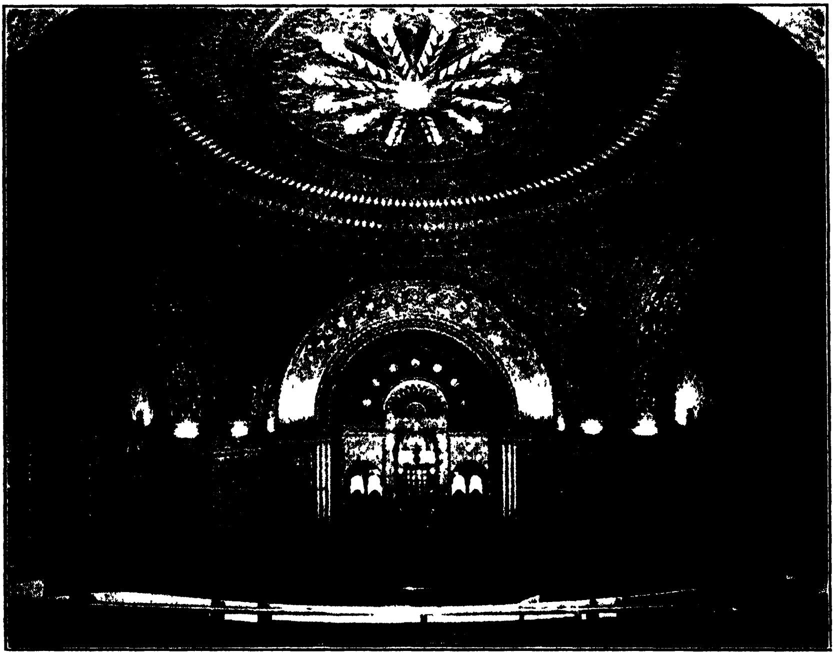

Fig. 213. Interior view of Rodeph Sholom Synagogue, Philadelphia. (*Simon and Simon, Architects.*) The entire ceiling above the spring line is treated with Johns-Manville "Nashkote," Type "C." White-faced "Akoustikos Felt" was used. The surface was sized and decorated.

The acoustical problem of the cathedral, in its relation to form and structure, should be appreciated first of all by the architect. He will then create forms which are intrinsically compatible with good acoustics. He will avoid domed or cylindrical ceilings with smooth, hard surfaces and centres of curvature near the audience; he will think of the organ chamber as a part of a great musical instrument instead of an appendix which is to be relegated to a space which is determined principally by convenience; he will choose building materials for the outer walls and ceiling, and will design doors and windows, that will exclude all outside noise from the inner shrine of worship; he will select materials for the interior walls of the chancel and sanctuary which will preserve the reverberation and resonance required for music; and he will choose materials for all other interior surfaces which will control the reverberation so that both speech and music will possess the highest degree of intelligibility and beauty in all parts of the nave, transepts, and aisles. If the architect appreciates these aspects of the acoustical problem in church design, he will not make such mistakes as were committed in the design of St. Paul's in London, St. Peter's in Rome, or the cathedral in Esztergom (near Budapest), not to mention equally flagrant errors in our own country and in all other parts of the world. On the contrary, he will recognize at the beginning the essentials of good acoustical design, and he probably will have his initial and subsequent drawings studied and criticized by a competent consultant on acoustics. With the proper understanding of acoustics, the architect will not submit to the acoustical consultant an impossible design, but will have created a design which, with slight alterations and proper choice and location of materials, will be not only a triumphant work of beauty, as judged by the eye, but also a musical instrument which will impart to speech and music a quality that will elevate the soul of the worshiper to the noblest yearnings.

Two practical considerations should never be overlooked in planning the acoustics of cathedrals: (1) Owing to the great height of the ceiling and the tall parallel walls of the cathedral, it is wholly inadequate to install acoustical treatment only in the ceiling, because the multiple reflections between the parallel walls will produce an excessive two-dimensional reverberation. The walls as well as the ceiling should be treated with absorptive material. (2) Owing to the enormous size of a cathedral, it is essential to provide artificial means, as a public address system, for amplifying the spoken service. The average speaker cannot possibly supply sufficient speech energy for satisfactory hearing in a large cathedral unless the speech has been suitably amplified. Provision should be made during the construction of the cathedral to house the amplifying equipment in a separate room, to mount the sound projectors in appropriate and concealed positions, and to install all necessary conduits for the equipment.

CHAPTER XXII

OPEN-AIR THEATRES

172. Historical Development of Classical Open-Air Theatres. In Chap. I a brief outline was given of the development of the classical open-air theatre of the Greeks and Romans. In the present chapter there will be given a somewhat more detailed account of those features which should be considered in working out the acoustical design of Greek, Roman, or more modern types of open-air theatre. As the name implies, the theatre (derived from the Greek word θέατρον, " a place for seeing ") was initially a place for seeing rather than a place for hearing. The first theatre was little more than a marked-out place in a hollow at the bottom of a hillside. The spectators stood on the hillside and watched the action — usually dancing — which took place on the cleared space or stage. Later this marked-out space developed into a circular *orchestra,* with circular banks of benches extending about two thirds of the way around the orchestra (see Fig. 214). A *skene* or platform was later added behind the orchestra, as shown in Fig. 215, but the *skene* was originally a place for utility, rest, and recreation of the actors — and all action occurred on the circular orchestra. The skene developed into the *logeion,* which was gradually deepened and elevated to form the type of stage developed in the Roman theatre, as shown in Fig. 216. The Roman theatre was not located in a hollow on the hillside, but was usually on a level plain outside the city, and was erected as a single unit — the *auditorium,* in the form of semicircular banks of benches, connecting directly to the stage structure. The *orchestra* was reduced to a semicircle, or less, and became a part of the *auditorium.* The *skene* became a large platform or stage, well elevated, and enclosed by side and rear reflecting walls,

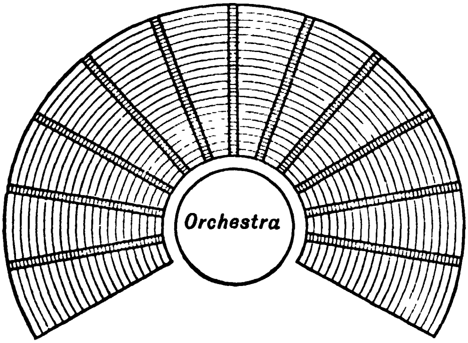

FIG. 214. Early form of Greek theatre showing circular *orchestra* which served as the stage or arena, and circular banks of benches, which later became the *auditorium.*

shown at *a* and *b*. These walls were permanently ornamented with all manner of relief work, and were pierced with five large doorways, three in the rear and one on each side. The reflecting walls and the elevated seats contributed markedly to the acoustical merit of the theatre which was rapidly developing into an art of sound as well as an art of scene.

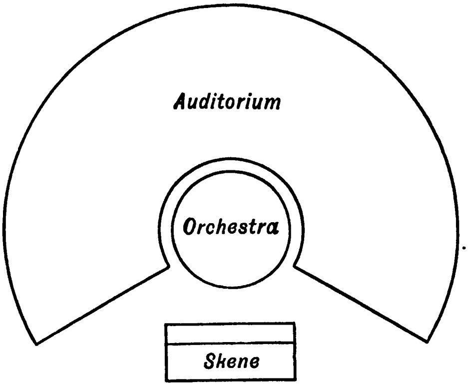

FIG. 215. Early form of Greek theatre showing a separate *skene* erected behind the *orchestra*.

One of the best existing accounts on the subject of Greek and Roman theatres is to be found in "The Ten Books on Architecture" by Vitruvius (translated by M. H. Morgan). The following selected quotations from Vitruvius are instructive, not only in describing the practice of the ancient architects in regard to the acoustical design of Greek and Roman theatres, but also in giving useful advice in the design of modern open-air theatres.

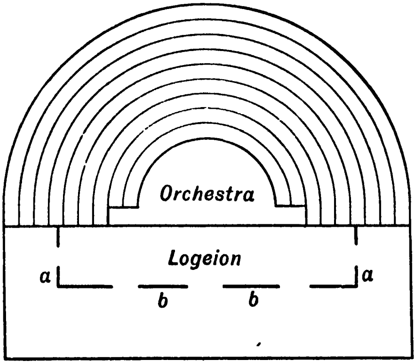

FIG. 216. Plan of early Roman theatre showing *logeion* and semicircular *orchestra*.

"Particular pains must also be taken that the site be not a 'deaf' one, but one through which the voice can range with the greatest clearness. This can be brought about if a site is selected where there is no obstruction due to echo.

"Voice is a flowing breath of air, perceptible to the hearing by contact. It moves in an endless number of circular rounds, like the innumerably increasing circular waves which appear when a stone is thrown into smooth water, and which keep on spreading indefinitely from the centre unless interrupted by narrow limits, or by some obstruction which prevents such waves from reaching their end in due formation. When they are interrupted by obstructions, the first waves, flowing back, break up the formation of those which follow.

"In the same manner the voice executes its movements in concentric circles; but while in the case of water the circles move horizontally on a plane surface, the voice not only proceeds horizontally, but also ascends vertically by regular stages. Therefore, as in the case of the waves formed in the water, so it is in the case of the voice: the first wave, when there is no obstruction to interrupt it, does not break up the second or the following waves, but they all reach the ears of the lowest and highest spectators without an echo.

"Hence the ancient architects, following in the footsteps of nature, perfected the ascending rows of seats in theatres from their investigations of the ascending voice, and, by means of the canonical theory of the mathematicians and that of the musicians, endeavoured to make every voice uttered on the stage come with greater clearness and sweetness to the ears of the audience. For just as musical instruments are brought to perfection of clearness in the sound of their strings by means of bronze plates or horn ἠχεῖα, so the ancients devised methods of increasing the power of the voice in theatres through the application of harmonics."

It is evident therefore that the ancient Greeks recognized that the power of the average voice was inadequate for distinct hearing in all parts of their theatres, some of which were large anough to accommodate an audience of 20,000 persons. According to Vitruvius and other authorities, attempts were made to increase the power of the voice by means of the application of *harmonics*. The word *harmonics*, as here used, probably has about the same meaning as our word resonance. This property of resonance was accomplished, we are informed in the writings of Aristoxenus, by distributing a large number of bronze vessels, fashioned into resonators, in regularly spaced niches throughout the theatre. In the larger theatres there were three horizontal ranges of resonators at equally spaced vertical levels, with twelve resonators in each horizontal range. All these resonators were carefully tuned to respond to the various notes of musical systems, and thereby would emphasize the more important frequency components of speech and music, and would particularly emphasize those notes in music which correspond to the harmonic scales. Thus, one range of the resonators was tuned for the enharmonic, another for the chromatic, and a third for the diatonic system — the three principal classes or *modes* used by the Greeks. Of these three modes Vitruvius gives the following description: "The enharmonic mode is an artistic conception, and therefore execution in it has a specially severe dignity and distinction. The chromatic, with its delicate subtlety and with the 'crowding' of its notes, gives a sweeter kind of pleasure. In the diatonic, the distance between the intervals is easier to understand, because it is natural." It is not improbable that these resonators (if they actually existed, since their authenticity has been questioned by some authorities) would contribute some value to speech and music, by emphasizing those particular frequency components which are harmonious in music and which contribute most to the intelligibility of speech. For example, in England and Germany, considerable attention is now being given to the matter of resonance in auditoriums. However, the actual merit of tuned resonators, such as were used by the Greeks for enhancing the loudness and pleasing qualities of speech and music, is rather difficult to assess. But the use of these resonators in the classical open-air theatres suggests certain possibilities of improving the acoustical quality of music rooms, and it will be seen in the chapter on music buildings that large resonant areas of wood paneling or plaster on lath are to be found in concert halls of the highest repute.

FIG. 217. Set of masks used in early Greek theatres. The mouths were often fashioned into megaphones. Note especially the masks for the old man and the servant. (*Nicoll.*)

There is one other practice of the Greeks which clearly indicates that they recognized the inadequacy of the loudness of the average speaker's voice; namely, the use of very large masks by the actors on the stage. (See Fig. 217.) These masks not only exaggerated the facial expressions so that they could be seen from the most remote seats, but they were shaped in such a way as would enhance the loudness of the voice by reason of their action as a megaphone.

One other quotation from Vitruvius is of interest in connection with the selection of the site for an open-air theatre, and it also indicates that the early Greeks and Romans appreciated many of the problems which arise in the acoustical design of theatres.

" All this having been settled with the greatest pains and skill, we must see to it, with still greater care, that a site has been selected where the voice has a gentle fall, and is not driven back with a recoil so as to convey an indistinct meaning to the ear. There are some places which from their very nature interfere with the course of the voice, as for instance the dissonant, which are termed in Greek κατηχοῦντες; the circumsonant, which with them are named περιηχοῦντες; again the resonant, which are termed αντηχοῦντες; and the consonant, which they call συνηχοῦντες. The dissonant are those places in which the first sound uttered that is carried up high, strikes against solid bodies above, and, being driven back, checks as it sinks to the bottom the rise of the succeeding sound.

" The circumsonant are those in which the voice spreads all round, and then is forced into the middle, where it dissolves, the case-endings are not heard, and it dies away there in sounds of indistinct meaning. The resonant are those in which it comes into contact with some solid substance and recoils, thus producing an echo, and making the terminations of cases sound double. The consonant are those in which it is supported from below, increases as it goes up, and reaches the ears in words which are distinct and clear in tone. Hence, if there has been careful attention in the selection of the site, the effect of the voice will, through this precaution, be perfectly suited to the purposes of a theatre."

W. C. Sabine, in his paper on Theatre Acoustics,[1] observes that this quotation from Vitruvius is an " admirable analysis of the problem of theatre acoustics. But to adapt it to modern nomenclature, we must substitute for the word *dissonance*, interference; for the word *circumsonance*, reverberation; for the word *resonance*, echo." The word *consonance*, as used by Vitruvius, signifies that the reflected sound unites with the direct sound with so little delay that there is no overlapping or confusing, but on the other hand there is, as Vitruvius describes it, a strengthening and supporting of the voice, so that the words which reach the ear are clear and distinct.

The classical open-air theatre of the Greeks and Romans was based upon a number of fundamental facts concerning the behavior of sound in the open, as is evidenced in the writings of Vitruvius and in the existing

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[1] "Collected Papers on Acoustics," 163.

ruins which can be found throughout southwestern Europe, but they were designed without the experimental knowledge of atmospheric acoustics and the nature of hearing which we possess today. The design of open-air theatres therefore should not only preserve and perpetuate those features of Greek and Roman design which have proved to be good, but also should be based upon our newer knowledge of acoustics. Accordingly, before considering the design of present-day open-air theatres, it will be helpful to consider a number of recent developments which have a pertinent bearing upon the acoustics of open-air theatres, such as atmospheric acoustics, hearing in the open, energy distribution in an open-air theatre having a stage with different types of reflecting walls and ceiling, and speech-articulation tests in a large, open-air theatre.

173. Atmospheric Acoustics. Certain facts in connection with the propagation of sound in the free atmosphere should be known in order to appreciate fully the nature of hearing in the open. In the chapter on elementary physical acoustics (Chap. II), it was shown that the speed of sound in still air, at a given temperature, is constant, and equal to about 1125 feet per second. If, however, the air be in motion, or if the temperature change, the speed of sound will be altered. Thus, the speed of sound in the direction of the wind is equal to the speed of the wind plus the speed of sound in still air. In like manner, the speed of sound against the wind is equal to the difference between the speed of sound in still air and the speed of the wind. In all cases of the propagation of sound in moving air, the vector velocity of the sound, with respect to an object at rest on the earth, is equal to the vector sum of the velocity of the sound in still air and the velocity of the wind. Also, since the velocity of sound in still air is given by $c = \sqrt{\gamma P/\rho}$ (Sec. 10), the speed of sound will be inversely proportional to the square root of the density of the air, and therefore directly proportional to the square root of the absolute temperature of the air.

It is to be expected therefore that both the motion of the air and changes of temperature in the air may have an influence upon the propagation of sound in the open and hence upon the acoustics of an open-air theatre. Indeed, many of the peculiarities of open-air acoustics can be explained by means of these two properties, as will be apparent from the following:

(*a*) *Effect of Wind upon the Propagation of Sound.* Suppose the wind is blowing past a source of sound *o*, as shown in Fig. 218. Then, since the speed of the wind is slowest at the surface of the earth and increases at higher elevations above the earth, the normal to the wave front of the sound that travels *with* the wind will be bent more and more toward the earth, whereas the normal to the wave front of the sound that travels *against* the wind will be bent more and more away from the earth. Consequently the upper portions of the sound waves which travel *with* the wind will be deflected downward and will contribute to the flow of sound energy near the level plain, thus intensifying the sound near the earth and making possible the propagation of sound to greater distances in the direction of the wind. On the other hand, the upper portions of waves which travel *against* the wind are relatively retarded so that they are directed away from the level plain, thus making impossible the propagation of sound to great distances in the direction against the wind.

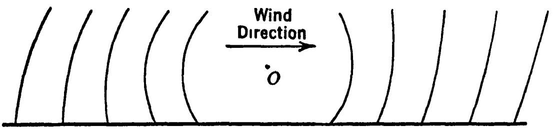

FIG. 218. Propagation of sound from a source *o* with the wind blowing from left to right.

The manner in which a wind affects the intensity of sound propagated in different directions is shown in Fig. 219.[2] The source of sound, located at *o* and directed as shown by the short arrow, consisted of a 512-cycle tone generated by a loud speaker with a short horn. The radius vector from *o* to the curve represents the amplitude of the sound wave in that direction at a fixed distance from the source. The wind in this test, conducted by Schindelin, is thus seen to have a marked effect upon the intensity distribution of sound — the amplitude of the sound wave in the direction of the wind, at a given distance from the source, amounting to at least four times the corresponding amplitude in the direction against the wind. Under these circumstances, it is to be expected that sounds will carry to much greater distances in the direction of the wind than they will against the wind, a fact which is commonly known and which can be readily verified. *Hence, in selecting a site for an open-air theatre where*

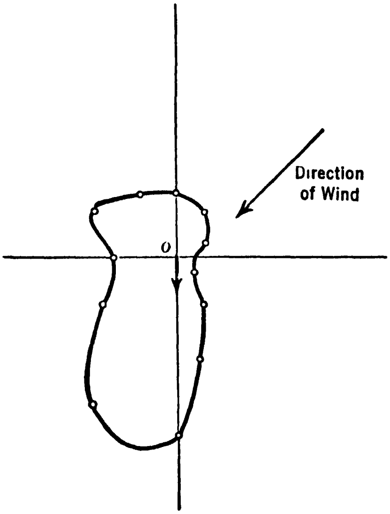

FIG. 219. Effect of wind on the intensity of sound propagated in different directions. The short arrow gives the direction the loud speaker was facing, and the long arrow gives the direction of the wind. (*Schindelin.*)

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[2] W. Schindelin, Ann. der Phys., **5**, Folge 2, 129 (1929).

there are prevailing wind directions, preference should be given to those sites where the wind will blow in the direction from the stage to the audience.

(*b*) *Effect of Temperature Differences in the Air upon the Propagation of Sound.* In the presence of a wind it was seen that the best condition for sound propagation was one where the upper portion of the waves traveled faster than the lower portion, thus bending the wave front downward and augmenting the flow of energy along the earth's surface. This condition may be favored by the vertical temperature gradient of the air. Thus, the speed of the upper portion of sound waves may be increased or decreased relative to the lower portion as a result of temperature differences in the lower and upper portions of the earth's atmosphere. Suppose that the temperature of the air decreases with the altitude above the earth's surface, as it most commonly does. Then the upper portions of sound waves originating at a source such as *o* in Fig. 218 will be retarded relatively to the lower portions, and consequently the wave front will be bent upward, as is shown in the left half of Fig. 218. On the other hand, suppose that the temperature increases with the altitude, as it may at times, especially over a smooth frozen lake. Then the upper waves travel faster than the lower ones do, and consequently the wave front will be bent downward, as is shown in the right half of Fig. 218. Under certain conditions of increasing temperature with altitude, an appreciable portion of the sound originating at a point source will be totally reflected by the upper and warmer layers of air. Under such circumstances there will be repeated reflections between the earth and the upper layers of air so that the sound confined between the earth and the reflecting layers of air spreads out circularly in sort of toroidal zone, and therefore the intensity dies away only as the inverse distance instead of the inverse square of the distance as is usual for a spherical wave in free space. These conditions often are approximated when it is possible on a quiet day to hear and understand ordinary conversation over a frozen lake at a distance of a half mile or even more.

If an open-air theatre be located where the temperature decreases with a rise in altitude, as is most usually the case, the slope of the seating area should rise slightly more than would be required in a homogeneous air or in a region where the temperature of the air increases with altitude. If the slope of the seated area rises more rapidly than do the advancing wave fronts, then all auditors in the theatre will be well elevated into the main current of sound energy and thus receive a relatively large amount of the sound energy coming from the stage.

Suppose, for the purpose of illustration, that the air 50 feet above the ground is 6° C. cooler than the air at the surface of the ground. Then, to a close approximation, we may think of the refraction all occurring at a single boundary 50 feet above the ground. The direction of the refracted rays can be calculated from the law of sines, namely

$$\frac{\sin \angle i}{\sin \angle r} = \mu \text{ (see Eq. [9])},$$

where i is the angle of incidence, r the angle of refraction, and μ the ratio of the velocities of sound in the warmer and in the cooler air. For a temperature difference of 6° C., μ will be approximately 1.01; and consequently when $i = 45°$, $r = 44.5°$; when $i = 30°$, $r = 29.6°$; when $i = 15°$, $r = 14.8°$; and when $i = 5°$, $r = 4.95°$. The effect of refraction in this case (which is perhaps an extreme instance, since the temperature, on the average, decreases only about 1° C. for a rise in elevation of about 600 feet) is seen to be rather small, but when such an effect of refraction is combined with the effect of a wind velocity of, say, 10 to 15 miles an hour in the direction from the audience to the stage, the combined result may be sufficient to cause the sound waves to bend up as much as 4 or 5° before the waves have reached the rear portion of the seated area. *Thus, it would seem desirable, at least from the standpoint of possible atmospheric effects, to grade the seating area of an open-air theatre so that the slope is at least* 8° *above the horizontal; that is, the grade should be at least* 9 *or* 10 *per cent.*

(*c*) *Effects of Clouds and Fogs upon the Propagation of Sound.* In most cases when a sound wave strikes a cloud or a fog bank, most of the sound energy is refracted (with a very small change of direction) into the cloud or fog, and only a small portion of the sound energy is reflected.[3] If, however, the sound wave strikes the cloud or fog bank at nearly grazing incidence (angles between about 85 and 90°) the sound wave may be totally reflected, in which case the direction of propagation of the sound wave may be appreciably altered. It is not often, however, that such reflections become a factor in the acoustics of open-air theatres. A notable exception recently was observed at one of the Easter sunrise services in the Hollywood Bowl (near Los Angeles, California). A low-hanging fog bank to the east of the Bowl gave rise to a peculiar and very distinct echo that was delayed at least 2 seconds behind the direct sound. The echo was returned nearly on the stage and was very annoying to both singers and speakers. As the fog bank lifted the echo disappeared.

174. Loudness of Speech in the Open Air. The loudness of sound required for satisfactory hearing is the limiting factor in determining the shape and size of open-air theatres. It will be helpful therefore to determine how the normal loudness of unamplified speech will affect the limit

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[3] Since the changes in density and elasticity are very small — only about 1 per cent. See Eq. (5).

in size of an open-air theatre. In one of the earliest of existing books on "Acoustics of Public Buildings," by T. Roger Smith (1861), it is recorded that the voice of a person reading aloud can be heard and understood to distances of 90 feet in front of the speaker, 75 feet to each side of the speaker, and 30 feet behind the speaker. Davis and Kaye[4] believe that these distances are somewhat excessive for voices of moderate strength, and seem to agree with the judgment of Christopher Wren, who adopts the following standard in the design of church buildings: "A moderate voice may be heard 50 feet in front of the speaker, 30 feet on each side, and 20 feet behind the pulpit, and not this unless the pronunciation be distinct." Quite different is the opinion of Sturmhoefel, who claims according to his tests that[5] it is possible to understand speech in a quiet open field at a distance of 30 meters (98.5 feet) in front of the speaker, 20 meters (66 feet) to the side of the speaker, and 10 meters (33 feet) behind the speaker.

It is instructive in connection with the determining of the distance at which speech can be heard in the open to make a few simple calculations based upon the amount of speech energy generated by the average speaker in the open, and upon the propagation of this sound energy with different types of reflecting surfaces located around the speaker. Measurements of the power output of the average speaker in large auditoriums indicate that the probable power output of a speaker in the open air would be of the order of 100 microwatts.

Suppose therefore that a speaker generating an average speech power of 100 microwatts has a plane reflecting surface directly behind him. Most of the sound energy generated under the supposed conditions will be confined to a quarter of a sphere bounded by the vertical wall and the horizontal seating area. It is required to determine the distance away from the speaker at which he can be heard satisfactorily, that is, the distance at which the intensity will have diminished to the level required for a speech articulation of 75 per cent. If reference be made to the curve shown in Fig. 170 it will be seen that the level of the speech should be about 47 db in order to give an articulation of 75 per cent.[5a] An average power flux of speech energy equal to about 4×10^{-6} microwatt per square centimeter will give a sound level of 47 db. If now it be assumed that the 100 microwatts generated by the average speaker spread out in a quarter of a sphere in accordance with the inverse square law, the area of the curved boundary of this quarter sphere, when the level of the speech has been attenuated to 47 db, will be $\frac{100}{4 \times 10^{-6}} = 25 \times 10^{6}$ square

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[4] Davis and Kaye, "Acoustics of Buildings" (Bell, 1927).

[5] E. Petzold, "Elementare Raumakustik," 23 (Bauwelt-Verlag, Berlin, 1927).

[5a] This is based on the assumption that the background noise produces a masking effect of 10 db, so that a speech level of 47 db would be only 37 db above the background noise.

centimeters. Since the area of a quarter sphere is equal to πr^2, where r is the radius of the sphere, r turns out to be 28.2 meters, or about 92 feet. Because of the directive action of the voice, which favors a greater intensity directly in front of the speaker, it would seem, on the basis of these calculations, that about 110 feet in front of the speaker and about 70 feet to either side of the speaker would be the upper limits of distance at which speech can be heard distinctly in an open-air theatre when there is a vertical wall behind the speaker.

Now suppose that a speaker in the open be located on a stage which is enclosed by a rear vertical wall, two diverging side walls and a sloping ceiling, as shown in Fig. 220. The intensity at any position in the seated area can be approximately calculated by assuming that the sound energy spreads out from the source and from the images of the source, such as I_1, I_2, and I_3, in accordance with the inverse square law, and that the intensity at any point is the sum of the intensities radiated by the source and all the effective images. In general there will be the three images from the rear and side walls, the image from the floor, and two images from the ceiling — one, the ceiling image of the source, and the other, the ceiling image of the floor image of the source. The intensities shown

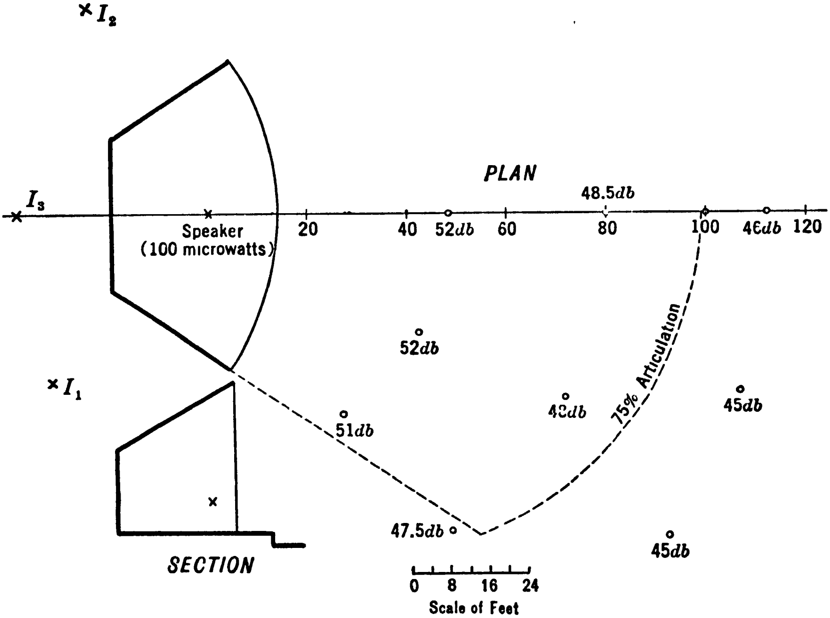

FIG. 220. Distribution of average speech level in front of a stage enclosed by a rear wall, diverging side walls and a sloping ceiling.

at the nine indicated positions on the diagram in Fig. 220 have been converted into decibels. It is assumed that the speaker delivers a speech power of 100 microwatts and that the reflection coefficients of the boundaries of the stage are 0.96. The distance from the speaker at which the sound level drops off to 47 db is seen to be about 100 feet along the longitudinal axis, and somewhat less than this in other directions. If the directional effect of the speaker be considered, the intensity would be a little greater along the axis than is indicated, and it would drop off more rapidly away from the axis than is indicated. Making a reasonable adjustment for this directional effect, and for this type of stage, about 120 feet would seem to be the greatest distance in front of the stage at which the hearing of speech would be satisfactory.

The different data which have been presented in this section on the distances at which speech can be heard satisfactorily in the open are not in very good agreement, but when it is considered that a small difference in the average intensity of the speaker's voice would account for all the existing differences among these data, the agreement is as good as might be expected.

However, in order to test these somewhat diverging opinions and findings, and to ascertain more accurately just how speech is heard in the open, some speech-articulation tests have been conducted in the Mohave Desert. The tests were similar to those already described for testing the hearing of speech in auditoriums. (See Sec. 113.) Six different individuals, all with normal hearing and normal speaking voices, were used in conducting the tests. The listeners were stationed at certain distances in front of the speaker, to the right and left of the speaker, and behind the speaker. All the speakers were instructed to speak as though they were addressing an audience seated in the open. The results of these tests, conducted on a quiet, level plain on the desert, with no wind present, are shown in Fig. 221. The curves indicate the distances from a speaker at which the speech articulation dropped off to 90 per cent, 80 per cent, and 75 per cent. Thus, a listener anywhere on the 90 per cent *contour* would hear correctly 90 out of every 100 of the called speech sounds. In a similar manner, the *contour* for 75 per cent would represent the approximate limiting distances at which speech can be heard satisfactorily in a quiet open place, since an articulation of 75 per cent is required for satisfactory hearing. It will be noted that these distances are 138 feet in front of the speaker, 98.5 feet to the side of the speaker, and 56 feet behind the speaker. These distances are considerably greater than those given by other authorities, and already presented in this section, but it is possible that these tests were conducted under more quiet conditions than prevailed during the tests of other investigators. The distances are also slightly greater than those based upon the calculations presented in this section, but this is readily explicable on the basis that the average speaker generates more than 100 microwatts when speaking in the open. The speech-articulation tests are based upon the most direct method of measurement, and the results to which they lead are probably more reliable than those which have been obtained by other methods. At the same time, the quantitative results obtained by the articulation tests in the open are consistent with the qualitative results which have been presented earlier in this section.

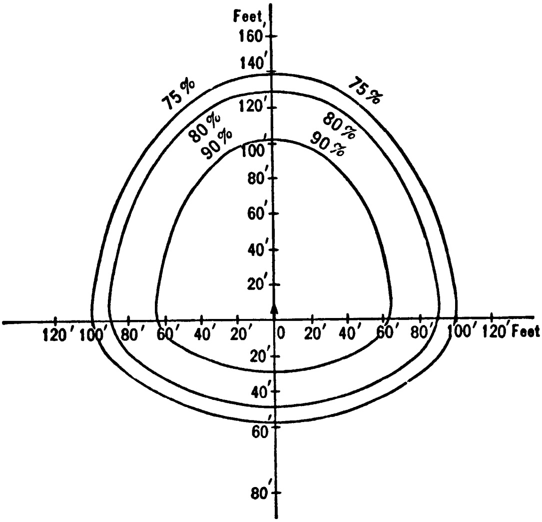

FIG. 221. Curves showing how the hearing of speech (percentage articulation) depends upon the distance and direction from the speaker. The speaker was located at *o* and facing in the direction of the arrow. The 75 per cent "contour" represents the limiting distances at which normal speech can be heard satisfactorily on a quiet, level plain.

In conducting the articulation tests in the open it was found that the slightest amount of noise from insects or from wind would interfere seriously with the hearing of speech, and therefore care was exercised to avoid these disturbances during the main series of tests. But in order to determine the effect of wind upon the hearing of speech in the open a series of tests was conducted in a wind which varied from about 20 to 25 miles an hour. The results of these speech articulation tests are shown in Fig. 222, which shows the distances from the speaker at which the speech articulation dropped off to 75 per cent, and also to 50 per cent. It will be noted that the wind interfered with the hearing in all directions — in a direction with the wind as well as in a direction against the wind. Thus, the speech articulation was reduced to 75 per cent at distances of 85 feet in front of the speaker, 52.5 feet to either the right or the left of the speaker, and 26 feet behind the speaker. The short arrow shows the direction the speaker was facing. Since the action of the wind was to decrease the articulation in all directions around the speaker, it is apparent that the wind interferes with hearing primarily because it introduces a noise near the ears of the listener. There is some evidence that the propagation of the sound is most favorable in the direction with the wind, although the effect is not so great as is generally supposed. Thus, in the quiet the ratio of the distances in front of, to the side of, and behind the speaker is 1.00 : 0.715 : 0.405; whereas in the wind, blowing toward the front listener, the ratio is 1.00 : 0.615 : 0.307. But, although the wind was blowing almost in the direction from the speaker to the listener in front of the speaker, the articulation dropped off to 75 per cent at a distance of 85 feet in the presence of the wind compared with a distance of 138 feet in the quiet. It is apparent therefore that the noise produced by the wind more than offsets the slight advantage gained from the downward refraction of the sound in the leeward direction.

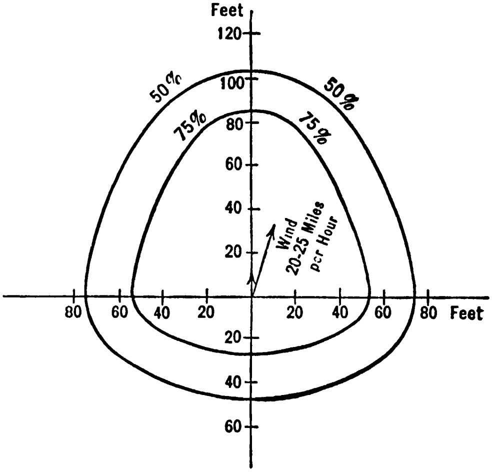

Fig. 222. Curves showing the effect of wind on the hearing of speech in the open.

Other articulation tests have been made with the wind velocity as low as 5 to 10 miles an hour, and even such gentle winds were found to interfere appreciably with the hearing of speech. All these tests seem to indicate conclusively that *an open-air theatre should be located in a site which is free from winds.* If such a site cannot be found, the theatre should be so oriented that the prevailing wind will blow from the stage toward the audience. If the prevailing wind exceeds about 10 miles an hour the size of the open-air theatre in such a site should be reduced by an amount which is roughly indicated by comparing the curves in Figs. 221 and 222.

The *contour* curves of equally good hearing shown in Figs. 221 and 222, and especially the *contours* for an articulation of 75 per cent, are serviceable in determining both the limiting size and the most favorable shape for the seating area of an open-air theatre provided there are no reflecting surfaces around the stage. Thus, in a quiet site and without reflecting surfaces around the stage, if the articulation is to be in excess of 75 per cent in all seats, the length of auditorium, from the most probable position of the speaker to the rear row of seats, should not exceed 138 feet, and the width of the auditorium should not exceed 197 feet. In practice, a *quiet* site is never realized, but the benefit from reflections from the stage walls and ceiling, and the benefit from the sloping seated area may be counted upon nearly to compensate for the interfering effect of unavoidable noises. Further compensation will result from the tendency of speakers to *raise their voices* when speaking in the presence of a noise.

However, the reflecting surfaces around most open-air stages, for example, surfaces similar to those shown in Fig. 220, add to the directional effect of the speaker so that the shape of the seated area should conform more nearly to the shape shown by the dotted lines in Fig. 220 than to the shape shown by the *contour* curves in Figs. 221 and 222. A seating area similar in shape to that shown in Fig. 220, and having a depth of about 140 feet and a maximal width of about 180 feet, would seem to mark the upper limits to the dimensions of an open-air theatre in which unamplified speech will be heard satisfactorily. Such a theatre will accommodate an audience of about 3000 persons. If open-air theatres are designed to accommodate a larger audience than this, it is probable that auditors sitting or standing beyond the limits here specified will not hear satisfactorily. However, it may be feasible in some communities to extend the auditorium so as to accommodate an audience as large as 5000 or even 6000, but under such circumstances it must be recognized that hearing will be difficult in the more remote seats unless the theatre be equipped with suitable apparatus for the amplification of speech.[6] With special forms of reflecting surfaces around the stage, such for example as are used for the Hollywood Bowl (in Los Angeles), it is possible to hear speech satisfactorily at a distance of 200 feet from the stage, but owing to the directional effects of such reflecting surfaces it is necessary to limit the width of the seated area.

The limits of size which have just been specified should be regarded as the maximal safe limits for good hearing, and then only when the speakers lift their voices and speak with deliberate clarity. If the

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[6] Open-air auditoriums for music may be somewhat larger than those which are designed principally for dramatic purposes.

theatre is to be used principally for oral expression the size should be considerably smaller than has been specified. An open-air theatre with a seating capacity of about 1500 should be regarded as the upper safe limit of size when the theatre is to be used principally for the spoken drama, and when it is desired that the actors may speak without undue effort and that all auditors may hear without undue strain.

175. Greek and Roman Theatres. In Figs. 223 to 226 are shown a number of photographs and drawings of both classical and modern Greek and Roman theatres. These are briefly described in the legends given under the photographs and drawings.

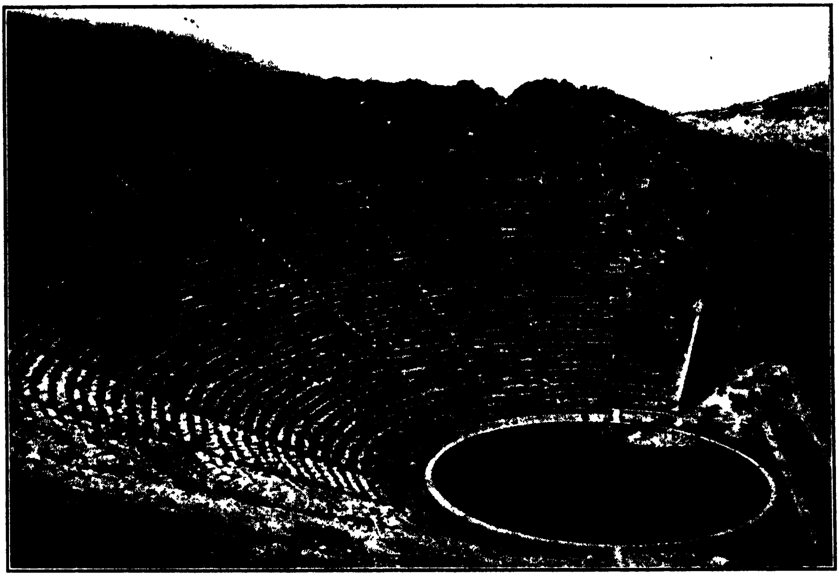

FIG. 223. Greek theatre at Epidauros. Note the circular orchestra and the steep slope of the auditorium. (*Nicoll.*)

It should be mentioned that nearly all Greek and Roman theatres are subject to a peculiar acoustical defect which results from the shape of the auditorium and the location of the stage. In the classical Greek and Roman theatres the action takes place on a stage or platform which is located near the centre of curvature of the regularly spaced and elevated rows of seats or benches. As a result, the speakers or actors are frequently disturbed by the converging reflections from these circular rows of benches. Not only do these reflecting surfaces return the sound and converge it to a focus near the source of the action, but the uniform spacing between the successive backs of the benches gives rise to a selective reflection of those frequencies of sound which have a wave length equal to twice the distance between successive rows. This type of reflection, as was described in Sec. 18, produces a musical but monotonous echo which is most disagreeable to speakers. The effect is of course most noticeable in the empty theatre, and when the speaker is located at the centre of curvature of the circular benches. If a complex sound, such as clapping or shouting or even talking, be produced near the centre of curvature of the terraced seats, as for example in the Greek Theatre at the University of California, the reflected sound is brought back to a focus near the origin of the sound. The reflected sound persists for an appreciable interval of time owing to the successively delayed portions of the reflected wave which come from more and more distant benches. And, as has been mentioned earlier, the reflected sound has a characteristic musical pitch which is determined by the spacing between the successive rows of seats. Thus, when the rows are spaced apart 30 inches, the reflected sound will be preponderantly composed of sound waves which have a wave length of two times 30 inches, or 5 feet. That is, the musical pitch of the reflected sound will be slightly below middle C, or about 225 vibrations per second. When all the seats are occupied this peculiar reflection of analyzed sound is diminished, but even under the most favorable circumstances the echo is not only noticeable but annoying. In the design of open-air theatres this condition should be

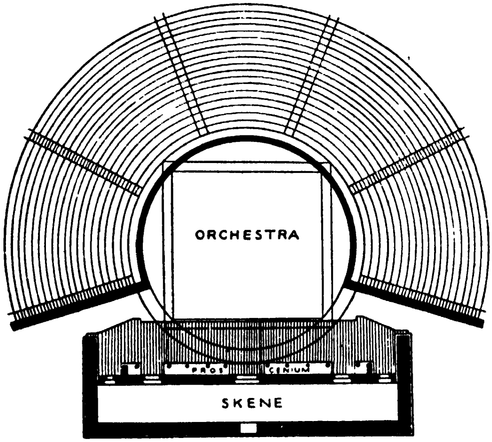

FIG. 224. Graeco-Roman theatre at Termessos. The orchestra has been reduced from its circular form and has been encroached on by the skene and logeion. Note that the logeion is partially surrounded by side and rear reflecting walls, that is, it is beginning to exhibit the features of the modern enclosed stage. (*Nicoll.*)

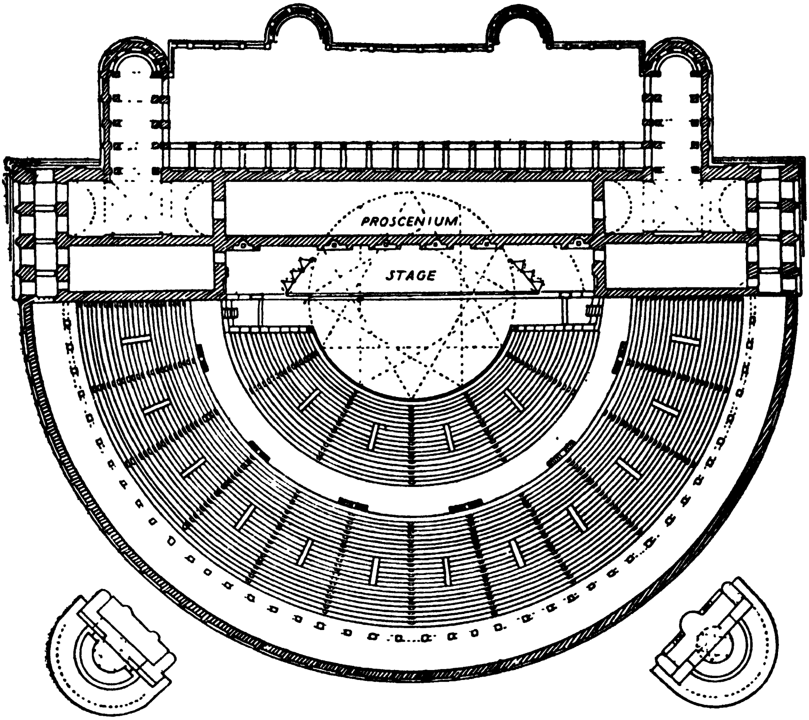

FIG. 225. Plan of a classical Roman theatre (the Marcellus Theatre at Rome). The orchestra and auditorium are both reduced to semicircles; the theatre is built on level ground instead of a natural slope, but the seats are elevated fully as much as in the Greek theatre; and the stage, which is well surrounded with reflective rear and side walls (and in some instances, as at Aspendos, with a ceiling splay), is brought near the auditorium. (*Streit*, "Das Theater," Plate VIII.)

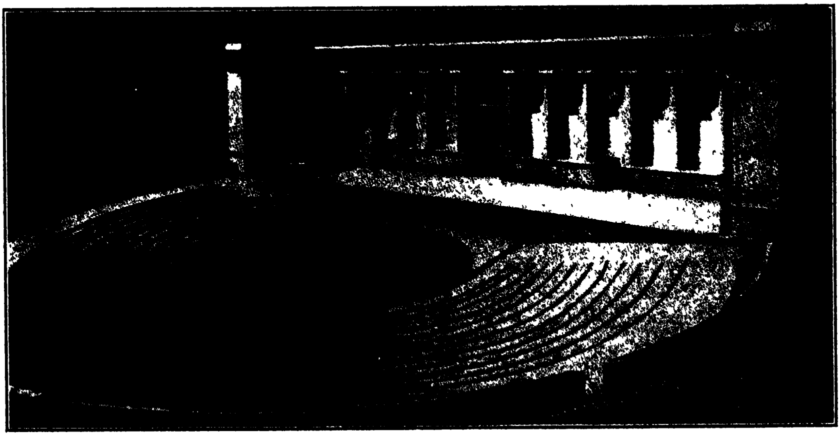

FIG. 226. The Greek theatre at the University of California, Berkeley, California.

avoided as much as possible. Other forms than the circle should be adopted for the arrangement of benches; or the centre of curvature should be well removed from the stage or scene of action. The defect is not so troublesome if the backs or risers of the successive rows of benches be inclined backward at a small angle from the vertical instead of rising vertically, or if the risers be covered with absorptive material, such as climbing vines, shrubs, or even flexible cushions which will withstand the weather.

176. The Hollywood Bowl. The Hollywood Bowl, located in an extraordinarily well shaped and protected hollow in the mountains which divide Hollywood and San Fernando Valley, California, has become famous because of its splendid acoustical quality and its summer programs of "Symphonies under the Stars." The general contour of the site, the seating arrangement, and shape of the orchestra shell are indicated in Fig. 227. The natural cove which forms the main seating area of the Bowl has been further excavated so that the Bowl is almost completely surrounded by hills or embankments, which protect the Bowl from the noise of busy metropolitan traffic arteries not more than 1500 feet away. The slope of the seated area is, on the average, about 12°

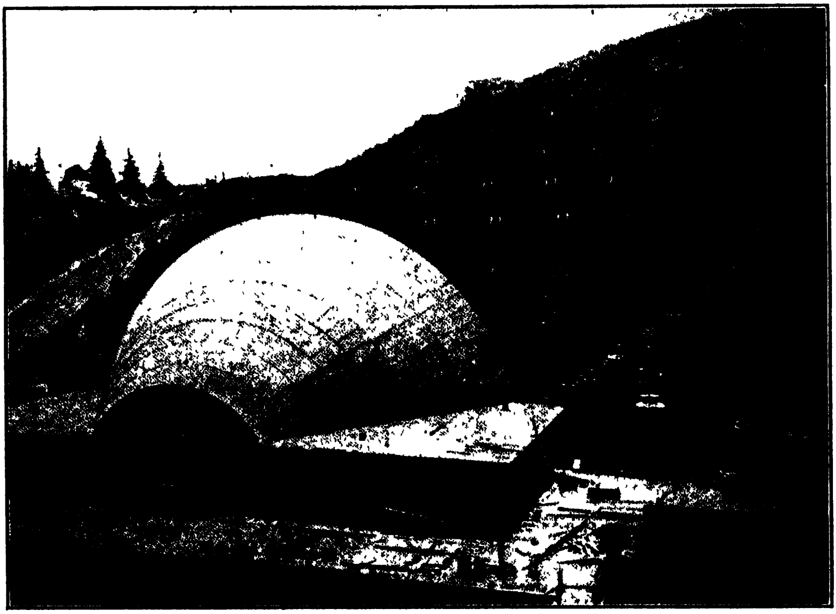

FIG. 227. Hollywood Bowl, showing the general contour of the site, the seating arrangement, and the shape of the orchestra shell.

above the horizontal. The total depth of the Bowl, from the front of the stage to the last row of seats, is 550 feet. The seating capacity is 22,500. Obviously, the Bowl is too large for dramatic purposes, or even for speaking purposes (without the use of appropriate amplifiers), but it is admirably adapted for open-air orchestra concerts. The extraordinary size of the Bowl calls for an acoustical shell or sounding board which will give a pronounced directional flow of sound toward the audience, and especially toward the more remote seats in the Bowl.

The most simple type of orchestra shell would consist of a highly reflective vertical wall placed directly behind the orchestra, such as was described in Sec. 174. Such a wall or sounding board would approximately double the intensity of the sound projected to the audience. This simple type of sounding board has much to commend it if it will provide a sufficient amount of sound energy for good musical effects. It is almost free from directional effects and is entirely free from focusing or converging action. Consequently, all instruments are almost equally reenforced in all directions in front of the sounding board, and therefore a nearly uniform flow of sound energy will be directed to all parts of the audience. However, in very large bowls, such as the Hollywood Bowl, it is necessary to increase the directive action of the sounding board or shell. Accordingly, the shell for the Hollywood Bowl has both overhead and side reflecting surfaces. If the audience were seated upon a plane at the same elevation as the stage, the overhead surface should have an inclination of about 45° above the horizontal. Since the seating area of this Bowl is inclined at an angle of about 12° above the horizontal, the overhead reflecting surface is pitched to an angle of 51° above the horizontal. This imparts to the reflected sound a directional flow which is approximately parallel to the slope of the seated area.

The present form of the orchestra shell was developed from several temporary structures which were used during the first few years of the Hollywood Bowl concerts. Vertical and inclined reflecting surfaces were placed behind and above the orchestra in one of the first shells constructed for the Bowl. Later, a shell was constructed which combined vertical walls behind and at both sides of the orchestra (similar in plan to the three-sided arrangement shown in Fig. 220) with plane parabolic surfaces above the orchestra. This shell gave a strong reenforcement to the sound, but it was not entirely satisfactory because it also gave an over-emphasis of tones for those instruments which were located near the focal lines of the three overhead parabolic surfaces.

The existing and permanent form of the shell, which is erected on a movable steel frame, is one half of a truncated right circular cone having an outside radius at the front of 45 feet, and a radius at the rear of 18 feet. The plan and sectional drawings for the shell are shown in Fig. 228, and the plan and profile of both the shell and the seated area are shown in Fig. 229. The truncated cone is made up of nine concentric reflecting bands. All these concentric bands are inclined at an angle of 51° above the horizontal, so that they selectively reflect sound in a direction parallel to the profile shown in Fig. 229. Further, these nine concentric bands break up the overhead surface so that there are no pronounced foci.

The primary function of the orchestra shell, which is to project the sound of the orchestra or soloists to all listeners in the very large Bowl, is quite satisfactorily attained. Furthermore, the shell is free from such defects as echoes and interfering reflections. The broken surfaces of the shell tend to reflect sound diffusely so that both performers and listeners receive a large amount of reflected sound.

Some tests have been conducted with the present type of shell in order to determine the distribution of intensity of sound in different parts of the Bowl. In these tests the source of tone was a radio loud speaker actuated by a vacuum-tube oscillator. The source was maintained at a constant output, and the intensity of the resulting tone at different positions in the Bowl was determined by masking the tone with a calibrated noise audiometer of the buzzer type. Test tones of 128, 512, and 2048 cycles were used, and the intensity distribution was determined for each test tone, first with the source located at the front central portion of the shell, and then with the source on the extreme right side of the shell. In each test the loud speaker was directed vertically upward so that the loud speaker would not contribute to the directional effect of the shell. At the same time, with the source directed vertically upward the reflective action of the shell would be somewhat overemphasized, so that the intensity-distribution measurements obtained in the different parts of the Bowl probably over-emphasize the directional effects of the orchestra shell. The results for the 512 tone with the source at the front central part of the shell are shown in Fig. 230. The locations at which measurements of the intensity were made are indicated by the small circles, and the number by each small circle indicates the level of the noise required to just mask the tone from the loud speaker. These results are typical of those obtained at 128 and 2048 cycles, and they show that, for a source located near the centre of the shell, there is a preferential reflection toward seats located near the longitudinal axis of the Bowl. In some instances the sound level falls off as much as 8 to 10 db in going from the longitudinal axis to the extreme sides of the Bowl. This falling off in intensity, however, is no greater than that frequently encountered in

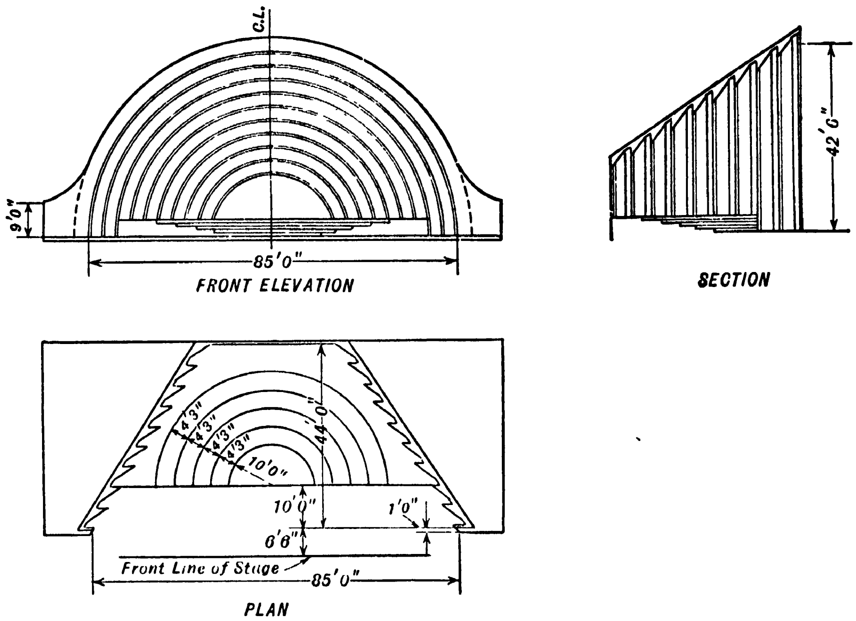

FIG. 228. Plan and sections of the orchestra shell for the Hollywood Bowl.

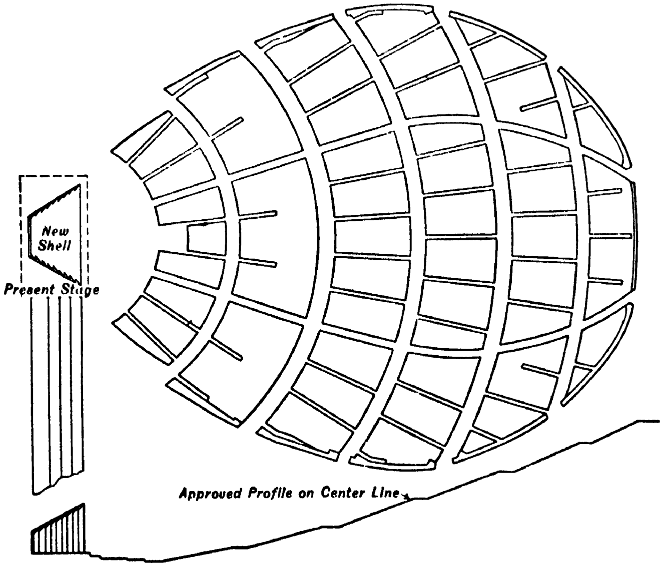

FIG. 229. Plan and profile of the Hollywood Bowl.

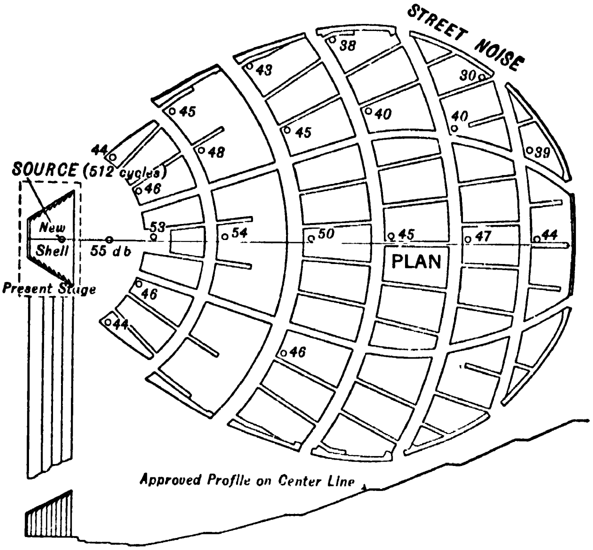

FIG. 230. Intensity distribution in the Hollywood Bowl of a 512-cycle tone located at the front central part of the shell. The numbers give the approximate sound levels, in decibels.

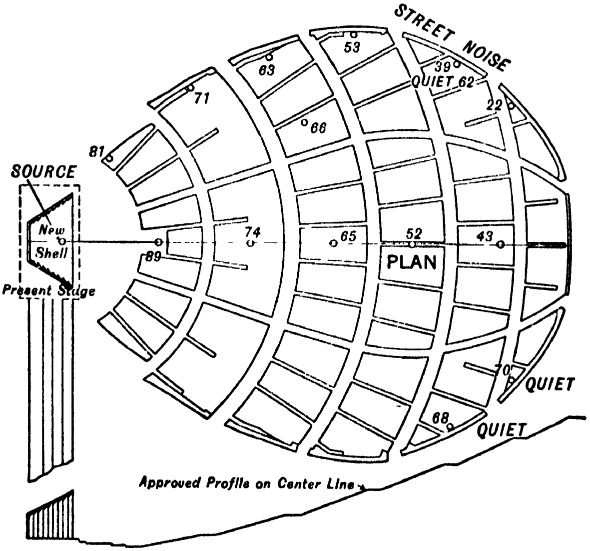

FIG. 231. Speech articulation in the Hollywood Bowl. The numbers give the percentage articulation.

many closed auditoriums, but is greater than would have resulted with no sounding board at all, or even with the two simple types of sounding board described in Sec. 174. (See, for example, Fig. 220.) With the source located at one side of the orchestra platform the intensity attains a maximum on the opposite side of the Bowl, the difference on the two sides amounting to as much as 8 db. This difference is approximately the same for low-, medium-, or high-pitched tones, so that the shell is free from a frequency selectivity in its directive action. However, the seats on the extreme sides of the Bowl suffer from the directive action of the shell, and this applies to low-pitched as well as to medium- and high-pitched tones. Thus, when one sits on the right side of the Bowl one hears the brass instruments (on the opposite side of the orchestra platform) too loudly and the double basses not loudly enough; whereas when one sits on the left side one hears the double basses very well but the brass instruments are not sufficiently prominent.

On the other hand, by reason of the reflective action of the shell, even the faintest notes of the violin are clearly audible in the most remote seats of the Bowl. The sound generated by dropping a No. 10 bird shot onto a kettle drum from a height of only ½ inch above the stretched membrane can be heard distinctly over three fourths of the Bowl. In spite of the defects owing to the directive action of the shell, the acoustical properties of the Bowl have been enthusiastically praised both by listeners and performers. The seats near the longitudinal axis are the choicest, and in all seats except those on the extreme sides the orchestra is heard to very good advantage.

Although the Bowl is used principally for orchestral and other musical concerts, it is sometimes used for speaking purposes. It is evident, however, that it is too large for speech to be heard distinctly in at least the rear half. Some speech-articulation tests have been conducted in the Bowl, the results of which are shown in Fig. 231. These tests were conducted, for the most part, during the early part of the night — at a time when disturbances from city traffic and other sources were comparable with the noise present during programs in the Bowl. The percentage articulation obtained at different positions is indicated in the figure. It will be noted that the articulation decreases from about 89 per cent near the front central part to a value as low as 22 per cent near the upper right-hand corner of the Bowl. This corner is near a busy boulevard, and is the only part of the Bowl which is not protected by an embankment or the natural slope of the hills. A number of articulation tests conducted at about 3:00 A.M., when there were practically no disturbances from noise, gave articulations as high as 65 to 70 per cent in the most remote parts. It is apparent therefore that if the Bowl were entirely free from outside disturbing noises it would be possible to hear speech fairly distinctly in all parts, even at distances as great as 550 feet from the speaker. Under the existing conditions, the articulation is in excess of 75 per cent for all listeners within about 200 feet of the stage; and if speakers raise their voices to a high level they can be understood in all parts of the Bowl. With the help of a public address system, and with the speaker not more than 3 feet from the microphone, it is not necessary for the speaker to raise his voice, and he can be heard very well throughout the entire seated area.

177. Design of Open-Air Theatres. The selection of the site for an open-air theatre should be based upon a thorough survey of the acoustical properties of all available locations for the theatre. Quietness is the most important of all acoustical considerations in the selection of the site. The site should be well removed from all traffic arteries, both on the ground and in the air; it should be shielded on all sides by the natural slope of surrounding hills, by artificial embankments, or by a dense growth of trees; and it should be free from winds which have velocities of more than 5 to 10 miles per hour. A noise survey (see Sec. 87) and speech-articulation tests should be made on all proposed sites. In order that a site be a satisfactory one, the noise level should not exceed 20 to 25 db, and preference should be given to the most quiet site. The speech-articulation tests will determine not only whether the site will be a suitable one for oral expression but also the limiting boundaries inside which the hearing of speech will be satisfactory. In general, a cove on a gently sloping hillside will be found to possess the highest merit. The slope of the seated area, that is, of the auditorium " floor," should be between 10 and 20°.

Fig. 232 shows an acoustical study of an open-air theatre which is based upon the principles and findings described in the preceding sections of this chapter. The shape and size of the auditorium conform very approximately with the recommendations suggested by the speech-articulation tests in the open (see Figs. 221 and 222) and with the calculations of the intensity distribution of sound in front of a stage bounded by side and rear walls and by floor and ceiling surfaces. (See Fig. 220.)

The design shown in Fig. 232 will seat approximately 2000. It represents about the practical upper limit of size in which speech of average loudness can be heard satisfactorily[7] — and only then when the site is a quiet one, and when the speakers raise their voices and place proper emphasis upon the consonantal endings of syllables and words. If the

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[7] In Sec. 174 the upper limit of size was placed somewhat higher than this — allowing a seating capacity of 3000. The smaller size here advocated is based upon conservatism, and provides a much-needed factor of safety.

theatre is to be used principally for dramatic productions, and if the actors are to be free from the necessity of raising their voices, the size should be reduced to about two thirds or three fourths that of the theatre shown in Fig. 232; that is, the seating capacity should be limited to about 1200 to 1500. On the other hand, open-air auditoriums for orchestra or band concerts may be as large as the Hollywood Bowl (seating 22,500) if the site be a quiet one and if the stage be bounded by properly designed rear, side, and overhead reflectors.

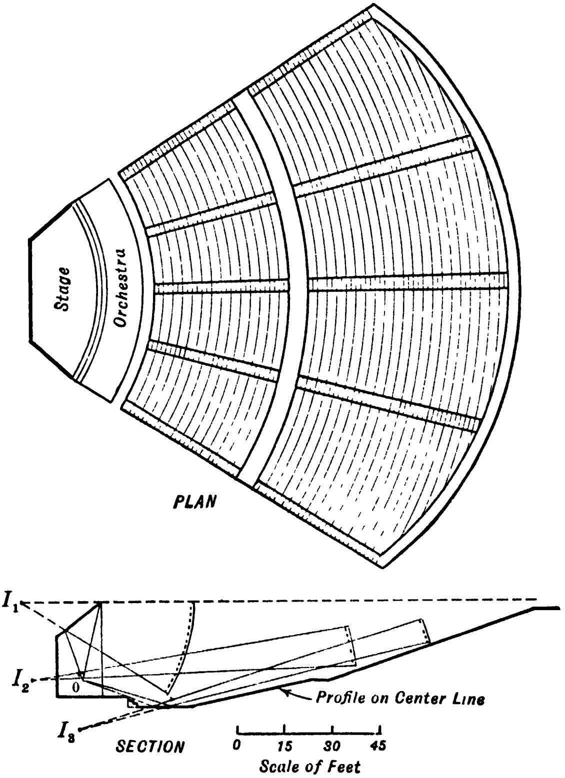

Fig. 232. Acoustical study of an open-air theatre.

In the design shown in Fig. 232 it will be noted that beneficial reflections are obtained from the rear and side walls, from the ceiling, and from the floor both of the stage and of the orchestra. All these surfaces should be highly reflective throughout the entire range of audible frequencies. If the theatre is to be used at times for musical productions, the reflecting surfaces should be of wood — three-ply wood veneer, stained and waxed or varnished, is very good for the walls and ceiling, and matched soft or hard wood over subflooring will be suitable for the floors. If the orchestra space is to be used at times for dancing, it is advisable to include a ½-inch fibre board between the rough and finished floor of the orchestra. This will prevent excessive noise or " drumminess " from footfalls on the floor.

The centre of curvature for the rows of seats is located 30 feet behind the rear wall of the stage; consequently there will be but little or no convergence of the sound which is returned to the stage from the concave surfaces comprising the backs of the seats or benches in the lower section of seats. The disturbing effect of this type of reflected sound (which reaches very annoying proportions when the centre of curvature of the rows of seats is on or near the stage, and when the auditorium is empty) can be further minimized by inclining the backs of the seats or benches about 10° from the vertical. This will not only tend to divert upward that sound which is reflected from the backs of the seats so that the sound will be returned above rather than on the stage, but it also will provide more comfortable seats.

The use of a fibre board covering for all treads in the aisles is a helpful expedient for reducing the noise of footfalls, and provides a comfortable and safe surface to walk upon. In mild climates a good grade of fibre board will wear for several years, and the cost of replacement will be nominal.

CHAPTER XXIII

THEATRE BUILDINGS

178. Introductory. Although the theatre is a place for seeing as well as a place for hearing, it is certainly in the interest of the good of the theatre to insist that good acoustics should come before all other requirements. This is so not only because of the importance of oral expression in the theatre but also because acoustics is one of the most difficult problems which enters into theatre design, and because it is more universally neglected than any other aspect of design. The modern theatre has developed around the art of oral expression, and ever since the introduction of speech in the theatre there has been a mutual interaction between the art of spoken drama and the art of theatre design. On the one hand, the theatre has developed into shapes and arrangements of spaces which will facilitate an effective flow of speech from the stage to the auditors. On the other hand, the actors have been required to adapt themselves to the acoustical conditions of the theatre — such as elevating the voice; reducing the tempo in order to avoid the overlapping of the successive words in speech; and in some instances adapting the pitch of the voice to the natural " tone " or resonance of the theatre. In the ideal design, of course, the highest consideration should be given to the freedom of the actors so that they can speak naturally and easily, and with the assurance that they are heard perfectly in all parts of the auditorium.

179. Historical Development of the Theatre. In the preceding chapter a brief account was given of the development of the classical Greek and Roman theatres. These were the forerunners to the enclosed theatre, and the first forms of enclosed theatre bear a very close resemblance to the Roman type shown in Fig. 216. The Theatre of the Olympian Academy, at Vicenza, Italy, was one of the earliest forms of the enclosed theatre. It is essentially a classical Roman theatre with the roof and side walls added. Its similarity in plan with that of the open-air Roman theatre is shown in Fig. 233. Note especially the five conventional entrances piercing the heavily ornamented walls. The avenues behind the entrances to the front part of the stage were set with various types of scene to add interest to the production. This appears to mark the advent of scenes in the theatre, and in the later types of theatre the scenes become of considerable importance from the standpoints of both seeing and hearing.

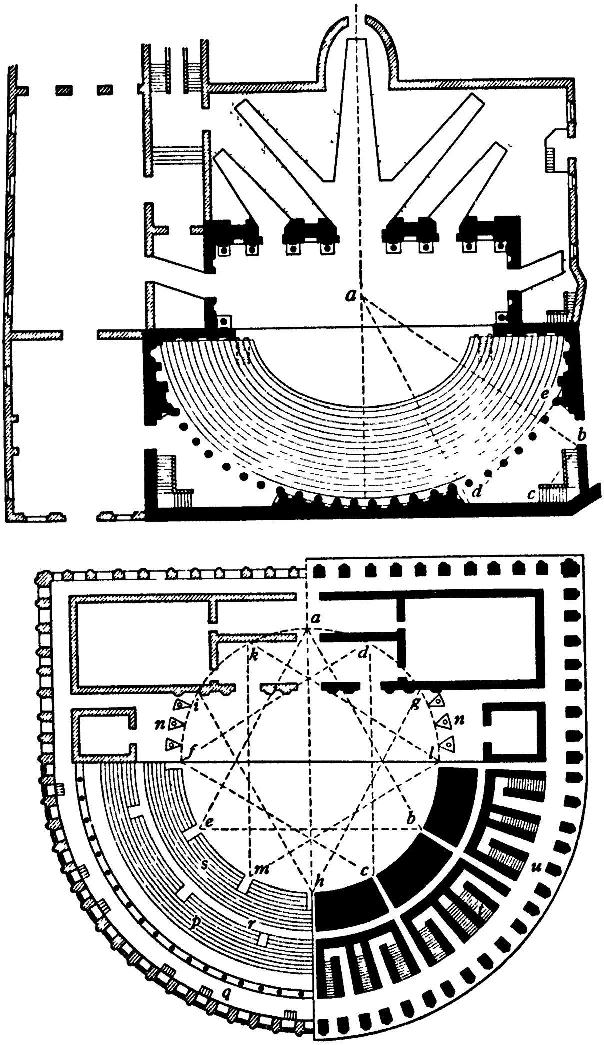

Fig. 233. Plan of the Teatro Olimpico, Vicenza, Italy (above), compared with that of a classical Roman theatre (below). (*Nicoll.*)

The next step in the development of the modern theatre which is of acoustical interest is represented in the Teatro Farnese at Parma, Italy. (See Fig. 234.) In this theatre, the permanent surrounding walls of the Roman stage have been " spread open "; the central door-way through the rear wall of the stage has become the stage opening; and the ornamented walls surrounding the stage have become the proscenium arch. Behind the opening or proscenium arch is the enlarged and curtain-enclosed stage, and in all subsequent theatres the curtained stage and the proscenium arch remain. It will be noted also that the semicircular auditorium has been elongated into the more modern U shape, the influence of which is seen in many eighteenth and nineteenth century theatres and opera houses of Europe — modified in many instances into the familiar but famous horseshoe. These forms were well adapted to the addition of balconies, which were necessary in order to keep the auditors near the stage. Often as many as four or five balconies are found, as in the San Carlo Theatre in Naples, the later Drury Lane Theatre in London, and the Burgtheater in Vienna. (See Fig. 235 for example.) Theatres of this type with flat or nearly flat ceilings were nearly always satisfactory acoustically, since the audience was brought near the stage, and the entire floor (and most of the walls) was covered with highly absorptive material (the audience), thus keeping the reverberation time down to a low value.

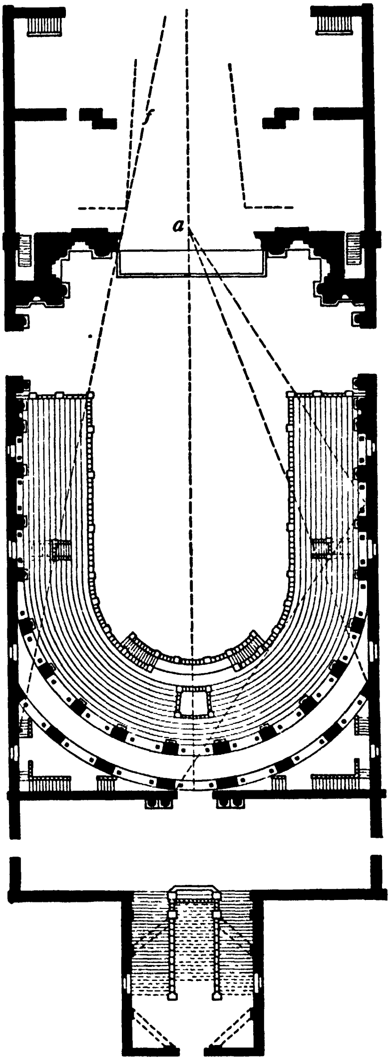

FIG. 234. Plan of the Teatro Farnese at Parma, Italy. (*Nicoll.*)

It was the addition of domes in the eighteenth century and the exclusion of all but one balcony in the nineteenth century[1] that led to the outstanding acoustical difficulties of the past fifty years. It has been pointed out repeatedly that high, domed

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[1] Many cinema theatres of recent design have abandoned all balconies. When old-style theatres were converted for use of talking pictures, most of them were found to be excessively reverberant.

ceilings give rise to echoes, interferences, and concentrations in the audience. Also, the exclusion of several balconies leaves a large unbroken surface on the rear wall — which is often concave — to reflect sounds back to the stage. In addition, the exclusion of the balconies and the use of hard plaster or other fireproof materials for the walls and ceiling lead to excessively long periods of reverberation. As a result of these faulty innovations, many theatres of recent times have been attended by acoustical difficulties which were not experienced a century ago.

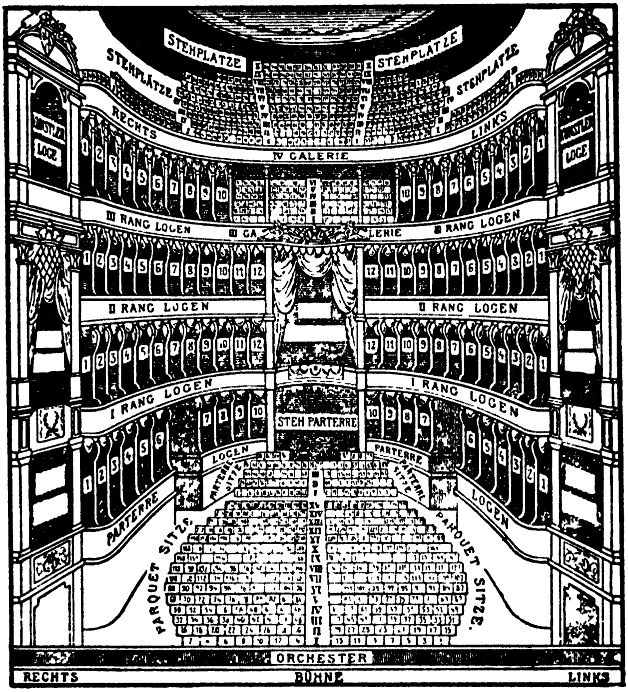

FIG. 235. Schematic interior of the Burgtheater, Vienna, showing four levels of loges and a gallery above the loges.

More recently, however, the acoustical design of theatres has been the object of considerable study, especially since the pioneer work of W. C. Sabine. As a result, it is now the exception rather than the rule that these defects of shape and reverberation are found in modern theatres. Modern forms, in plan, are frequently similar to the one shown in Fig. 236, which is a modification of the horseshoe, and resembles a fan. The sloping side walls, and the splayed ceiling of the proscenium, which should be free from too much ornamentation, can be designed to be very effective for reflecting sound to the auditors in the rear part of the auditorium. The general fan shape, with a single balcony, is usually accompanied by an increase in the slope of the orchestra floor, which represents an attempt to provide the best seats on the main floor level. However, if the overhang of the balcony be more than five or six rows of seats, the audition in the balcony will be better than under the balcony.

A number of shapes which are based upon good acoustical design, and which are adapted to modern needs in theatre productions, will be found in the recent book of Bagenal and Wood,[2] and others will be shown in subsequent sections of this chapter.

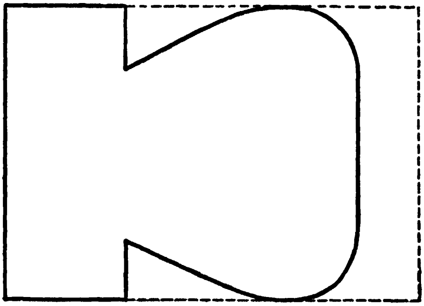

FIG. 236. Fan-shaped theatre.

In the design of every theatre the architect should base his acoustical study upon the four following factors:

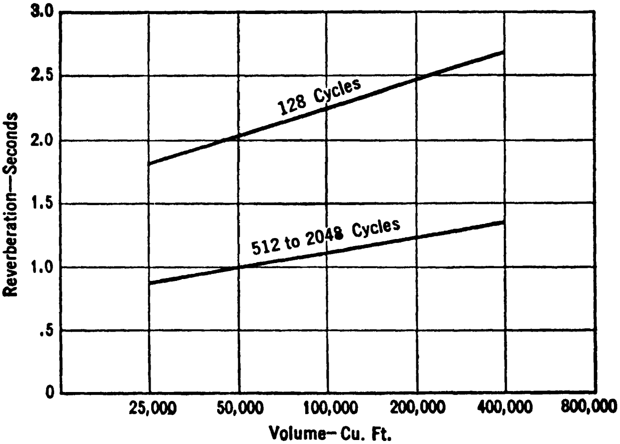

FIG. 237. Curves showing satisfactory reverberation times for legitimate theatres.

1. A noise survey made upon the proposed site for the theatre. The noise in the vicinity of the site should determine the amount of sound-insulation which is to be built into the theatre to give complete freedom from outside noise — a requirement which is of prime importance.

2. Limitation of the size of the theatre so that the average inten-

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[2] *Loc. cit.*

sity of normal speech in even the more remote parts of the theatre will be loud enough for distinct hearing.

3. Design of a shape which will be free from echoes, concentrations, and delayed reflections, and the development of diverging side walls and proscenium which will act as sounding boards to reenforce the sound which reaches the auditors.
4. Control of reverberation throughout the range of frequencies which are important for distortionless transmission of speech. The curves in Fig. 237 give reverberation times which have proved to be highly satisfactory for the design or correction of the acoustics in legitimate theatres.

These four factors have been discussed in connection with the design of school and church buildings, and now will be further considered in connection with the design of specific types of theatre.

180. The Little Theatre. The little theatre affords the architect an opportunity for designing a theatre which embodies the highest attainable standards of *perfect acoustics.* If the seating capacity be limited to 300, the volume of the auditorium need not exceed 50,000 or 60,000 cubic feet, and in a room of this size the articulation of conversational speech will attain the very satisfactory level of 88 to 90 per cent. All seats generally will be located on the main floor, which should have a very substantial slope, so that auditors will have good sight lines and good sound lines in all parts of the auditorium. The ceiling should not be more than 25 feet high, and in general should be left smooth; and it should be finished with a highly reflective material so that it will serve as a sounding board for all auditors. Diverging walls are desirable but not so necessary as in larger theatres. The lower 8 or 10 feet of the walls should be of hard material, and the front portions of these walls should not be pierced with boxes or exit doors, so that the lower portion of the walls will be efficient reflectors. The upper walls should be treated with sound-absorptive material having such coefficients of absorption as will impart to the room the optimal times of reverberation for tones of low, medium, and high pitch. The reflective action of the rear wall should be carefully studied. A smooth concave rear wall with radius of curvature near the stage — as is found in many theatres — should be avoided, as it is almost certain to produce an echo on the stage. The rear wall, if vertical, should be broken with deeply inset doors, hangings, or other ornaments which will prevent the reflection of sound to the stage. If the rear wall be inclined from the vertical toward the stage, it can be left in hard, smooth material, in which case it will direct very beneficial reflections to auditors in the rear part of the theatre.

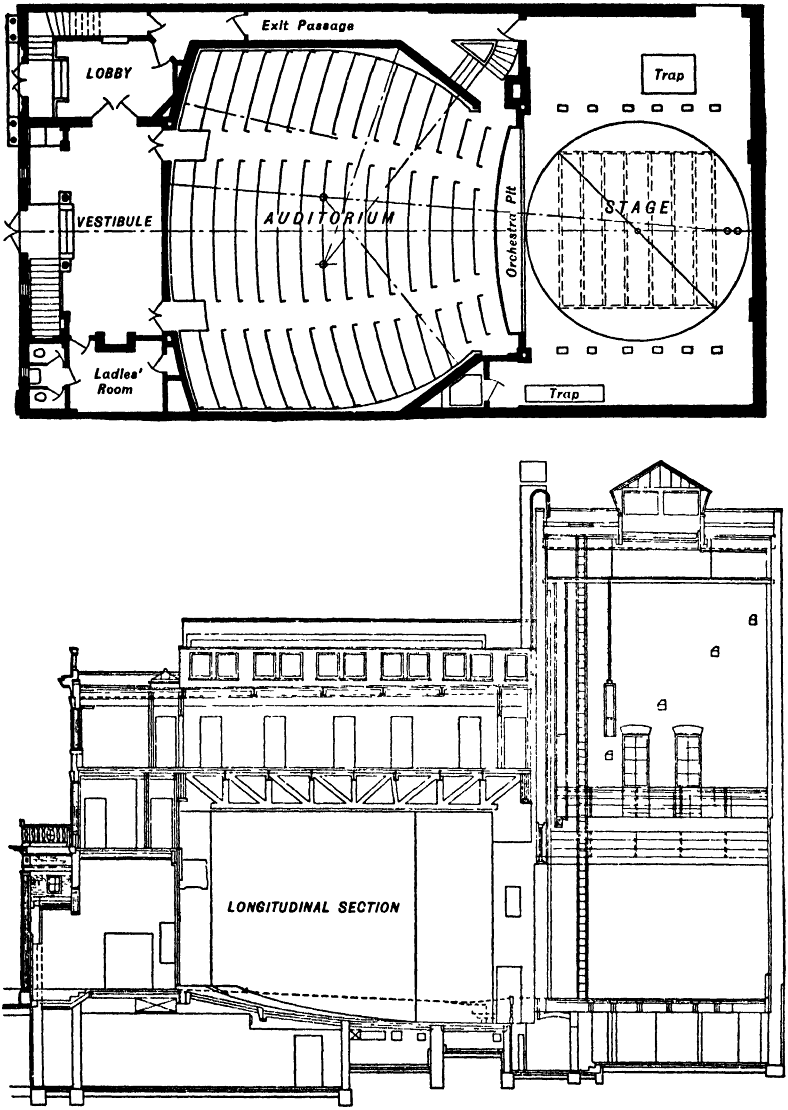

Fig. 238. Plan and section of the Little Theatre, New York, (*Ingalls and Hoffman, Architects; W. C. Sabine, Consultant on Acoustics.*) The auditorium is 28 feet high in front, 23 feet high at the rear, 48 feet long and 49 feet wide, with a stage opening 18 by 31 feet. Felt panels on the rear and side walls reduce the reverberation, with a capacity audience of 299, to 2.2 seconds at 128, 1.2 seconds at 512 and 1.5 seconds at 2048 cycles. (These times of reverberation were calculated by Sabine on the basis of the old reverberation formula, Eq. [23]. If Eq. [26] be used, the resulting times of reverberation would be about 10 to 20 per cent lower.)

The optimal times of reverberation for the auditorium in a little theatre having a volume of about 50,000 to 60,000 cubic feet are approximately 2.0 seconds at 128 cycles and 1.0 second at 512 and 2048 cycles. A reverberation time slightly longer than 1.0 second is desirable at 2048 cycles (see Fig. 175) but it may be difficult to attain with existing materials, including the audience.

The exclusion of both outside and inside noise should receive study whether the site is a quiet or a noisy one. The level of noise in the auditorium should not exceed 15 db, and if the highest standards of acoustics are sought the level of noise should be reduced to 10 db. This will necessitate a noise survey of the site, the routine calculations on sound-insulation such as have been described in Sec. 106, the choice of wall and ceiling structures and of entrance and exit doors which will satisfy these calculations, and the suppression of all ventilating and other equipment noises in the theatre.

In Fig. 239 is shown a sketch of a plan and section for a little theatre which is based upon a study of the requirements for ideal acoustics. The auditorium is everywhere enclosed by double walls which will provide an insulation of at least 60 db. This amount of insulation will be sufficient to exclude all outside noises even in a noisy metropolitan locality. If the theatre is located in a quiet site, it is of course unnecessary to provide such an amount of insulation. On the other hand, if the site is subject to excessive earth vibrations, such as result from near-by bus or trolley lines, as well as to excessive air-borne noise, it is advisable not only to provide double walls but also to insulate from the earth the inner walls of the auditorium. The vestibule and promenade for the design shown in Fig. 239 are completely carpeted over a flexible carpet pad; and absorptive material is used in the ceilings of the vestibule and promenade. The treatment of these spaces with absorptive material not only helps to reduce outside noises but it also excludes the possibility of having any reverberant rooms coupled to the main auditorium.

The splayed proscenium walls and ceiling, the flat ceiling of the auditorium, and the lower portion of the side walls are designed to reflect useful sound upon the audience, and accordingly are finished with hard plaster. If the room is to be used at times for music it would be helpful to apply this hard plaster to wood or metal lath, which would give added resonance to the room. A movable apron is indicated to fit over the orchestra pit when the theatre is used for productions without orchestra. This permits a part of the action to take place in front of the proscenium opening, and not only improves the audition in the auditorium but gives a unified combination of the classical *logeion* and *skene*.

The control of reverberation in this proposed theatre has been effected by the use of absorptive material on the upper side walls and on the rear wall. The aisles in the auditorium are heavily carpeted, and all seats are heavily upholstered, so that the theatre will have essentially the same acoustical properties whether the auditorium is empty, or partially or completely filled with an audience. The absorptive material for the upper side walls and the rear wall should have such absorptive properties as will give to the auditorium a reverberation characteristic which will approximate that shown in Fig. 175.

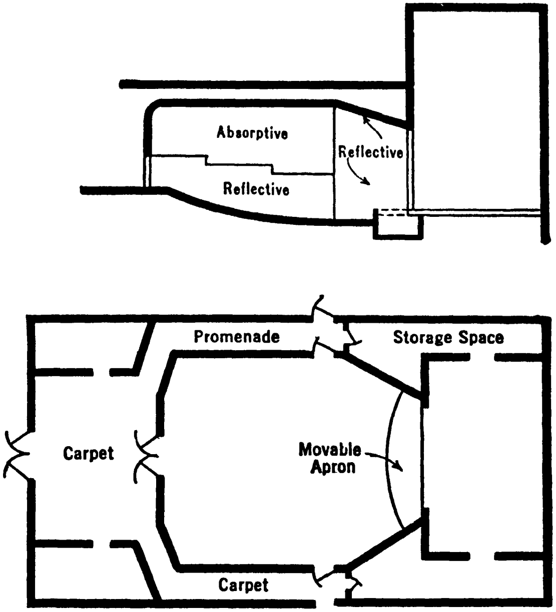

Fig. 239. Acoustical study of a little theatre.

The calculations for reverberation in this theatre are given in the following table.

The analysis given in the table assumes that the theatre will be equipped with a good grade of upholstered opera chairs, and that the central aisle will be carpeted over a ½-inch felt pad. The absorption for each seated person has also been adjusted slightly to include the added absorption of the occupied chairs. It will be noted that the analysis leads to the conclusion that the 1150 square feet of upper side walls and rear wall should be treated with an absorptive material having coefficients of sound-absorption of 0.11 at 128 cycles, 0.37 at 512 cycles and 0.22 at 2048 cycles. It no doubt will be difficult to select a material which will have precisely the coefficients called for in the tabulated

CALCULATIONS FOR REVERBERATION IN LITTLE THEATRE

Volume = 50,000 cubic feet; surface = 8650 square feet; $k = 0.05$; seating capacity = 300.

	128 cycles	512 cycles	2048 cycles
Optimal time of reverberation (on assumption that theatre will be used almost wholly for speech)	2 05 seconds	1.00 second	1 00 second
$-\log_e (1 - \alpha)$ . . .	0.141	0 289	0.289
α . . .	0 130	0 251	0.251
Total units of absorption required = $S\alpha$.	1124	2170	2170

Absorptive Material in Auditorium	Coefficient	Sabines	Coefficient	Sabines	Coefficient	Sabines
Absorption of 200 auditors in upholstered opera chairs	2 0 per person	400	4 4 per person	880	5 2 per person	1040
Absorption of 100 upholstered opera chairs	1 5 per chair	150	2 5 per chair	250	2 5 per chair	250
300 square feet carpet strips over ½-inch pad	0.15	45	0 40	120	0 45	135
1950 square feet linoleum flooring, waxed. . . .	04	78	04	78	04	78
450 square feet proscenium opening . . .	40	180	50	225	50	225
4800 square feet hard plaster on metal lath	03	144	04	192	04	192
Total absorption from above required materials		997		1745		1920
Therefore required additional absorption to be supplied by 1150 square feet of upper side walls and rear wall		127		425		250
Therefore required coefficients of the 1150 square feet of absorptive treatment.	11		.37		.22	

calculations. However, there are many materials which will have approximately the required coefficients at 128 and 512 cycles; and if a selection of a material be made which is in good agreement at these two frequencies and in fair agreement at 2048 the result will be entirely satisfactory. For example, the ½-inch mineral wool acoustical plaster listed in the table on acoustical plasters will closely approximate the type of material needed. The use of such materials as are indicated in the table will give reverberation times which do not differ more than 2 or 3 per cent from the optimal times recommended for an audience of 200 persons; and with audiences between 100 and 300 persons the times of reverberation will not depart by more than 5 to 10 per cent from the optimal times, which is entirely satisfactory for ideal acoustical quality. Finally, it is necessary to control the reverberation on the stage. A reverberation time of about 1.0 to 1.10 seconds at 512 cycles is satisfactory. This condition of reverberation can be closely approximated if the stage be fully equipped with the usual flies and with velour or monks cloth masking units. Measurements of reverberation should be made in the finished and equipped stage to determine whether different types of setting will provide the proper reverberation, and to determine what changes, if any, are desired. A small enclosed set, placed forward on the stage, affords the best means of projecting an abundant supply of sound energy to the audience, and its use should be encouraged whenever feasible.[3]

The speech articulation in such a little theatre as has been described in this section will approximate 90 per cent; and it will not be necessary for the actors to lift their voices. They can therefore give their entire thought and feeling to the type of oral expression which will best portray the drama, and they can act with the assurance that every word, no matter how finely modulated, will be heard by the audience.

181. The Legitimate Theatre. In this section consideration will be given to theatres for the spoken voice which are larger than the little theatre described in the preceding section. The same general principles of design which were discussed for the little theatre apply with equal force to the larger legitimate theatre. There is, however, one very important difference which results from the difference of size. One of the most serious mistakes in modern theatre design has been a consequence of the tendency to make bigger and bigger theatres. In the older type of theatre with three or four balconies it was possible to seat an audience of 2000 or even 3000 in an auditorium having a volume of 200,000 cubic feet, whereas in the modern theatre with a single balcony the volume required to accommodate the same number of auditors may be of the order of 400,000 to 500,000 cubic feet. By referring to Fig. 179, which gives the percentage articulation in auditoriums of different size and for different times of reverberation, it will be seen that if an articu-

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[3] Some tests conducted in the El Capitan Theatre, Hollywood, California, show the importance of having the action take place on the front of the stage, or of having an enclosed set to direct the speech to the audience. With a speaker on the front part of the stage, the speech articulation in the balcony of the El Capitan Theatre was 85 per cent. When the speaker moved to the rear part of the stage (with an open setting on the stage) the articulation was reduced to 60 per cent.

lation as great as 80 per cent is desired — and this should be considered as the acceptable minimum for a legitimate theatre — the size of the auditorium should not exceed 400,000 cubic feet, and it is rather precarious to depend upon entirely satisfactory acoustics in an auditorium as large as this, unless the walls and ceiling have been designed properly. But if the proscenium walls and ceiling and the main ceiling are properly designed to act effectively as sounding boards, a volume of 400,000 cubic feet will not be too large for satisfactory hearing. If these surfaces are not properly utilized to enhance loudness it is advisable to keep the volume down to not more than 200,000 cubic feet. The upper limit to the size of the legitimate-theatre auditorium should be fixed therefore at about 200,000 to 400,000 cubic feet, unless artificial means be provided for amplifying the speech, in which case the limit may be extended almost indefinitely. It may seem that this upper limit of size has been given a " wide spread " in specifying a limit that may vary from 200,000 to 400,000 cubic feet, but it should be remembered that a change of 100 per cent in volume may not introduce a change in loudness of more than 2 or 3 db, and therefore it is not feasible to fix a very definite limit of size. For this reason, one does not notice a great deal of difference in the acoustical properties of two theatres which differ in volume in the ratio of 1 to 2. But in determining the limiting size of a theatre one should keep in mind the data given in Fig. 179. One will then realize in advance of construction just how much the hearing of speech will be affected by any proposed change in the size of the auditorium.

Since the loudness of average speech in the legitimate theatre is at a relatively low level, even in theatres having a volume of less than 200,000 cubic feet, it is of the utmost importance to design the auditorium of such a shape as will provide the audience with the greatest possible amount of direct and of once-reflected sound. The divergence of the side walls, the slope of the overhead proscenium splay, and the slope of the main ceiling of the auditorium should be carefully designed to provide the optimal flow of once-reflected sound to all auditors, giving a slight preference to the more remote auditors in the rear seats under and in the balcony.

Fig. 240 shows an acoustical study of a longitudinal section of a theatre in which the ceiling surfaces have been designed to reenforce sound by reflection. The overhang of the balcony is short, and the opening under the balcony is high, so that adequate sound will reach the rear seats under the balcony. These seats, which are usually the poorest ones in most theatres, are further benefited in the indicated design by the reflections of sound from both the splayed walls and ceiling of the proscenium. The main part of the ceiling has a gently rising slope in order to provide the most favorable reflection of sound to the seats in the balcony. If heavily upholstered seats be used throughout, and if the aisles be carpeted over a ½-inch carpet pad, it is not likely that much additional absorption will be required, since the volume of this theatre is relatively small for the seating capacity. If any absorptive material be required in order to provide the optimal reverberation, it should be applied to the rear wall under the balcony and to the rear wall above the balcony. All materials for the interior of the theatre should be chosen in such a manner as will give the optimal reverberation for low-, medium-, and high-frequency sounds. Calculations, such as have been described in Chap. XIII, should be made in order to provide insulation against outside noise, and to suppress all noise of inside origin, such as that from ventilating equipment. If the theatre is to be used for musical comedies as well as dramatic productions, the reverberation should be based upon the requirements for both speech and music, and the absorptive materials should be carefully located in such a manner as will insure a uniform rate of decay of sound in all directions and in all parts of the theatre. An enclosed set, such as is shown by the dotted lines, should be used with the stage setting whenever possible. Such an enclosed set reflects toward the audience a large and much-needed amount of sound which would otherwise be lost by absorption in the upper part of the stage. (See footnote 3 in preceding section.)

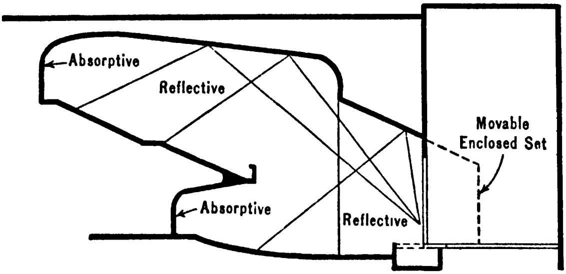

FIG. 240. Acoustical study of a section of a legitimate theatre, showing beneficial reflections from the proscenium arch and ceiling.

Theatres which are circular or elliptical in plan, or theatres with domed or cylindrical ceilings, are especially likely to give difficulty, although when the curved surfaces are well broken, or coffered, or treated with a material having a coefficient of absorption in excess of 0.70, the difficulty from the curved surfaces will be largely overcome. For example, the Wrigley Theatre at Catalina Island is circular in plan with the stage opening forming a part of the cylindrical boundaries of the walls. If the walls of this theatre had been finished with reflective materials there would have been a very pronounced focusing of sound at a point about half way between the rear and the centre of the auditorium. To overcome this anticipated defect, two layers of 1½-inch hair felt separated by a 2-inch air space — the two layers covered with a perforated membrane — were applied to the side and rear circular walls in the form of a cylindrical band extending in length approximately three fourths of the way around the interior walls, and in height from about 3 feet up to 16 feet from the floor. This expedient gave entire satisfaction, and there is no noticeable focusing of sound in any part of the theatre. The front portions of the side walls were left in hard material so as to give helpful reflection toward the central and rear parts of the theatre.

In the case of another theatre, elliptical in plan, the introduction of small recesses at regular intervals in the wall, and the use of a highly absorptive plaster for the wall surfaces, was sufficient to prevent both focusing effects and the tendency for sound to *creep* around the curved and smooth contour of the walls.

The use of a finely perforated grille with highly absorptive material back of it is also a useful means of treating curved surfaces so as to eliminate objectionable reflections. The grille can be made of perforated sheet metal which can be decorated with any kind of paint. Further, the perforations can be so small that they will not be visible at a distance of, say, 20 or 30 feet from the audience. Finally, by dividing large concave surfaces into secondary convex surfaces, as is indicated in Fig. 160, it is possible to overcome the serious defects of troublesome concave surfaces. Although it is possible to treat curved surfaces in such a way as to largely overcome their defects, it is preferable to use forms which are free from undesirable curvatures. This does not mean that curved surfaces are always to be avoided, for if they are judiciously handled they may contribute largely to good acoustics; but if they are used without careful consideration of the acoustical consequences they may lead to disastrous results.

182. Sound-Picture Theatres. The acoustical problem for the theatre in which sound is reproduced by electro-acoustical equipment is markedly different from the acoustical problem in the legitimate theatre. This difference is attributable to two outstanding factors which characterize reproduced sound: (1) the reproducing equipment is capable of generating an adequate intensity of sound even in extremely large theatres, and (2) the projecting equipment, such as the horn, has directional properties which tend to concentrate the sound along the principal axis of the projector. It has been noted in previous chapters that the optimal loudness for the hearing of speech is about 70 db, and that this optimal loudness level is not attained in the legitimate theatre, owing to the limited amount of sound energy generated by the average speaker and the large volume in which this energy is distributed. On the other hand, it is a simple matter to design sound-reproducing equipment which will maintain an average level of at least 70 db in large theatres. It is not necessary therefore to prolong reverberation as a means of increasing the loudness of sound, as is the case in all auditoriums where the loudness of the sound is limited to the level which can be maintained by the unamplified speech of the average speaker. The optimal time of reverberation for a sound-picture theatre is therefore considerably shorter than the optimal time for a legitimate theatre. If 1.05 or 1.10 seconds be the optimal time of reverberation for a small room where the average level of sound is 65 or 70 db, there seems little justification for increasing the time of reverberation for larger rooms when it is possible to maintain this same sound level, as is done in sound-picture theatres.

Another factor which must be considered in determining the optimal time of reverberation for sound-picture theatres is the effect of the studio *reverberation* which is permanently recorded on the sound track of the *movie* film or on the sound groove in the wax record. The sound recordings are generally made in studios which have a certain amount of reverberation — of the order of 0.6 to 0.8 second. When these records are released in the theatre, the reverberation of the auditorium is " added " to the reverberation which has been previously recorded on the film or wax. Although the resulting reverberation time is less than the sum of the reverberation times in the recording room and in the theatre, the effective reverberation is *longer* than would be the case if the sound had originated in the theatre without the intervening action of the sound recorder and reproducer. Finally, if we accept the theory upon which the optimal time of reverberation in auditoriums is based, namely, that the product of the level of the sound multiplied by the time required for that sound to die away to inaudibility should be constant (see Secs. 132 and 146), we are obliged to use a shorter time of reverberation in sound-picture theatres than in legitimate theatres, since the intensity of reproduced sound is nearly always at a higher level than the level of speech or music in the legitimate theatre.

All these considerations point to the necessity of relatively short periods of reverberation for the reproduction of sound in the cinema theatre. These considerations and the observations and experience of many acoustical authorities give very substantial support to the choice of the times of reverberation shown in Fig. 241. These times of reverberation should be provided for two thirds of a capacity audience, which will insure an acceptable condition of reverberation for either small or capacity audiences. The upper curve gives the optimal time of reverberation as a function of the volume of the theatre (the auditorium proper) for 128 cycles, and the lower curve gives the optimal time of reverberation for the frequency range between 512 and 2048 cycles.[4] The times of reverberation given in these curves are somewhat shorter than are advocated by some authorities, but both theory and experience give support to these relatively low times of reverberation. However, it should be borne in mind that a departure of 10 or even 15 per cent from these recommended times will not have an appreciable

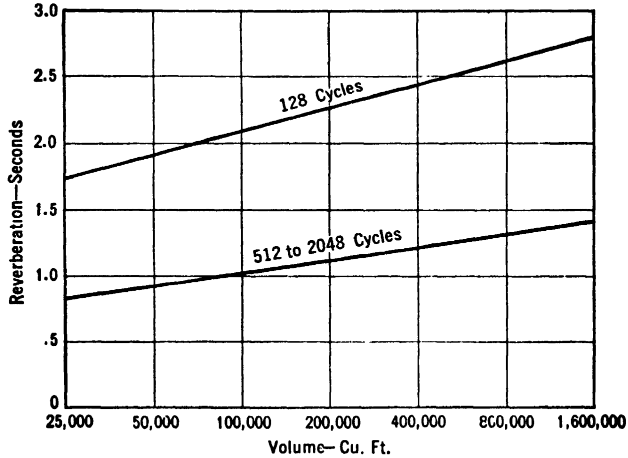

FIG. 241. Recommended times of reverberation for sound picture theatres.

effect upon the acoustics of the room, and that if the theatre is to be used for vaudeville or other legitimate productions it would be advisable to make a compromise between the time specified in these curves and the time specified in the corresponding curves for legitimate theatres.

The shape and size of the cinema theatre do not offer the difficulties which are encountered in the design of legitimate theatres. Thus, it is not necessary to design proscenium arches, side walls, and ceilings to act as sounding boards in order to augment the sound reaching the audience. Further, the directional properties of the sound projectors are of such a nature that by using a number of them it is possible not only to radiate an adequate supply of sound energy to the most remote auditors in the theatre without the aid of reflections from the boundaries of the theatre,

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[4] Compare with curves for legitimate theatre, Fig. 237.

but also to overcome the difficulties from delayed reflections in large theatres.

The directional effects of loud-speaker horns are shown in Figs. 242 and 243. These curves indicate that loud-speaker horns have a pro-

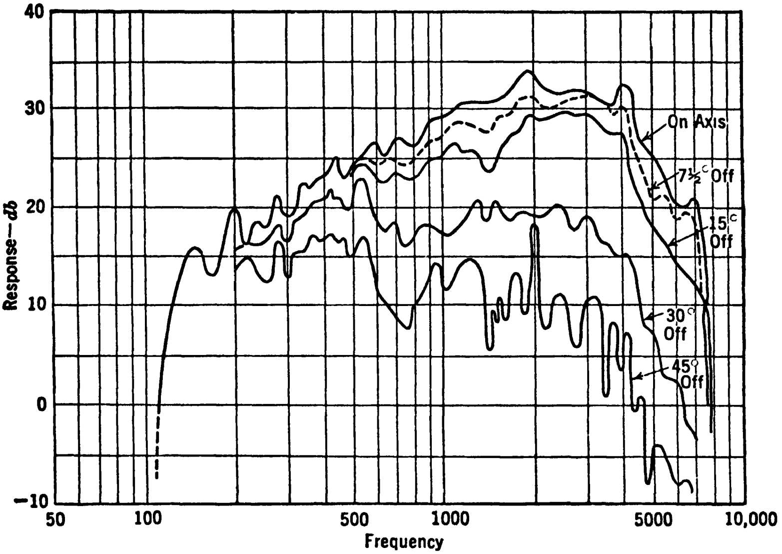

FIG. 242. Directional effects of a loud speaker horn. The frequency-response curves are plotted for certain directions with respect to the axis of the horn. (*Bostwick.*)

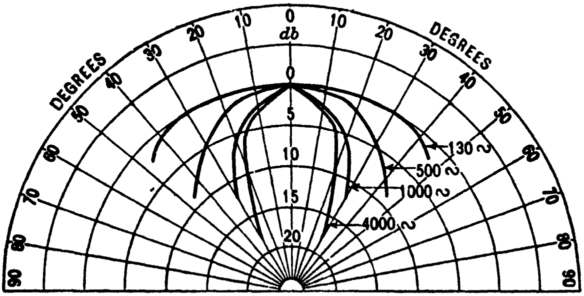

FIG. 243. Directional effects of a loud-speaker horn, showing how the sound level of certain frequency components decreases with increasing divergence from the axis of the horn. (*Bostwick.*)

nounced directional effect, especially for the high-frequency components of sound. Thus, it will be noted that for a frequency of 4000 cycles, at an angle of 20° from the axis of the horn, the sound level is 10 db lower than the intensity along the axis of the horn. This means that if an auditor sits far away from the axis of the horn he will hear the low components of the reproduced sound, but the high-frequency components will be largely suppressed. It is necessary therefore to use a sufficient number of horns and have them so oriented that all auditors will be located within the angle for which there is no appreciable loss of the high-frequency components.

Since the sound projectors have directive properties, it is important that the surfaces against which these beams of sound are directed be relatively absorptive, otherwise difficulties are likely to arise from pronounced reflections, especially in large houses where the differences in path may be sufficient to cause interfering effects or even echoes. It is generally advisable therefore to treat the side and rear walls with highly absorptive material; experience has shown that wall treatment is preferable to ceiling treatment, although in some instances it is necessary to treat both walls and ceiling in order to reduce suitably the reverberation. The treatment of the walls with absorptive material also tends to maintain a uniform rate of decay in all directions, whereas if the absorptive treatment be applied only to the ceiling the rate of decay is greater in the vertical than it is in horizontal directions, and the persistence of these horizontal reflections may give rise to a troublesome one- or two-dimensional reverberation. The treatment of the walls also eliminates the flutter which results from multiple reflections between parallel walls.

Many cinema theatres are designed without balconies; it is especially important to use sound-absorptive material on the walls in such theatres, since the absence of the balcony tends to increase markedly the mean free path and thus prolong the reverberation. In theatres without a balcony it is usually necessary to treat at least the entire side and rear walls with a material having coefficients of sound-absorption of not less than 0.25 at 128 cycles and not less than 0.50 at 512 cycles. It also is extremely important to have all seats heavily upholstered, since the theatre is often attended by a comparatively small audience.

During the first few years of sound pictures it was not necessary to go to great extremes in the insulation of noise since the recording and reproducing equipment itself introduced a noise level of about 25 to 35 db. In the presence of such a noise, that from the outside or from the ventilating equipment was not disturbing. But in recent years improvements in the recording and reproducing equipment have almost completely eliminated the ground or surface noise, and it therefore becomes necessary to provide a high degree of insulation against outside noise and to suppress adequately all inside noises.

Since an almost unlimited amount of sound energy is available in the sound-reproducing equipment, it is not necessary to limit the size of the

Fig. 244. Cinema theatre with stenciled "Auditec" panels on side and rear walls.

Fig. 245. New Fox Theatre, Tucson, Arizona. "Trutone Acoustical Tile" applied to side and rear walls.

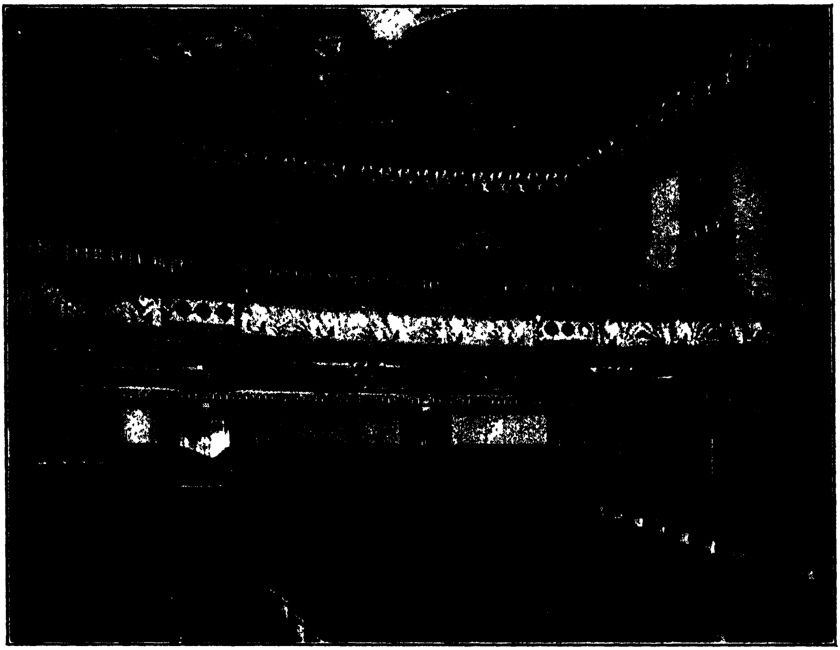

FIG. 246. Warner Brothers' Beverley Hills Theatre, California, showing "Kalite" acoustical plaster on the upper side walls and in the ceiling. (*B. Marcus Priteca, Architect.*) Note the heavy ceiling decorations which were done on acoustical plaster with non-bridging lacquer and stenciling.

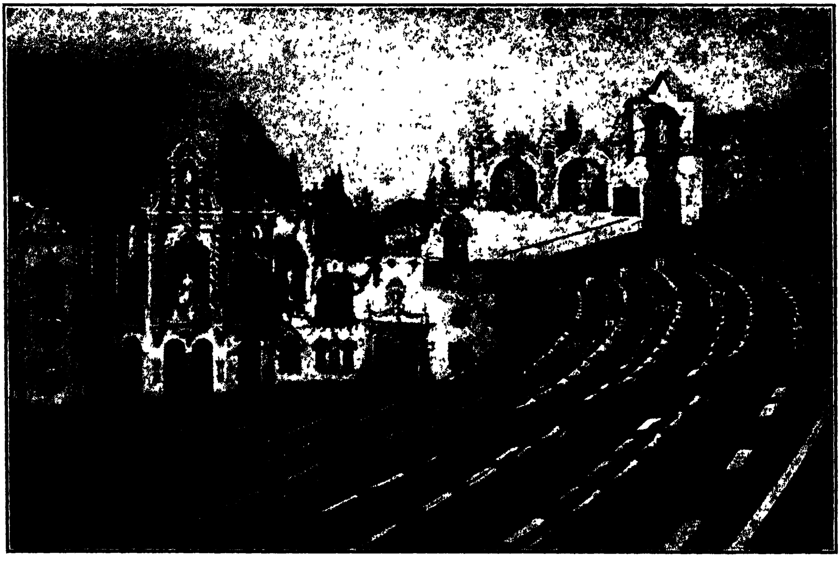

FIG. 247. Loew's Akron Theatre, Akron, Ohio. (*John Eberson, Architect.*) *Sky effect* and control of reverberation accomplished with "Macoustic plaster."

theatre as it is in the case of the legitimate theatre; for example, it would not be difficult to design cinema theatres seating as many as 10,000 or even 20,000 persons. In fact, the only necessary precautions would be the elimination of echoes and the proper reduction of reverberation. There are a number of dependable types of theatre design which would be entirely satisfactory.

A number of interiors of talking-picture theatres which have been successfully designed and treated for acoustics are shown in Figs. 244 to 247. The type of material used and its extent of application are mentioned in the legends under the photographs. In general, it may be stated that the material should be durable, decorative, and easy to maintain, and it should have an absorption coefficient in excess of 0.15 at 128 cycles and 0.30 at 512 cycles.

If a theatre be free from defects of shape, if it be insulated against disturbing noise, and if it have a reverberation time shorter than about 1.5 seconds, it will have satisfactory acoustics for talking or singing pictures.

CHAPTER XXIV

MUSIC BUILDINGS

183. Introductory. The general theory of the acoustics of music buildings was developed in Chap. XVIII. In the present chapter consideration will be given to the practical problems which arise in the design of music studios, recital halls, concert halls, opera houses, and dance halls. A comparison of the effects of reverberation upon speech and upon music demonstrates very conclusively that an excess of reverberation can be more readily tolerated in music rooms than in speech rooms. In fact, a deficiency of reverberation in music rooms may be as objectionable as an excess. It is important therefore in the design of music rooms to provide a time of reverberation that will agree closely with the optimal time, which will depend both upon the size of the room and upon the type of music which will be performed in the room. (See Fig. 183.) The tests of W. C. Sabine showed that musical critics can readily detect an excess or a deficiency in the reverberation time of a room amounting to as little as 10 per cent. It should be the aim of all good design, therefore, to keep the reverberation time in a music room within a 10 per cent variation from the optimal time.

Other considerations, such as the shape and size of the room, the exclusion of noise, and room resonance, are vitally important in determining the outcome of a music room, and all these factors must be studied carefully in working out the acoustical design of music rooms. Specific problems which arise in the design of music rooms, and methods of obtaining a satisfactory solution of these problems, will be considered in the following sections.

184. Music Studios. Fig. 248 shows a plan and sections of a small music studio which has been designed for good acoustics. Large areas of wood — the floor, the greater part of the walls, and the front two sections of the ceiling — are used to add resonance to the room. A large rug, or small throw rugs, are specified for the audience end of the room. The floor under and about the piano is uncovered, thus adding resonance and volume to the tonal quality of the piano and other instruments which make contact with the floor, as the cello. The generating end of the room is thus made relatively reverberant, by the use of hard plaster and wood surfaces; and the listening end of the room is made relatively "dead," by the use of rugs and absorptive material in the ceiling and on the upper walls. This arrangement of a relatively reverberant and resonant space for the performers, and a relatively non-reverberant space for the listeners, is not only in accord with the recommendations of musical critics but has been demonstrated to be highly satisfactory in some experiments of Professor F. R. Watson.[1] (It is important, however, not to carry this type of treatment to extremes. For example, the author recently was consulted concerning the acoustics of a music room in which the absorptive material was located entirely in the rear third of the room. As a result, the front part of the room was too reverberant. A better condition would have resulted if the absorptive material had been distributed more uniformly over the entire boundaries of the seated area.)

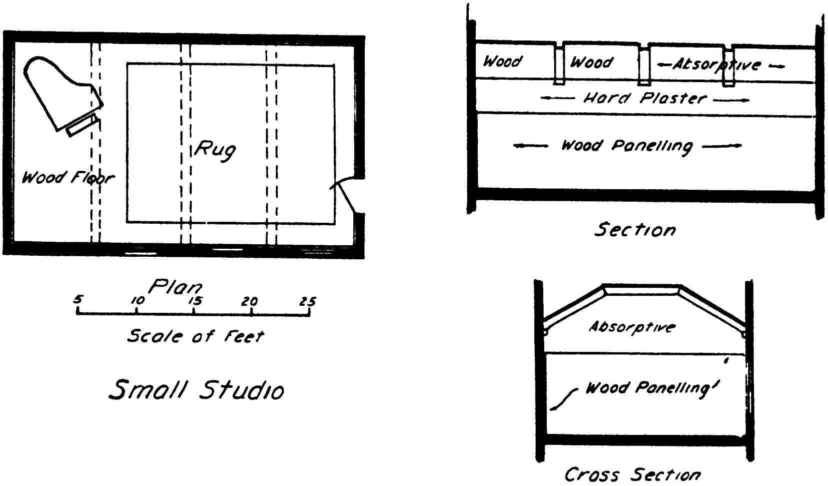

FIG. 248. Acoustical study of plan and sections for a small music studio.

The absorption on the end wall, the window recesses on the one side wall, and the broken ceiling, treated in part with absorptive material, all help to prevent multiple reflections between parallel surfaces, and also insure a uniform rate of decay of sound in the three cardinal directions in the room. If, for example, all the absorbing material had been concentrated on the ceiling and floor, and if the ceiling had been level instead of broken into three sections, there would have been an excessive damping of sound in the vertical direction between the floor and the ceiling, and an excessive prolongation of the sound between the highly reflective and parallel walls. The room would therefore have two differ-

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[1] F. R. Watson, "Ideal Auditorium Acoustics," Jour. Amer. Inst. of Architects, **16**, 259 (July, 1928).

ent rates of decay — one in which the rapid rate of absorption between the floor and the ceiling was predominant, and a slower rate of absorption between the walls which became predominant after the vertical components were largely suppressed. This condition is always objectionable, and in extreme cases leads to a characteristic " flutter " between the parallel reflecting walls. It is extremely important therefore in the design of music studios to distribute the absorptive material in such a manner as will provide an approximately uniform rate of decay of sound in directions parallel to the three principal axes of the room. The optimal times of reverberation for a small music studio, not exceeding 10,000 to 15,000 cubic feet in volume, is about 2.0 to 2.2 seconds at 128 cycles and 1.1 to 1.2 seconds at 512 to 2048 cycles. Calculations for reverberation and for sound-insulation should be made in advance of construction, along the lines suggested in Secs. 180 and 158.

In the design of buildings where many music studios are to be located in the same building, it is of the greatest importance that the separate studios be adequately insulated from each other. The insulation between studios should be not less than 50 db, and in studios where complete insulation is required, it should be as great as 60 or 65 db. These amounts of insulation cannot be obtained with ordinary types of construction or in buildings which depend upon the windows for ventilation. If single-sashed windows are used, and the separation between windows in two adjacent rooms be of the order of 15 feet, the insulation from room to room *via* the closed windows will be of the order of 50 db. If the windows are opened this insulation will be reduced[2] to about 25 db. Either floated floors or suspended ceilings are necessary to provide sufficient insulation between studios on adjacent floor levels; and usually a double-wall partition, with an air space containing an absorptive blanket, is necessary between adjacent studios on the same floor level. Several types of floor and wall construction will be found in the tables on sound-insulation (see Chap. XII and especially Fig. 140) which will provide the required amount of sound-insulation. Since pianos and other musical instruments as the cello and the bass viol rest directly upon the floor of the studio, it is exceedingly important to provide insulation against solid-borne vibrations. The mounting of the floor on flexible steel cushions, with a flexible felt joint between the floor and the side walls, is one of the most effective means of preventing the transmission of this solid-borne vibration.

If artificial ventilation be provided for the building it is also necessary

[2] Measurements by the author of the sound-insulation between two adjacent office rooms showed that the average insulation value varied from 25 db with all windows open to 45 db with all windows tightly closed.

to provide adequate insulation in the ducts between adjacent studios. It is possible to design filters which can be placed in the ducts between adjacent openings which will provide the required amount of insulation. The heating and ventilating contractor should be required to guarantee an amount of insulation equivalent to the insulation of the wall section separating the adjacent rooms. In some instances separate ducts are run from each room to the ventilating fan, but this is a much more expensive procedure, and if the filter sections are properly designed they will be fully as effective.

Where studios are located near each other, and face the same corridor, it is extremely important that heavy and tightly fitting doors be used. Rubber or felt strips should be placed around the edges of the door so that the door will seal tightly into the frame. The transmission of sound from studio to studio by the route of the doors will be further reduced by the use of highly absorptive material for the walls and ceilings of the corridors.

Fig. 249 shows a typical floor plan and details of the floor, ceiling, and walls of the Sherman Square Studios, New York, Tillon and Tillon, architects, in which the sound-insulation is reputed to be very good. The door jambs are felted so that all doors close tightly, and the doors to adjacent rooms are far apart. The heating supply risers to each apartment are separate, and the vent shafts for service pantries and bathrooms are separated from each studio by two or more partitions. The corridor walls are finished with acoustical plaster.

185. Recital Halls. The acoustical design of a recital hall will follow very closely the design of a music studio, as outlined in the preceding section. In general, the only difference will be in regard to the size of the room. Since the recital hall is usually larger than a studio, it is necessary to design the room of such a shape and size as will eliminate every possibility of echoes, interfering reflections, and sound foci. The plan and sectional drawings shown in Fig. 250 incorporate the principal features of good acoustical design. The stage floor is wood, and is surrounded by diverging wood walls and ceiling. If doors are used in the side walls of the stage, as indicated, they should be nearly flush with the inner wall surfaces, so that the full value of the reflecting side walls will be unimpaired. The reverberation is controlled by the use of absorptive material in the rear half of the ceiling and on the rear wall. If additional absorptive material be required, it can be extended forward another section in the ceiling. The use of heavily upholstered seats is recommended as a means of providing a uniform condition of reverberation for either small or capacity audiences.

The most satisfactory times of reverberation for a recital hall which

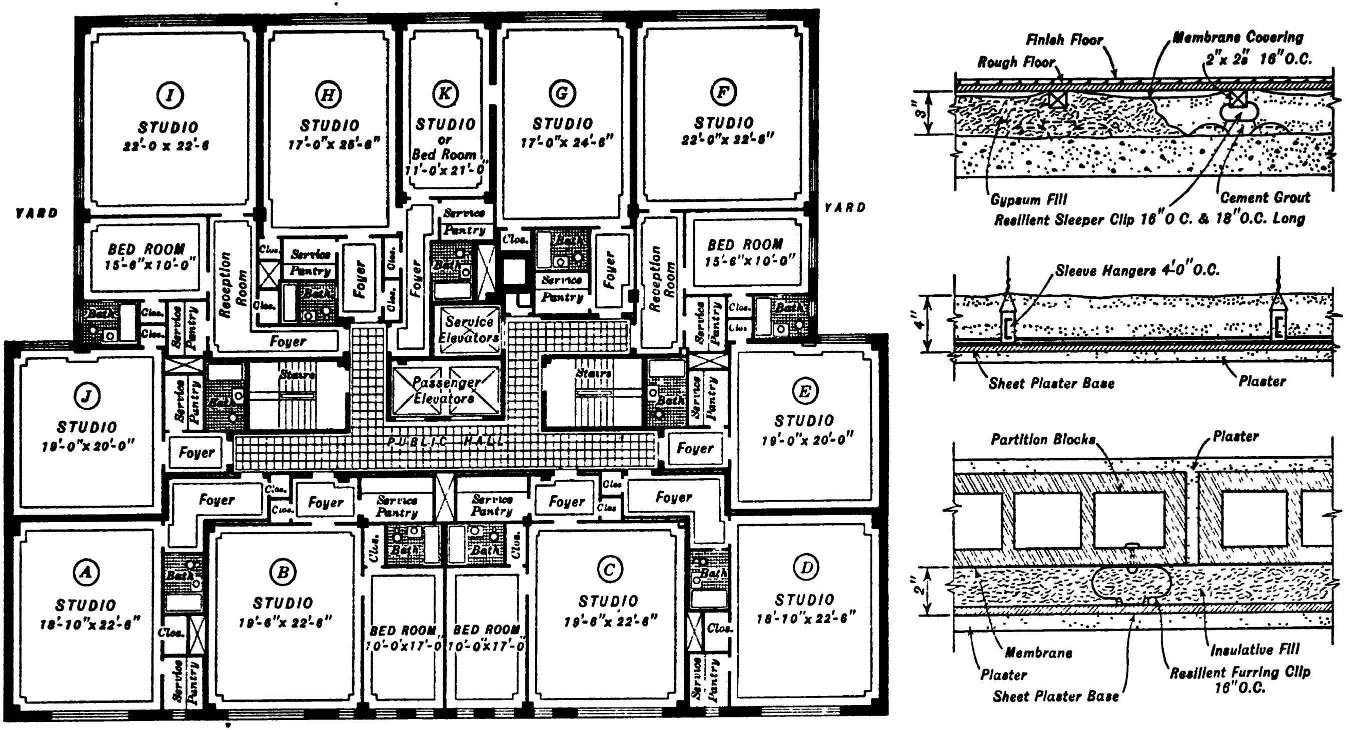

FIG. 249. Typical floor plan and details of floor, ceiling and walls in the Sherman Square Studios, New York, (*Tillon and Tillon, Architects*). (*American Architect.*)

has a volume of about 25,000 to 50,000 cubic feet, and which will be used for all kinds of musical programs, will be about 2.6 seconds at 128 cycles and about 1.3 seconds at 512 to 2048 cycles. (See Fig. 183, Chap. XVIII.) Materials should be used which will be relatively reflective for frequencies above 2000 cycles. This will overcome the high absorption in the air at high frequencies, and thus preserve the true tonal quality of music. The use of a very smooth hard plaster — preferably painted — and of varnished wood will help greatly to preserve the high-frequency components of music. On the other hand, the use of thin wood paneling — preferably not more than ¼ inch thick, and with variable spacing of the studding or furring strips for the paneling — will help to provide both the high absorption and the rich resonance required for the low-pitched tones. According to Fig. 183, the optimal time of reverberation will depend upon the type of music which is to be played in the room. In the better type of recital hall it therefore would be desirable to be able to adjust the reverberation time to both the size of the audience and the type of music which will be played in the room. Thus, solo and chamber music would sound better with a relatively short period of reverberation, whereas choruses and organ music would require a relatively long period of reverberation. The use of a variable number of rugs on the floor, or of heavy hangings drawn either across the windows or to the sides of the windows, provides a simple means for

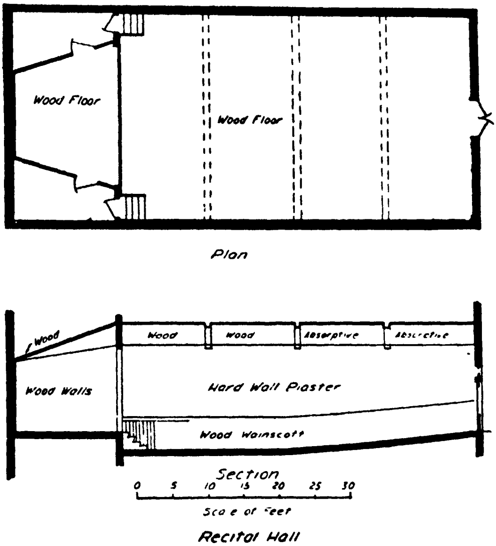

FIG. 250. Acoustical study of plan and longitudinal section for a recital hall.

controlling the reverberation. Or a controllable shutter in the ceiling which could be adjusted so as to cover either partially or completely an absorptive treatment of the ceiling would afford a more flexible and satisfactory means for controlling the reverberation.

186. Concert Halls. The acoustical design of a concert hall differs from that of a recital hall in the important properties of shape and size. The cubical contents of a concert hall may be anywhere between about 150,000 cubic feet and 1,000,000 cubic feet, and in the larger halls it is extremely important that the shape be of such a nature as will avoid troublesome reflections. The size of the concert hall should be governed by the size of the orchestra as well as the size of the audience it is to accommodate. Thus, an orchestra of about forty or fifty will sound best in a concert hall having a volume of about 100,000 to 200,000 cubic feet, and a complete symphony of about ninety to one hundred and ten instruments will give the best acoustical effect in a hall having a volume of about 300,000 to 800,000 cubic feet. Considerable latitude may be exercised in determining the most favorable size of a concert hall, since a variation of 100 per cent in the size of the room will make a difference of only 2 or 3 db in the average sound level of music in the room. (See Sec. 143.) However, it would be a mistake to crowd an orchestra of one hundred into a small hall or to expect a small orchestra to sound right in a large hall.

In connection with the acoustical design of concert halls, it will be instructive to consider the acoustical aspects of a number of existing halls in Europe.

(*a*) *Albert Hall, London.* This hall, of royal fame, is interesting because it exhibits nearly all the acoustical defects which should be avoided in the design of concert halls. Two sections of the hall are shown in Fig. 251. The hall is excessively reverberant; there are numerous echoes, delayed reflections, and sound concentrations owing to the high, concave ceiling; and there are no adequate reflecting surfaces in close proximity to the orchestra platform. As is shown in the sectional drawings in Fig. 251, the reflected sound from the ceiling may be delayed as much as 200 feet behind the direct sound, or nearly one fifth of a second; and with the converging effect of the concave ceiling the reflected sound may be as loud as the direct sound. The installation of the indicated velarium has helped to reduce these concentrated reflections but they yet constitute a serious annoyance, especially on the main floor.

(*b*) *Salle Pleyel, Paris.* The Salle Pleyel in Paris, a large concert hall erected in 1927, has been proclaimed by many, including some engineers,[3] as the solution of the problem of architectural acoustics.

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[3] P. Calfas, "La Nouvelle Salle de Concert Pleyel," Génie Civil (October 29, 1927).

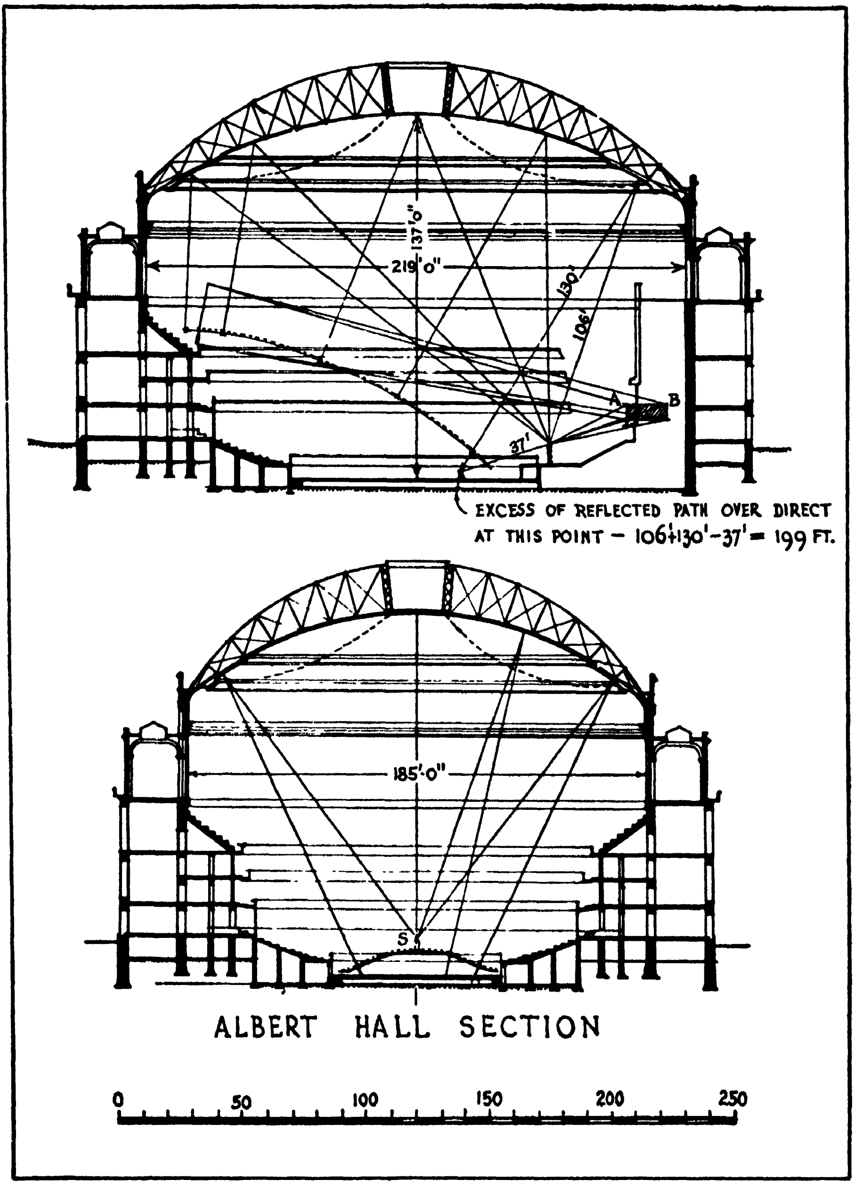

FIG. 251. Sections of Albert Hall, London, showing defects of shape. (*Bagenal.*)

At the same time, it has received unfavorable criticism from other sources.[4] The form of the hall represents a rather wide departure from conventional shapes; if it does not prove as epochal as its sponsors had anticipated, it at least provides a large and important experiment in the acoustics of music rooms, and it undoubtedly will exert a helpful influence on future design.

The shape of the concert hall embodies several features of good acoustical design, as can be seen from the plan and two sections of the hall in Figs. 252 to 254. Exclusive of the stage, it is 164 feet long, 68 to 102 feet wide, and about 64 feet from floor to ceiling. The auditorium seats 3000 persons, and the stage will accommodate a combined chorus and orchestra of 500. The plan shows how the side walls diverge in fan shape, allowing a good view of the stage, as well as a free flow of sound from the stage to the audience, by both direct and reflected sound. The side walls are not vertical but incline inwardly, and thus favor the reflection of sound down toward the audience. The non-parallel walls also help to prevent multiple reflections between the side walls, a defect which is sometimes noticeable in rooms with parallel walls.

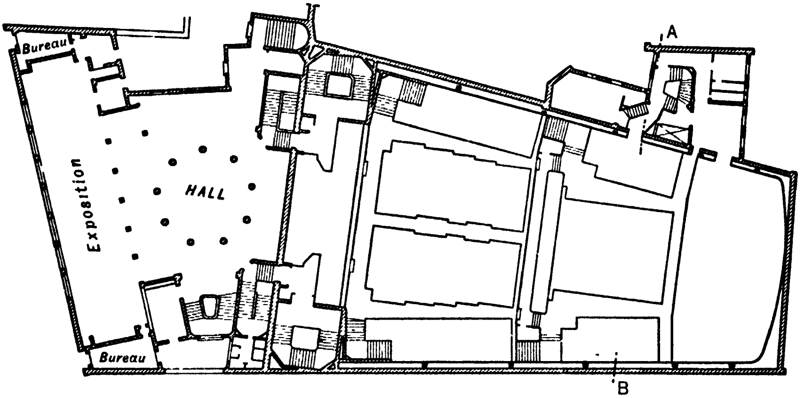

FIG. 252. Plan of Salle Pleyel, showing the divergence of the side walls.

But the chief acoustical interest in Salle Pleyel lies in its longitudinal section, which is made up of three nearly parabolic sections each 22 feet high, and all having their foci near the central part of the stage. These three sections provide a nearly uniform flow of once-reflected sound to all seats in the parquet and the balconies. This reflected sound is not delayed enough to produce an echo, but because of the great height of the ceiling some of the reflected sound is delayed enough to produce a

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[4] See, for example, Osswald, "Akustische Parabelsälle," Schweizer Bauzeitung, 95, 3 (January 25, 1930).

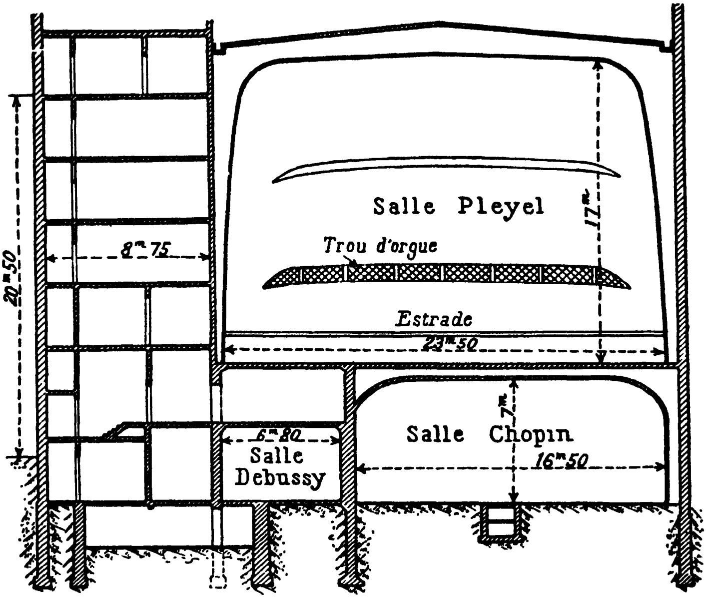

FIG. 253. Cross section of Salle Pleyel, showing the inclination of the side walls.

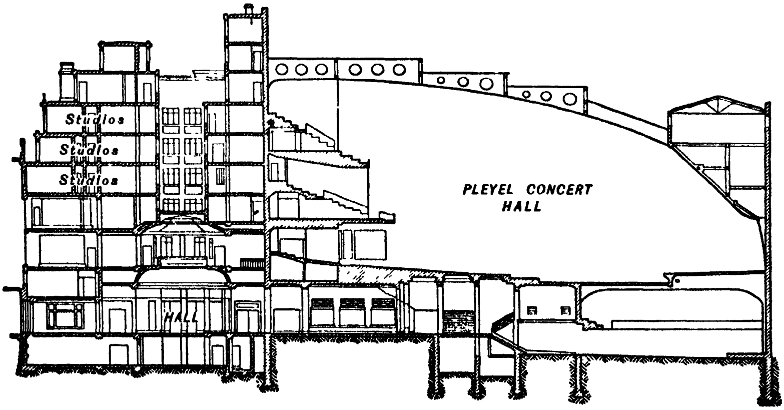

FIG. 254. Longitudinal section of Salle Pleyel, showing the approximately parabolic ceiling.

slight interfering effect in the central portion of the parquet. This interference, however, cannot be detected by the ear except during very rapid movements.

The shape is admirable for directing an abundant supply of sound energy to the audience, so that even the softest tones of the violin are heard clearly in all parts of the auditorium. The shape, however, offers a difficulty in its reversible reflection of sound. That is, noises originating in the audience are reflected toward and concentrated upon the stage. This often produces an annoyance to both performers and conductor, and it constitutes the most serious objection to halls of this shape.

The history of the control of reverberation in Salle Pleyel is instructive. It was constructed initially without regard to the customary calculations of reverberation. The walls and ceiling were hard plaster over reenforced concrete. The acoustical engineer, Gustave Lyon, who was largely responsible for the design, proceeded on the principle that it is the *once-reflected sound* that largely determines the acoustical quality of a room, and he wanted to favor this reflection as much as possible. As initially completed, the time of reverberation in the empty auditorium was, according to Osswald,[5] slightly over 4.0 seconds, and with 2000 persons present it was about 2.2 seconds. Subsequently some vegetable felt material was introduced on portions of the side walls above the balconies, and on the faces of the balcony rails. This reduced the reverberation time to about 2.0 seconds, with an audience of 2000. After a fire in the hall, in 1928, a large amount of mineral felt was installed in the soffits of the balconies, the ceilings above the balconies, and on the side walls above the balconies. In addition, the floor was heavily carpeted and very absorptive upholstered seats were installed. In August, 1930, with the auditorium in this condition, the author made some reverberation measurements with a 512-cycle organ pipe and obtained a time of reverberation of 1.75 seconds with no audience present. With an audience of 2000 persons the reverberation time would not exceed 1.55 seconds, and with a capacity audience of 3000 it would be about 1.45 seconds. These are rather short reverberation periods for a room having a volume of nearly 800,000 cubic feet, but no complaints are made about the room being too *dead*. Although the absorptive treatment was added primarily for the purpose of preventing the reflection of audience noise to the stage, it is probable that its effect upon reverberation was also a potent factor in providing an improved acoustical condition in the hall. The acoustical properties of the hall, in its present condition, are highly satisfactory.

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[5] *Loc. cit.*

(*c*) *Musikvereinssaal and Konzerthaus, Vienna.* There are two concert halls in Vienna which afford an interesting comparative study of room acoustics. The Musikvereinssaal enjoys an unusually fine reputation — both performers and listeners proclaim it as an ideal hall. The Konzerthaus, on the other hand, which is approximately of the same size and shape, and which has nearly the same time of reverberation at 512 cycles, is not held in as high repute as is the Vereinssaal, either by performers or listeners. Fig. 255 shows approximate plans of both the Musikvereinssaal and the Konzerthaus. The Musikvereinssaal is rectangular in shape, has a flat ceiling about 50 feet high, a volume of about 290,000 cubic feet, and side and rear balconies, and it seats about 1800 persons. The Konzerthaus is approximately rectangular in shape, but has a concave wall behind the stage, and a slightly concave ceiling. There are loges on the sides, and a balcony and gallery at the rear. The ceiling height is approximately 57 feet, and the seating capacity is 2076. The volume of the Konzerthaus is approximately 420,000 cubic feet.

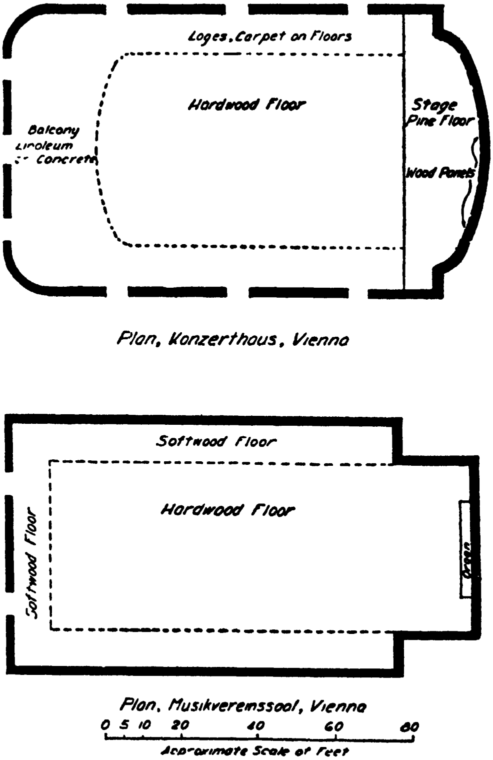

FIG. 255. Approximate floor plans for the Vienna Konzerthaus and the Vienna Musikvereinssaal.

All floors in the Musikvereinssaal are exposed wood, the walls are plaster on brick, except the stage walls which are wood, and the ceiling is suspended lath and plaster. The plaster is a three-coat job, is fairly soft (according to a knife test), and is finished with a special plastic material which is so soft and elastic that it yields perceptibly to even the pressure of one's knuckles. The surface has been sized with a starchy material and decorated with a flat porous paint. The only fabric in the room is a narrow hanging around the rail in front of the loges, which totals about 700 square feet.

The main floor of the Konzerthaus is wood, the floor in the loges is covered with a thin carpet, and the floor in the balcony is covered with linoleum. The walls are hard plaster on concrete, covered with damask; and the ceiling is plaster on concrete slab. The seats are upholstered with a padding less than 1 inch thick. There is therefore considerable material (damask on walls below balcony and on the rear walls above balcony and gallery, thin carpet on part of the floor, and thin cushions on the seats) which is highly absorptive for high-pitched sound and only slightly absorptive for low-pitched sound.

The Musikvereinssaal is free from echoes, interfering reflections, and sound foci. The Konzerthaus has a number of echoes and sound foci, owing to reflections from the concave wall behind the orchestra platform, and from the concave ceiling.

The reverberation times in the two halls, based upon measurements made in the empty halls with a 512-cycle organ pipe, are given in the following table:

SIZE OF AUDIENCE	MUSIKVEREINSSAAL	KONZERTHAUS
No audience	5 1 seconds	4 6 seconds
Two thirds filled	1 8 "	2 2 "
Capacity audience	1.35 "	1 6 "

If these two halls were appraised on the basis of the generally approved reverberation times for music rooms, the Konzerthaus probably would be given the higher acoustical rating, which is just contrary to a definite preference for the Musikvereinssaal. What then are the physical facts which are responsible for the superior acoustics in the Musikvereinssaal? They appear to be the following:

1. The shorter time of reverberation in the Musikvereinssaal with an audience present.
2. The over-absorption of the high-frequency and the under-absorption of the low-frequency components in the Konzerthaus, owing to the damask-covered walls, the carpet in the loges, and the hard plaster on concrete.
3. The better shape and size of the Musikvereinssaal, thus eliminating sound foci and delayed reflections, and providing an adequate loudness without the support of excessive reverberation.
4. The large area of resonant materials in the Musikvereinssaal, such as wood and plaster on lath, which seems to enhance the quality of music.

(*d*) *Leipzig Gewandhaus.* The Leipzig Gewandhaus is quite universally regarded as a model among the concert halls of the world. The plan and sections for this room, as prepared by Bagenal,[6] are shown in Fig. 256. W. C. Sabine[7] and Bagenal have described the acoustical properties of this hall, and have calculated its reverberation period at 512 cycles. From the standpoint of shape it is much like the Musikvereinssaal except that the corners both in plan and section are coved. It has a volume of 360,000 cubic feet. It is free from delayed reflections, echoes, and harmful foci; and it is bounded by surfaces which have good reverberation characteristics and are well suited for resonance — lime plaster on wood lath, wood floor, and a large area of wood paneling.

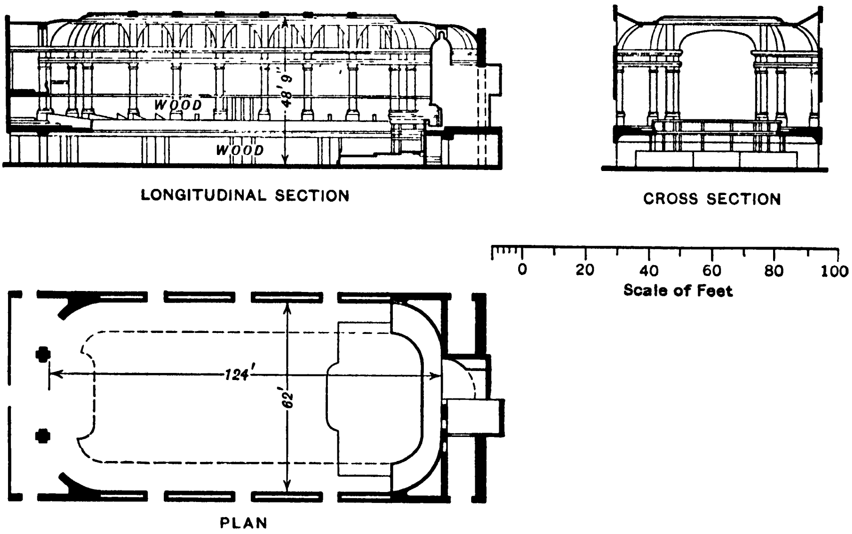

FIG. 256. Plan and sections for the Leipzig Gewandhaus.

Sabine calculated the reverberation time at 512 cycles as 2.30 seconds, with a capacity audience; Bagenal calculated it as 4.2 seconds, empty, and 1.99 seconds with a capacity audience. The discrepancy between the two calculations is largely attributed to differences in the ceiling height — Sabine had to depend upon measurements which were furnished him from abroad, and the ceiling height he used was too high.

In September, 1930, the author obtained some measurements of the reverberation time in the empty hall. The measured time was only 2.4 seconds. The seats were covered with a light canvas spread over the entire seated area, which introduced some uncertainty in calculating

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[6] Hope Bagenal, "The Leipzig Tradition in Concert Hall Design," Jour. Royal Inst. of Brit. Arch., p. 756 (September 21, 1929).

[7] W. C. Sabine, "Collected Papers on Acoustics," 60–68.

the reverberation for different-sized audiences, but if each seat as covered be assumed to have an absorption of 2.5 sabines, which is approximately correct, the time of reverberation with a capacity audience of 1560 and an orchestra of 80 will be of the order of 1.5 seconds. This is 0.8 second shorter than W. C. Sabine's, and 0.5 second shorter than Bagenal's, calculated times. But a large part of this difference is attributable to the difference between the old and the new reverberation formulas, and the remainder can be attributed to errors of measurement or in estimating the coefficients of the plaster and wood surfaces in the room.

Although it would be desirable to obtain more precise measurements in the Gewandhaus with an audience present, there is ample evidence that the reverberation time with a capacity audience is not much, if any, in excess of 1.5 seconds. Here, as in the Musikvereinssaal, good acoustical properties are identified with rather short reverberation times (1.35 and 1.5 seconds at 512 cycles, and about double these values at 128 cycles), with shapes that are free from pronounced concave surfaces, and with rooms that are bounded, in large part, with resonant materials. Finally, both the Gewandhaus and the Vereinssaal are remarkably free from outside noises.

(*e*) *Beethoven Saal, Berlin.* Beethoven Saal in Berlin is of conventional rectangular shape, seats 1000 persons, and has a volume of about 225,000 cubic feet, a measured reverberation time of about 4.0 seconds, empty, and a calculated time of 1.7 seconds with a capacity audience. The floor is wood; there is a wainscot of hard wood around the entire room including the orchestra platform; the upper walls around the platform or stage are lined with an absorptive felt covered with brocaded cloth; and the walls and ceiling of the main part of the hall are of hard or ornamental plaster. The room does not enjoy a high reputation in the matter of acoustics, although it is regarded as satisfactory by some authorities. It would appear that the felt treatment on the upper walls of the stage had been introduced as a corrective measure for excessive reverberation. The result is a rather *dead* stage and a too reverberant auditorium, and it is likely that this condition constitutes a cause for complaint. In addition, the hall is not adequately insulated against outside noise.

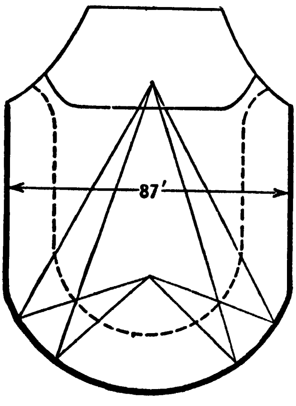

FIG. 257. Plan of Queen's Hall, London, showing concentration of reflections from the rear wall.

(*f*) *Queen's Hall, London.* Queen's Hall, shown in plan in Fig. 257, having a volume of 420,000 cubic feet and a seating capacity of 2000, possesses very good tonal quality although there are one or two imperfections owing to curved surfaces. As is shown in the figure, sound originating at any point on the stage is brought to a conjugate focus in the rear central part of the main floor. Although the path differences are not great enough to produce a distinct echo, some of them are great enough to cause interfering effects, and in addition the focusing effect of the curved rear wall over-emphasizes the intensity of certain instruments at the expense of others.

In the matter of reverberation and resonance Queen's Hall has very good acoustical quality. The large areas of wood flooring and wood paneling impart richness and sustenance to tonal quality, and the convex splayed walls on either side of the stage give a good flow of sound energy to the audience. The reverberation time in Queen's Hall is about 3.5 seconds empty, and 1.6 seconds with a two-thirds capacity audience.

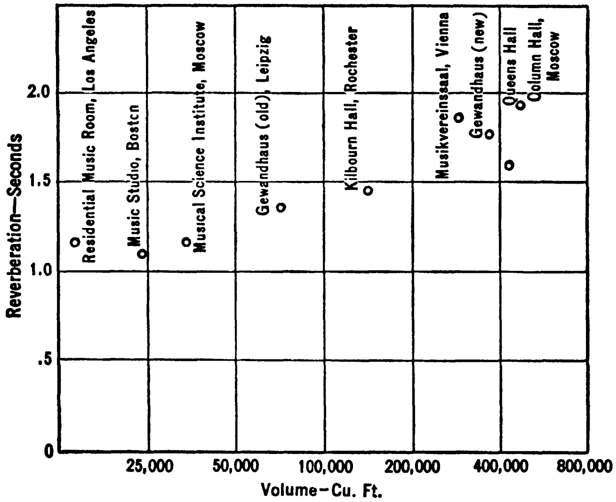

FIG. 258. Reverberation times (at 512 cycles) in concert halls and music rooms having good acoustics.

The times of reverberation (at 512 cycles and for two thirds of capacity audience) for a number of concert halls which are reputed to have good acoustical quality have been plotted in Fig. 258. The reverberation time is plotted as a function of the volume of the concert hall. Although there is a general trend of increasing reverberation time with increasing size of the concert hall, there are considerable deviations from any straight-line relationship between size and reverberation time. Thus, the Musikvereinssaal, the new Gewandhaus, and Queen's Hall are nearly all of the same size, but there are appreciable differences in the times of reverberation — amounting to about a quarter of a second for Queen's Hall and the Musikvereinssaal. Thus, as has been mentioned before, experience seems to indicate that differences of one or two tenths of a second from the optimal time of reverberation can be readily tolerated. This is fortunate since it allows the architect considerable freedom in his choice of materials for the control of reverberation. The times of reverberation for capacity audiences in the halls charted in Fig. 258 are in fairly good agreement with the optimal times based upon the theoretical considerations in Sec. 146.

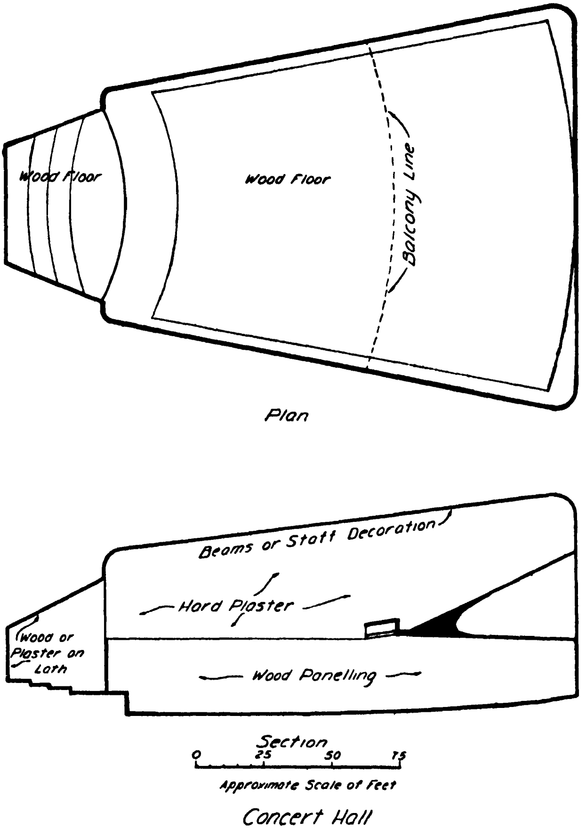

FIG. 259. Acoustical study of a concert hall.

In Fig. 259 are shown a plan and sectional sketch of a concert hall embodying the essential features of good acoustical design. The diverging walls and ceilings surrounding the orchestra space are of wood or plaster on lath, and not only reflect an abundant supply of sound to the audience, but enable the different individuals in the orchestra or chorus to hear each other — and the instruments or singers far away are heard nearly as well as those close by. The wood floor and the wood paneling provide large areas having a good absorption characteristic for low, medium, and high frequencies, and also add resonance to the room. The rear wall is straight rather than concave so that the sound reflected back toward the stage will not be convergent. The rear wall should be treated with absorptive material, and broken with doors or hangings or other ornamentation which will reduce the reflection from this surface. The concert hall should be equipped with heavily upholstered seats so that the acoustical properties of the room will be largely independent of the number of auditors present. In general, no additional absorptive material will be required if the volume per person be kept as low as about 200 cubic feet.

187. Opera Houses. In general, the acoustical requirements for opera houses do not differ from those for concert halls. Most forms of choral music call for slightly longer periods of reverberation than are required in orchestra halls, but on the other hand shorter reverberation times make it easier for auditors to recognize the words in songs. Measurements and observations made in several of the leading opera houses in Europe reveal that the reverberation time is usually very short — not more than 1.6 seconds with no audience present in the Royal Opera Houses in Berlin (Unter den Linden), Vienna, and Budapest, and only one or two tenths of a second longer than this in the opera houses at Paris, Leipzig, and Dresden. In the Berlin Opera House, for example, the measured time in the empty auditorium with the asbestos curtain down is only 1.55 seconds, and it is certainly shorter than this with an audience present. Nearly all the European houses are of the conventional horseshoe shape, with three or four levels of boxes, balconies, or galleries completely encircling the rear and side walls. This not only brings the audience near the stage but it provides a highly absorptive surface for nearly the entire interior of the auditorium, with the exception of the ceiling. With an audience present — and an audience is nearly always a capacity audience at the opera — the time of reverberation in these famous opera houses does not exceed 1.3 to 1.4 seconds. The Berlin Opera House appears to be slightly *dead* for Wagnerian operas, but the short reverberation times in the Berlin and Vienna opera houses are exceptionally meritorious for the melodious music of such composers as Verdi and Mozart.

In contrast with most of these famous opera houses in Europe, all having relatively short periods of reverberation, the Wagner Theatre at Bayreuth has a relatively long period of reverberation. According to calculations made by Bagenal,[8] the reverberation time in the empty auditorium is 7.4 seconds; with a one-third audience it is 4.0 seconds; and with a capacity audience it is 2.25 seconds. These times are based upon the Sabine reverberation formula, and therefore are slightly high, but on the basis of the newer formula the reverberation period would be over 2.5 seconds with two thirds of a capacity audience and approximately 2.0 seconds with a capacity house. The Bayreuth Theatre is especially adapted for Wagnerian music, and music lovers and critics

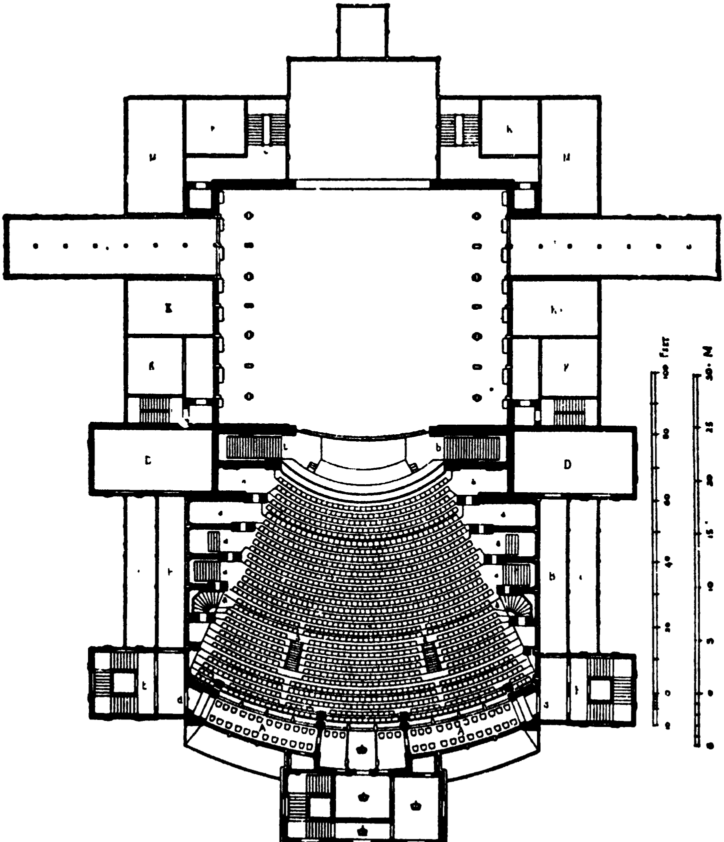

FIG. 260. Plan of the Wagner Theatre at Bayreuth. (*Bagenal and Wood.*)

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[8] Bagenal and Wood, "Planning for Good Acoustics," 187.

throughout the world acclaim it with the highest praise. In fact, many critics are so enthusiastic in their praise that they state that Wagnerian opera has not been heard until it has been heard in the Wagner Theatre at Bayreuth. At the same time, most of these same critics are agreed that the Wagner Theatre is not suited to the lighter and more melodious music of the Italian composers.

The outstanding characteristics of the Wagner Theatre, besides its long reverberation time, are the fan shape, steeply sloping ramp on which most of the audience is seated, and the deep orchestra pit extending under the stage. (See Figs. 260 and 261.) Wagner's chief aim was to unify the orchestra with the singers rather than interpose the orchestra between the singers and the audience, and it appears that the Bayreuth pit has been very successful in accomplishing this end. The orchestra pit is made large enough to accommodate an orchestra of 130 instruments. The brass and drums are placed at the bottom of the pit, and the overhang of the stage floor helps very much to tone down the intensity of these instruments. Further, the sound from all the musical instruments is well blended before it emerges from the pit opening. In this manner the orchestra is made to support rather than submerge the singing on the stage, and the unity of the entire musical effect is remarkably fine.

It is apparent, therefore, that the acoustical requirements of an opera house, like other music rooms, will depend upon the type of music which is to be performed. The plan and sectional sketches shown in Fig. 262 embody features which represent a reasonable compromise for different types of opera, especially in this country where the seating capacity must be large and the seats confined to the main floor and a single balcony.[9] The walls and ceiling follow somewhat the general lines of the new Chicago Opera House. They diverge from the stage opening in rectangular steps, and thus provide the principal advantages of the fan shape; that is, they reduce the volume of the auditorium and give diffuse but useful reflections to auditors both on the main floor and in the balcony. The diffuse reflections from the angular surfaces on the side walls and in the ceiling are also helpful in preventing concentrations, echoes, and interfering reflections. The deep orchestra pit with a projection under the stage, and the rather high partition between the orchestra and the audience, help to maintain a proper balance between the orchestra

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[9] There is an unfortunate tendency in this country to build excessively large opera houses. In some instances they are so large that many soloists are unable to generate sufficient energy to "fill" the auditorium. The volume of the auditorium should not exceed about 500,000 cubic feet, and the stage setting should be designed in such a manner as will divert the sound to the auditorium rather than permit its wastage in the large spaces above and around the setting.

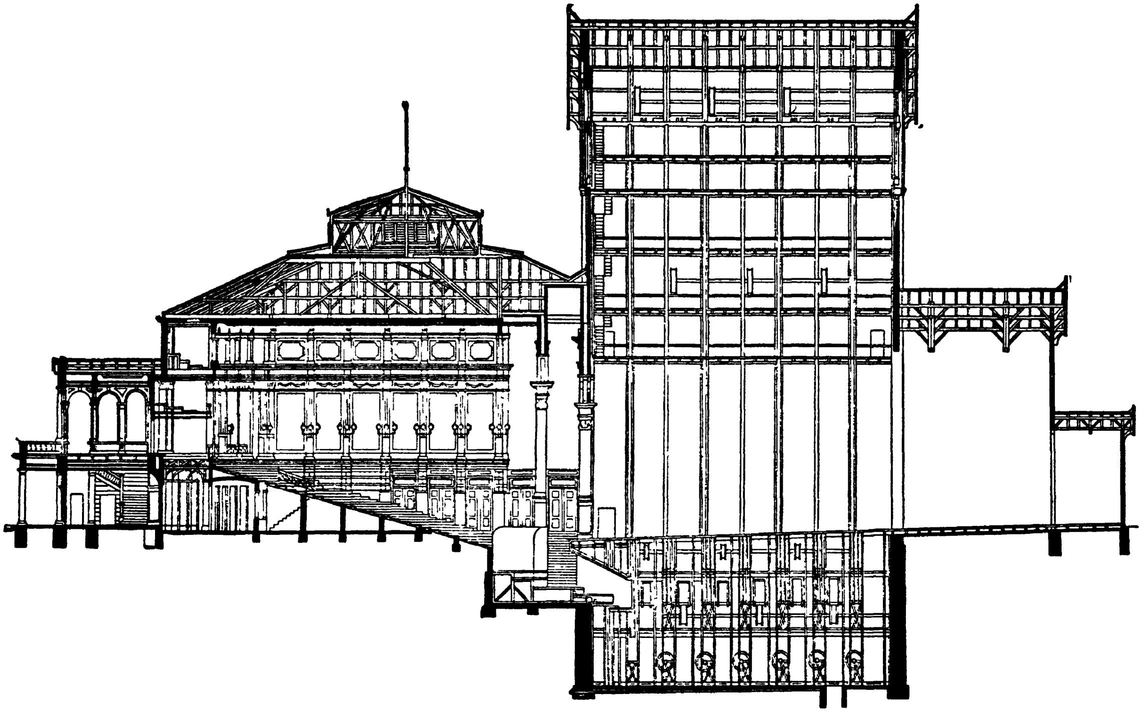

FIG. 261. Section of the Wagner Theatre at Bayreuth. (*Bagenal and Wood.*)

and the singers. By placing the brass instruments and drums in the rear part of the pit they are not heard too loudly. Enclosed wood veneer sets, with diverging walls and sloping ceiling, for example, as is indicated on the sketches by dotted lines, should be used whenever possible. This can be done for many interior scenes, and should always be done when the opera house is used for a symphony orchestra, a concert band, or for speaking purposes. The use of highly absorptive hangings for such settings is almost universal, but is always objectionable both from the standpoint of the performers and the listeners.

188. Dance Halls. The principles which have been used in the preceding sections in connection with the design of music rooms apply to the acoustical design of dance halls. The requirements for sound-insulation are not so rigorous as they are for other types of music rooms, since dance music is rarely below a sound level of about 45 to 50 db. It is desirable, however, to provide enough insulation to reduce the noise level in the dance hall to about 30 db or less.

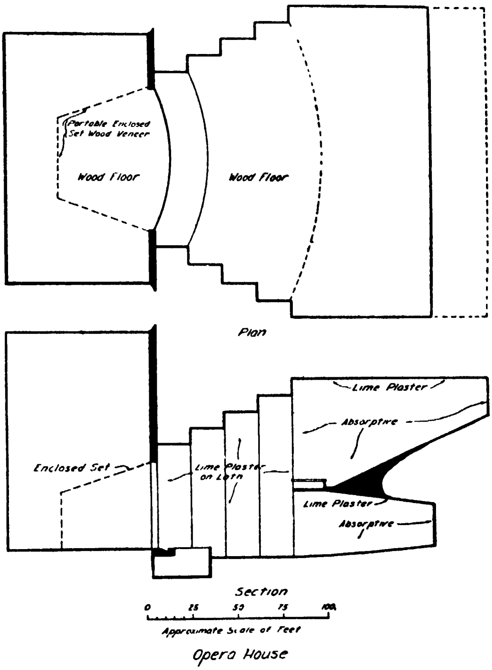

FIG. 262. Acoustical study of a large opera house with a single balcony.

Many dance halls are defective because of circular or elliptical shapes. As a rule, such shapes give rise to troublesome concentrations, and in some instances to sound interferences or even echoes. A hall, approximating a rectangle in plan, and having a low, level ceiling of high reflective power, is likely to prove the most satisfactory. If the size of the hall demands a ceiling height in excess of about 35 feet it is necessary, as a rule, either to coffer the ceiling or break up its surface in some other manner so as to prevent regular reflections which will produce interferences or echoes, or to elevate the orchestra platform sufficiently to avoid these troublesome reflections. In most instances the best location for the orchestra platform is on the side of the hall midway between the two ends of the hall. The platform should be elevated at least 3½ or 4 feet above the dance floor, and the floor of the platform should be stepped up toward the rear. The platform should be enclosed by a rear wall, diverging side walls, and a sloping ceiling. The floor of the platform should be wood, and the walls and the ceiling should be either wood or hard plaster. The matter of reenforcing the orchestra by an efficient sounding board is quite important since most dance halls employ a smaller orchestra than is needed to supply the required loudness level of sound.

The optimal times of reverberation for dance halls will vary between about 1.25 seconds for a hall having a volume of 25,000 cubic feet and about 1.8 seconds for a hall having a volume of 500,000 cubic feet. These times of reverberation are for 512 cycles. The reverberation times at other frequencies should be such that the reverberation characteristic for the room will resemble that given in Fig. 182. The optimal time of reverberation should be provided for the probable average attendance, or, if this be uncertain, for two thirds of capacity attendance (allowing 10 square feet per couple). The absorption per person in a dance hall is a quantity which depends upon the variable fashions of dress, but the assumption of 4.0 sabines per person will lead to satisfactory results. If the ceiling height of the hall be less than 30 feet, the ceiling should be left smooth and reflective so that it will be an effective sounding board, and the required absorptive material should be applied to the walls, or to the floor surrounding the dancing space. It often happens that the dance hall is surrounded by loges, or a lounging space. The use of carpet and upholstered furniture in these parts of the hall will often be sufficient to reduce the reverberation time to a suitable value.

CHAPTER XXV

HOTELS, APARTMENT HOUSES, AND RESIDENCES

189. Introductory. The noise incident to modern life, especially in urban centres, places a high premium upon quiet in the home. City dwellers in all parts of the world are demanding that their living quarters be insulated against both outside noise and the noise from their neighbors. Throughout the day, either at work or at play, man is distraught by the incessant din of machinery, automobiles, and all types of reproduced sound. When he is at home he wants to be free from the harassing noises which throughout the day have worn upon his nerves. In several foreign countries the building codes require that hotels and apartment houses provide a specified minimal amount of sound-insulation between separate rooms or family units. In Hungary, for instance, this required amount of insulation is equivalent to the insulation of a 6-inch brick-and-mortar wall. Such a wall will provide approximately 45 to 50 db of insulation, and in general this is sufficient for nearly all practical purposes in the construction of hotels and apartment houses. It is probable that building codes in our own country will soon call for an adequate amount of sound-insulation between the separate units in apartment houses and hotels. The need for such insulation is urgent, and rapid progress is being made in the development of effective and economical methods for obtaining this much-needed insulation.

There has been a widespread promiscuity in the use of various so-called insulating materials in the construction of hotels, apartment houses, and other buildings. Many of these materials when properly used are very effective in the insulation of sound; whereas other uses of these same materials may be only a waste of money and material without added insulation. For example, a number of years ago the author made an investigation of the relative and absolute values of different sound-insulation materials which are ordinarily used between matched and rough flooring, or between wall or ceiling partitions. Measurements of the insulation supplied by different floor models indicated that all porous materials placed directly between rough and finished flooring were useless for the insulation of air-borne sound, such as conversation or the music from a radio or phonograph. If the rough flooring was of the usual 1 inch by 6 inch Oregon pine, with fairly large cracks between the separate boards, slightly more sound (256 to 512 cycles) was transmitted through the floor section when the porous material was placed between the rough and finished flooring than when the porous material was omitted. The situation is different when the sub-flooring also is matched, in which case the use of suitable porous materials between the sub-floor and the finished floor has some insulation value. Also, the use of such porous and flexible materials between the finished and sub-floor is of considerable value in preventing the transmission of solid-borne sounds. (See Sec. 94.) The flexible material should then be used as a cushion to prevent the vibrations which are set up in the finished floor from being transmitted to the sub-floor. When the finished floor is properly cushioned or *floated*, it not only provides a high degree of insulation against impact noises but it also contributes to the insulation against air-borne noise.

It probably is appropriate to repeat once more the statement that air-borne sounds are best insulated by the use of two or more partitions structurally separated from each other, or by heavy, non-yielding walls and partitions. In separated partitions the use of sound-absorptive materials in the air spaces between the rigid partitions is of definite value, since the absorptive action of the material reduces the intensity of the sound which can be communicated to the adjacent partition. In single rigid partitions, most of the sound energy which is communicated through the room is by means of the mass vibration of the entire wall or partition.

190. Hotels. There are two types of rooms in hotels which require consideration with respect to acoustics: (1) community and social rooms, such as lobbies, dining rooms, ball rooms, convention rooms, and the corridors; and (2) guest rooms. The principal requirements in the community and social rooms are the proper control of reverberation, and adequate insulation against noise from the outside or from adjacent rooms. The curve for the optimal time of reverberation for rooms which are used for both speech and music, as school auditoriums (see Fig. 187), will serve as a guide for determining the best time of reverberation for these community and social rooms. The acoustical problem in guest rooms is primarily one of sound-insulation, although it also is necessary to have enough absorptive materials in these rooms to reduce the reverberation time below 1 second. In hotels which depend upon open windows for ventilation — and nearly all hotels are in this class — the amount of insulation which can be provided between rooms or against outside noise usually is determined by the windows or by connecting doors. The amount of insulation between two adjacent rooms when the windows for both rooms are open is not more than about 25 db. When the windows are tightly closed the insulation over this route may be as high as 50 to 55 db. It is apparent therefore that the only means of providing a satisfactory condition of quiet in metropolitan hotels is to provide mechanical ventilation for all rooms and to install windows which can be kept permanently closed, or to design suitable window mufflers which will admit air but exclude noise.[1] In very noisy locations double-sashed windows may be necessary.

In order to determine the amount of insulation required in the exterior walls, noise surveys should be made in the proximity of the proposed site in advance of construction. Then the exterior walls should be designed to provide an amount of insulation which will reduce the noise reaching the guest rooms to a level of not more than 15 or 20 db. Thus, if the outside noise be at a level of about 65 db, the reduction supplied by the outside walls and the absorptive material in the room should amount to 45 or 50 db. Double-sashed windows separated by an air space of at least 4 inches and walls equivalent to 6 or 8 inches of masonry or concrete will be required to provide this amount of insulation. Also, since the noise level of average conversation in a small room is of the order of 65 db, the amount of insulation between adjacent guest rooms should be not less than 45 db. If the rooms are connected by doors, there should be two doors in each frame. The two doors should be separated by an air space of not less than 4 inches, and both doors should fit tightly against the jamb. The required amount of insulation between guest rooms will not be supplied by ordinary channel iron or wood stud and plaster partitions, or by plastered gypsum or clay tile partitions. It is necessary therefore to select a type of wall construction which will have an insulation value in excess of 45 db. A staggered stud partition, plastered to a total thickness of $\frac{7}{8}$ to 1 inch on each side, and with an absorptive blanket suspended between the studding, will usually be sufficient. Other types of wall, floor, and ceiling construction providing this required amount of absorption will be found in the tables on sound-insulation. (See Chap. XII and especially Fig. 140.) The floors of all guest rooms and corridors should be carpeted over a $\frac{1}{2}$-inch carpet pad. This will take up the noise of footfalls, and will help very much to prevent the transmission of other impact sounds. The telephone bell should be mounted on a portable telephone table rather than on the solid wall. All points of contact between the pipes and the solid structure of the building should be broken by means of a flexible felt wrapping. Plumbing fixtures should be selected which will operate quietly, and all other sources of noise such as the heating and ventilating equipment, the elevators, and other apparatus should be thoroughly insulated from the solid structure of the building and housed

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[1] A number of such mufflers have been developed in recent years, and some of them are effective both for excluding noise and for providing air.

in rooms which provide sufficient insulation against air-borne noise to prevent the machinery noises from reaching the guest rooms.

191. Apartment Houses. The demand for soundproof apartments increases with the growth of cities and the machine age. More and more units are crowded into a single building, and the mounting costs of building sites in large cities make it necessary to reduce to the utmost unused space. Even the partitions between separate rooms and units must be as thin as possible. This type of investment economy often defeats its own purpose, and though tenants may not be willing to pay a large premium for quiet apartments, the quiet ones will be in demand and the " turnover " will be slow.

In the large metropolitan apartment house the acoustical problem is not essentially different from that already discussed in connection with hotels, and the principles and recommendations set forth in the preceding section can be followed in the design of large Class A apartment houses.

The all-important problem in the design of apartment houses is the insulation of sound, and from what has been said repeatedly it is obvious that the question of sound-insulation is not a simple matter of the selection of materials, but an involved problem in design and methods of construction. In the chapter on the insulation of sound and in the tables on the insulation values of different types of construction, it will be possible to find wall and floor partitions which will be adapted to different types of apartment construction. For satisfactory insulation between the separate units in an apartment house it is necessary to provide a noise reduction of at least 45 to 50 db. It is of course impossible to provide this amount of insulation between adjacent units when the windows are open, especially when the separate units face a narrow court with high walls. In such cases, the insulation between adjacent rooms will not be more than 25 db with the windows open, and often may be very much less than this, but the insulation may increase to 45 or 50 db with the windows tightly closed. It therefore is desirable to design the walls to provide an amount of insulation comparable with the insulation *via* the route of the closed windows. If provision can be made for ventilation by standard methods of air conditioning, or by means of the corridors and transoms, it will be possible to keep the windows closed, at least when quiet is desired, and thus remove the most potent of all means of transmitting sound from room to room, or from unit to unit. There is no escape from a procedure of this type if adequate sound-insulation is to be provided for apartment houses.

One of the most troublesome sources of sound transmission in apartment houses is the transmission of impact noises through the floor and ceiling sections. This is especially troublesome in the smaller and cheaper types of apartment. One of the most effective means of reducing these impact noises is to completely carpet the floor. But in apartments where the carpeting of all floors is impracticable it is better to support the floor on flexible steel cushions or other elastic materials. The value of such methods of insulating impact noises is indicated in Sec. 94.

A number of wall and floor-ceiling sections which are satisfactory for apartment-house construction are indicated in Fig. 140. The approximate transmission loss of each section is also indicated, but it must be remembered that the over-all insulation is determined by the " weakest link in the chain," and therefore the entire building must be designed and constructed in accordance with the principles set forth in Chap. X.

Finally, all plumbing fixtures, pipes, elevators, and other mechanical equipment should be selected and installed in accordance with the recommendations outlined in Sec. 190.

192. Residences. There are a number of acoustical problems in the design of residences, too frequently overlooked on the drafting board, which require careful study. The acoustical design of the music room, the reduction of noise in the halls, kitchen, and dining room, and the insulation of noise between different rooms are the problems of greatest importance; and their satisfactory solutions contribute largely to the comfort and pleasure the home affords.

Even the modest home which has no other music than that furnished by the radio should have the living or music room adjusted to have a time of reverberation of about 1.0 second — a condition which not only will give to music the most pleasing effect, but also will make the room an *easy* room in which to converse. It usually will be possible to provide this condition of reverberation by the suitable selection of rugs and hangings for the room. Thus, a room 14 feet by 20 feet by 9 feet containing an ordinary 12-foot by 18-foot rug over a ½-inch carpet pad, 100 square feet of heavy window drapes, and two or three pieces of overstuffed furniture will have approximately the optimal condition of reverberation. If the floor is to be less than 50 per cent carpeted it generally is advisable to use an absorptive material in the ceiling, as a ½-inch fibre board. A fibre board ceiling also furnishes an excellent surface for painting or stenciling.

In larger residences containing a separate music room, the acoustical design should be worked out along the lines suggested for the design of music studios. (See Sec. 184 and Fig. 248.) If the music room contains an organ, it is desirable to locate the organ at one end of the room so that it speaks directly into the room along its longitudinal axis. The use of thin wood paneling furred out an inch or more from the solid walls is desirable as a means of adding resonance and brilliance of tone quality to the room. In rooms smaller than about 20,000 cubic feet it is possible to secure the optimal reverberation (about 2.25 seconds at 128 cycles and 1.10 seconds at 512 to 2048 cycles) by over-stuffed furniture, rugs, and deeply folded hangings. However, the reverberation of every music room should be studied in advance of construction, and if the contemplated furnishings for the room are not sufficient to reduce the reverberation to the optimal time, absorptive material should be used for the ceiling or walls in such amounts as required by the calculations for reverberation.

The use of hard plaster or other highly reflective materials for the walls and ceilings of halls, kitchen, dining room, and breakfast room often results in reverberant and consequently noisy rooms. Reverberant halls are not only noisy and annoying to persons walking through them, but they also provide efficient conveyors of sound between different parts of the home. If the hall floors and stairways are 75 per cent carpeted, and if the windows are draped with heavy hangings, it usually is not necessary to use additional absorption on the walls and ceiling; but if the floors and stairways are tile, marble, or hard wood, the walls or the ceiling, or both the walls and the ceiling, should be treated with an absorptive material having a coefficient of sound-absorption at 512 cycles of not less than 0.25.

The dining room should contain large areas of highly absorptive material. A reverberation time as low as 0.60 second is desirable. If the floor is completely carpeted over a ½-inch felt pad, and if the windows are draped with heavy hangings, it may not be necessary to use absorptive material for the walls and ceiling, but in the absence of these absorptive furnishings the use of an absorptive material for the ceiling or walls is much to be desired.

In a dining room in a certain residence in Los Angeles, the entire ceiling is treated with an acoustical tile having an absorptivity of about 0.50, the entire floor is heavily carpeted, and doubly lined drapes are used for all windows and for one large door opening. The social conversation of as many as 12 persons sitting at dinner in this room does not produce the usual din of noise that would result if this same conversation took place in an untreated room. In fact, it is easy to converse at one end of the table while a general conversation is in progress among the other guests in the room. The playful chatter of children, in like manner, is reduced to a level which can be readily tolerated, whereas this same chatter in a reverberant dining room is almost of a nerve-wrecking magnitude. The absorptive material also helps to suppress the noise from the kitchen, from other adjacent rooms, and from the outside.

The breakfast room also needs to be treated with absorptive material, especially when the floor is finished with tile, linoleum, or other highly reflective material. An absorptive tile or felt in the ceiling, covered with a perforated and washable membrane, is one of the most satisfactory methods for reducing noise in the breakfast room. This same treatment should be applied to the ceilings of the kitchen and pantry, especially in large homes. Most acoustical plasters are not suitable for use in residences since they offer difficulties in cleaning, washing, and decorating. But they are being improved at an astonishing rate, and it is probable that acoustical plasters will soon be available which will be entirely satisfactory for the home.[2]

The rooms in which telephones are located should be reasonably free from reverberation. A telephone located in a reverberant hall imposes difficulties on both hearing and talking, and in extreme cases it becomes almost impossible to use the telephone. If the telephone is located in a hall it is desirable to treat at least the walls of the hall with absorptive material; or if a separate room or booth is provided, both the walls and ceiling should be treated with absorptive material. Such rooms cannot contain too much absorption.

Other rooms in the home which should receive study in regard to acoustics are the library, study, and social rooms. The problems which arise in these rooms and the methods of solving them have been considered in the preceding paragraphs.

The most important acoustical problem in the design of residences is the insulation of sound between rooms, and, in noisy localities, the insulation against outside noise. Tall and dense planting around the house in a noisy site will help greatly to reduce traffic and other outside noises. Sleeping rooms and other rooms where quiet is at a premium should be ventilated from windows which open upon the quiet side of the lot. Windows and doors, especially those facing the street or those near the neighbor's house, should be of heavy, rigid construction and should fit tightly in their frames. The insulation of bathrooms from the other rooms in the home is a difficult problem. In the first place, great care should be exercised in the selection of bathroom fixtures. The architect should obtain data on the amounts of noise produced by the flushing of different types of toilet, and by the filling or draining of different types of bathtub. Water and drain pipes should be large enough to allow relatively low speeds of the water, so as to prevent turbulent flow, and the more noisy pipes should be wrapped with a fibrous blanket covered on both sides with heavy, tough paper. The

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[2] See Sec. 166. The acoustical plaster being installed in the Los Angeles County Hospital can be washed repeatedly.

pipes should be insulated from the rigid frame of the building by means of flexible felt, and the entire bathroom floor should be insulated from the rest of the building by means of flexible steel or cushioned chairs or by means of felt, fibre, or corkboard. The floor and ceiling section under the bathroom should have an insulation value of not less than 45 to 50 db.

The acoustical engineer or consultant is often called upon to make recommendations for the correction of faulty acoustics in residences. The correction is nearly always a hopeless one, or at best a prohibitively expensive one, involving the tearing up of floors and walls and the replacement of bathroom fixtures. These problems should and can be anticipated in advance of construction. Proper planning at that time will assure both the owner and the architect not only that the home will be free from the defects of inadequate sound-insulation but also that it will possess an atmosphere of quiet restfulness which will impart to it comfort, luxury, and dignity.

CHAPTER XXVI

RADIO BROADCAST AND SOUND-RECORDING STUDIOS

193. Introductory. Acoustical problems of a very special nature arise in the design of radio broadcast and sound-recording studios. Some of the first attempts to *broadcast* or *record* sound in rooms which were regarded as having good acoustical properties for either speech or music revealed that these same rooms were unsatisfactory for broadcasting or recording sound. The reason for this apparent anomaly is to be found chiefly in the difference between monaural and binaural hearing. When we listen to sound binaurally the vibrations reaching the two ears may differ in phase and intensity. These differences enable us to determine with reasonable accuracy the location of the source of sound, and therefore impart an extension or a *perspective* to sound, and at the same time enable us to fix our attention upon sound coming only from a certain direction. If, on the other hand, we listen to sounds in a room with only one ear by occluding the other ear with the finger tip we are conscious of two alterations in the acoustical aspects of the sound or the acoustics of the room. The room seems markedly more reverberant, and adventitious noises in the room seem to have been augmented.[1] It would appear therefore that the acoustical requirements for monaural hearing in a room are different from those for binaural hearing in the same room. For hearing with one ear it is necessary that the room have a lower reverberation period and a lower level of noise than would be required for satisfactory hearing with two ears. Since in binaural hearing the attention can be focused upon sound coming from a definite direction to the exclusion of sound coming from other directions, the delayed reflections from the walls (reverberation) and noises which come from all other directions are discriminated against when listening with both ears. But in monaural hearing this faculty for listening to sounds coming from a single direction and ignoring sounds from all other directions is very much weakened, or almost completely gone, and therefore reverberation and noise are much more disturbing to monaural hearing than they are to binaural hearing.

The microphone responds to sound very much as does a single ear, and consequently it is subject to the limitations of monaural hearing.

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[1] See articles by J. P. Maxfield, Jour. Soc. Mot. Pict. Engineers (January, 1930); Jour. Acous. Soc., 3, 69 (1931).

It is necessary therefore in the design of sound-recording rooms to remove the sources of difficulty or confusion incident to monaural hearing; namely, to reduce reverberation to a relatively short period, and completely eliminate noise. Experience has shown that the most satisfactory reverberation time for radio or sound-recording studios is about two thirds of the accepted optimal time for speech or music rooms. Thus if 1.2 seconds has been found to be the optimal time of reverberation for listening to a particular type of music when produced in a certain room, then about 0.8 second will be the best time of reverberation in the same room for broadcasting or recording that same type of music. This empirical rule concerning the optimal reverberation time, and an equally important rule requiring that the residual noise in the studio should not exceed about 5 to 10 db, are two criteria which should guide the design of both radio broadcast and sound-recording studios.

194. Radio Broadcast Studios. From the introductory remarks in the preceding section it is obvious that a radio broadcasting studio must be carefully designed with regard to the control of reverberation and the insulation of noise. A noise survey should always precede the design of the studio so that an adequate amount of insulation will be provided by the walls, floors, ceilings, doors, and windows. Thus, if the outside noise is of the order of 70 db, it is necessary to design the studio in such a manner as will provide a noise-reduction factor of at least 60 to 65 db. This will require, as a rule, the equivalent of double walls, floated floors, suspended ceiling, and two sets of tightly fitting doors and windows. In all cases the selection and design of the insulating structures should be based upon calculations similar to those outlined in Sec. 106. Viewing windows between adjacent studios or between studios and waiting rooms should consist of at least two heavy plate-glass windows set in separate frames, insulated from the rigid structure of the wall by felt or rubber strips, and separated from each other by an air space of at least 4 inches. The high degree of sound-insulation required in studios cannot be attained if open windows are depended upon for ventilation. In the better studios all windows are omitted, and it is necessary in such cases to install a complete air-conditioning system. This equipment must be thoroughly insulated from the studios. The fans and motors should be mounted suitably on elastic supports, the boundaries of the ventilating equipment room should be of high insulative value for air-borne sound, and the ventilating ducts should contain suitable filters which will prevent the transmission of sound through the ducts from the equipment room to the studios, or from studio to studio.

The control of reverberation in broadcasting studios should be worked out very carefully. For most types of program the times of reverberation given in Fig. 263 will be found highly satisfactory. For small studios a reverberation time at 512 cycles of about 0.70 second will be satisfactory, and in larger studios a somewhat longer time — approaching 1.1 or 1.2 seconds in large studios — will be found more satisfactory. The reverberation time at 128 cycles should not be more than double the time at 512 cycles, and for frequencies above 512 it should remain approximately constant, or even increase slightly at very high frequencies.

As was pointed out in Chap. XVIII, different types of music require different amounts of reverberation, but nearly all forms require more reverberation than speech does. It is desirable therefore to have either a number of studios with different times of reverberation, or studios in which the reverberation can be adjusted to the most favorable condition for any particular type of broadcast. The latter arrangement is preferable since it often may be desirable to change the reverberation time during the program of a single artist or group of artists.

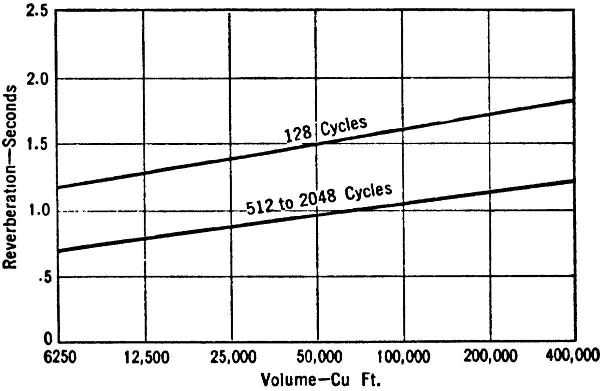

FIG. 263. Curves giving recommended reverberation times for broadcast and sound-recording studios.

There are several methods which may be used for adjusting the time of reverberation in a room. In many studios this is now done by removing or bringing in rugs or by spreading out or drawing together hangings on the walls. In the main studio of the Hungarian Radio Company at Budapest the entire walls and ceiling can be completely covered with deeply folded hangings, or any or all of the hangings can be rolled up on rollers or spread out on suitable supports. By exposing part or all of these hangings the reverberation time can be varied from about 0.5 to 4.0 seconds, thus providing conditions which will be suitable for speech, for soft and melodious chamber music, for orchestra or band, for choral or oratorio, or for cathedral organ music. For quickly moving staccato selections the reverberation time should be short, and for slowly moving adagio or largo selections it should be considerably longer. Cathedral organ music, for example, will sound most natural with 3 or 4 seconds of reverberation. This *cathedral* effect is further emphasized in the Budapest studio by exposing a highly polished marble wall at one end of the studio, at least 50 feet away from the source of the sound. The delayed reflection from this remote surface gives the effect which would be obtained in a spacious room.

A simple means of providing a studio with variable reverberation is to cover the walls with hinged panels, treated with highly absorptive material on one side and with highly reflective material on the other side.

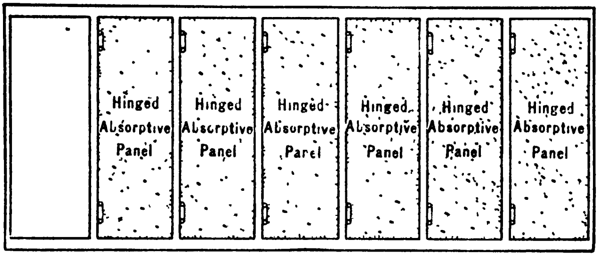

FIG. 264. Proposed treatment of walls of broadcast studios, showing hinged panels which are absorptive on one side and reflective on the other.

(See Figs. 264 and 268.) By exposing the absorptive or reflective surfaces of different numbers of these hinged panels it is possible to control the reverberation throughout the limits required for all types of broadcasting. The studio can be made reverberant or non-reverberant, or it may be made reverberant in the end of the room where the sound is produced and non-reverberant in the end where the microphone is located. It would be a simple matter to open or close these hinged panels by means of a control at the console of an organ or at the mixing panel, and thus vary the reverberation to give the best effects to music.

As in other speech and music rooms, it is not sufficient that the broadcasting studio be only free from noise and have an optimal time of reverberation. It is required, for example, that the reverberation be uniform in all directions. To accomplish this end, the absorptive material should not be located only on the floor and in the ceiling, or on opposite and parallel walls, but should be distributed in such a manner as will prevent the excessive persistence of multiple reflections between parallel surfaces, that is, in such a manner as will eliminate the possibility of a prolonged one- or two-dimensional reverberation. Care should be exercised to eliminate the resonant effects of window panes, doors, wall panels, or cavities. A resonant window pane, especially one near the microphone, often will introduce a troublesome distortion which will be picked up by the microphone. Finally, it is necessary to insulate the studios and the electrical equipment rooms from solid-borne vibrations. The delicate vacuum tubes in the amplifying equipment are especially sensitive to mechanical vibrations, and it therefore is imperative that adequate insulation against vibration be provided for all amplifier racks.

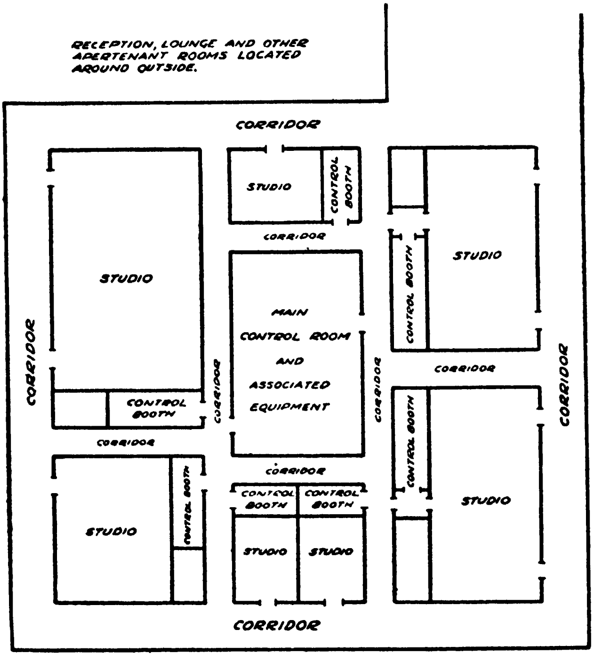

FIG. 265. Ideal layout for a group of broadcast studios. (*Hanson and Morris.*)

The design and construction of the broadcast studios for the National Broadcasting Company are described in a paper by Hanson and Morris.[2] This paper contains many practical suggestions and recommendations concerning the general layout and the details of construction of broadcast studios. Fig. 265 shows an ideal layout for a group of studios, proposed by Hanson and Morris. It consists of a central control and

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[2] O. B. Hanson and R. M. Morris, "The Design and Construction of Broadcast Studios," Proc. of Inst. of Rad. Engineers, **19**, 17 (January, 1931). This article should be consulted for further details.

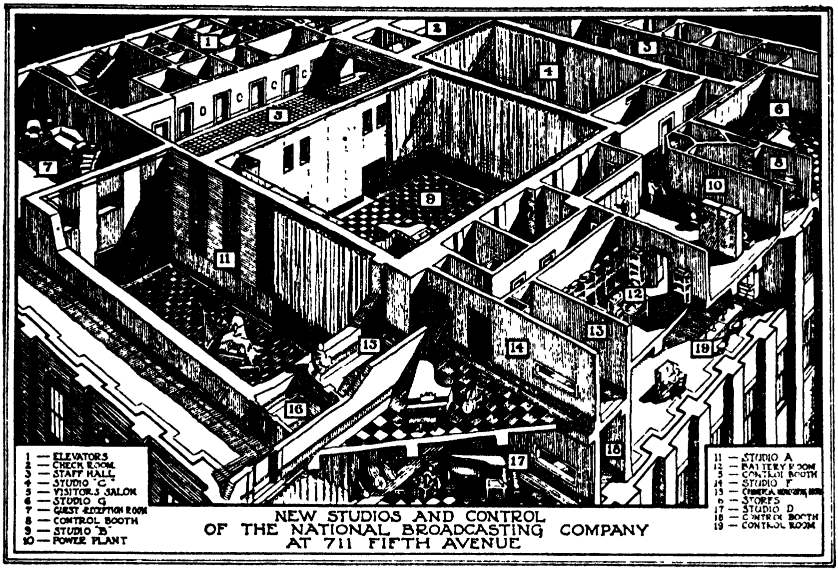

FIG. 266. Cutaway view of the N.B.C. Fifth Avenue Studios, New York. (*Hanson and Morris.*)

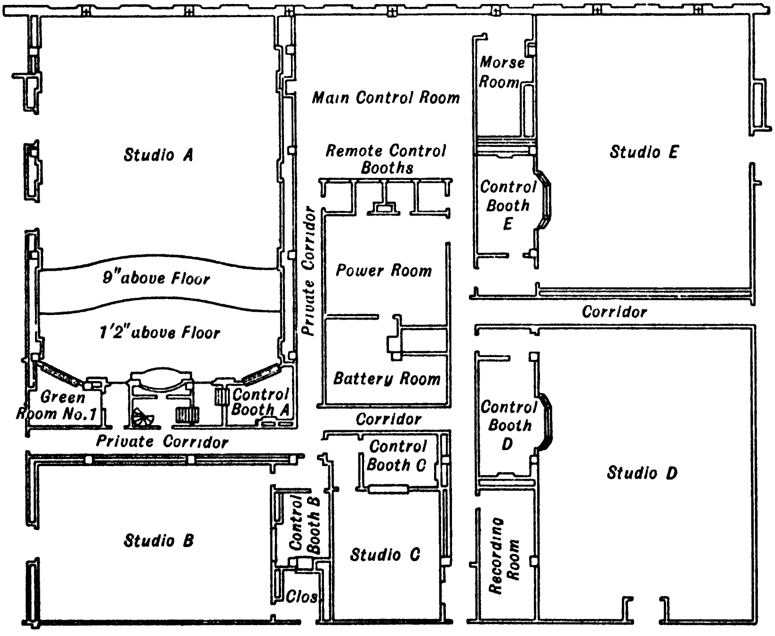

FIG. 267. Plan of studios and control rooms of the N.B.C. at Chicago. (*Hanson and Morris.*)

equipment room surrounded by the studios, with each studio having its own control booth near the central control room. Since it is necessary to have as many as five to fifteen hours of rehearsal for each hour of broadcast, at least six or seven studios are required to maintain a single channel. A central system of studios, such as is shown in Fig. 265, requires the utmost care in providing adequate insulation between separate studios as well as between the studios and the outside. All the studios are surrounded by corridors which are treated with highly absorptive material, and the larger studios are well separated from each other. All studios and control rooms are completely air conditioned, and are therefore free from windows. Both the supply and exhaust ducts are equipped with sound filters or attenuators (see Sec. 92) which prevent the transmission of sound through the ducts. The entrance to each studio, which is from the outer corridor, is by means of tightly fitting double doors with an absorptive air space between the doors. Fig. 266 shows a cutaway view of the N.B.C. studios at 711 Fifth Avenue,

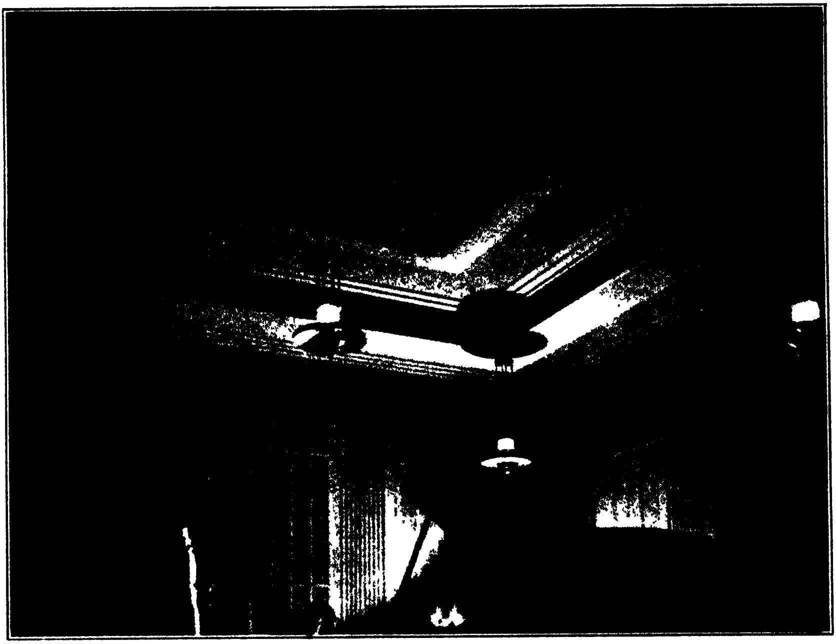

FIG. 268. Studio E, N.B.C., Chicago. "Acoustone" in ceiling and on walls. Wall panels are absorptive on one side and reflective on the other, and are reversible so that the reverberation time can be varied. (*Graham, Anderson, Probst and White, Architects*)

New York, and Fig. 267 shows the general layout of the N.B.C. studios at Chicago. An interior view of Studio E in the Chicago group is shown in Fig. 268. Hanson and Morris recommend that the dimensions of the studio be such that the ratio of height, width, and length be approximately 2 : 3 : 5. Empirical data concerning the optimal dimensions of a studio as a function of the number of artists the studio can accommodate are given in Fig. 269.

Several features of soundproofing in the Chicago N.B.C. Studios are worthy of mention. Quoting from Hanson and Morris: " The main walls of the studio are erected of a single layer of 4-inch terra cotta tile. On the studio side of these walls are placed steel spring clips on 18-inch centres, and on these clips in turn is placed metal lath. The same treatment is applied to the ceiling. . . . Absorptive felt is placed on the main wall in the spaces between the spring clips and the walls. (See lower part of Fig. 270.) The ordinary layer of rough plaster is then applied to the metal lath, and on top of this the acoustic treatment or hard plaster, as may be specified.

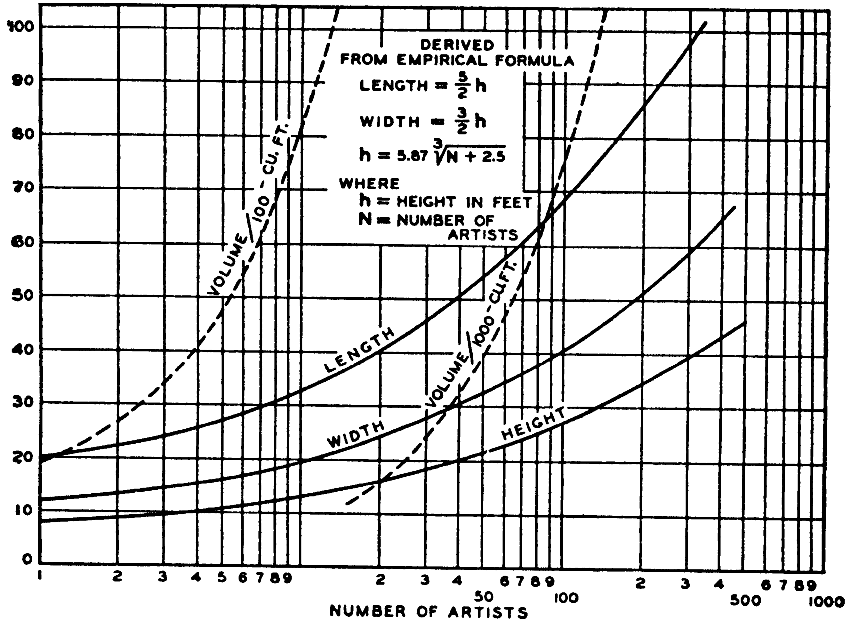

Fig. 269. Relations between studio capacity and studio dimensions recommended by Hanson and Morris.

" A similar system of soundproofing is placed upon the floor except that the springs in this case support the wood sleepers. Before laying the wood floor, the space between the concrete slab and the top of the sleepers is filled with some absorbing material, such as mineral wool or thermo-fill, to prevent resonance in the floating floor.

" This construction provides walls, floors and ceilings which are floating on spring clips. The attenuation to sound originating in the studio through such a partition when completed is approximately 60 db, even at frequencies as low as 64 cycles. The attenuation of course is much greater at higher frequencies."

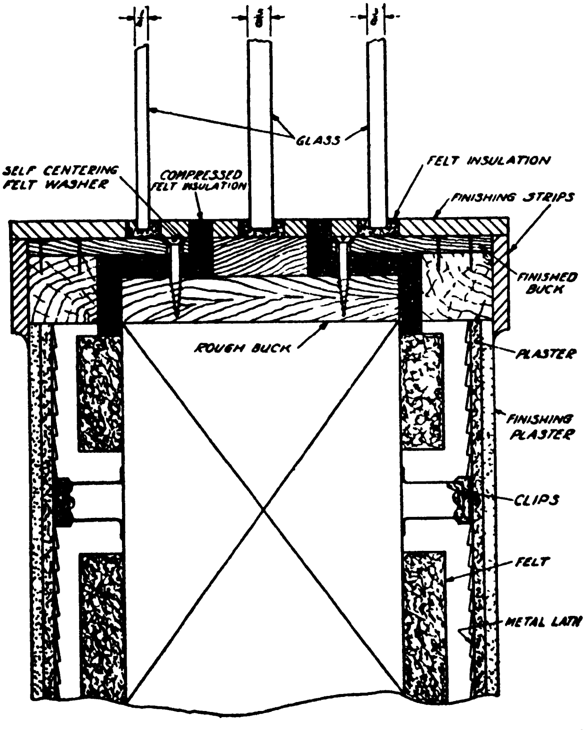

FIG. 270. Details of construction of studio walls and transparent partition. (*Hanson and Morris.*)

The construction of the transparent partitions between each studio and its control room is shown in the upper part of Fig. 270. Three separate pieces of glass, having thicknesses of $\frac{1}{4}$, $\frac{5}{8}$ and $\frac{3}{8}$ inch, are mounted on separate bucks. One buck is mounted on the terra-cotta partition and the other two on the plaster partitions. The three different thicknesses of glass prevent the action of a " band-pass " filter since the three panels have different natural frequencies.

The reverberation characteristics of the studios approximate those given in Fig. 263, varying from about 0.7 second (at 512 cycles) in small studios to 1.1 seconds in large studios. About two thirds of the wall area is treated with acoustical material having the proper absorption characteristic (as mounted on the resilient steel clips). The remainder of the wall and ceiling areas are well broken with pilasters, coffers, and ornamental plaster.

195. Sound-Picture Studios. The design of studios for the purpose of synchronizing sound with motion pictures follows rather closely the design of broadcasting studios. There are two differences: (1) the sound-picture studio is very much larger than the broadcasting studio and therefore problems of shape and of delayed reflections must be considered; (2) there are nearly always a number of *sets* or stage settings erected in different parts of the large studio, and the acoustical properties of these sets influence largely the sound recordings. If the large studio be very free from reverberation, resembling outside conditions with perfectly absorbing boundaries, the acoustical quality of the sound recording will be determined almost wholly by the set materials and dimensions. This is much to be desired, as it permits a greater freedom and simplicity in the acoustical design of the sets. It is customary therefore to make the walls and ceiling of the sound stage as absorptive as possible. It has become almost standard to treat the inner walls of the sound stage with a 4-inch fill of mineral wool between 2-inch by 4-inch wood studs covered with a cloth or wire screen, and to treat the ceiling with a 1½- to 2-inch mineral wool blanket. With a treatment of this type a large sound stage (say 100 feet by 150 feet by 40 feet) will have a reverberation time of about 1.0 second at 128 cycles and about 0.8 second at 512 to 2048 cycles. Stages with these reverberation times are found to be very satisfactory.

The problem of sound-insulation in sound stages requires unusual care, especially where two or more units are combined into a single building. With a symphony orchestra playing in one stage it is impossible to make recordings in an adjacent stage unless the insulation between the two stages be as great as 65 db.

Experience and measurements in connection with the insulation of sound stages have suggested the following general conclusions:

1. If the walls and ceiling, including all doors, have an over-all insulation value of 50 db, the stage will be acceptable if it is a single unit and in a moderately quiet location. If two or more stages of this type adjoin each other it may be necessary to shut down in one stage while recording in another.
2. If the walls and ceiling of the stage have an insulation value of

60 db, it will be satisfactory under nearly all conditions met in practice. Outside noises such as the passing of a heavy truck or the racing of a motor will be adequately insulated. In general, it will be possible to record in adjacent stages at the same time, except when there are very loud sounds in one stage, such as a large band or orchestra, or loud shouting or gunfire.

3. If the walls and ceiling of the stage have an insulation value of 70 db, it will be entirely satisfactory for all types of recordings even if the stage be located on a very noisy site. There will be no interference between adjacent stages, and it will not be necessary to stop recording in one stage while recording in an adjacent stage.

Two methods have been in general use in the design of the insulating walls and ceilings for sound stages: (1) the construction of heavy, rigid walls and partitions, and (2) the use of multiple layers of such materials as " Gunite," plaster board, fibre boards, mineral wool blankets, and felted materials, separated by air spaces.

As has been shown previously, the insulation value of rigid partitions is very nearly proportional to the logarithm of the mass per square foot of wall section. (See Sec. 96.) The insulation provided by concrete or brick and mortar walls varies from about 23 db for a wall having a mass of 1 pound per square foot up to about 52 db for a wall having a mass of 100 pounds per square foot. These values are for a frequency of 512 cycles. At low frequencies (128 cycles) the insulation value is about 20 per cent lower and at high frequencies (2048 cycles) it is 15 to 20 per cent higher than the values given for 512 cycles. Rigid partitions provide a fairly satisfactory means of providing an insulation up to about 45 or 50 db, but since the insulation value is proportional to the logarithm of the mass of the wall, the cost of construction becomes prohibitive for obtaining a greater insulation than about 45 db.

The use of multiple layers attains its highest insulation value when the separate layers are free from all connections or ties. Thin, rigid panels separated by air spaces which are lined with a highly absorptive blanket have proved to be both effective and economical. One of the most satisfactory types of construction consists in erecting one structure inside of the other with separate foundations, walls, and ceilings, with no rigid ties between the two structures, and with an absorptive blanket facing the air space between them.[3] Such double structures separated by an air space of 3 or 4 feet give an insulation which is nearly

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[3] This type of structure has been developed by a series of tests on models conducted at Metro-Goldwyn-Mayer's Culver City Studios under the supervision of Fred Pelton and D. W. Robinson.

equal to the sum of the insulations provided by the separate structures. If any rigid ties be made between the two structures, the over-all insulation is very much reduced, and if there are many ties the two walls approach the condition of a single rigid wall.

A number of typical wall and ceiling sections which have been used and tested in sound studios are shown in Fig. 271. The measured insulation value (transmission loss) of each partition is given opposite the sectional drawing. Sections marked (*e*) and (*f*) were separately measured for sound-insulation, and then the total insulation for the two walls on separate foundations was measured. The results are indicated in Fig. 271. Note that the total insulation through the two walls is about 3 or 4 db less than the sum of the insulations through the separate walls, indicating a relatively small amount of coupling between the two walls. The sections shown in Fig. 271 also indicate the more commonly

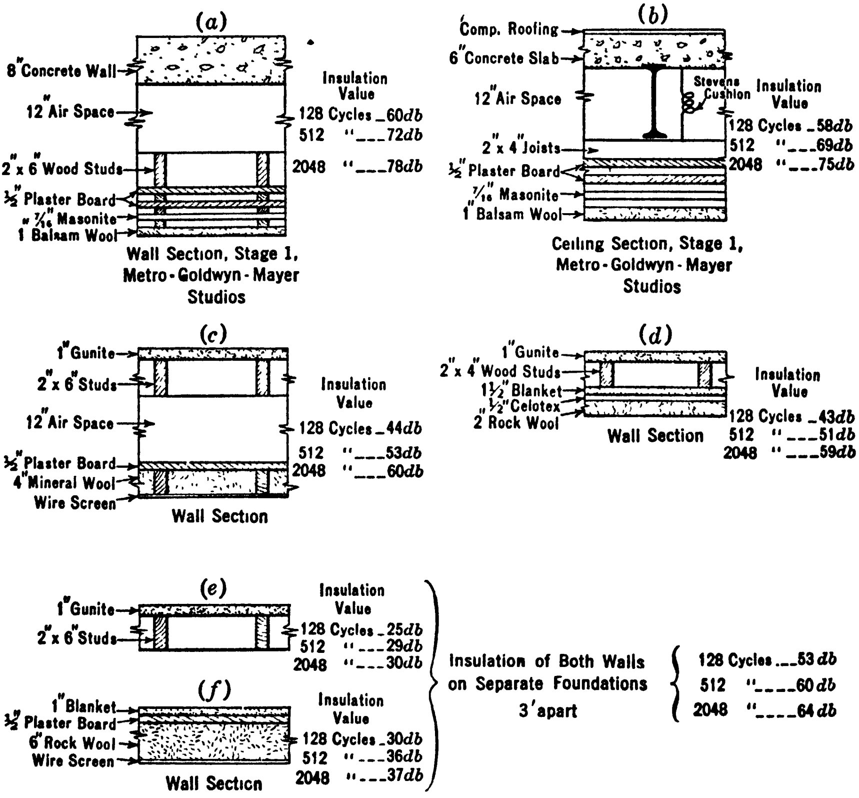

FIG. 271. Typical wall and ceiling sections for sound stages.

used methods of applying absorptive materials to the inner walls and ceilings of sound stages.

Sound stages are equipped with large doors, sometimes as large as 25 feet by 50 feet. The construction of the door usually is similar to that of the wall, in which case the insulation value of the door is determined by the method of closing and sealing the door in its frame. The larger doors are built on rollers which are moved on tracks by motor power. The door is forced tightly against a rubber-lined jamb by means of large mechanical locks. A type of seal which has proved very satisfactory is shown in Fig. 272. Three wood half rounds, nailed to the edge of the door as shown, are forced against the soft rubber strips embedded in the jamb. If the door be forced against the jamb with a pressure of about 30 pounds per running foot, measured along the edge of the door, the insulation value of the seal will be comparable with the insulation value of the door. Tests have shown such a seal to have a transmission loss of about 40 db. It is important that the door make tight contact against the jamb. A poor contact may reduce the insulation value to as little as 15 or 20 db.

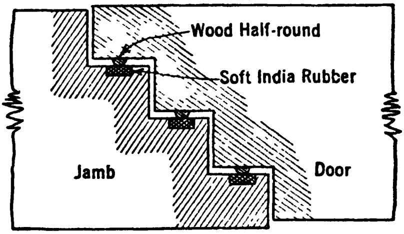

FIG. 272. Effective means of obtaining seal of door against jamb.

PROBLEMS

CHAPTER II

1. Calculate the velocity of sound c in meters per second and in feet per second in the materials listed in the following table (ρ is the density of the material in grams per cubic centimeter, and E is the volume modulus of the material in dynes per square centimeter):

Material	ρ	E	c (m. per sec.)	c (ft. per sec.)
Steel	7.8	20×10^{11}		
Aluminum	2.7	7×10^{11}		
Oak (along fibre)	0 75	11×10^{10}		
Cork	0 24	6×10^{8}		

2. Calculate the velocity of sound in feet per second in air, at temperatures of 0° C. (32° F.), 10° C. (50° F.), 20° C. (68° F.), and 30° C. (86° F.).

3. Why is the velocity of sound in air independent of the pressure? Devise an experiment for testing this conclusion.

4. If two chambers for an organ (say the chamber for the echo organ and the chamber for the main part of the organ) have temperatures of 20° C. and 30° C., what will be the percentage difference in the frequencies of two pipes of the same length, one of which is a pipe in the echo organ and the other a pipe in the main part of the organ? Is this difference large enough to be recognized by the average musical audience?

5. Calculate the wave lengths in air (at 21° C.) of pure tones having frequencies of 64, 128, 256, 512, 1024, 2048, 4096, and 8192 cycles per second.

6. What common experiences show that the velocity of sound in air is (at least nearly) independent of the amplitude and frequency of vibration?

7. The fundamental frequency of a stretched string is equal to $1/2l\,\sqrt{T/\rho_0}$. T is the tension of the string, l is its length, and ρ_0 is its mass per unit length. Specify the T and ρ_0 for the string of a monochord (or sonometer) such that when the string is 100 cm. long the fundamental frequency of the string will be 100 cycles per second. Calculate the required length of this string to give frequencies of 128, 256, 512, and 1024 vibrations per second. Why do the overtones of a vibrating string form a harmonic series? Show that the wave length of the fundamental vibration in a stretched string is $2l$. Describe an experiment with the monochord which would show whether the velocity of waves in the string is proportional to $\sqrt{T}$.

8. Compare the frequencies of two strings of the same size, length and tension, but one of aluminum (density = 2.7) and the other of steel (density = 7.8). Two strings of the same material and of the same length require tensions of 20 and 30 kg., respectively, in order that they be tuned in unison. Compare the diameters of the two strings.

9. A plane wave traveling normally toward a plane wall is described by the equation $y_1 = a \sin 2\pi(nt - x/\lambda)$ and the reflected wave (assuming complete reflection) by $y_2 = a \sin 2\pi(nt + x/\lambda)$. Show, by composing the direct and reflected waves, that the resulting vibration will be made up of stationary waves and that either the maxima or minima will be separated by $\lambda/2$, i.e., by one half of the wave length. How does the kinetic energy of vibration vary from point to point along the stationary waves?

10. The fundamental frequency of an open pipe is $1/2l\sqrt{\gamma p/\rho}$, and the fundamental of a closed pipe is $1/4l\sqrt{\gamma p/\rho}$, where l is the length of the pipe and the other symbols have the significance assigned in Chap. II. From a consideration of the reflection of sound from open and closed ends of a pipe show that the open pipe will produce both odd and even harmonics and that the closed pipe will produce only odd harmonics.

11. How far away from a reflecting surface should one be able to hear an echo of an impulsive sound, such as a short and sudden hand clap? Determine by experiment how far away from a wall you must stand in order just to hear an echo of your own hand clap. What is the shortest observable time interval between the direct and echoed sound?

12. The density of a certain type of fibrous material is 0.50 and its volume modulus is 2×10^6 dynes per square centimeter. What is the theoretical coefficient of reflection of this material? (Assume that the incident sound wave is in air and that it is normal to the plane surface of the material.) What percentage of the sound energy in the incident (normal) sound wave is transmitted into the material? What would be the theoretical coefficient of absorption of this material for a plane (normal) sound wave?

13. Two sound waves, one in air and one in water, have the same root mean square pressures, namely, 10 dynes per square centimeter. Calculate the intensities of the two waves in microwatts per square centimeter.

14. Why do whispered sounds show up the characteristics of a " whispering gallery " better than spoken sounds do? Select a large room which is circular or elliptical in plan (which has smooth unbroken walls) and test it for " whispering gallery " effects.

15. Ten sound waves, all of the same frequency and the same amplitude a but having phase angles of 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°, unite at a certain point in a room. Find graphically the resultant amplitude of vibration at this point.

16. A plane sound wave in air at a temperature of 10° C. encounters, at an angle of 45° from the normal, a region of air at a temperature of 30° C. Calculate the angle between the incident and the refracted beams. Calculate also the coefficient of reflection of the encounter.

17. When is it necessary to consider the diffraction of sound in planning the acoustics of rooms? How does diffraction alter the reflection of sound from the parapet of a balcony? Why is the diffraction of sound usually more pronounced than the diffraction of light?

18. Locate graphically all of the first and second order images of a point source in a rectangular room.

19. Explain the series of echoes one hears when one makes an impulsive noise between two large parallel walls. Why are the echoes heard differently at a point half way between the two walls and at points nearer to one wall than the other?

20. An impulsive sound, as hand clapping, produced in front of a wide and high bank of steps is reflected as a musical sound having a frequency of 500 cycles. What is the horizontal distance between successive risers? Why does sound reflected from a picket fence have a musical quality?

21. Explain and describe the apparent change in pitch of a tone (*a*) when the source is moving toward a listener, (*b*) when the source is moving away from a listener, (*c*) when the listener is moving toward or away from the source, (*d*) when the wind is blowing from the source to the listener, and (*e*) when the wind is blowing from the listener to the source.

22. Two tuning forks have nearly the same pitch so that beats are heard when both forks are sounded together. If one fork has a calibrated frequency of 512 cycles, how can you determine the frequency of the other fork? If two organ pipes tuned to exact unison be sounding in opposite ends of a room, a person will hear beats as he walks from one end of the room to the other. Explain, and calculate the approximate frequency of beats if both pipes are tuned to 512 cycles.

23. A thin wood panel in an auditorium has a prominent resonant frequency at about 200 cycles. How will this panel affect the quality of sound as heard by listeners who are near the panel? Discuss the *free* and *forced* vibrations of such a panel.

24. If a tuning fork is set into vibration and held in the hand it may remain audible two minutes or longer. What will happen to the intensity and to the rate of decay of the tone produced by the fork if it is held against a sounding board? Explain.

25. If the wave length of a ripple on a ripple tank is 1 in., to what scale should a model of a room be constructed in order that the ripple should represent a 700-cycle tone in the room? Why is it desirable in some cases to study the form of a proposed auditorium both by the optical method (Sec. 30) and the sound-spark method (Sec. 29)?

CHAPTER III

1. Describe the function of the middle ear in transmitting aerial vibrations into the fluid within the cochlea.

2. What is the nature of the evidence that fixes the frequency limits of hearing at about 20 and 20,000 cycles per second?

3. From the sensitivity curves in Fig. 42, calculate the decibel difference between the threshold of hearing and the threshold of feeling at frequencies of 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, and 16,384 cycles. Compare the amplitudes of vibration of the drum membrane at the two thresholds for a tone of 1024 cycles.

4. In many cases of partial deafness a bony fringe develops around the foot plate of the stapes which impedes the mobility of the stapes (or stirrup). Why should this type of deafness produce the greatest impairment for low-pitched sounds?

5. Persons with conductive types of deafness claim they hear conversation very readily when they are in a noisy place, as in an automobile or on a trolley car; and persons with normal hearing experience difficulty in a noisy place in hearing the speech of those with conductive impairments. Explain. What possible use could be made of this phenomenon in improving the hearing conditions in large speech rooms?

6. A certain tuning fork vibrating with an amplitude of 1 mm. produces a tone which has a sound level (when held near the ear) of 60 db. What will the sound level be when the amplitude is reduced to (*a*) 0.5 mm., (*b*) 0.2 mm., (*c*) 0.1 mm., (*d*) 0.01 mm.? By what per cent must the amplitude change in order to produce a change in the sound level of 1 db? By what per cent must the amplitude change in order to produce the smallest perceptible change of loudness?

7. With what speed need one approach or recede from a pure tone source (of

500 or more cycles per second) in order that one will recognize a change of pitch? (Assume a velocity of sound of 1125 ft. per sec.)

8. Determine the loudness levels of tones having frequencies of 150, 200, 340, 500, 1000, and 4000 cycles when each tone has a sound level of 50 db.

9. Owing to the non-linear response of the ear to sound, subjective tones are heard which consist of the harmonics of the physical vibrations communicated to the ear and of the summation and difference combinations of these vibrations and their harmonics. If two pure tones of 200 and 300 cycles are communicated simultaneously to the ear, determine the summation and difference tones which result from these two tones and their first three overtones.

10. Why do loud sounds of low pitch interfere with the hearing of speech and music more than do equally loud sounds of high pitch?

CHAPTER IV

1. Describe the distinguishing characteristics of noise, speech, and music.

2. Compose graphically two simple harmonic vibrations having the same amplitude but frequencies in the ratio of two to one, first when they start in phase, second when they start with a phase difference of 90°, and third when they start with a phase difference of 180°. Would these different combinations be heard differently? Explain.

3. Compose graphically the first three terms of two harmonic series, one containing only odd terms (i.e., the first, third, and fifth harmonics) and the other both odd and even terms (i.e., the first, second, and third harmonics). Let the amplitudes of the three component vibrations in each series be 4, 2, and 1, respectively. What do you observe concerning the symmetry of the resulting vibrations?

4. Why are nearly all the errors in the recognition of the sounds of speech attributable to the consonants rather than to the vowels? Why do persons with nerve deafness complain that they can hear speech quite loudly but that it sounds confused?

5. If a single voice produces an average sound level of 55 db in a room, what level will be produced by 10 such voices? by 20? by 50? by 100? If loudness is proportional to the cube root of the sound intensity how many times louder than a single voice will 10 voices sound? 20 voices? 50 voices? 100 voices?

6. Why does phonograph music or the music that is reproduced in the cinema theatre sound unnatural?

7. Why does excessive reverberation in a room interfere more with the hearing of speech than it does with the hearing of music? Why are echoes especially troublesome in music rooms?

8. Which instruments in an orchestra produce the lowest frequencies? the highest? What is the range of frequency in orchestra music? What is the approximate range of sound level?

9. Why can the organ imitate so many string and wind instruments? Why is the imitation imperfect?

10. On the basis of the frequency distribution of the vibrational energy in music, would it be good design to treat the interior of a music room with materials which are six or seven times more absorptive at 4000 cycles than they are at 100 cycles? Give reasons for your answer.

CHAPTER V

1. Sound originates at the centre of a hollow sphere which has a diameter of 25 ft., and the inner surface of the sphere has a reflection coefficient of 0.95. What will be the rate of decay of this sound in decibels per second? How many seconds after the source is stopped will be required to reduce the intensity of the sound 60 db? (Velocity of sound = 1125 ft. per sec.)

2. A rectangular room has a volume of 100,000 cu. ft. and an interior surface of 16,000 sq. ft. What is the mean free path for sound in this room? If the interior boundaries of the room have a coefficient of sound-absorption of 0.10, how many reflections will be required to reduce the intensity of decadent sound to one millionth of its initial intensity? What is the time of reverberation in this room?

3. Calculate the time of reverberation in the room of problem 2 both by Eq. (23) and by Eq. (26) when the average absorption coefficient of the interior boundaries is 0.05, 0.10, 0.20, 0.40, 0.60, 0.80, and 1.0. Which equation gives the more reasonable results?

4. The reverberation formula holds strictly only for rooms in which all boundaries have the same coefficient of sound-absorption. Calculate the rates of decay of sound in a room having a mean free path of 30 ft. (*a*) when all boundaries of the room have a coefficient of absorption of 0.10, and (*b*) when five sixths of the area of the boundaries has a coefficient of 0.02 and the remaining sixth has a coefficient of 0.50. Assume in (*b*) that the first five reflections of the decay are from surfaces having a coefficient of 0.02 and the sixth one from surfaces having a coefficient of 0.50. Calculate the corresponding times of reverberation from these rates of decay, and compare with the time obtained by Eq. (26).

5. The condition of complete diffuseness assumed in the development of the reverberation formulas is never realized in rooms. For example, when highly absorptive material is applied only to the ceiling of a small room with a high ceiling the room may sound very reverberant even though the time of reverberation according to Eq. (26) may be less than 1 second. Explain. Such rooms should be treated by distributing the absorptive material on the walls and in the ceiling. Why will this provide a better condition of reverberation in the room?

6. On the basis of the data given in Fig. 74, calculate the attenuation in decibels per mile, at 20 per cent relative humidity and at 70 per cent relative humidity (both at 21° C.), of a free plane sound wave for frequencies of 2048 cycles, 4096 cycles, and 6000 cycles. Why is it necessary to use low-frequency sounds for long-range signaling? How will the quality of music be affected after it has been transmitted through 1 mile of air (20 per cent relative humidity and 21° C.)?

7. A rectangular room has a volume of 18,000,000 cu. ft. and an interior surface of 720,000 sq. ft. Calculate the reverberation times at 2048 and 4096 cycles, first, neglecting the absorption in the air, and second, including the absorption in the air when the relative humidity is (*a*) 20 per cent and (*b*) 60 per cent. Temperature is 21° C. The average absorptivity of the interior boundaries is 0.20 at both frequencies.

8. Why is the " mean free path " in the case of the cruciform church somewhat longer than the theoretical value $4V/S$? Why is it somewhat shorter in the case of a large office room with a low ceiling, especially for the first few reflections, when the source of sound is near the centre of the room?

9. A private office has a reverberation time of 0.5 second at 512 cycles, and the waiting room adjacent to the office has a reverberation time of 5.0 seconds. The acoustical quality of the office is very good when the door to the waiting room is closed, but when the door is open the office appears to be very reverberant. Explain. What does this suggest regarding the acoustical treatment of rooms which are connected by openings?

10. Why is it advisable to treat the space under a balcony in such a manner that it will be less reverberant rather than more reverberant than the main part of an auditorium?

11. Why is it inadvisable to use highly absorptive material only in the ceiling of a high church and highly reflective materials for walls? If equal and sufficient areas for absorptive material are available either in the ceiling or on the walls, where should the absorptive material be placed? Explain.

12. Plot the decay curves for a 60-db tone of 512 cycles in a room in which V is 50,000 cu. ft., S is 10,000 sq. ft., and α is 0.10, 0.20, and 0.30, respectively.

13. Why are the growth and decay of sound in a room somewhat irregular, as shown in Figs. 83 and 84, rather than regular as predicted by Eq. (26)?

14. It is sometimes possible to hear "beats" in a room during the decay of a pure tone. Explain.

CHAPTER VI

1. Describe the physical requirements, with respect to density and compressibility, of a non-porous material which is to have a high coefficient of sound-absorption (*a*) when the material is in air, and (*b*) when the material is in water.

2. Why is a dense material (as hard plaster) with only large pores in it — say 1/16 in. in diameter — a relatively poor sound-absorbent? Describe the process of sound-absorption by porous materials.

3. Calculate the reflection and absorption coefficients at frequencies of 200, 400, 800, 1600, 3200, and 6400 cycles for a closely packed honeycomb structure of circular pores, the pores having an average diameter of 0.01 cm. How does a change in the size of the pores affect the absorptivity at different frequencies?

4. The absorption coefficients of a thin stretched membrane may be as high as 0.25 at 128 cycles and only 0.10 at 2048 cycles. Explain. Why may such materials prove beneficial in rooms which contain large areas of thin, porous materials?

5. How would you design an acoustical material so that it would have high absorptivity throughout a wide range of frequencies?

CHAPTER VII

1. Discuss the assumptions which underlie the reverberation formulas (23) and (26). Describe methods and devices for obtaining diffuse sound in a room.

2. A small test room, for example 6 ft. by 7 ft. by 10 ft., has hard plastered walls and ceiling (no doors or windows) and has its floor completely covered with a highly absorptive material. Describe the decay of sound in such a room. If the measured time of reverberation, i.e., the time for a decay of 60 db, be used in connection with Eq. (26) for determining the absorption coefficient of the material on the floor, it will be found that the resulting coefficient is too low. Explain. How can this type of error be minimized in making absorption measurements in a room?

3. A reverberation room 19 ft. by 20 ft. by 18 ft. has an absorption of 29 sabines at 512 cycles with one person in the room. A 512 organ pipe blown by the person in the room remains audible for 16.2 seconds. What is the initial sound level of the tone produced by the pipe? What would be the duration of audibility of a tone produced by this pipe in a quiet room having a volume V and an interior surface S with an average absorptivity α? How can the pipe be used for making approximate reverberation measurements in rooms?

4. Why is it necessary to use pure tones, especially at low frequencies, for making reverberation measurements in a room? Why is a quiet room necessary for the precise measurement of reverberation, when the ear is used as the detector?

5. If decay curves be obtained for the room described in problem 2 it will be found that the rate of decay is rather rapid during the early stages of the decay but that the rate becomes slower and slower. Which part of the decay curves should be used for calculating the total amount of absorption in the room? Explain.

6. Enumerate the conditions and apparatus adjustments which must be maintained in the measurement of sound-absorption in a room by the intensity method.

7. Mention the advantages of instrumental methods of measuring the rate of decay of sound in a room. If a single straight line is obtained by plotting the sound level (in decibels) against the time of decay, how can you determine the time of reverberation for the room? If two straight lines are obtained, showing that the decay is relatively rapid at first and relatively slow during the latter stages of decay, what is a probable explanation?

8. Why are warble tones advantageous for many acoustical measurements in rooms?

9. Why are reverberation measurements in a room subject to considerable errors at very low and at very high frequencies?

10. Suppose an empty reverberation room, 18 ft. by 20 ft. by 16 ft., to be completely lined with cement plaster having a coefficient of 0.018 at 4096 cycles. What will be the reverberation time in the room (*a*) when the relative humidity is 30 per cent, and (*b*) when it is 60 per cent? Temperature is 21° C. If the empty room had been calibrated at the 30 per cent humidity and if a material (72 sq. ft.) had been tested in the room at the 60 per cent humidity, how large an error would result in the coefficient at 4096 cycles if no correction were made for the effect of humidity?

11. Why are measurements of absorptivity by the tube method subject to certain limitations? Would you expect the coefficient of absorption to depend upon the angle of incidence? What are the advantages of the tube method?

12. In comparing the absorptivity of porous materials by the apparatus described in Sec. 72, what factors should be considered besides the rate of flow of air into the porous material?

13. Prepare rough sketches and specifications for a test room, including equipment, for making absorption measurements of building materials.

CHAPTER VIII

1. Given a room which has a volume of 240,000 cu. ft., a surface of 30,000 sq. ft., and a time of reverberation at 512 cycles of 2.1 seconds. It is desired to reduce the reverberation time to 1.5 seconds by applying absorptive material to 4000 sq. ft. of ceiling panels (hard plaster having a coefficient of 0.04). What coefficient of absorption should the material have? Use Eq. (26) for your calculations. Select from the tables in Chap. VIII a number of materials which will have the required absorptivity. If you select a material which has a coefficient 10 per cent lower than the calculated coefficient, what will be the resulting time of reverberation?

2. Why does an increase in thickness of a loosely felted material increase absorption more than does a corresponding increase in thickness of a dense acoustical plaster?

3. Suppose it is desired to increase the absorptivity of a relatively dense and nonporous plaster by stippling. Would you recommend many small holes per square inch or a few large ones? Why?

4. Describe methods of decorating acoustical plaster without greatly impairing the absorptivity. Describe simple tests for determining the effect on absorption of painting acoustical plasters.

5. If you had 1000 sq. ft. of absorptive material to install in a room, and you wished to obtain the greatest possible reduction in reverberation, would you apply the material to a single continuous surface or to many separated panels? Why?

6. Select from the tables in Chap. VIII several materials which have coefficients between 0.50 and 0.60 at 512 cycles. Arrange the selected materials in what you would consider their order of desirability with respect to (1) structural strength, (2) appearance, (3) maintenance, and (4) fireproofness.

CHAPTER IX

1. Design and describe a mechanical device for imparting to a tuning fork a hit of standard intensity. If such a standard hit should impart to a tuning fork an initial sound level (when held near the ear) of 70 db, what would the initial level be if the fork had been hit with double the intensity of the standard hit? Is it necessary in making routine measurements of noise by the tuning fork method to provide a high degree of precision in the device which excites the tuning fork? How will the rate of decay of a tuning fork be affected if the shank of the fork be in contact with a resonant material?

2. Describe at least two methods for determining the rate of decay of a tuning fork. Describe a method for determining the initial sound level produced by the fork (when held in front of the ear canal).

3. The calibration of three tuning forks having frequencies of 128, 512, and 2048 cycles indicates that the forks have rates of decay of 1.0, 1.2, and 2.0 db per second, and initial sound levels of 60, 76, and 72 db, respectively. How long will these forks remain audible in a perfectly quiet place? These three forks remain audible 30, 28, and 20 seconds, respectively, in a certain room. Determine the noise audiogram (which shows the masking effect) of the noise in this room.

4. Discuss the value of noise surveys preliminary to the designing of buildings. Why is it desirable to know the level of the noise at several frequencies throughout the speech and music range?

CHAPTER X

1. Suppose that a steel wall separating two rooms is so thick and rigid that one can neglect the yielding of the wall so that the only sound that gets through the wall is the truly *transmitted* or *refracted* beam of sound (assumed to be normal to the wall). Calculate the ratio of the intensities of the emergent and incident beams. (First calculate fractional part of the incident beam that enters the steel wall, and then the fractional part of the beam in the steel that emerges into the air on the opposite side of the wall.)

2. Why is it futile to use elaborate wall constructions for sound-insulation when there are unavoidable threshold cracks around the edges of doors and windows?

3. Why does the lining of ventilating ducts with an absorptive material impede

the transmission of sound through the ducts? Why is the absorptive lining more effective at the source end of the duct than it is at the outlet end?

4. It is desired to insulate a room against certain solid-borne vibrations which have a characteristic frequency of 100 cycles per second. Describe the physical characteristics of resilient supports for the room which will provide a high degree of insulation against these vibrations. What would happen if the supports were of such a resiliency that the natural frequency of (the mass of) the room on its supports were near 100 cycles?

5. A certain resilient support for a ventilating fan and motor is compressed 1 cm. by a load of 50 kg., which is the normal load each support should carry. Ten such supports are placed under a fan and motor weighing 500 kg. What will be the natural frequency of the (load of the) fan and motor on these supports? If the characteristic vibrations of the fan and motor are in excess of 50 cycles per second, will the resilient supports provide a high degree of insulation?

6. A motor generator weighing 1000 lbs. is to be insulated from the floor of a building by means of 2-in. cork (0.70 lb. per board foot, similar to that described in Table XXI). Design suitable supports so that the cork is loaded to 8 lbs. per sq. in., and calculate the ratio a_2/a_1 for frequencies of 50, 100, 200, and 2000 cycles.

7. Why is the transmission loss (in decibels) for a loosely felted material directly proportional to the thickness of the material? If the material is compactly felted and tightly stretched the transmission loss is not directly proportional to the thickness. Why?

8. Why does the transmission loss for rigid panels increase with increasing frequency of the incident sound? Why does the transmission loss depend largely upon the weight per square foot of the panel?

9. Two panels, each 5 in. in thickness, the one a rigid panel and the other a loosely felted one, have the same transmission loss of 35 db. What would be the transmission loss of each panel if they were made 10 in. thick?

CHAPTER XI

1. Would you expect the T.L. for a panel, as measured by the beam method, to depend upon the angle of incidence? Why?

2. Why should both the source room and the test room be completely lined with highly reflective material when determining the τ or T.L. of a panel by means of measuring the intensity in both the source and the test rooms? What other measurements are required besides I_1 and I_2?

3. A source room and a test room are separated by a panel 4 ft. by 6 ft. The test room is 8 ft. by 10 ft. by 9 ft. and is completely lined with cement plaster having an absorptivity (at 512 cycles) of 0.02. Rotating vanes are provided in both rooms which "mix" the sound and break up stationary wave patterns. The average measured r.m.s. sound pressure in the source room is 10 bars and in the test room it is 0.08 bar. Calculate the τ and T.L. (at 512 cycles) for the panel.

4. A large gong has a decay rate of 3.0 db per second. When it is struck a standard blow in either room A or room B, a listener in the room in which the gong is struck hears the gong for 24 seconds. The same listener in room B will hear the gong only 10 seconds when it is again struck a standard blow in room A. What is the approximate effective insulation, in decibels, between the two rooms?

5. Why is any method which is based upon minimal audibility subject to serious limitations in all field measurements of sound-absorption or sound-insulation?

6. Describe a masking method of measuring the insulation between two rooms which does not require quiet surroundings.

7. Why is it insufficient to determine the τ or T.L. of a wall or floor panel at a single frequency? Will measurements at, say, 128, 512, and 2048 cycles suffice for practical purposes in case the panels are heavy and free from resonant effects? Why?

8. Suppose that noise measurements in the vicinity of a proposed building should reveal an average noise level of 45 db at 128 cycles, 55 db at 512 cycles, and 50 db at 2048 cycles, and that you can use either of two types of wall construction, the one having T.L.'s of 35 db, 45 db, and 40 db, and the other having T.L.'s of 25 db, 50 db, and 45 db, at 128, 512, and 2048 cycles, respectively. Which type of wall construction will provide the better insulation, and why? Is it a good procedure therefore always to rely upon average values of T.L. which are obtained by taking the arithmetical mean of the T.L.'s at a number of frequencies?

9. In rating the insulation value of floor and ceiling panels, what other factor should be considered besides the T.L. for air-borne sounds? Describe a method for rating the insulation value of panels with respect to this factor.

10. Why does the carpeting of floors contribute so beneficially to the prevention of solid-borne sounds?

11. Mention the precautions which should be observed in measuring sound-insulation by the reverberation method.

CHAPTER XII

1. Compare the insulation values of lime and gypsum plasters applied to the same type of lath and studding.

2. Compare the insulation values of brick, clay tile, and gypsum tile walls, (1) when all have the same thickness, and (2) when all have the same weight per square foot of wall.

3. Compare the insulation values of plaster on wood studs or metal channel irons. Why is it helpful to use staggered studs?

4. Compare the insulation values of different types of floor and ceiling construction. Why is it helpful to " float " a floor on flexible supports?

5. Under what conditions are felted materials beneficial in sound-insulation? Under what conditions are they of little or no value?

6. Mention uses of fibre board which contribute to sound-insulation.

7. Select from the tables several types of fireproof wall construction having an average T.L. between 45 and 50 db. Which of these would be suitable for hotels and apartment houses? Which ones would you select if it were necessary to reduce the dead weight on the building to the lowest possible amount?

CHAPTER XIII

1. A theatre faces a street where the average noise level is 50 db at 128 cycles, 65 db at 512 cycles, and 60 db at 2048 cycles. The wall of the theatre which faces the street has an area of 3100 sq. ft. and has transmission coefficients of 0.00012 at 128 cycles, 0.000014 at 512 cycles, and 0.000010 at 2048 cycles. In addition, this wall contains two doors each having an area of 50 sq. ft. and transmission coefficients of 0.0040 at 128 cycles, 0.0015 at 512 cycles, and 0.00080 at 2048 cycles. The total absorption in the theatre is 3500 sabines at 128 cycles, 6000 sabines at 512 cycles, and 6500 sabines at 2048 cycles. Calculate the level of the street noise in this theatre

at the three mentioned frequencies. What would be the noise level in the theatre with the two doors completely opened?

2. A large office faces a street where the average noise level is 63 db. The noise which disturbs the employees in the office comes mainly through the windows which have a total area of 600 sq. ft. and an average transmission coefficient of 0.0020. The total absorption in the room is 800 sabines. Calculate the average noise level in the room (*a*) with all windows closed, and (*b*) with 100 sq. ft. of the windows open. Repeat these calculations with a total absorption of 4000 sabines in the room, which is the amount of absorption the room should contain. Compare the noise reduction which is obtained from the closing of the 100 sq. ft. of windows with the reduction which is obtained from the addition of 3200 sabines of absorption.

3. A room in a large office building has a volume of 10,000 cu. ft. and a total absorption of 500 sabines. There are 4 windows in the room each having an area of 30 sq. ft. and an average transmission coefficient of 0.0015. If the average noise level outside be 63 db, and if only the noise transmitted through the windows be considered, what will be the average noise level in the room (*a*) when all windows are tightly closed, (*b*) when 4 sq. ft. of the windows are open, (*c*) when 30 sq. ft. are open, and (*d*) when 10 sq. ft. of the windows are replaced by a window muffler or unit ventilator having an average coefficient of transmission of 0.01?

4. What would be the average noise level in the room in problem 3, under conditions (*c*) and (*d*), if the total absorption were (*a*) reduced to 80 sabines, (*b*) increased to 1000 sabines?

5. Two adjacent guest rooms in a hotel are connected by a door which has an area of 25 sq. ft. and an average coefficient of transmission of 0.005. The absorption in each room is 100 sabines. Assuming that all the sound which is transmitted from one room to the other comes through this door, what is the noise-reduction factor between the two rooms? If the door be eliminated, and if the two rooms be separated by a wall having an area of 180 sq. ft. and an average transmission coefficient of 0.000080, what will be the noise-reduction factor between the two rooms?

6. Two rooms each having a total absorption of 100 sabines are separated by a wall having an area of 150 sq. ft. and an average coefficient of transmission of 0.000085. Average conversation in one of the rooms will have a sound level of about 70 db. What will be the level of the speech transmitted into the other room? If the separating wall contains a 3 ft. by 7 ft. door having a coefficient of 0.0020, what will be the level of the transmitted speech?

7. If the street noise reaching the two rooms of problem 6 have a level of 30 db, is it probable that conversation will be heard through the wall separating the two rooms?

8. A small auditorium having a total absorption of 2000 sabines has 60 sq. ft. of ventilator openings. If the average level of the fan noise at the openings be 45 db, what will be the average level of the fan noise in the auditorium?

9. A church auditorium has an absorption of 4500 sabines. The walls and ceiling provide a high degree of sound-insulation against outside noise, but the windows (400 sq. ft.) offer a possible source of noise transmission. Assuming that only the windows transmit noise into the church, what coefficient of transmission should the windows have in order that the noise-reduction factor will be 45 db?

10. Measurements of the noise issuing from the outlet of a ventilating duct indicate that the average r.m.s. pressure at a frequency of 256 cycles is 10 bars. The opening has an area of 8 sq. ft. and the room contains 400 sabines of absorption.

What will be the average noise level in the room at the frequency of 256 cycles? What would the noise level be if there were four such outlets in the room?

11. A private office with several windows facing a noisy street has an adjoining waiting room with no outside windows. Persons in the waiting room can hear nearly everything that is spoken in the private office, while the occupants of the private office cannot hear even loud conversation in the waiting room. Explain.

CHAPTER XIV

1. Discuss different types of distortion in public address systems.

2. In close proximity to a speaker's mouth the intensity of the speech diminishes almost with the inverse square of the distance from the mouth. If the speaker moves from a distance of 6 in. from the microphone to a distance of 5 ft., how much will the level of the amplified speech be affected?

3. Why is it necessary to keep the transmitter and loud speaker well separated? Why does the amplified voice of a speaker sound better when the speaker is close to the microphone than it does when he is an appreciable distance from it?

4. Why are public address systems more satisfactory for speech than they are for music?

5. The seats in an auditorium which are equipped with telephone sets for the hard of hearing should be located where the users will have a good view of the face of the speaker. They are then able to hear at least the vowels, and if they cannot " hear " the consonants they can at least " see " them. Explain.

CHAPTER XV

1. Name the principal factors which affect the hearing of speech in auditoriums. Which of these factors are beyond the control of the architect or the acoustical engineer?

2. With the help of three or more assistants, conduct series of speech articulation tests in one or more auditoriums. Use the vowel and consonant word lists in Table XXXIII, and by means of Eq. (59) convert the results into percentage syllable articulation. Practice at least 1 hour before recording any data. If possible, conduct one series in an auditorium with reputedly good acoustics and another in an auditorium with reputedly poor acoustics. Have listeners stationed in at least three parts of the room — for example, in the front, central, and rear seats.

3. What other factors besides diminished loudness make the articulation poorer in the rear seats than it is in the front seats? Why is the articulation usually poorer under the balcony than it is in the balcony?

CHAPTER XVI

1. Make a number of sketches of conventionally shaped auditoriums which will be troubled with echoes.

2. Make a number of sketches of auditoriums which will be free from echoes and which also will provide beneficial reflections of sound to all auditors in the seated areas.

3. Prepare a number of rear wall designs and treatments which will avoid pronounced reflection of sound back to the stage or the front rows of orchestra seats.

4. Devise methods of ceiling treatment, which will be free from acoustical defects, for a room in which the ceiling is so high that reflections from a plane or concave ceiling would give rise to echoes or interfering reflections.

5. Devise a number of designs of proscenium arches articulating with splayed ceiling and side walls which will possess acoustical merit.

6. Make a sketch of a long section of an auditorium with balcony, showing (*a*) a carefully planned seating elevation for both the main floor and the balcony (based on Eq. 61), and (*b*) a properly designed recess under the balcony.

7. Show by a number of sketches the acoustical advantages of splayed or coved articulations between walls and ceilings.

CHAPTER XVII

1. Why do tones of very high pitch (for example, above 4000 cycles) interfere very little with the hearing of speech, whereas tones of low or medium pitch interfere very much?

2. Why does noise interfere with the hearing of consonants much more than it does with the hearing of vowels?

3. Why does reverberation interfere with the hearing of final consonants more than it does with the hearing of initial consonants?

4. A 1000-cycle sound generator emits acoustical energy at a rate of 100 microwatts in a room which has a total absorption of 2000 sabines. Calculate (*a*) the average intensity, (*b*) the average root mean square pressure, and (*c*) the average sound level (in decibels) in the room. At what rate would this generator need to emit acoustical energy in order to maintain an average sound level of 65 db in the room?

5. Discuss the power requirements of a sound generator (as a loud speaker) which will provide a speech level of 70 db in auditoriums seating between 5000 and 20,000 persons.

6. Compare the percentage speech articulation in small offices having reverberation times (at 512 cycles) of 5.0 seconds, 2.0 seconds, 1.0 second, and 0.5 second, respectively. Compare the noise levels in these four rooms, assuming that the same amount of noise vibration reaches each room.

7. Why is there an optimal time of reverberation for the hearing of unamplified speech in a room? Why does this optimal time increase as the size of the room increases? What would be the optimal time (that is, the time which would give the highest possible articulation) if the power of the source could be increased so as to maintain an average speech level of 70 db?

8. Why is it necessary to consider the reverberation throughout the entire pitch range rather than at a single frequency, as 512 cycles? Why is it usually sufficient to consider the reverberation at three frequencies, as 128, 512, and 2048 cycles?

9. Why should the reverberation time at 128 cycles be approximately twice as long as that at 512 cycles? Why should the reverberation time increase slightly at very high frequencies, as above 2000 cycles?

10. Calculate the probable percentage articulation in the following rooms, assuming $k_s = 1.0$ and $k_n = 1.0$:

Room No.	Volume cubic feet	Reverberation Time (512 cycles) seconds	Percentage Articulation
1	100,000	1.5	
2	200,000	3.0	
3	500,000	1.4	
4	1,000,000	4.0	

11. Calculate the probable percentage articulation in an auditorium which has a volume of 400,000 cu. ft. and a surface of 40,000 sq. ft. (average absorption coefficient = 0.20), first with no audience present, second with an audience of 1000, and third with an audience of 2000. Assume that each person, as seated in the audience, adds 3.0 sabines of absorption to the room; and assume $k_s = 1.0$ and $k_n = 0.95$.

12. Repeat the calculations in problem 11, assuming that the interior surface of the auditorium has an average absorption coefficient of 0.05 instead of 0.20, and that each person, as seated, adds 4.0 sabines instead of 3.0.

13. From the data in Table XXXVII, make a detailed study of the nature of the errors of speech in reverberant rooms.

CHAPTER XVIII

1. Enumerate conditions for good acoustics which apply both to speech rooms and music rooms. Discuss conditions which apply only, or essentially, to music rooms.

2. Why is reverberation one of the most essential elements in the acoustical design of music rooms?

3. Why is excessive reverberation more readily tolerated in music rooms than it is in speech rooms?

4. Why are different amounts of reverberation desirable for different kinds of music? What kind of music should have a relatively reverberant room, and what kind a non-reverberant room?

5. What general principles should determine the size of a music room?

6. What general principles should determine the shape and the arrangement of spaces in a music room?

7. Why should reverberation be considered throughout the entire range of frequencies instead of for a single frequency only? Discuss the nature of the defects which arise (*a*) from too much reverberation in the low frequencies, and (*b*) from too much reverberation in the high frequencies.

8. In what respects do the acoustical requirements for performers and listeners differ in a music room?

9. Why is it poor design to attempt to obtain the optimal reverberation time in a rectangular music room by localizing all the absorptive material on the floor and in the ceiling? How should the absorptive material be distributed in a room to give the best acoustical effect?

10. Why is it necessary to provide a high degree of sound-insulation for music rooms, especially in urban localities?

11. Discuss the effects of resonance in music rooms. To what extent is it beneficial; to what extent detrimental?

CHAPTER XIX

1. Describe a plan for making a noise survey on and near a proposed school site preliminary to the preparation of plans and specifications. Show how the information obtained from the noise survey can be used in working out the acoustical design for the school.

2. In case it is necessary to design a school building for a site where the average level of street noise is as high as 65 db, what recommendations would you propose for providing adequate insulation against outside noise?

3. A school building is to contain an auditorium, an oral English room, a music room, and several recitation rooms, all on the same floor level. Prepare a rough sketch of a floor plan which will provide a high degree of sound-insulation between the first three mentioned rooms.

4. Outline a general type of absorptive treatment for each of the rooms and the corridors for the school building of problem 3 so that the optimal condition of reverberation will be closely approximated in all rooms.

5. Prepare rough sketches of a plan and long section of a gymnasium which will have good acoustics and, also, hard wearing interior surfaces.

6. Prepare rough sketches for a plan and long section of an auditorium, with a balcony, which is to be designed for good acoustics. Provide for an effective insulation of at least 40 db, and give special consideration to shape and reverberation.

7. Outline the steps which should be taken to insure quiet operation of the heating and ventilating equipment for a proposed school building.

8. Make an acoustical survey of a school building, and prepare a report of your findings, setting forth practical recommendations for providing good acoustics throughout the building.

CHAPTER XX

1. Outline the general principles which should guide the acoustical design of a municipal auditorium.

2. A municipal auditorium has a volume of 600,000 cu. ft. and an interior surface of 58,000 sq. ft. Specify the type and extent of absorptive treatment required to provide the optimal times of reverberation at 128, 512, and 2048 cycles. Assume an audience of 2000 persons of 2.5 sabines per person at 128 cycles, and 4.0 sabines per person at 512 and 2048 cycles.

3. Prepare rough sketches of an acoustical study of a court room, showing (1) a suitable insulation against outside noise; (2) location of judge, jury, witness, attorneys, news reporters, and public; and (3) distribution of absorptive material.

4. Prepare rough sketches of an acoustical study of a council chamber.

5. Outline the steps which should be taken in working out the acoustical design of an office building.

6. Describe practical methods of securing quiet in hospitals. Name a number of absorptive materials which are suitable for the interior walls and ceilings of hospitals.

7. Compile data which reveal the economic value of providing quiet and good acoustical qualities in office and work rooms.

CHAPTER XXI

1. Prepare a rough sketch of a plan for a small Protestant church, giving acoustical consideration to the location of the organ, the console, the choir, and the pulpit.

2. Discuss practical methods of coping with the problem of sound-insulation in the design of city churches.

3. Prepare rough sketches of the plan and sections for a modern church auditorium, giving acoustical consideration to the problems of the shape of the auditorium and the distribution of absorptive and reflective materials for the treatment of the walls and ceiling. Indicate the extent and nature of absorptive treatment required to give the optimal condition of reverberation.

4. It is required to install absorptive treatment in a Protestant church auditorium having a volume of 225,000 cu. ft. and an interior surface of 29,500 sq. ft. The ceiling and walls are hard plaster, and the floor is tile or concrete. Reverberation measurements in the empty auditorium reveal that the reverberation time is 11.5 seconds at 128 cycles, 8.6 seconds at 512 cycles, and 5.5 seconds at 2048 cycles. Specify absorptive treatment for the auditorium that will provide the optimal condition of reverberation with an audience of 800 persons.

5. A large church is to be built near a street where the average noise level is 62 db. It is required that the average noise level in the church be reduced to 20 db. The wall and ceiling construction will afford a high degree of insulation, so that the only means of noise transmission will be through the doors and windows. Show an arrangement of doors (in connection with a vestibule and a narthex) which effectively will eliminate transmission through the doors. The area of windows is 900 sq. ft., and the total absorption in the auditorium is 21,000 sabines. What coefficient of transmission is required of the windows?

6. Study the absorptive materials in Tables XII to XIX and make a list of materials which will be suitable for the interiors of churches. State reasons for your choice.

CHAPTER XXII

1. Name the requirements for good acoustics in an open-air theatre.

2. What should be the approximate acoustical power output of a public address system which is to provide an adequate loudness of speech in a circular coliseum which has an average radius of 400 ft.? Assume that the loud speakers are all located at the centre of the coliseum, that the intensity falls off with the inverse square of the distance, and that the speech level at a distance of 400 ft. from the source is to be 70 db.

3. Discuss the refraction of sound in the atmosphere owing to wind and change of temperature. How does wind interfere with the hearing of speech or music in the open?

4. Suggest practical methods of excluding noise from open-air theatres.

5. Prepare rough sketches for an open-air band stand which is to be located on level ground in a public park.

6. Prepare a report on the acoustical properties of an open-air auditorium which is in or near your community.

CHAPTER XXIII

1. Discuss the acoustical difficulties which are likely to be encountered in large theatres. Why is it especially important that the volume of a legitimate theatre be kept as small as possible?

2. Prepare rough sketches of a plan and long section of a legitimate theatre, giving special consideration to (1) the development of an acoustical shape; (2) the location of doors, foyer and corridors so that a high degree of sound-insulation will be provided; and (3) the distribution of absorptive material so that the optimal condition of reverberation will prevail in all parts of the auditorium.

3. Prepare rough sketches of stage sets which will be effective for reflecting sound to the audience.

4. Why is complete insulation against noise more important for the legitimate theatre than it is for the cinema theatre?

5. Discuss the acoustical problems involved in the design of a cinema theatre which would seat say 25 or 30 thousand.

6. Prepare a report on the acoustics of a theatre in your community, and, if necessary, make recommendations for improving the acoustics.

CHAPTER XXIV

1. Discuss the general problem of the distribution of absorptive and reflective materials in music studios.

2. Prepare rough sketches of a number of adjacent music studios having an effective insulation from room to room of not less than 50 db. Indicate also the type of absorptive treatment required in each room.

3. Prepare rough sketches of a plan and long section of a small concert hall, showing (1) a type of design and construction that will provide an effective insulation of not less than 45 db; (2) an acoustical arrangement of spaces for organ, orchestra, chorus, soloists, and audience; (3) a distribution of absorptive materials which will provide a satisfactory condition of reverberation in all parts of the hall; and (4) a use of thin wood paneling which will add resonance to the hall.

4. Discuss the need of adjustable reverberation for music rooms, and devise a means for accomplishing such an adjustment in a music studio.

5. Prepare a report on the acoustics of a music room in your community, and make recommendations, if necessary, for improving the acoustics of the room.

CHAPTER XXV

1. Discuss the insulation of guest rooms in a hotel, and mention a number of methods of securing an adequate amount of insulation between the rooms.

2. What can be done to minimize the noise coming from water pipes and bathroom fixtures?

3. Describe effective means for preventing the transmission of footfalls and other impact noises.

4. In the designing of a hotel, which rooms, besides guest rooms, should be studied from the standpoint of acoustics? Why should the corridors have carpeted floors, and why should the ceilings and walls of the corridors be finished with absorptive material?

5. What can be done to absorb and minimize noise in kitchens, pantries, and breakfast rooms?

6. Prepare sketches of a living room or a music room, showing an acoustically correct arrangement of piano, radio, and other furniture.

CHAPTER XXVI

1. Why is it necessary to have less reverberation in sound recording and broadcasting studios than it is in ordinary speech and music rooms?

2. Why should provision be made for adjustable reverberation in recording or broadcasting studios?

3. Why is it necessary to have a high degree of sound-insulation for recording or broadcasting studios?

4. Is it good design to localize all the absorptive material on the floor and in the ceiling of a studio? Why? How should the absorptive material be distributed?

5. Why is it necessary that recording and broadcasting studios be free from mechanical vibrations?

APPENDIX I

DEFINITIONS OF TERMS USED IN ACOUSTICS[1]

General Definitions

1001 **Sound** — (*a*) Sound is a wave motion in an elastic material medium.
(*b*) Sound is also the sensation produced through the ear by a wave motion as defined above.

1002 **Cycle** (∽) — One complete set of the recurrent values of a periodic phenomenon is called a cycle.

Note: The term " cycle " is often used as an abbreviation of " cycles per second."

1003 **Period** (T) — The time required for one complete cycle of a periodic quantity is the period. The unit is the second.

1004 **Frequency** (f) — The number of cycles occurring per unit of time, or which would occur per unit of time if all subsequent cycles were identical with the cycle under consideration, is called the frequency. The frequency is also the inverse of the period. The unit is the cycle per second, or merely the " cycle " (*see* 1002).

1005 **Frequency Level** (f_L) — The frequency level of a sound is defined as the logarithm to the base 2 of the frequency

$$f_L = \log_2 f.$$

The unit is the octave.

1006 **Phase** (ϕ) — Phase is the fraction of the whole period which has elapsed, measured from some fixed origin.

1007 **Wave Length** (λ) — The wave length of any progressive wave is the least distance, measured along the path of progression, between two points differing in phase by one period.

1008 **Diffuse Sound** — Sound is said to be in a diffuse state when in the region considered the energy density, averaged over regions large compared to the wave length, is uniform; and when all directions of energy flux at all parts of the region are equally probable.

1009 **Bel** — The bel is defined by the relation $N = \log_{10} P_1/P_0$, where N is the number of bels by which the power P_1 exceeds the power P_0. The decibel (db), equal to one-tenth of a bel, is very commonly used.

1010 **Bar** — A bar is a pressure of 1 dyne per square centimeter.

1011 **Static Pressure** (P_0) — The static pressure is the pressure that would exist in the medium with no sound waves present. The unit is the bar.

1012 **Instantaneous Sound Pressure** (P_i) — The instantaneous sound pressure at a point is the total instantaneous pressure at the point minus the static pressure. The unit is the bar.

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[1] Selected from the Report of the Committee on Acoustical Standardization of the Acoustical Society of America, Jour. Acous. Soc., **2**, 311 (1931).

1013 **Sound Pressure** (P) — The sound pressure is the root mean square value of the instantaneous sound pressure over a complete cycle. The unit is the bar.

1014 **Maximum Sound Pressure** ($P_{\max}$) — The maximum sound pressure for any given cycle is the maximum absolute value of the instantaneous sound pressure during that cycle. The unit is the bar.

1015 **Peak Sound Pressure** (P_p) — The peak sound pressure for any specified interval is the maximum absolute value of the instantaneous sound pressure over that interval. The unit is the bar.

1016 **Sound Energy Flux** (J) — Sound energy flux is the average over one period of the rate of flow of sound energy perpendicularly through any specified area. The unit is the erg per second.

Note: In a gas of density ρ, for a free progressive wave of velocity C, the sound energy flux perpendicularly through the area a (square centimeters) corresponding to a sound pressure P is

$$J = \frac{P^2a}{\rho C} \text{ ergs per second}$$

which for air under average conditions becomes

$$J = \frac{P^2a}{41} \text{ ergs per second.}$$

1017 **Sound Energy Density** (E) — Sound energy density is the sound energy per unit volume. The unit is the erg per cubic centimeter.

1018 **Sound Intensity** (I) — The intensity of a sound is defined in terms of the sound pressure P, the wave velocity C, and the density of the medium ρ, by the relation

$$I = \frac{P^2}{\rho C}.$$

This is equal to the sound energy flux per unit area for a free progressive wave having the same values for P and C in the same medium of density ρ. The unit is the erg per second per square centimeter.

1019 **Intensity Level** — The intensity level of a sound is defined as the logarithm to the base 10 of the intensity. The unit is the bel.

Note: In air under average conditions the intensity level of a sound is given by I.L. $= -1.6 + 2 \log_{10}P$, where P is the sound pressure.

1020 **Interference** — Interference is the destructive or reenforcing action of two or more waves arriving at the same position simultaneously.

1021 **Diffraction** — Diffraction is the change in direction of propagation of the sound, due to the passage of the wave around the edge of an obstacle.

1022 **Refraction** — Refraction is the change in direction of propagation of a sound wave due to changes in speed of the wave in different parts of the path. The speed must be relative to some fixed reference system.

1023 **Regular Reflection** — Regular reflection of a sound is a reflection which gives rise to an image of the source of sound.

1024 **Diffuse Reflection** — Diffuse reflection is reflection from many surfaces not in the same plane, so that no single image of the sound source can be formed.

1025 **Beats** — Beats are the periodic variations of the sound intensity at a point due to the interference of two sound waves of different frequencies.

1026 **Stationary Waves** — Stationary waves result from the interference of two or more wave trains of the same frequencies, and are characterized by the existence of the medium of certain points (lines, or surfaces) at which the amplitude of vibration is zero, and by a zero average sound energy flux at all points.

1027 **Semi-stationary Waves** — Semi-stationary waves result from the interference of two or more wave trains of the same frequencies, and are characterized by the existence in the medium of certain points (lines, or surfaces) having a minimum amplitude of vibration.

1028 **Nodes** — Nodes are the points, lines, or surfaces of a stationary wave system which have a zero amplitude.

Note: It is thus possible to have different types of nodes, such as pressure nodes or velocity nodes, and hence the type must be specified.

1029 **Partial Nodes** — Partial nodes are the points, lines, or surfaces of a semi-stationary wave system which have a minimum amplitude of vibration.

1030 **Antinodes** — Antinodes are the points, lines, or surfaces of a stationary wave system which have a maximum amplitude.

1031 **Echo** — The sound received after reflection and arriving sufficiently later than the initial sound impulse to be definitely distinguished from it is called an echo.

1032 **Multiple Echo** — A succession of separately distinguishable echoes from a single source is called a multiple echo.

1033 **Harmonic Echo** — If in the reflection of a complex tone the higher-frequency components predominate in the echo it is called a harmonic echo.

1034 **Flutter Echo** — A flutter echo is the conversion of a single pulse into a periodic succession of reflected pulses. If the frequency of the flutter echo is in the audible range it is called a musical echo.

1035 **Unpitched Sound** — An unpitched sound is any sound to which no definite pitch can be assigned, or an irregular succession of sound waves.

1036 **Noise** — Noise is any undesired sound.

1037 **Background Noise** — Any noise accompanying the artificial reproduction of music or speech is called background noise. Background noise may result from needle scratch in playing phonograph records, amplifier noises, line noises, transmitter noises, etc.

Architectural Acoustics

2001 **Acoustic Reflectivity** — The acoustic reflectivity of a surface, not a generator, is the ratio of the rate of flow of sound energy reflected from the surface, on the side of incidence, to the incident rate of flow. Unless otherwise stated, the incident flow is assumed to be diffuse. Also, unless otherwise specified, the values given apply to a portion of an infinite surface thus eliminating edge effects.

2002 **Acoustic Absorptivity** — The acoustic absorptivity of a surface is equal to 1 minus the reflectivity of that surface.

2003 **Total Absorption** — The total absorption of an object is the ratio of the sound energy absorbed by the object to the energy absorbed per unit area (exclusive of edge effects) of a surface of unit absorptivity placed in the same diffused sound field. The unit is the sabine provided the unit area is the square foot.

2004 **Acoustic Transmittivity** — The acoustic transmittivity of an interface or septum is the ratio of the rate of flow of transmitted sound energy to the rate of the incident flow.

2005 **Reverberation** — Reverberation is the persistence of sound in an enclosure due to repeated reflections after the source has been cut off.

2007 **Reverberation Time** — The reverberation time for a given frequency for an enclosure is the time required for the average energy density, initially in a steady state, to decrease along any simple or complicated decay curve to one millionth of its value when the source was cut off. The unit is the second.

HEARING

3001 **Pitch** (p) — Pitch is that subjective quality of a sound which determines its position in the musical scale. Pitch may be measured as the frequency of that pure tone having a sound pressure of 1 bar which seems to the average normal ear to occupy the same position in the musical scale. The unit is the cycle per second or the octave.

3002 **Lower Frequency Limit of Audibility** (f_L) — The minimum frequency, for a sinusoidal sound wave, that will produce a sensation of tone, is the lower frequency limit of audibility.

3003 **Upper Frequency Limit of Audibility** (f_m) — The maximum frequency, for a sinusoidal sound wave, that will produce a sensation of tone, is the upper frequency of audibility.

3004 **Threshold of Audibility** — The minimum value of the sound pressure of a sinusoidal wave of a specified frequency which gives the ear a sensation of tone in a silent place is called the threshold of audibility for that frequency and for that particular ear. This term is often used to denote the minimum value of the sound pressure of any specified complex wave (such as speech or music) which gives the ear a sensation of sound in a silent place. It is expressed in bars.

Note: The threshold of audibility is also expressed in terms of the sound intensity in ergs per second per square centimeter, or in terms of the intensity level in decibels corresponding to the above intensity.

3005 **Normal Threshold of Audibility** — The normal threshold of audibility is the average of the threshold intensity levels of a large number of normal ears. The result is often expressed in bars.

Note: The term may be shortened to " Normal Threshold " when no danger of confusing it with the normal threshold of feeling exists.

3006 **Threshold of Feeling** — The threshold of feeling is the minimum sound pressure which at a given frequency will stimulate the ear to a point at which there is the sensation of feeling. It is expressed in bars.

3007 **Normal Threshold of Feeling** — The normal threshold of feeling is the average of the threshold intensity levels of a large number of normal ears. The result is often expressed in bars.

3008 **Sensation Level** — The sensation level of a sound is the difference between the intensity level of the sound and the intensity level at the threshold of audibility. It is expressed in decibels. [Author's note: This is equivalent to the term *sound level* as defined and used in this book. See Sec. 37.]

3009 **Deafness** — The deafness of an ear at a frequency is the difference between the threshold level of audibility for that ear and the normal threshold level, at the same frequency. It is expressed in decibels.

3010 **Per Cent Deafness** — The per cent deafness at any given frequency is 100 times the ratio of the deafness in decibels to the number of decibels between the normal threshold levels of audibility and feeling at that frequency.

3015 **Loudness** — The loudness is that subjective quality of a sound which determines the magnitude of the sensation produced by that sound for the average normal ear. Loudness is usually measured as the intensity level of the 1000-cycle pure tone which gives the same magnitude of sensation for the average normal ear.

3016 **Masking Effect of a Sound** — The masking effect (at any given frequency) of a sound is the shift of the threshold of audibility at that frequency due to the presence of this masking sound. The unit is the decibel.

3017 **Auditory Sensation Area** — The auditory sensation area is the area on the frequency pressure diagrams enclosed by the curve defining the threshold of feeling and the threshold of audibility.

3019 **Noise Audiogram** — A noise audiogram is a graphical record of the masking effect, due to a given noise, as a function of frequency of the masked tone.

3020 **Loudness Contours** — Loudness contours are graphs of intensity level plotted against frequency level for sinusoidal sound waves of equal loudness.

3021 **Instantaneous Speech Power** — The instantaneous speech power is the rate at which sound energy is being radiated by the speaker at any given instant. It is measured in ergs per second.

3022 **Average Speech Power** — The average speech power for any given period is the average value of the instantaneous speech power, over that period. It is measured in ergs per second.

3023 **Mean Speech Power** — The mean speech power is the value of the average speech power when taken for a period of 1/100 second. It is measured in ergs per second.

3024 **Phonetic Speech Power** — The phonetic speech power is the maximum value of the mean speech power of a vowel or consonant sound. It is measured in ergs per second.

3025 **Peak Speech Power** — The peak speech power is the maximum value of the instantaneous speech power over the time interval considered. It is measured in ergs per second.

3027 **Discrete Word Intelligibility** — The discrete word intelligibility is the percentage of the total number of spoken words which are correctly understood, when the words are selected at random, but in relation to their normal frequency of use.

3028 **Syllable Articulation** — The syllable articulation is the percentage of the total number of spoken syllables which are correctly recognized, for syllables of the consonant-vowel-consonant type and without meaning.

3030 **Vowel, Consonant, Initial Consonant, or Final Consonant Articulation** — The vowel, consonant, initial consonant, or final consonant articulation is the percentage of the total number of spoken vowels, consonants, initial consonants, or final consonants, respectively, that are correctly recognized, when the sounds are spoken in syllables of the consonant-vowel-consonant type and without meaning.

MUSIC

4001 **Tone** — A tone is a musical sound giving a definite pitch sensation.

4002 **Pure Tone** — A pure tone is a tone produced by an instantaneous sound pressure which is a simple sinusoidal function of the time.

4003 **Interval** — The interval between two tones is the numerical difference of the frequency levels of the two tones. The unit is the octave, or its submultiple the millioctave.

Note 1: The interval between two tones can also be expressed as the ratio of the higher frequency to the lower.

Note 2: Interval $= (\log_2 f_2 - \log_2 f_1)$ 1000 millioctaves
$= 3{,}320\ (\log_{10} f_2 - \log_{10} f_1)$ millioctaves.

4004 **Note** — A note is a character designed to represent to the eye the relative duration of a tone and, by its position on the staff, the relative pitch of that tone.

4005 **Octave** — An octave is the interval between two frequencies having a ratio of 2 : 1. One octave is equal to 1000 millioctaves.

4006 **Chord** — A chord is a combination of several tones sounded together whose frequencies are in the ratios of small whole numbers.

Note: In the case of the tempered scale these relations are only approximate.

4007 **Diad** — A diad is a combination of two tones sounded simultaneously whose frequencies are related as the ratio of small whole numbers.

4008 **Tetrad** — A chord of four tones is called a tetrad.

4009 **Major Triad** — A major triad is a chord of three tones whose frequencies are as 4 : 5 : 6.

Note: The use of the term major triad has also been extended to include any case of a fundamental tone sounded together with its major third and perfect fifth. On any but the natural scale the frequencies of these tones do not bear the simple ratios given above.

4010 **Minor Triad** — A minor triad is a chord of three tones whose frequencies are as 10 : 12 : 15.

Note: The use of the term has been extended to include any case of a fundamental tone sounded together with its minor third and perfect fifth. On any but the natural scale, the frequencies of these tones do not bear the simple ratios given above.

4011 **Diminished Triad** — A diminished triad is a chord of three tones whose frequencies are as 25 : 30 : 36.

Note: In a more general sense a diminished triad consists of a fundamental tone sounded together with its minor third and its minor fifth.

4012 **Augmented Triad** — An augmented triad is a chord of three tones whose frequencies are as 16 : 20 : 25.

Note: In a more general sense an augmented triad consists of a fundamental tone sounded together with its major third and its augmented fifth.

4013 **Musical Scale** — A musical scale is a series of tones ascending or descending in frequency by definite intervals.

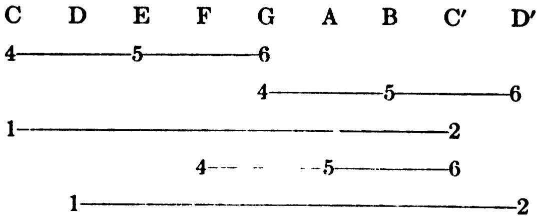
4014 **Natural Scale** — The natural scale is a musical scale in which the intervals can be expressed by the ratios of small numbers. (See 4003, Note 1.)

4015 **Equally Tempered Scale** — An equally tempered scale is a musical scale in which all the intervals are made equal.

Note: In the equally tempered scale ordinarily used, the intervals are all equal to 83.3 millioctaves, or expressed as a ratio they are $2^{1/12}$.

4016 **Major Diatonic Scale** — The major diatonic scale is a musical scale containing seven intervals to the octave and based upon the intervals of the major triad.

Note: This relationship can be represented as follows:



4017 **Chromatic Scale** — The chromatic scale is a musical scale containing twelve intervals to the octave and obtained from the diatonic scale by the addition of five half-step intervals placed so as to make the resultant scale have approximately equal intervals.

4018 **Harmonic** — A harmonic is a component of a periodic quantity having a frequency which is an integral multiple of the fundamental frequency. For example, a component the frequency of which is twice the fundamental frequency is called the second harmonic.

4019 **Overtone (Partial)** — An overtone is a component of a tone having a frequency which may or may not be an integral multiple of the frequency of the fundamental. For example, the frequency of the first overtone of a certain type of vibrating reed is 6.27 times the fundamental frequency of the tone.

4020 **Tone Quality** — The tone quality is that subjective character of the sound sensation which depends primarily upon the number of overtones and upon the relative magnitudes, frequencies, and durations of the fundamental and the overtones.

SOUND TRANSMISSION

5001 **Acoustic Impedance** — The acoustic impedance of a sound medium on a given surface is the complex quotient of the pressure (force per unit area) on that surface by the flux (volume velocity, or linear velocity multiplied by the area) through that surface. The acoustic impedance may be expressed in terms of mechanical impedance, acoustic impedance being equal to mechanical impedance divided by the square of the area of the surface considered. The unit is the acoustic ohm.

5008 **Resonance (Velocity Resonance)** — Resonance exists between a body, or system, and an applied sinusoidal force when any small change in the frequency of the applied force causes a decrease in velocity at the driving point; or when the frequency of the applied force is such that the absolute value of the driving-point impedance is a minimum.

Note: In the case of a single resonant system consisting of a mass reactance, a stiffness reactance, and a resistance in series, the frequency of resonance as defined above is also the frequency at which the mass and the stiffness reactances are numerically equal, and hence the frequency at which the applied sinusoidal force and the resulting sinusoidal velocity are in phase.

5009 **Resonant Frequency** — A frequency at which resonance exists. The unit is the cycle per second.

5014 **Forced Vibration** — A forced vibration is any vibration which is imposed upon a system by external force and whose frequency is controlled thereby. It is opposed to the term " free vibration."

5015 **Free Vibration** — A free vibration is any vibration in which no external forces are applied to the system. It is opposed to the term " forced vibration."

5016 **Natural Frequency** (f_0) — The natural frequency of any system is the frequency at which its vibrating element will vibrate after the external force displacing it from its normal position has ceased to act. The unit is the cycle per second.

5017 **Natural Period** — The natural period is the reciprocal of the natural frequency. The unit is the second per cycle.

APPENDIX II

A DISCUSSION OF THE TRUE COEFFICIENT OF SOUND-ABSORPTION — A DERIVATION OF THE REVERBERATION FORMULA

BY R. F. NORRIS

"In going over some experimental results which persisted in showing the sound-absorption value of certain materials as more than 100 per cent it seemed advisable to start with the standard assumptions adopted by Wallace C. Sabine and to check through to determine the maximum value of his absorption coefficient (a). If it should be possible to show that this coefficient could reach values greater than unity the experimental results would be justified. A certain amount of doubt was cast on the validity of Sabine's coefficient since his reverberation formula $0.05\ V/as = t$ did not fit the facts at both limits. If a becomes 0 then t becomes infinite as it should, but if a becomes unity t does not become 0 as it should. For this reason it appeared that the equation did not correctly express the relation between volume, surface, absorption, and period of reverberation.

"Let the following assumptions be made:

E = the average sound intensity in a room at any moment.
E' = the maximum average sound intensity in a room when the source has just ceased.
t_p = the period of reverberation.
$\frac{4V}{S}$ = mean free path (Jaeger).
V = volume of room in cubic feet.
S = surface of room in square feet.
t' = time sound takes to travel the mean free path in seconds.
t = total time expressed in units of t'.
α = true coefficient of absorption.
v = velocity of sound in air.

"Assuming the sound source to have just stopped and that the sound is decaying in the room, E and t may be tabulated as follows:

t	E
0	E'
t'	$E'(1-\alpha)$
$2t'$	$E'(1-\alpha)^2$
$3t'$	$E'(1-\alpha)^3$
....	......
$(n-1)t'$	$E'(1-\alpha)^{(n-1)}$
nt'	$E'(1-\alpha)^n$

"The value of E at any moment may be written as:

$$E = E'(1 + \alpha)^{\frac{t}{t'}}. \tag{1}$$

Since t' is the time it takes sound to travel the mean free path it may be expressed as the mean free path divided by the speed of sound, or

$$t' = \frac{4V}{S} \times \frac{1}{v} = \frac{4V}{Sv}.$$

Substituting this value of t' in Eq. (1)

$$E = E'(1 - \alpha)^{\frac{tSv}{4V}}. \tag{2}$$

Now let $(1 - \alpha) = e^x$ from which $x = \log_e (1 - \alpha)$.
Eq. (2) now becomes

$$E = E'e^{\frac{xtSv}{4V}}. \tag{3}$$

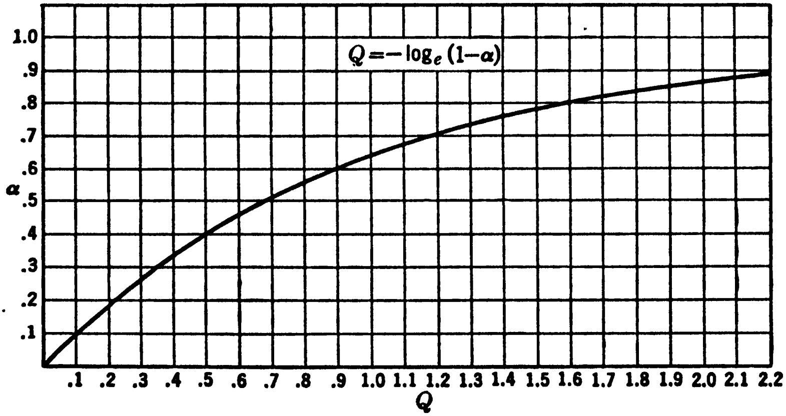
Or substituting $\log_e (1 - \alpha)$ for x

$$E = E'e^{\log_e \frac{(1-\alpha)vSt}{4V}}, \tag{4}$$

Eq. (4) is the equation for the decay of sound.
"Compare (4) with the equation developed by Sabine,

$$E = E'e^{\frac{-avSt}{4V}},$$

and it is evident that Sabine's coefficient (a) has been replaced by $-\log_e (1 - \alpha)$; otherwise the equations are identical. From this it is evident that Sabine's coefficient (a) is related to the true absorption (α) by the equation $a = -\log_e (1 - \alpha)$.



"Substituting this value for a in Sabine's reverberation formula it becomes

$$t_p = \frac{0.05V}{-\log_e (1 - \alpha)S}.$$

"This expression fits at both limits, for when α becomes 0, t_p becomes infinite; and when α becomes unity, t_p becomes 0, as it patently should.

"In the accompanying curve Sabine's (a) has been plotted against the corresponding values of α in order to allow the true values of absorption to be read off from the Sabine coefficient.

"Sabine in assuming that a = unity for a perfect absorber has actually assumed a value of approximately 63 per cent as perfect absorption. From the curve it is evident that values of (a) may be obtained which range between 0 and α, whereas the true absorption α will vary only between 0 and unity."

APPENDIX III

This table gives the values of α for different values of $-\log_e (1 - \alpha)$.

$-\log_e (1 - \alpha)$	α	$-\log_e (1 - \alpha)$	α
0.010	0.010	0.260	0.229
.020	.020	.270	.237
.030	.030	.280	.244
.040	.039	.290	.252
.050	.049	.300	.259
.060	.058	.310	.267
.070	.068	.320	.274
.080	.077	.330	.281
.090	.086	.340	.288
.100	.095	.350	.295
.110	.104	.360	.302
.120	.113	.370	.309
.130	.122	.380	.316
.140	.131	.390	.323
.150	.139	.400	.330
.160	.148	.410	.336
.170	.156	.420	.343
.180	.165	.430	.349
.190	.173	.440	.356
.200	.181	.450	.362
.210	.189	.460	.369
.220	.197	.470	.375
.230	.205	.480	.381
.240	.213	.490	.387
.250	.221	.500	.393

APPENDIX IV

Approximate values of loudness reduction factor k_l for rooms of different volume having times of reverberation (at 512 cycles) between 0.5 and 8.0 seconds.

Time of Reverberation in Seconds	Volume of Room in Cubic Feet							
	12,500	25,000	50,000	100.000	200,000	400,000	800,000	1,600,000
0 50	0 96	0 94	0 92	0 90	0 88	0 85	0 81	0 76
0.75	.97	.95	93	.91	.89	87	.84	.80
1 00	.97	96	94	.92	.90	.88	.86	.82
1 25	.97	96	.95	.93	.91	.89	87	.83
1 50	.98	.96	.95	.94	.92	.90	.88	84
2 00	98	.97	.96	.95	.93	.91	89	.36
3 00	.98	.97	97	.96	94	.92	91	.88
4 00	98	.98	.97	96	95	94	.92	89
6 00	.99	.98	98	97	96	95	93	91
8 00	99	.99	98	97	96	95	94	.92

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