THE PRINCIPLES & PRACTICE OF SOUND-INSULATION

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BY

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PREFACE

THIS book is a collection of information from widely scattered sources, many of which will not be readily available to readers out of reach of well-equipped technical libraries. Students of the new and rapidly developing subjects of noise-reduction and sound-insulation will it is hoped find such a collection useful, if only for the sake of the references it contains. Those who are already specialists in this field may perhaps find something to stimulate them, if only to write a better book about it. Busy people such as architects and engineers, who have to be acquainted with many techniques, may like to have a fairly comprehensive book at hand for reference; the tables of data which have been included have been selected mainly for this purpose. These people, like Edison, may value information about the many ideas which won't work as well as about the few which will; the limitations of the methods and the difficulties of the subject have been indicated accordingly. Apart from Chapter VI, which deals with the insulation of machinery and which has perhaps more interest for the specialist, the book as a whole will, it is hoped, interest the general public, who have to endure the noises of modern civilization. If it should interest them sufficiently to arouse an insistent demand for more peace and quietness, it will have been worth writing.

The bulk of the book was written before 1940. The publication and revision has been a long task interrupted, as was the progress of research itself, by the War. The constant encouragement and advice of Dr. G. H. Aston and other colleagues and friends of the late Dr. J. E. R. Constable have been invaluable. The publishers, Sir Isaac Pitman and Sons, Ltd., and their general editor, Mr. A. S. Andrews, have given every possible assistance. Miss I. M. McK. Duncan kindly helped with the proofs.

K. M. C.

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CHAPTER I

THE NATURE OF SOUND

THE very considerable progress that has been made in the subject of noise-reduction during the past fifteen years is largely the result of scientific research. To enable those readers who are not knowledgeable in acoustical matters to appreciate recent developments, an elementary account of the properties of sound waves is given in this chapter, together with explanations of the acoustical terms used later in the book. Many readers may prefer to omit this chapter altogether, at any rate on a first reading. Those who require a complete and systematic list of acoustical terms are referred to the *British Standard Glossary of Acoustical Terms and Definitions* (British Standards Institution, 1936).

The Nature of Sound. Sound is essentially something which can be heard by humans (and animals), but on account of the wide variations in ear sensitivity arising from age, physical defects, and so on, what is sound to one man may very well be nothing to another. The sensation of sound arises when vibration falls upon the ear.

Sound is generated in air when a surface vibrates. As an example may be taken the familiar loudspeaker diaphragm, the vibration of which can often be observed directly. The process by which the diaphragm radiates sound is as follows—

If its backward and forward motion is slow enough, the air will merely flow past it and very little disturbance will result. (The physicist's way of stating this is that if the area is small compared with the wavelength it forms an inefficient generator of waves). If, however, the motion is rapid enough (and the phenomenon can be very easily illustrated by moving a piece of wood to and fro in water and noting the stage at which ripples appear), perceptible waves are formed. The forward movement of the surface compresses the air in front; and this, when it tries to expand back to normal dimensions, compresses the air in front of *it*, and so on. In fact, as a result of compressing the one layer of air, a compression travels forward away from the surface. (See Fig. 1.) Similarly, a rarefaction caused by the surface moving backward will also travel away from the surface. So it comes about that the surface, by moving backward and forward periodically, generates a series of compressions and rarefactions which travel outward. The travelling compressions and rarefactions form a sound wave which, when it impinges on the ear, is heard because the alternating pressures which travel with it, though minute,* are sufficient to cause movements of the ear drum

* The smallest alternating pressure that the ear can detect is less than 1/1,000 dyne/sq. cm. This, put in terms of a barometer, means the ear detects a pressure change corresponding to 0·00000003 in. of mercury.

which the auditory nerve can translate into the sensation of sound. We have considered only the transmission of waves in air, but the process is similar in liquids and solids.

Frequency. The number of times per second the vibrating surface goes through the complete cycle (that is to say, moves to the right, then to the left, and back again) is termed the *frequency of vibration*, and is given as so many cycles per second (c.p.s.). A special symbol (written ∼) is often used for "cycles per second"; thus 100 cycles

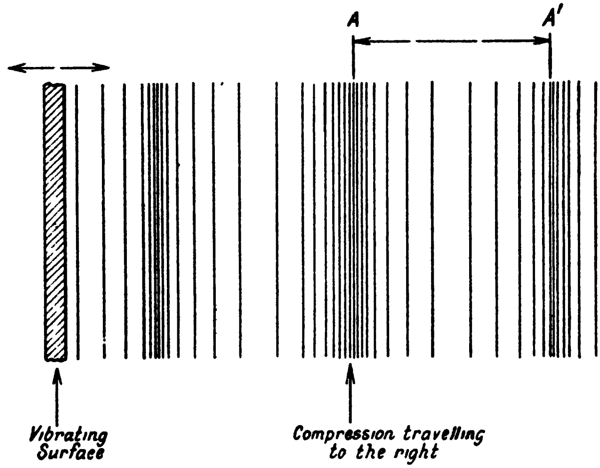


FIG. 1. VIBRATING SURFACE GENERATING COMPRESSION WAVES

per second may be written "100∼." It will be seen from Fig. 1 that each time the vibrating surface goes through its cycle of movement it generates one compression and one rarefaction. If the frequency of vibration of the surface is 100 c.p.s., 100 compressions per second pass an observer some distance away. Hence we see that we can speak of the frequency of the sound wave, which is equal to the frequency of vibration of the surface which generated it. There will be many occasions in this book in which the frequency of a vibration or of a sound wave is mentioned.

The range of frequency to which the human ear is sensitive is not very definite. Roughly speaking, the audible range may be taken to lie between 20 and 20,000 c.p.s. The upper limit decreases markedly with advancing age. Animals, particularly the smaller ones, can hear sounds of considerably higher frequency than humans. Table I, which gives the frequency of some common sounds, may assist readers to appreciate the significance of frequency.

A sound which consists of a single frequency is called a *pure tone*. It is rare for a sound to consist of a pure tone. Most sounds consist

TABLE I

CHARACTERISTIC FREQUENCY OF SOME COMMON SOUNDS

	Cycles
Lowest note audible to average human ear	16
Lowest note of large organ	16
Lowest note of piano	27
Lowest note of bass voice	80
Hum of static transformer on 50-cycle supply	100
Fog horn	180
Middle C (piano)	256
Electric motor horns	500–1,000
Highest note of soprano voice	1,200
Highest note of piano	3,480
Highest note audible to average human ear	20,000

of a large number of pure tones, the intensity and frequency of which can be obtained by various means.

Pitch. The musically minded will recall the connexion between the pitch and frequency of a note, namely, that the pitch rises as the frequency is increased. There are many simple numerical relations between the frequencies of notes separated by common musical intervals: for example, if two notes are an octave apart in pitch, the frequency of the higher is twice that of the lower. A full account of these relations will be found in almost any standard textbook dealing with Sound.

Wavelength. Another term besides frequency is required to describe a sound wave, namely its wavelength. In the case of a surface wave on water, the wavelength is the distance separating successive wave crests. A sound wave in air does not, of course, have any actual wave crests associated with it, because the air displacements are in the same direction as that in which the sound is travelling (see Fig. 1) instead of at right angles as in the case of a water wave. The wavelength is accordingly defined in a somewhat different, though analogous, fashion, namely as the distance between successive regions of maximum compression such as are shown at A and A' in Fig. 1. The distance AA' in Fig. 1 is accordingly the wavelength of the sound.

Velocity of Waves. The velocity with which sound waves travel depends only upon the physical properties of the medium. It is shown in textbooks dealing with sound that the velocity (V) of a sound wave in a given medium is given by the formula—

$$V = \sqrt{\frac{E}{d}}$$

where E = the elasticity of the medium and d its density. Elasticity is the relation between the fractional deformation and the load per unit area which produces it, i.e. it equals the stress divided by the strain. "Stiffness" is a term which usually expresses the relation between the force applied and the actual deformation which occurs. Unlike elasticity, therefore, it is not independent of the shape of the specimen.

The velocity of sound in some common media is given in Table II.

TABLE II

VELOCITY OF SOUND IN SOME COMMON MEDIA

Medium	*Velocity of Sound (feet per second)*
Rubber	100–200
Air	1,100
Cork	1,600
Water	4,900
Brickwork	12,000
Steel	16,000

The frequency, wavelength, and velocity of sound are all connected by the simple relation: wavelength equals velocity of sound

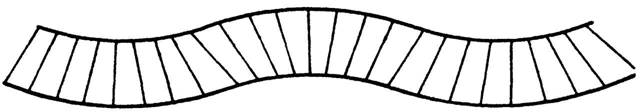


FIG. 2. ONE TYPE OF FLEXURAL WAVE IN A SOLID
Solids in the form of rods or sheets can vibrate in this way.

divided by its frequency. Thus for a given frequency, the greater the velocity of the sound the greater will be its wavelength. If sound passes from one medium to another in which the velocity is different, the frequency remains unchanged, but the wavelength will alter: for example, when sound passes from air to brickwork, its wavelength is multiplied approximately tenfold.

Intensity of a Sound Wave. The greater the extent of the pressure variations in a sound wave, the more intense is the sound. "Intensity" is an expression sometimes used in a rather loose manner, but the word has a precise significance to the physicist in that the "intensity" of a progressive sound wave is defined as the rate of flow of acoustical energy through a unit area at right angles to the direction in which the wave is travelling. "Intensity" must not be confused with "loudness," although the two are connected. This point is dealt with later.

Types of Wave Motion. In air and water only one type of wave motion can occur, namely compressional (also called longitudinal) waves: these are the type illustrated in Fig. 1. In solids, on the other hand, flexural waves (see Fig. 2), in which the displacement is at right angles to the direction of motion, are also possible, since solids, as opposed to fluids, have rigidity as well as compressional elasticity. There is very little difference between the properties of the various types of wave. In a solid the velocities of the two types of wave motion differ because they involve different elasticities.

Behaviour of Sound Waves. Sound has many of the properties of light (which also consists of waves): it can be reflected (as an echo) and can be absorbed (just as light is absorbed at a dead-black surface).

The reflection of waves can be observed by watching the progress of water ripples near an obstacle. The echo arising from reflection of sound can be readily observed by clapping or shouting at a fair

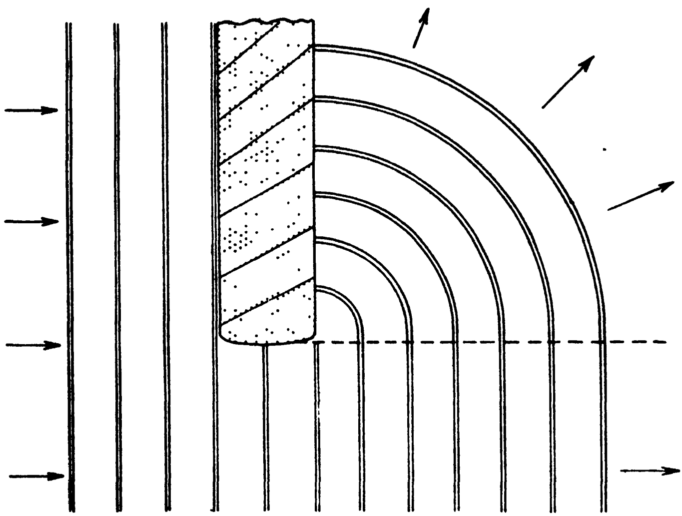


FIG. 3. WAVES SPREADING INTO THE "SHADOW" BEHIND AN OBSTACLE

distance away from a building or belt of trees. In some cases reflection increases noise; in others, by creating a "sound shadow," it reduces noise.

Except in the case of high-frequency sound (for which the wavelength is short), ordinary obstacles do not cast the sharp-edged shadows which occur in the case of light. The difference, of course, arises from the minuteness of the wavelength of light. Sound shadows have diffuse edges, because sound, by virtue of its comparatively large wavelength, can spread round corners. This phenomenon is termed *diffraction*. The explanation is too complicated to give here; perhaps it will suffice to show a diagram illustrating the effect (Fig. 3). The figure shows plane waves approaching a sharp-edged obstacle and spreading into the "shadow" region. The relation between size and effectiveness of an obstacle can be readily observed in the case of ripples on a pond. If they meet a small obstacle, such as a walking stick, the appearance of the ripples a few inches beyond the stick is scarcely affected by its presence.

A larger obstacle can be seen to cast a definite "shadow." The significance of this effect in connexion with noise-reduction is explained later (Chapter XVI).

Similar effects occur when sound falls upon an aperture. Waves falling upon and being transmitted by an aperture are shown diagrammatically in Fig. 4. It will be noticed that the wave transmitted through the aperture spreads outwards into what would have been shadow in the case of light.

Passage of Sound from One Material to Another. We have so far

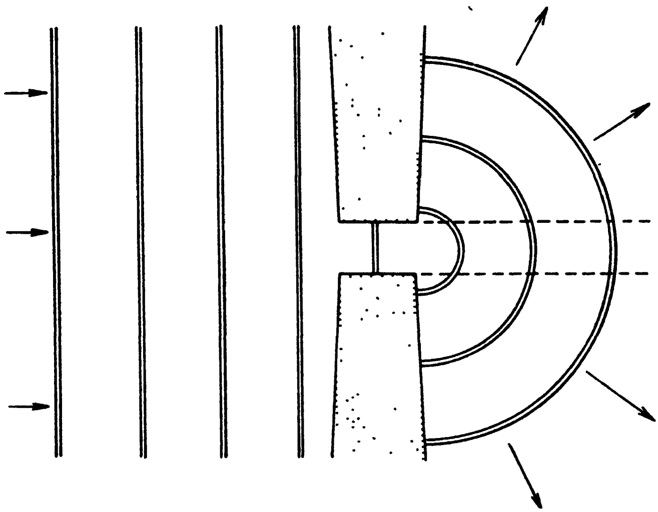


FIG. 4. WAVES SPREADING INTO THE "SHADOW" AFTER PASSING THROUGH AN APERTURE

tended to devote most attention to sound waves in air—a natural course, since this is the type of sound with which one is most familiar. Sound conducted through solid materials is, however, quite as important a factor in the transmission of sound in buildings.

An important question in this connexion is the degree to which sound can travel from one medium to another; to take an actual example, how easily is sound transmitted from brickwork to air? When sound in one medium reaches a boundary and enters another medium, it splits up into two sound waves, one of which is reflected back again into the first medium, the other being transmitted into the second medium. The splitting of a wave train as it passes from one medium to another is shown in Fig. 5. It will be noticed that this figure, which is taken from a photograph of high-frequency sound waves in liquids, also shows the phenomenon of refraction, namely that when sound passes between two media in which the velocities are different, the direction in which it travels is changed.

This phenomenon is, in the analogous case of light, responsible for the functioning of prisms and lenses.

Transmission from one medium to another has been carefully studied,* and the relation between the sound intensities in two unlimited adjoining media is determined by what are known as the *specific acoustic resistances* of the two media in question. The specific acoustic resistance can easily be calculated for any given medium, since it is the product of the density of the medium and the velocity of sound in it. For ease of reference, the value of this quantity for various common materials is given in Table III.

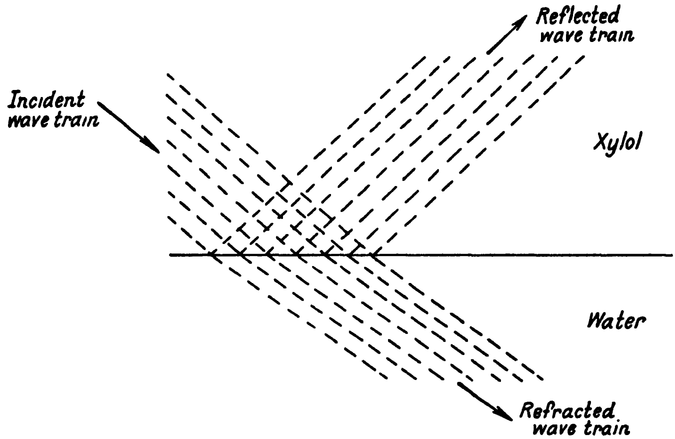


FIG. 5. REFLECTION AND REFRACTION OF WAVES AT THE SURFACE OF SEPARATION OF TWO MEDIA

TABLE III

SPECIFIC ACOUSTIC RESISTANCE OF COMMON SUBSTANCES

The specific acoustic resistance is the product of the velocity of sound (centimetres per second) and the density of the substance (grammes per cubic centimetre).

Air	0·0042		
Porous materials	0·0100–	0.0400	× 10^4
Rubber	0·29 -	0·66	× 10^4
Cork	1·2		× 10^4
Water	14·6		× 10^4
Wood	40·0	– 5·0	× 10^4
Brick	80·0	– 51·0	× 10^4
Marble	99·0		× 10^4
Lead	140·0		× 10^4
Glass	354·0	–120·0	× 10^4
Steel	390·0		

Fig. 5 exhibits what is termed *oblique incidence*, the sound falling at an angle to the surface of separation of the media. The mathematics of this are complicated, and are unnecessary for our present

* See, for example, RAYLEIGH: *Theory of Sound* (Macmillan & Co.).

purposes. As only a qualitative presentation of the facts is necessary, it will be sufficient to consider the very much simpler case of sound falling perpendicularly upon the surface of separation. This is illustrated in Fig. 6. If the specific acoustic resistances of the two media are R_1 and R_2 respectively and the sound is travelling from medium 1 to medium 2, it can be calculated that—

$$\frac{\text{Intensity of sound travelling in medium 1}}{\text{Intensity of sound entering medium 2}} = \frac{(1 + r)^2}{4r}$$

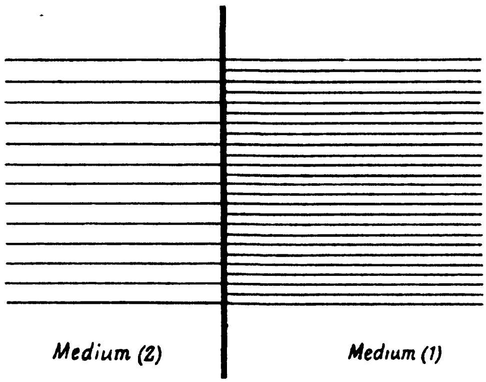


FIG. 6. LOSS OF INTENSITY WHEN SOUND CROSSES THE INTERFACE SEPARATING TWO DIFFERENT MEDIA

where r = ratio of specific acoustic resistances = R_1/R_2. It will be found that the same formula is obtained if the direction of the sound is reversed.

We can take as a practical example the transmission of sound from air to water. As shown in Table III, the specific acoustic resistances of these materials are 42 and 146,000 respectively; hence only about 1/1,000 of the energy of the incident sound wave would enter the water. This is the reason that the shouts of surrounding bathers are completely cut off when one dives below water.

The transmission losses which occur at the junction of two media are fortunate, for without them it is probable that buildings would be much noisier than they actually are. For example, sound from a hissing tap travelling through the water in the pipes is not easily conducted to the walls of the pipe and hence to the surrounding air. Similarly, only a fraction of the structure-borne sound travelling through the walls of a building is conducted to the air and heard, as may be verified by placing the ear against the wall of a building the structure of which is being hammered.

It should perhaps be pointed out that the transmission losses occur whatever the type of wave motion, whether longitudinal or flexural.

The above formula applies only when both media are unlimited in thickness (the atmosphere and the ocean are sufficiently close approximations to this). It is more usual for one of the media to be comparatively thin—for example, a brick wall. Fig. 7 represents an example of this state of affairs, medium 2 (e.g. a brick wall), of thickness t, being between two stretches of medium 1 (e.g. air).

It might be thought that because there is a certain transmission

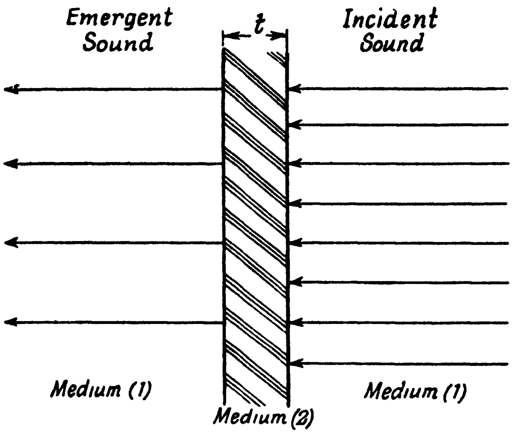


FIG. 7. LOSS OF INTENSITY WHEN SOUND PASSES THROUGH A SHEET OF A DIFFERENT MEDIUM

loss when sound passes from medium 1 to medium 2 and a similar loss in passing from medium 2 to medium 1, one would get the loss twice over by using medium 2 in the form shown in Fig. 7, whereby it is ensured that the sound has to cross the surface between the two media twice. This is not the case. The explanation is, roughly speaking, as follows—

On account of the difficulty of transmitting sound across the boundary between the two media, sound which has entered medium 2 is, so to speak, trapped within it. It consequently builds up until the vibration within medium 2 is sufficient to ensure that the sound entering it equals the sound leaving it from its two surfaces. On this basis a theoretical formula for the transmission through a layer of a different medium has been calculated.*

Transmission Loss due to a Change in Area. Transmission losses similar to those which occur at a change of medium occur also at a change of area of the medium. For example, if sound is travelling along a tube (a practical case would be a ventilating duct) and it

* See A. H. DAVIS: *Modern Acoustics.*

reaches a point at which the cross-section changes (becoming larger or smaller), reflection occurs and only part of the sound energy is transmitted beyond this point. The formula expressing the transmission loss is as follows—

$$\frac{\text{Intensity of sound waves approaching the change of section}}{\text{Intensity of sound waves leaving the change of section}} = \frac{(m+1)^2}{4m}$$

where m is the ratio of the areas of cross-section.

The similarity of this formula to that for the loss at a change of medium will be apparent. As an example may be considered a ventilating duct the area of which changes abruptly from $\frac{1}{4}$ sq. ft. to 2 sq. ft.: the transmitted sound intensity would be only about two-fifths of the incident sound intensity. Formulae for the loss of intensity produced by several consecutive changes of cross-section can be obtained from text-books.*

Sounding-board Effects. There is one other effect which may be considered briefly, namely reinforcement by what might be termed the sounding-board effect. If a source of vibration has a small area it causes little airborne sound; if, however, it is mechanically connected with a large area which is easily moved, the volume of airborne sound can be greatly enhanced. Examples are to be found everywhere: possibly a musical instrument such as a piano gives one of the best illustrations. The vibration of the wires can generate little sound, on account of their small cross-section: the vibration is rendered audible by the large sounding board to which they are secured. The principle has practical importance in reducing noise in buildings: it is a bad practice, for example, to fix an electric motor rigidly to a wood panel or even to a wall or floor, as these would act as sounding boards.

Tyndall has shown a very interesting experiment which illustrates this effect and also illustrates the conduction of vibration along solids. The description given in his textbooks of sound is so clear that we reproduce it here—

"We are now prepared to appreciate an extremely beautiful experiment, for which we are indebted to Professor Wheatstone and which I am now able to make before you. In a room underneath this, and separated from it by two floors, is a piano. Through the two floors passes a tin tube $2\frac{1}{2}$ in. in diameter, and along the axis of this tube passes a rod of deal, the end of which emerges from the floor in front of the lecture table. The rod is clasped by india-rubber bands, which entirely close the tin tube. The lower end of the rod rests upon the sound board of the piano, its upper end being exposed

* See A. H. Davis: *op. cit.*; also G. W. Stewart and R. B. Lindsay: *Acoustics*.

before you. An artist is at this moment engaged at the instrument, but you hear no sound. I place this violin upon the end of the rod: the violin instantly becomes musical—not, however, with the vibrations of its own strings, but with those of the piano. I remove the violin, the sound ceases; I put in its place a guitar, and the music revives. For the violin and the guitar I substitute this plain wooden tray: it also is rendered musical. Here, finally, is a harp, against the sound board of which I cause the end of the deal rod to press: every note of the piano is reproduced before you. I lift the harp so as to break its connexion with the piano: the sound vanishes; but the moment I cause the sound board to press upon the rod, the music is restored."

Detection and Measurement of Sound Waves. Sound waves in air are detected and measured in a variety of ways. Excluding the ear, which although a sensitive sound detector is not a good measuring instrument, a microphone is the most common method of observing and measuring sound. Usually the microphone depends for its action upon the motion of a thin sheet of material when exposed to the minute pressure changes in the sound wave, the mechanical oscillations being converted to electrical oscillations by appropriate means; the electrical oscillations can then be amplified and measured. There are also other devices such as the Rayleigh disk, which is only suitable for specially equipped laboratories and which is used for calibrating microphones.

Sound waves in liquids can be detected photographically, but more usually a microphone is used. In the case of acoustical depth-sounding at sea, in which measurement of the time taken for a sound wave to travel from the ship to the sea bottom and back again provides a means of determining the depth of the sea, microphones constructed of quartz crystals are used. The deflection of the quartz by the pressure due to the sound wave creates small changes of electric potential, which can be amplified and used to detect the wave.

Waves in solids are observed by vibration detectors: a gramophone pick-up is an example of such a detector, though the instruments usually employed are constructed somewhat differently.

It is also possible, besides measuring the intensity of the sound as a whole, to determine the intensity (and frequency) of each individual component. Alternatively, the intensity of any desired frequency ranges can be measured, as shown in Fig. 8, for various noises. Such measurements, or noise analyses, are valuable in all kinds of noise-reduction problems, as will become apparent in the following chapters.

Intensity and Equivalent Loudness: the Decibel and the Phon. The intensities of common sounds vary over a very wide range, and it is remarkable that the ear should be able to respond to such variations. For instance, at medium frequencies the intensity of very loud sound, such as a pneumatic road drill at close quarters, is ten times that of a just-audible sound. A convenient method of expressing such a ratio is supplied by a logarithmic scale, which is

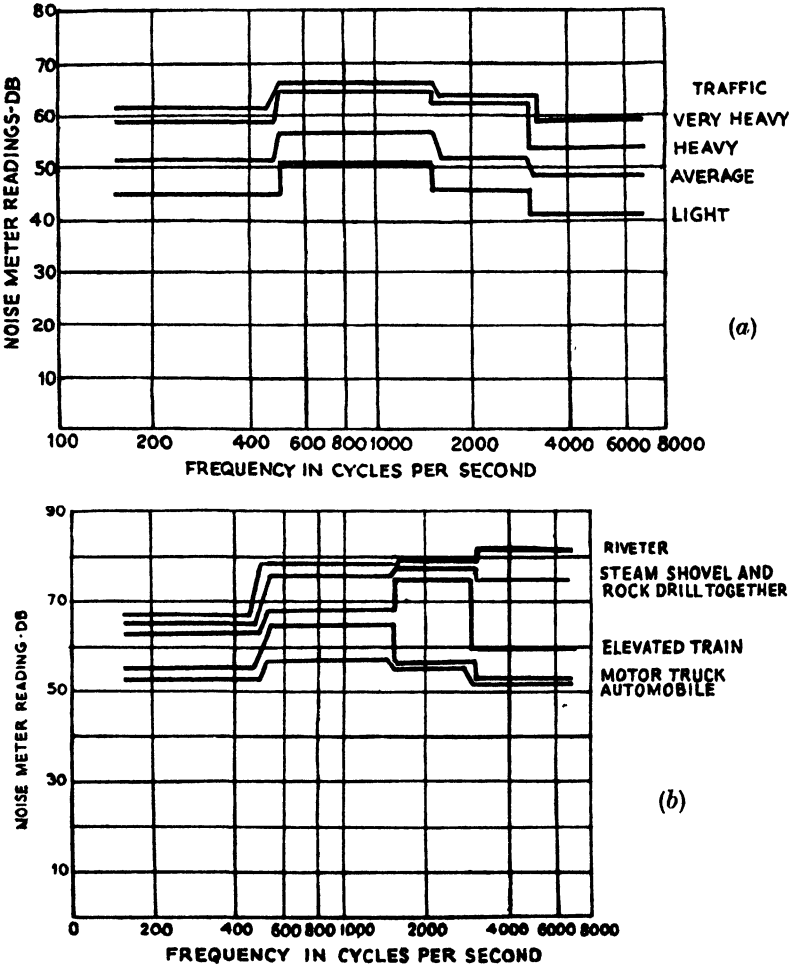
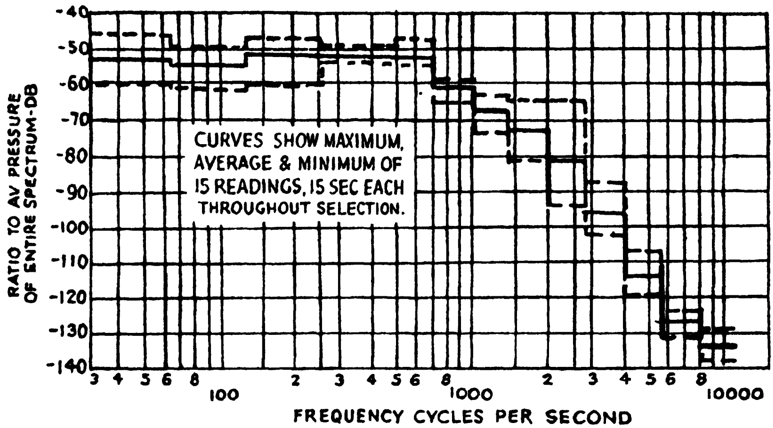


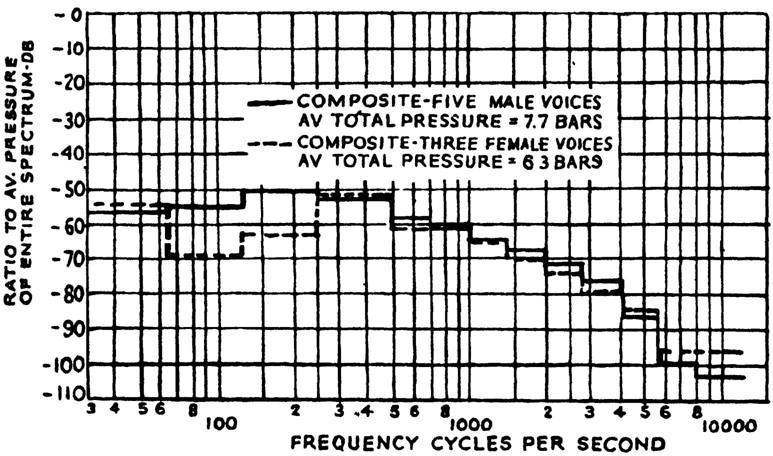
FIG. 8. ANALYSES OF SOME COMMON NOISES

(*a*) Physical analyses of typical New York street noises.
(*b*) Physical analyses of various noises.

often used in other branches of physics. Through the use of such a scale the frequently mentioned but less frequently understood unit, the decibel (abbreviated as db.), has come into being. The relationship between two sound intensities, expressed in decibels, is ten times the common logarithm of their ratio. Thus a ratio of 10 is equivalent to 10 db., 100 is equivalent to 20 db., 1,000 to 30 db., and so on. A table enabling numerical ratios to be converted to



(c)



(d)

FIG. 8—(*contd.*) ANALYSES OF SOME COMMON NOISES

(*c*) Average pressures per frequency interval of 1 c.p.s. (piano selection of Liszt's "Hungarian Rhapsody No. 2"—average total pressure, 3·5 bars).

(*d*) Average speech pressures per frequency interval of 1 c.p.s. (normal conversational voice—distance, 2 in.).

In each figure relative values of the intensity (in logarithmic units) in various frequency ranges can be seen (the absolute values of the intensity need not detain the reader). In (*a*) and (*b*) it will be noticed that the ranges are: less than 500, 500–1,500, 1,500–3,000, and above 3,000 c.p.s., while in (*c*) and (*d*) the ranges are smaller.

decibels and conversely is given at the end of this book (Table XXVII). It is important to notice that the decibel unit applies only to ratios. A sound intensity is sometimes loosely expressed in decibels, but this always should be understood as "decibels above a certain zero." Usually the zero chosen is one which approximates to the limit of audibility.

We have so far dealt only with the intensity of a sound: this is a physical quantity which is easily measured as described earlier. In questions of noise in buildings, however, we are more directly concerned with the sensation of loudness experienced by the ear when stimulated by the aerial sound wave. The sensation of loudness is related to the intensity, but the relationship is by no means a simple one. To begin with, the ear reacts differently to sounds of the same intensity but differing in pitch. The first step in simplifying the position is to choose arbitrarily a pitch to serve as standard, 1,000 ~ being usually chosen for the purpose. Then the loudness of sounds of other frequencies is matched against the loudness of the 1,000 ~ sound. There are two methods of doing this—the subjective and objective methods. These are closely analogous to the methods commonly used for determining the candle-power of lamps. The subjective method, in which the loudness is assessed by determining the intensity of a standard 1,000-cycle note which appears to the ear to be as loud as the noise in question, is analogous to determining the number of standard candles necessary to provide the same illumination as the lamp in question. The objective method, in which the noise is picked up by a microphone, the output of which is determined by the aid of a valve amplifier specially made to simulate the characteristics of the human ear, is analogous to the photometers which employ photo-electric cells with colour filters to simulate the characteristics of the eye. Just as in photometry we endeavour to express the illumination obtainable from a lamp (whatever its colour) in terms of the illumination from a lamp of standard colour, so do we express the loudness of a noise (whatever its frequency or composition) in terms of the loudness of a noise of standard frequency. Corresponding to the accepted unit of illumination, viz. the foot-candle, there has been adopted a unit of "equivalent loudness" termed the phon.* In other words, the phon scale is used to get over the difficulty that sounds of the same intensity but different frequency do not sound equally loud to the ear. For a full definition of the phon, readers are referred to the *British Standard Glossary of Acoustical Terms and Definitions*. Briefly, the phon scale is related to the decibel scale in the following way: If a noise is as loud (under certain conditions) as a 1,000-cycle pure tone of intensity n db. above an agreed zero near the threshold of audibility, then the noise has an "equivalent loudness" of n phons. It should be explained that the word "equivalent" is for shortness' sake often omitted in the literature of the subject (including later sections of this book).

The variation of ear sensitivity with frequency deserves closer

* Mr. L. S. Lloyd, in his book, *Decibels and Phons*, develops an interesting musical analogy to explain the relation between the two units.

study. It is, for example, a matter of common observation that sounds can be too low or too high in pitch to be heard. Some people put the lowest notes of an organ in the former category (the 32 ft. pipes on a certain large organ were once described as an expensive draught), while the sound made by some insects is usually quoted as an example of the latter (the cricket for instance, is often inaudible to elderly people who are not otherwise deaf). Between

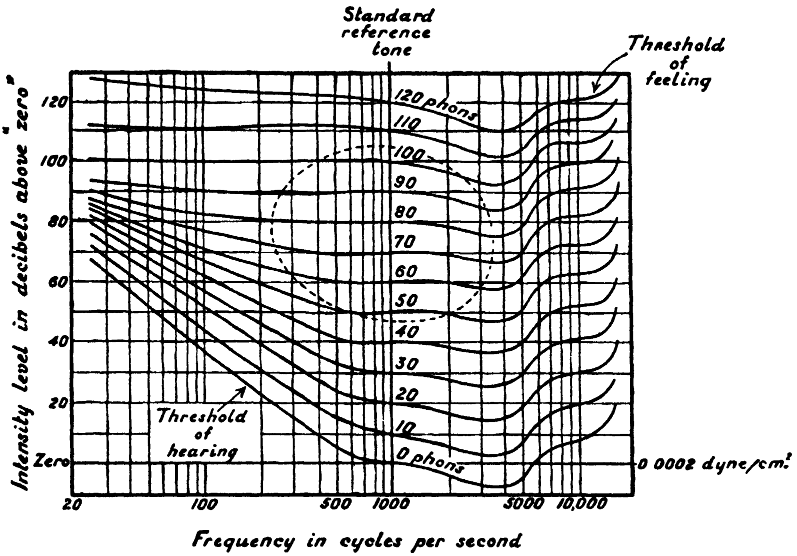


FIG. 9. CURVES SHOWING HOW THE INTENSITY OF A SOUND MUST BE VARIED AS THE FREQUENCY CHANGES IF THE LOUDNESS SENSATION IS TO REMAIN CONSTANT

these two limits the ear sensitivity increases as the region of 3,000–4,000 c.p.s. is approached. The curves reproduced in Fig. 9, obtained by Fletcher and Munson,* show how the intensity of the sound must be varied as the frequency changes if the apparent loudness is to remain constant. Only within a limited range (represented by the dotted line in Fig. 9) is the equivalent loudness in phons roughly equal to the intensity in decibels above zero. Each curve gives the intensity of sound of a specified frequency which is necessary to attain the loudness marked on the curve, and it will be noticed how very much more sensitive the ear is to quiet sounds of medium pitch than to notes of high or low pitch.

Another important fact is disclosed by the above curves. It will

* H. FLETCHER AND W. A. MUNSON: *Journ. Acoust. Soc. Amer.*, Vol. 5, p. 82, 1933.

be seen that the curves are spaced farthest apart in the medium-frequency region. This indicates that to change from one loudness to another a greater intensity change is required at medium frequencies than at high or low frequencies. In fact, it appears that whereas for frequencies in the neighbourhood of 1,000 c.p.s. a 1 db. change of intensity is by definition a 1 phon change of loudness, in the neighbourhood of 100 c.p.s. the same intensity change is appreciated as about 1½ phons change in loudness. The fact has important consequences in noise-reduction problems, for it happens that most sound-reducing treatments produce the smallest reductions of intensity at low frequencies (for example, absorbent treatment or soundproof walls). The peculiarities of the ear mentioned above do, however, provide a valuable degree of compensation for this effect.

Loudness Sensation Units. While it is not so difficult to match up sounds of equal loudness but varying pitch, it is a matter of considerable difficulty to listen to a sound of constant pitch but varying intensity and decide how the sensation of loudness varies with the intensity. Yet this is very important, for the whole practice of noise-reduction depends upon this characteristic of the ear. Early work led to the conclusion that the response of the ear was proportional to the logarithm of the intensity, in other words proportional to the intensity as given in decibels, but further investigation showed that this was an extremely rough approximation. There have been various attempts at compiling a scale of loudness sensation, and while no finality has yet been reached on this point, probably the most useful scale for our purpose is one proposed by Churcher* in connexion with industrial noise measurements (See Fig. 10). This scale has been established by ascertaining the change of sound intensity to halve or double the apparent loudness. The actual magnitude of the loudness sensation units chosen has no special significance, being chosen for convenience. For practical purposes, the following simple approximate formula has been suggested by Churcher for use instead of the curve in Fig. 10—

$$\text{Number of loudness sensation units} = p^5 \times 10^{-8}$$

where p is the "equivalent loudness" in phons.

For illustration, Table IV gives the equivalent loudness of some commonly occurring noises in phons, with the corresponding loudness sensation units.

This table may be taken as a general guide, but it should be remembered that the loudness sensation scale is an attempt at a subjective assessment, which is a very difficult matter to reduce to a numerical quantity. The table shows quite clearly, however, that a given change of loudness in phons produces a much greater effect at high noise levels than at low, thus a few phons reduction in the loudness of a pneumatic drill is a welcome improvement, while the

* B. Churcher: *Journ. Acoust. Soc. Amer.*, Vol. 6, p. 216, 1935.

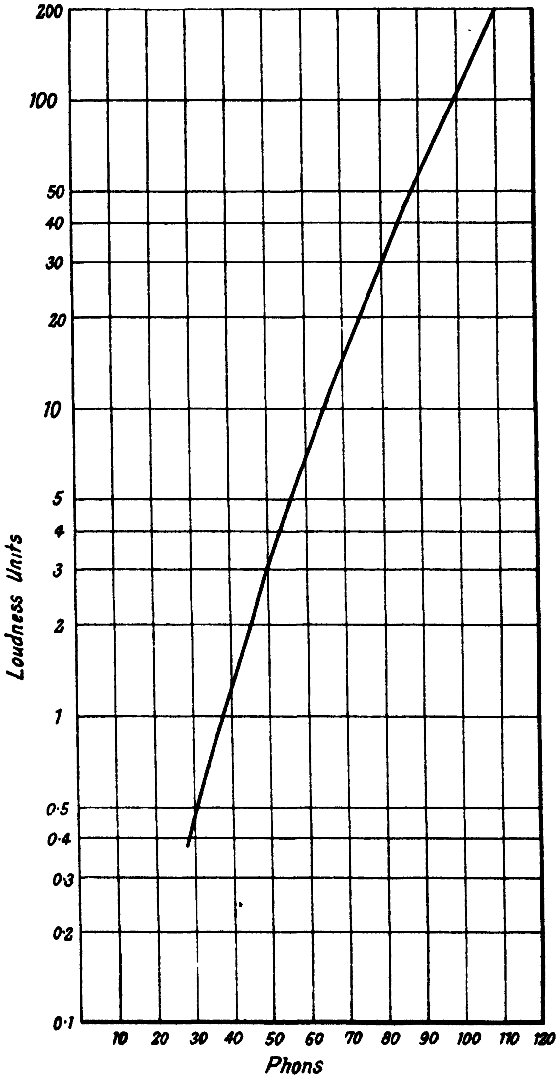


FIG. 10. A LOUDNESS SCALE FOR INDUSTRIAL NOISE MEASUREMENTS

TABLE IV

EQUIVALENT LOUDNESS AND LOUDNESS SENSATION UNITS

Noise	Phons	Loudness Sensation Units
Turning over newspaper	40	1
Quiet radio . .	50	3
General conversation .	60	8
Average radio . .	70	14
Noisy typing office .	80	33
Heavy traffic . .	90	59
Near loud motor horn .	100	100
Near pneumatic drill .	110	161
Near aero engine . .	120	248
Pain in the ear . .	130	425

same change in the loudness of a small ventilating fan would not be nearly so noticeable. A convenient fact to remember is apparent from the table, namely that for sounds of medium loudness an increase of 10 phons approximately doubles the loudness sensation.

Table IV presents very vividly the problem confronting, say, the designer wishing to reduce the noise in a room full of machines. To halve the loudness sensation it would be necessary to obtain a reduction of about 10 phons, that is to say, the intensity of noise emitted by each machine would have to be reduced to one-tenth, or the number of machines in the room would have to be reduced to one-tenth. Even halving the intensity of the noise would reduce the loudness by 3 phons only, which though appreciable at high levels, is not a spectacular reduction in loudness sensation.

The ear has another property which should be borne in mind when dealing with noise-reduction problems, namely that there is a limit to the smallness of the change of loudness which can be detected. This is about 3 phons at low noise levels, about 1 phon at medium levels, and at high levels is a fraction of a phon.

Resonance. One more phenomenon must be discussed before this chapter is brought to a close. This is the phenomenon of *resonance*. Many illustrations of resonance occur in daily life: very good examples can be observed in cars (provided they are not too well made). In an average car it can nearly always be noticed that there are certain speeds at which certain parts of the car buzz or rattle: the gear lever may vibrate violently at one speed and a loose ash tray at another. Frequently quite a small change of speed will stop the vibration. These are examples of resonance. Another example, which the builder and architect will appreciate, is the way in which a scaffold plank will vibrate to an almost dangerous extent if the person walking on it steps at the right frequency. Analogous to this is the resonant vibration of a bridge when walked upon, particularly a suspension bridge. It is usual, on this account, to give orders for soldiers to break step when marching across a bridge. The danger of this type of resonant vibration was demonstrated in 1831, when a suspension bridge at Broughton, near Manchester, gave way while a party of soldiers was marching over it.

Resonance effects may occur whenever an alternating force is applied to a system which is capable of vibration, i.e. possessing mass and stiffness. To fix our ideas, we may consider the simple system consisting of a weight suspended on a spring (Fig. 11). If the weight is deflected from its natural position of rest and is then released, it will execute vibrations of a definite frequency, which is determined by the mass of the weight and the stiffness of the spring, but which does not depend on the magnitude of the deflection. The frequency of vibration in cycles per second of a weight of m lb. suspended on a spring which requires a weight of W lb. to deflect it 1 in. is equal to $3{\cdot}17\ \sqrt{(W/m)}$. This frequency is called the *natural frequency of vibration* of the system, and the vibrations are called *free vibrations*. If, however, instead of simply releasing the weight it is driven by an alternating force, the resulting vibration is termed *forced vibration*. (In the case of the bridge, the alternating force is supplied by the regular footfalls of the soldiers, and the resulting forced vibration is measured by the extent of the up-and-down motion of the bridge.)

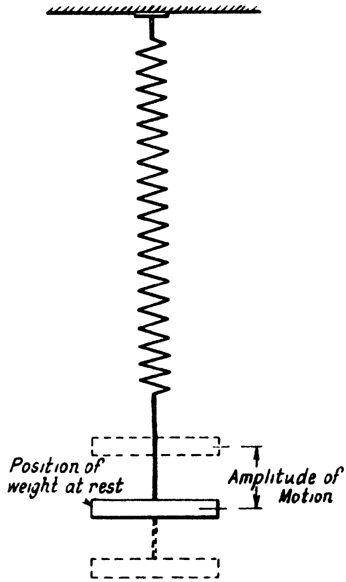


FIG. 11. VIBRATION OF A WEIGHT SUSPENDED BY A SPRING

If now, the force being kept constant, the amplitude of motion (i.e. its maximum displacement from its position of rest) of the weight is plotted graphically as the frequency of the alternating force is varied, a curve similar to that in Fig. 12 will be obtained. The greatest amplitude will result when the frequency of the force approximately equals the natural frequency of vibration of the system. This is a general condition for the occurrence of a resonance.

The importance of resonance effects will appear in many ways in subsequent chapters; at this stage it is unnecessary to do more than make the general remark that whenever a resonance occurs, the disturbance of the system will usually be very much more than it would have been had the frequency of the applied force not been approximately equal to a natural frequency.

The magnitude of the resonance amplitude is determined by the size of the dissipative forces (friction, etc.) which are always associated to a greater or less extent with vibrating systems. In the case of a weight suspended on a spring and vibrating in free air, the dissipative forces would almost certainly be small (since for all practical purposes they would be supplied by the air only). If the same system

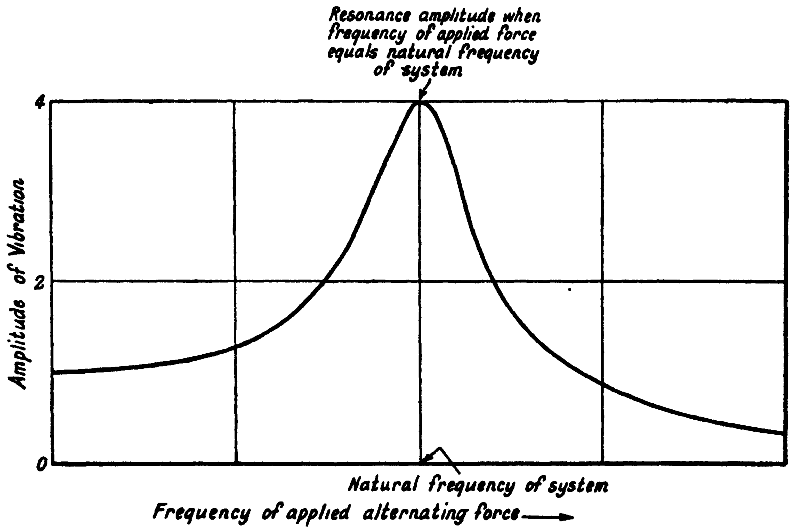


FIG. 12. RESONANCE CURVE

were immersed in oil, the viscosity of this material would cause a marked increase in the dissipative forces, and it is important to note the effect of this upon the resonance. It can be shown theoretically, and it is confirmed by common experience, that the greater the dissipative forces, the smaller is the resonance amplitude. For this reason these forces are spoken of as having a *damping* effect. In Fig. 13 resonance curves are drawn for three different degrees of damping.

It will be seen that the greater the damping, the less is the difference between the magnitude of the resonance amplitude and of amplitudes for other frequencies of vibration. In other words, the greater the damping, the less marked is the resonance. It should, perhaps, be pointed out that the damping produces this effect by decreasing the amplitude of vibration at all frequencies, and particularly for frequencies at or near the natural frequency of the system. There is no question of the vibration at frequencies away from the resonance being increased by the damping as is sometimes thought.

So far we have spoken of vibrating systems which have only one natural frequency of vibration. This state of affairs is actually quite uncommon, and it is more usual for systems to have a large number

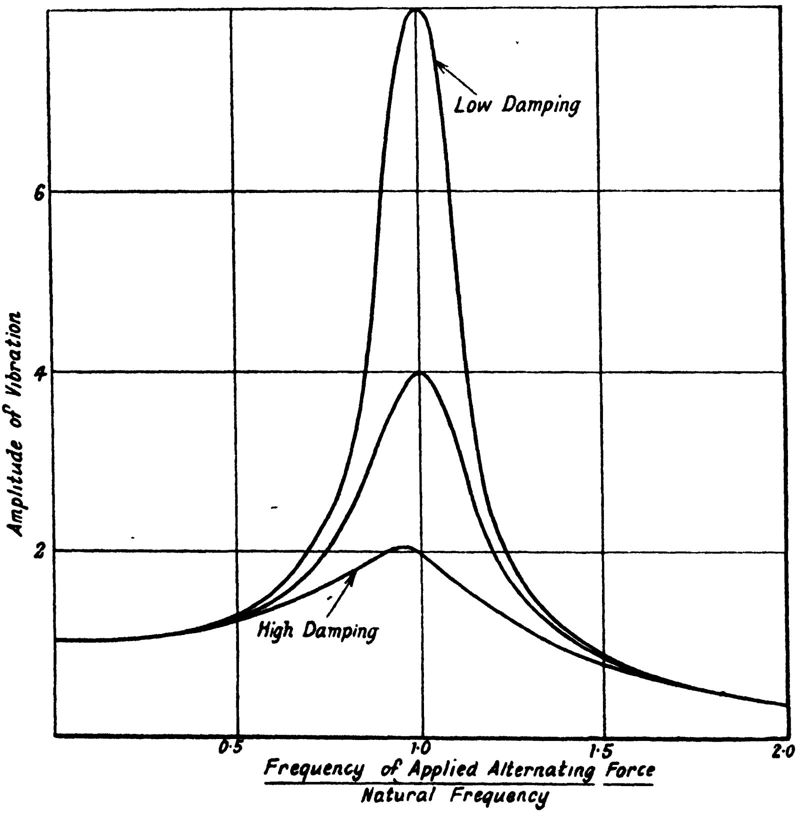


FIG. 13. RESONANCE CURVES FOR THREE DIFFERENT DEGREES OF DAMPING

of resonance frequencies, some of which, quite possibly, are more important than others. A typical example is a metal plate. The fact that this has a number of resonances can be heard when it is struck: the discordant nature of the sound emitted shows that a number of notes (each due to some particular resonance) has been excited. This may be compared with the note from a tuning fork, which is designed so that one resonance predominates. The reason for the large number of resonances is that a plate, unlike a weight

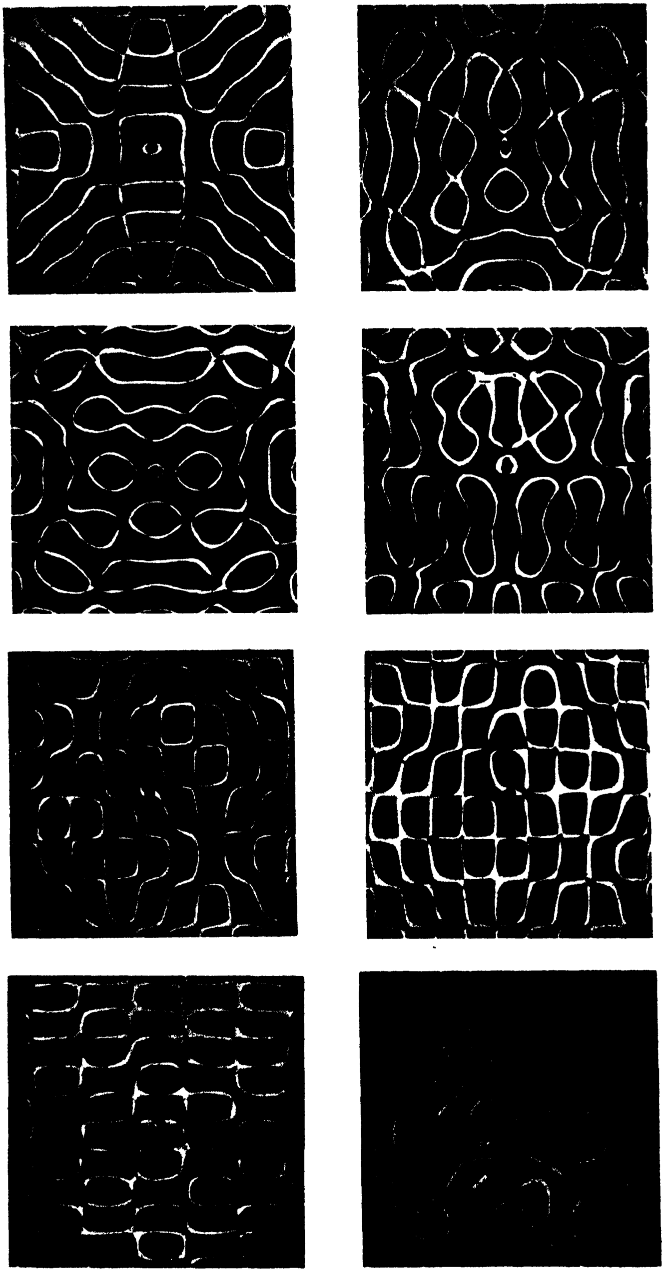


Fig. 14. Chladni's Figures

on a spring, can vibrate in a number of different ways. More or less complicated bending takes place, with the result that some parts of the plate move one way, others move in an opposite direction, and parts between are motionless. This was first shown by Chladni, whose name has been given to the beautiful vibration patterns which can be obtained from vibrating metal plates. Chladni conceived the idea of sprinkling sand on a vibrating plate, and since the sand naturally collected on the parts of the plate which were

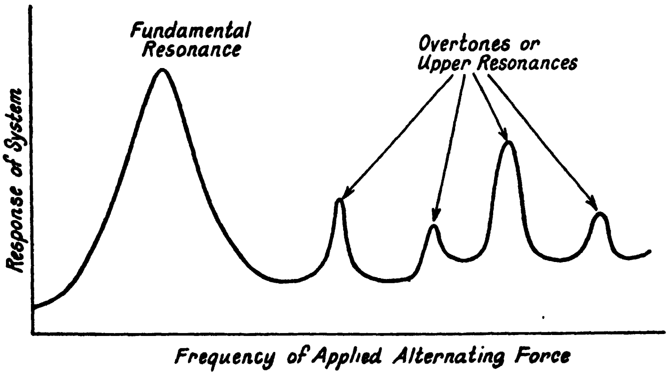


FIG. 15. RESPONSE OF A SYSTEM POSSESSING SEVERAL RESONANCES

motionless, he was able to study the form in which the plate vibrated. A selection from the patterns obtained in this way is shown in Fig. 14. Similar patterns obtained for a brick wall vibrating under the influence of sound falling on it are shown in Fig. 86.

The large number of resonances possessed by metal plates is typical of vibrating systems: one can instance the resonances of a violin string and the air in an organ pipe, in this connexion. These resonances, as musicians will appreciate, determine the character or "timbre" of the note of a musical instrument. The lowest natural frequency is termed the *fundamental frequency*, the remainder being termed *overtones* or merely *upper resonances*. In the neighbourhood of each resonance the relation between the response and the frequency of the driving force is similar to that shown in Fig. 12 for the case of a single resonance. As a consequence, the response curve of a system possessing several resonances is somewhat as shown in Fig. 15.

CHAPTER II

THE PROBLEM OF NOISE-REDUCTION IN BUILDINGS

THE purpose of this short chapter is to make one point only, namely that reducing noise in a building is a problem which needs to be tackled systematically. It is, of course, possible to apply treatment in a haphazard fashion and achieve a measure of success. It must often happen, however, that the treatment (applied maybe on the advice of a salesman or advertisement) has practically no effect, and a new treatment has to be applied or the problem abandoned. Most architects will have met cases in which a number of noise-reducing treatments have been tried one after the other with little success. For the best results, each problem should be studied individually. Even if a particular treatment has proved successful in one set of circumstances, it may prove strangely unsuccessful in an apparently similar set of circumstances, and the reason for the failure may not emerge until a careful quantitative study has been made of the various factors involved.

In designing a large building in which noise-reduction is an important matter, the busy architect will probably prefer to call in a specialist for assistance in some aspects of the problem. Better results are likely to be obtained, even in such cases, if the architect has a good general knowledge of the principles involved. Ordinarily, however, no great subtlety is called for in dealing with noise problems, and a knowledge of the general principles should enable an architect to deal with most, if not all, of the problems which come his way.

It is perhaps relevant to point out here the value of a scientific study of building problems. The experience which an architect gains during his career is an extremely valuable foundation upon which to base future designs. There can be no doubt, however, that it is important from every point of view that this experience should be supplemented with reliable information concerning building methods and materials. The need for such information is one of the reasons for the establishment of research institutions such as the National Physical Laboratory and the Building Research Station. These institutions are in a position to determine the value of proposed constructions, to carry out extensive investigations with the object of ascertaining fundamental principles, and to collate the information obtained from the numerous other laboratories interested in problems of building construction. It should be added that the information so obtained is normally freely available to all inquirers.

Choice of a Sound-insulating Construction. Certain recommendations have been made, principally in connexion with housing schemes, as to the minimum acceptable degree of sound-insulation in certain positions (see Chapter XVI). In some other countries recommendations or legislation had been made prior to 1939 on similar lines; these are included in Chapter XVIII for the sake of interest. The chief aim of this book, however, is to set out clearly the effects of the various factors which influence sound insulation, so that where past experience has shown insulation to be defective, the steps which should be taken to effect an improvement will be known. A knowledge of these factors also makes it possible to avoid those errors of design and faults in construction which prevent the attainment of the maximum possible insulation.

General Methods of Reducing Noise in a Building. Building noise may originate as a structural vibration, e.g. impacts on a wall or floor, or as an air vibration, e.g. sound from a loudspeaker. Correspondingly, noise can be conducted from place to place either through the structure (structure-borne sound) or through the air (airborne sound). Although there are cases in which noise is conveyed about a building purely as airborne sound, e.g. through a ventilating duct, it is more usual for the conduction to be partly through the structure and partly through the air. A simple example is transmission through a wall; the sound originates in the air, is conducted through the air to the wall, passes as structure-borne sound through the wall, and reappears as airborne sound on the other side. A rather more complicated example would be transmission of sound from a room through the structure of the building to a distant room.

Noise problems as met by the architect are almost certain to lie within one of the following three groups—

1. Preventing noise from entering a building.
2. Preventing noise from leaving a building.
3. Preventing noise from being transmitted from point to point within a building.

In the short table below, the broad lines which treatment should follow are set out. It will be noted that there is a close relationship between the treatments in the three cases.

1. *Preventing Noise from Entering a Building.*

(*a*) Select the site and plan the building with a view to minimizing the need for special sound-insulating measures. (See Chapter III.)

(*b*) Take steps to impede transmission of airborne sound. (See Chapters V, VIII, IX, X, XI, XII.)

(*c*) Take steps to impede transmission of structure-borne sound. (See Chapters VI and XIV.)

2. *Preventing Noise from Leaving a Building.*

(*a*) Select the site and plan the building with a view to minimizing the need for special sound-insulating measures. (See Chapter III.)

(*b*) Reduce noise at the source. (See Chapter IV.)

(*c*) Take steps to impede the transmission of air-borne sound. (See Chapters V, VIII, IX, X, XI, XII.)

(*d*) Take steps to impede the transmission of structure-borne sound. (See Chapters VI and XIV.)

The subject is dealt with as a whole in Chapter XVI.

3. *Preventing Noise from being Transmitted from Point to Point within a Building.*

(*a*) Plan the building so as to minimize the need for special sound-insulating measures. (See Chapter III.)

(*b*) Take steps to reduce the noise in question at the source. (See Chapter IV.)

(*c*) Take steps to impede the transmission of airborne sound. (See Chapters V, VIII.)

(*d*) Take steps to impede structural transmission of sound (including transmission along water pipes, etc.). Included in this section is the prevention of transmission through floors of noise due to footsteps. (See Chapters VI, VII, XIII, XIV.)

(*e*) Reduce sound originating as airborne sound and transmitted through the structure, e.g. sound transmitted through walls. (See Chapters IX, X, XI, XII, XIII, XIV.)

The above table, while convenient for laying out the lines upon which sound-insulation treatment can be provided, does not provide a suitable basis for discussing the treatments. The book has accordingly been planned to deal with the insulated building member by member; doors, windows, and walls for example each receiving separate chapters.

It is hoped that once the principles governing insulating treatment of the various members of a building have been described and have been illustrated with practical examples it will be possible for adaptations and special designs to be evolved for each problem which is encountered.

Finally, and this cannot be said too often, prevention is better than cure. Alterations which are simple while the building is still at the drawing-board stage may become very expensive once the building is erected.

CHAPTER III

PLANNING TO AVOID NOISE IN BUILDINGS

THE greater part of this book is concerned with the special treatments which can be used for dealing with noise problems. While in existing buildings such treatment may be unavoidable, new buildings should be designed so that special insulating treatment is required at as few points as possible. Such treatment almost always involves additional expenditure and in any event cannot be relied upon as a complete cure for noise problems, its efficacy being usually limited. Some treatment will almost inevitably be required in any building, but its extent can be kept down by skilful planning and by selecting quiet equipment. Planning is discussed in the present chapter, and quiet equipment in the next.

It is not intended to discuss comprehensively the lines which good planning should follow—the subject is too intricate for this to be done. The most that is aimed at is to call attention to the need for careful planning and to describe a few simple points which should be borne in mind when designing a building. Doubtless many others drawn from his own experience will occur to the reader.

Selection of Site. Bacon wrote: "He that builds a fair house upon an ill seat, committeth himself to prison"—a saying no less true of noise than of other evils. Planning of a quiet building should, in fact, commence when the site is being selected. Here it is of the first importance that local town planning authorities should be consulted to discover any projected schemes for the area concerned or for any adjacent area. It may well be that an undeveloped site may adjoin a projected industrial trading estate, arterial road, airport, or other source of noise. If, on the other hand, assurances are received from the authority concerned that the area is scheduled as a purely residential area, the developer may rest assured that future neighbouring developments will not be a source of disturbance.

In the case of built-up areas, a noise survey may help in the choice of a site, though no well-defined noise limits appear yet to have been laid down. Only one authority seems to have expressed an opinion regarding noise levels of sites suitable for different types of building: it is suggested that 40–50 phons is suitable for a residential quarter, 60–70 phons for business quarters, while 80–90 phons is to be expected in industrial areas.*

* "Das lärmfreie Wohnhaus," *Fachauschuss für Lärmminderung beim Verein deutscher Ingenieure*, Berlin. (The noise levels given above have been corrected to the international scale.)

It often happens that of necessity a building has to be placed near a railway, busy road, or other source of noise. In such cases a site which offers a natural screen, such as a belt of trees or an existing building, is to be preferred. The effect of sound shadows cast by buildings has been studied by Cockcroft and Brookes,* who have given figures for the considerable reductions in noise levels which can be obtained in this way. In addition, they showed that the noise level 120 ft. away from a busy road was about 32 phons less than the noise level in the road itself. In theory, there will be a

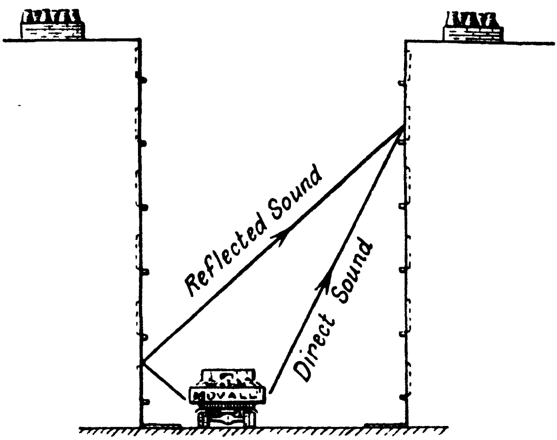


FIG. 16. REFLECTION OF SOUND FROM A BUILDING OPPOSITE MAY CAUSE UNNECESSARILY NOISY CONDITIONS AT THE WINDOW FACE OF THE BUILDING CONCERNED

reduction of 6 db. in the intensity of a noise emitted from a point source every time the distance from the source is doubled. In practice the reduction will usually be less than this on account of reflection of sound from hard road surfaces and so on. The value of placing the buildings as far as possible from the source of noise is obvious. Positions on main roads near a bus or tram stop, or on corners or hills where much stopping or gear-changing occurs, are likely to be particularly noisy. Sites near aircraft stations, where low flying is to be expected, are best avoided altogether.

Sites facing open ground are to be chosen in preference to those facing high buildings, for sound reflected from the building opposite will probably cause unnecessarily noisy conditions at the window face of the building concerned. (See Fig. 16.)

Planning to Avoid Entry of Noise from Outside. The planning of the building to exclude noise commences when the layout of the

* J. D. COCKCROFT AND A. M. P. BROOKES: *Journ. R.I.B.A.*, Vol. 42, p. 1048, 1935.

site is considered. One feature which should be given attention is the position of the access roads. These should be arranged so that traffic does not pass near rooms in which quiet is desired; another device is to provide several roads so that the traffic along any one road is thinned out. This was done in the flat group shown in Fig. 17. In planning a large site such as a housing estate, a cul-de-sac type of development may be used, both to prevent through traffic, and also to ensure that most of the houses face the access roads rather than a main road. From the point of view of amenity (including

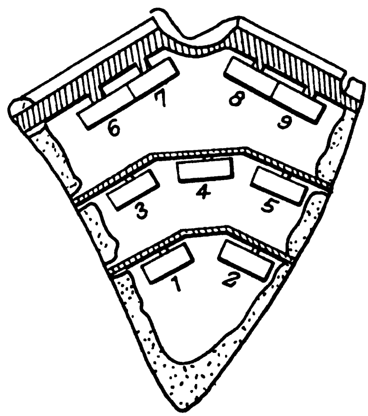


FIG. 17. GROUP OF FLATS LAID OUT TO OBTAIN SCREENING FROM ROAD-TRAFFIC NOISE

quietness) this type of development is far preferable to ribbon development.

Several noise-reducing features are commonly used in planning the building itself: setting the rooms back behind a balcony which affords a degree of screening against noise coming from below is an obvious example (see Fig. 18); projecting balconies, however, are inadvisable, since they may reflect sound into the window below. If windows facing a source of noise are necessary for natural lighting, alternative means of ventilation should be provided so that the windows may be of sound-insulating construction. Providing rooms on the top floor with ceiling lights for ventilation instead of opening windows in the wall is another example; planning the buildings so that only unimportant rooms or corridors, which act as buffers, are on the noisy side is yet another.

The central court type of plan may be sometimes useful but should be used with discretion; in blocks of flats for instance considerable noise may be made in the court by children playing, tradesmen calling and so on; also radio emerging from the windows of one room overlooking the court can disturb all the other rooms similarly situated.

Planning to Prevent Internal Noise Problems. Care in planning can be particularly valuable in avoiding disturbance caused by noise of internal origin. Common internal sources of noise are lifts, kitchens, garages, water services, and ventilating systems, and, of course, the more formidable noise caused by the occupants. Under the latter heading comes the noise of footsteps, dancing, conversation, loudspeakers, musical instruments and office machinery.

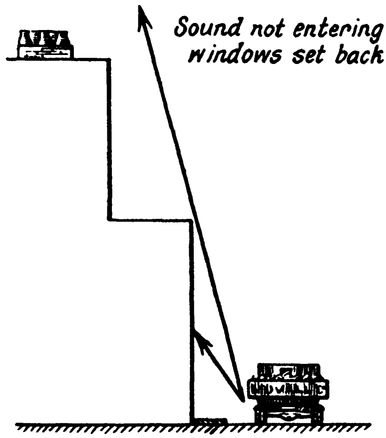


FIG. 18. METHOD OF REDUCING THE NOISE HEARD FROM TRAFFIC BY INTRODUCING A SETBACK IN THE BUILDING ELEVATION

Some of the noise in a building arises from traffic to and from the various rooms, and this can be reduced by providing entrances to staircases and lifts with lobbies fitted with self-closing doors. The noise heard in any one room is then mainly due to that arising in the corridor which serves that room. Noise in the corridor can be reduced by measures advocated elsewhere in this book, such as suitable sound-absorbent treatment and heavy carpets.

Lift shafts should not adjoin rooms in which quiet is desired, since there is almost always a certain amount of mechanical noise associated with the movement of the lift car; for this reason service rooms and the like are placed next to the lift. Plumbing should not, for similar reasons, be rigidly attached to bedroom walls, and bathrooms and water-closets should not adjoin habitable rooms unless, of course, the bathroom forms a part of a private suite of rooms. The flushing tank of a w.c. suite should not be fixed to the wall of a habitable room, nor should the water-closet be above a living-room. It has been suggested that the floor of the water-closet should not be continuous with that of adjoining habitable rooms. In hospitals, for instance, lavatories may be grouped vertically in a structurally separate section of the building.

As regards noise arising from the occupants of the building, the general principle to be followed is to place rooms which are likely to be noisy as far as possible from those which are to be quiet. At the risk of appearing elementary, it may be pointed out that this applies to vertical as well as horizontal juxtaposition. The problem is possibly not so difficult to solve in offices as in flats. In the latter it is more important to plan so that the noise in one flat will not be

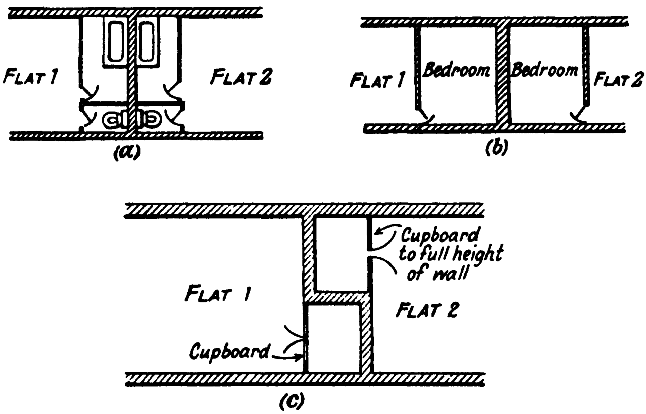


FIG. 19. PLANNING TO MINIMIZE DISTURBANCE FROM ADJOINING FLATS

a nuisance in neighbouring flats than to plan individual flats so that noise made, for example, in a living-room cannot be heard in a bedroom of the same flat. The reason is, of course, that it is generally easier for occupants of individual flats to control noise arising in the same flat than that arising in a neighbouring one.

It is generally agreed that flats are best planned so that party walls between neighbouring flats separate bathrooms, service rooms, or the like; the next best scheme is for the party wall to separate bedrooms. In the latter case, a cupboard built against the wall for its full height provides a useful buffer. (See Fig. 19.) It is obviously undesirable to plan so that the party wall divides a bedroom from a living-room, as even a 9 in. brick wall is considered inadequate to afford protection against the noise of radio at the strength usually preferred. Living-rooms in one flat should be above and below living-rooms rather than bedrooms of other flats.

Fig. 20 shows a well-planned block of flats containing several interesting features.

Internal noise in flats can be prevented to some extent if the

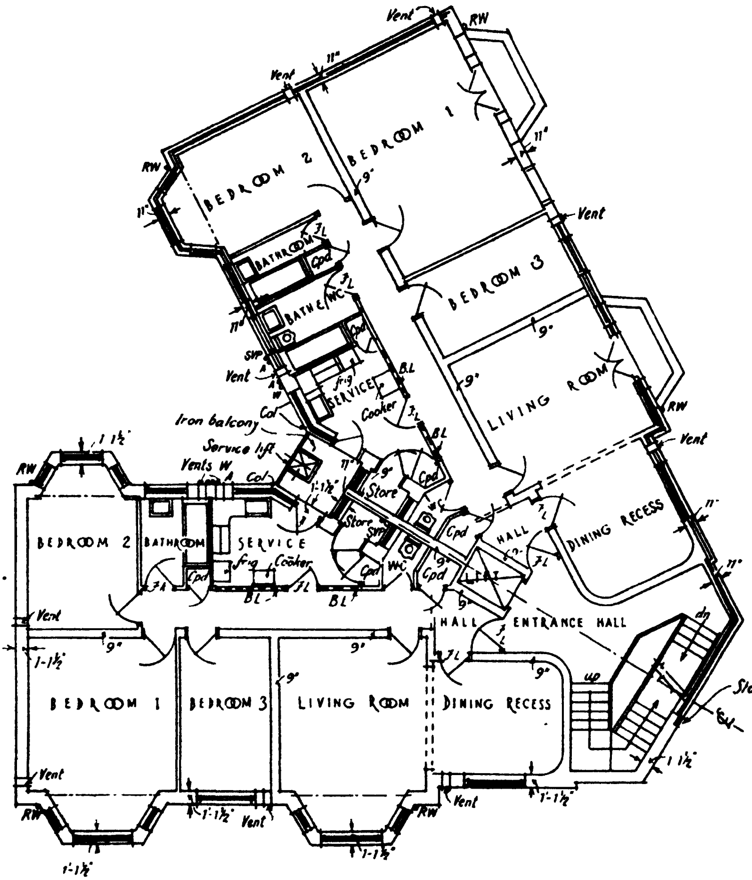


FIG. 20. A WELL-PLANNED BLOCK OF FLATS

The following features should be noticed—

In each flat

1. All noisy rooms (service, bath, lift, etc.) are grouped together and are separated from most of the bedrooms and living-rooms by a corridor.

2. The windows of the bedrooms and living-rooms do not face the noisy rooms.

In each pair of flats

1. The bedrooms and living-rooms are well separated from those of the adjoining flat by service rooms and corridors.

2. The windows of the bedrooms and living-rooms do not face those of adjoining flats.

(*John Laing & Son Ltd. Architect, B. L. Sutcliffe, F.R.I.B.A.*)

tenants can be persuaded to sign suitable agreements precluding the use of musical instruments or noisy pets. The management does not necessarily hold the tenants to the strict letter of this agreement, but reserves it to support any action they have to take following complaints. Carpeting clauses might, whenever possible, be included in agreements, as carpets are of considerable value in reducing noise due to footsteps.

Schools present a problem in that some rooms (music rooms, gymnasia, workshops, etc.) are unavoidably noisy at times during which quiet is required in other rooms near by. The problem can be eased by keeping the noisy sections away from the quiet ones and introducing a screen of high buildings between them if possible. It is particularly unwise to place the gymnasium above classrooms.

"As regards noise entering from outside, the school building should retreat from the sources of disturbance rather than arm itself against them: a school is justified in turning its back on a noisy thoroughfare notwithstanding some sacrifice in appearance."*

The planning of offices is probably not so difficult, because often a comparatively high noise level is expected in all the rooms except a few, which can be grouped together in a suitable location. Often the lower floors are necessarily noisy on account of traffic outside, and accordingly there are good reasons for putting rooms for which quiet is not needed, on these floors. Board rooms and the offices of senior members of the staff can then be put higher up in rooms which, if necessary, are set back to some extent.

Offices in factories are a special problem where the office block cannot for reasons of space be placed sufficiently distant from sources of noise. Any partition between office block and works should be sound-insulating, and direct communication by doors between the two should be the minimum necessary for working purposes. Lobbies with self-closing doors, and if possible double doors, should be the rule. If windows designed to open must be used in the office block, they should not be placed in walls on the noisy side of the block. If natural light on that side is essential, sound-insulating windows should be used, or part of that wall should be made of glass bricks or other heavy glass. Offices of supervisory staff which must be actually in the works, with good observation windows, present a particularly difficult problem if the works is a noisy one. Planning is not of much assistance here, except that advantage may sometimes be taken of the fact that the noise in a shop is by no means equally loud at all points. In fact the noise from a group of machines falls off quite rapidly with the distance from the source if sound absorbent material such as stacks of soft goods happen to be spread over an appreciable area of floor.

* "Suggestions for the Planning of Buildings for Public Elementary Schools," Board of Education Educational Pamphlets No. 107 (H.M. Stationery Office, 1938).

Hospital planning is of course a specialized matter, and in modern hospitals care has been devoted to the separation of the wards from sources of noise such as corridors, staircases, and sanitary blocks, by intervening spaces devoted to stores and other purposes where quiet is not so important.

CHAPTER IV

THE SELECTION OF QUIET EQUIPMENT AND MACHINERY

THIS chapter is included chiefly for the purpose of pointing out that a number of manufacturers pay special attention to the production of quiet equipment, and that it is wise, when considering the purchase of machinery, particularly domestic machinery, to ascertain whether quiet models are obtainable. In the majority of cases where mention is made of a particular item as being quiet, this is to be understood as meaning that while there are no measurements available which would definitely establish that the item in question is quieter than the average, it is evident that the manufacturers have taken certain steps which should lead to a diminution of the sound output.

That the purchase of equipment and machinery which is and will remain quiet in operation is a wise investment is now well recognized. In industry, systematic investigation* of the output of workers has shown that noise has a deleterious effect on working efficiency. Other cases have been reported in America† of increase of output in factories where a disturbing noise has been removed. For instance, workers assembling instruments near a noisy boiler shop, on moving to a quiet position increased the number of articles assembled in a given time from 80 to 110, with considerably fewer imperfections. It has also been suggested that the reduction of noise in industry may well tend to reduce accidents, particularly in mines.‡ Evidence was also found that noise was a factor tending to increase absence from work among women employed in a war factory in the United States.

The effect of noise-reduction in offices has also been studied in the United States, where records were kept for a year both before and after noise-reducing treatment had been applied. In the case of typing rooms, typist's errors were reduced by 29 per cent, and in calculating machine rooms, machine operators' errors were reduced by 52 per cent.

It is usually cheaper to purchase quiet equipment than to silence equipment which, when installed, is found to be unduly noisy, even if the initial outlay is greater. As a general rule, the more noisy a machine is, the less is its mechanical efficiency. The reason for this

* Industrial Health Research Board, Report No. 65.

† S. W. WYNNE: *Journ. Acoust. Soc. Amer.*, Vol. 2, p. 14, 1930.

‡ H. HENSHAW AND W. A. JOHNSON: *Trans. Inst. Min. Eng.*, Vol. 95, p. 14, 1938. Various suggestions have been made as to methods of reducing the noise of cutting and haulage equipment, and silencers have been described suitable for compressed-air engines and pneumatic picks.

is not, however, that the energy lost as sound represents an appreciable loss, but that noise is very often an indication of faulty design or inferior construction.

Selection of Quiet Equipment. The first step in the selection of quiet equipment is to decide what noise level can be tolerated in the particular building or part of the building where the equipment is destined to work. This is not easy to do. If the building is still in the design stage, recourse may be made to the table of permissible noise levels in different kinds of rooms, reproduced at the end of this book (Table XXIV). If it is felt that somewhat noisier conditions than recommended in this table can be tolerated, a suitable adjustment can be made in the noise level to be specified for the equipment. The contract for the equipment can then contain a clause that, when installed, the noise level is not to exceed so many phons.

Specifications of this type are at present apparently more common in America than in Great Britain. If the equipment is required for an existing building, the specification can include a clause to the effect that the noise made by the equipment should not noticeably increase the existing noise level. Generally, the operation of equipment which by itself would give rise to a noise level five or more phons less than that of the existing sound will not cause a noticeable increase in the noise level. There are occasions, however, when the equipment, owing to the production of a distinctive sound, should be very much quieter than the general noise level if it is not to be noticed. P. H. Geiger* has instanced cases in which it was necessary for the equipment to be 15 or 20 phons less noisy than the general level. A point such as this can only be decided either by drawing on specialized knowledge or by inspecting the equipment on the site.

Perhaps a word of warning should be inserted here. If, when the equipment is selected, it is inspected elsewhere than on the site on which it is ultimately to be used, some attention should be paid to its surroundings. It may, for instance, be examined in a room in which, owing to office noise or street noise, there is a higher background noise level than would exist in the building in which it is to be used, or again, it may be examined in a very absorbent room, e.g. with a heavy carpet, curtained walls, and heavily upholstered furniture, whereas the room in which it is to be used is of "hygienic" design, with a bare terrazzo floor and painted walls and ceilings. The equipment may then sound considerably noisier when installed than it did when first viewed. The type of machine support also influences the surrounding noise level, for if rigidly attached to the floor the latter may act as a sounding board, while on an insulated base (see Chapter VI) the machine would sound much quieter.

A number of manufacturers, particularly in America, now include

* P. H. Geiger: *Heating, Piping, and Air Conditioning*, December, 1936.

a figure for the noise level among the other performance data for the machine, and as such measurements become common, the possibility of the architect and his advisers selecting quiet equipment from its specification, draws nearer. Many manufacturers also make noise measurements as a part of the routine works tests, a reading on an instrument replacing the rapid aural inspection which was previously made. Fig. 21 shows refrigerator units, on a conveyor, emerg-

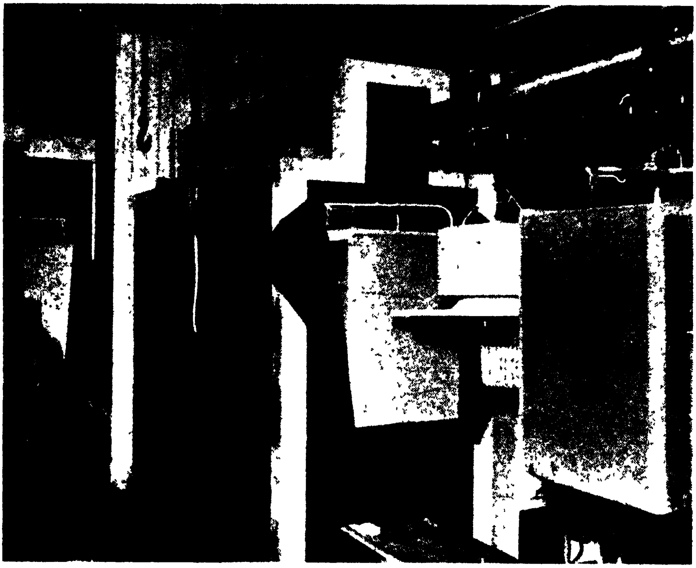


FIG. 21. REFRIGERATOR UNITS LEAVING A NOISE-TESTING ROOM
(*International General Electric Co. of New York Ltd.*)

ing from the works test room. Readers interested in this aspect of the question may consult the papers referred to at the end of the chapter.

Whether these measurements are suitable for actual noise specifications has still to be determined, but they are certainly valuable in ensuring a uniform product. They are also useful when comparing different models supplied by the same maker, but not necessarily for comparing equipment supplied by different makers whose test methods may not be the same. When making comparisons of this kind it should be recalled that over the range of noise levels likely to occur in building equipment, differences of less than 2 phons (see Chapter I) have practically no significance, but improvements of 5 phons and upwards are valuable. Until conditions and methods of test are more closely standardized, it is probably as well for the final selection to be based upon inspection.

Quiet Equipment. The remainder of this chapter is devoted to mentioning equipment in which special care has been devoted to obtain quietness.

Sound-deadening materials and devices may also be included under this heading. Of these, rubber has found a wide application in noise-reduction. One may instance in this connexion—

(*a*) Rubber table and counter tops in hotels, etc.

(*b*) Rubber rims for jugs, pails, coal buckets, dustbins.

(*c*) Rubber buffers and stops for doors, furniture, children's toys, etc.

(*d*) Rubber sink linings, washing-up bowls, rubber-covered plate racks, surgical bowls for hospitals.

(*e*) Rubber flooring and paving, trolley wheels, furniture feet.

(*f*) Rubber-lined coal chutes.

(*g*) Rubber conveyer belts for coal or other material.

(*h*) Rubber insulating mats and pads for machinery including items such as typewriters and sewing machines. (See Chapter VI.)

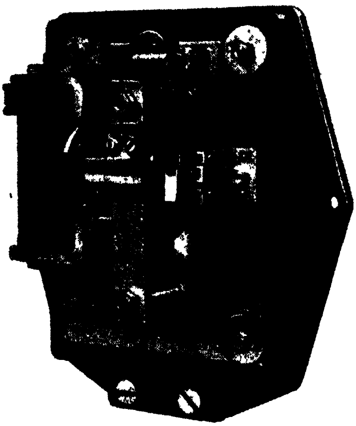


FIG. 22. MOVEMENT OF SILENT CLOCK (*Gent and Co. Ltd.*)

Lead has found one or two ingenious applications for noise-deadening. One municipal water supply in America, having a supply of old lead on hand, had this melted down and cast into gaskets to fit under man-hole covers. The objectionable clanking caused by traffic passing over the covers was stated to be completely cured.

As regards reducing noise in business premises, mention may be made of silent typewriters, and also silent clocks; the latter are of the impulse type driven by a central master clock, but the usual half-minute click is avoided by making the armature in the form of a small motor, the rotor of which is energized on the arrival of the impulse (Fig. 22). Door bells, staff locators, and telephone bells can all be replaced by light signals.

Radio, if other people's, is usually regarded as a noise, and it has been suggested that the nuisance could be mitigated in hotels and flats by using a rediffusion service, since the volume and number of programmes can then be controlled by the central amplifier.

More attention appears to have been paid to the silencing of electrical machinery than to any other class of apparatus, probably owing to the increasing use of small and fractional horse-power motors for ventilating, refrigerating, and other equipment where silence is at a premium. Motors designed for quiet running usually incorporate special features, such as a heavy frame, resilient mounting, plain sleeve bearings rather than ball bearings, devices to prevent end-bumping of the shaft, and, in the case of small motors, total enclosure. One make is shown in Fig. 23. To ensure silent running, motors should be worked well within their capacity.

A small point, attention to which is well repaid, is the fitting of silent switches for domestic lighting and power circuits. One type (Fig. 24) relies for its quiet action chiefly upon rubber buffers. Lübcke* has recorded that treatment has effected a reduction of 10 phons in the noise made by the ordinary small domestic lighting switch and also points out that switches mounted on a wall can be considerably noisier than when held in the hand, a fact which is useful to remember when selecting switches for silence.

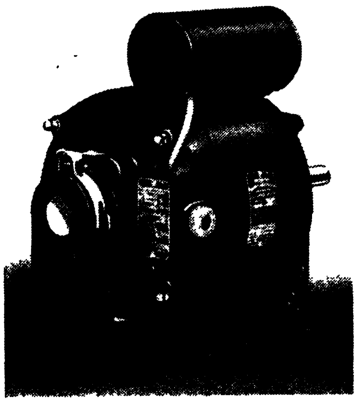


FIG. 23. ELECTRIC MOTOR DESIGNED FOR QUIET OPERATION
(*British Thomson-Houston Co. Ltd.*)

Vacuum Cleaners. Vacuum cleaners show considerable variation in their noisiness, and care in their selection is advisable. Some manufacturers make a feature of quiet operation. When considering cleaning equipment, the advantages, from the point of view of quietness, of central vacuum-cleaning installations should not be overlooked. In these installations, the fan and container are in a basement or cellar and connected by means of a pipe system to one or more points in each room. The suction outlets when not in use are tightly closed with heavy metal caps, thus preventing noise from entering any room except that in which cleaning is proceeding. (Of course, if the caps are not well made, or are damaged in use, they may allow considerable noise to escape.) It is advisable that the machinery used for this purpose should be on an insulated mounting (see Chapter VI) and situated in a room from which sound cannot easily emerge. The connexion to the main duct should be flexible.

Other Domestic Equipment. Most good domestic refrigerator models are nowadays reasonably quiet. In large blocks of flats central compressor systems may be used, for which various advantages are

* E. LÜBCKE: *Zeits. für d. Phys. u. Chem. Unterricht*, Vol. 21, p. 2, 1938.

claimed, and which have the acoustical advantage that all machinery with moving parts is placed in the basement or other place where it will not cause disturbance.

Kitchen, laundry, and dry-cleaning machines, and even the ordinary domestic sewing machine, can all cause a good deal of disturbance, particularly if there is an occupied room beneath. Insulating supports (see Chapter VI) may be found helpful in this connexion.

Lifts. Hydraulic lifts are very quiet in operation, but for carriage of passengers they are seldom now installed owing to the convenience

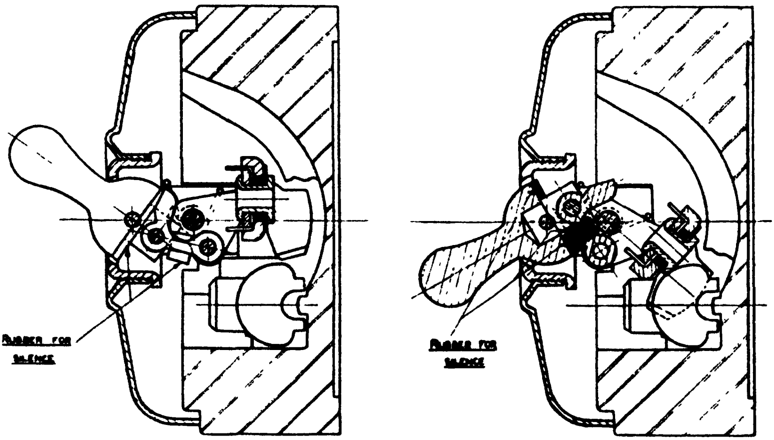


FIG. 24. SILENT LIGHTING SWITCH
(*J. H. Tucker and Co. Ltd.*)

of operation and other merits of the modern electric lift. The selection of a particular type of electric lift is of course mainly governed by the type of power supply available, the nature of the traffic and the peculiarities of the site. The usual sources of noise in lift operation are the closing and opening of car and hoistway gates, and the closing of contactors on the control panel, in addition of course to the noise of the motor and gearing. The most obvious precaution to take is to place the machine unit and control panel in a compartment which does not adjoin rooms in which quiet is desired. The control panel should be of substantial construction, mounted if necessary on a resilient mounting, and possibly totally enclosed. The essential openings in the machine room should be kept as small as possible, the walls of the machine room should be of substantial construction and access doors should be sound-insulating: If the particular case is a bad one, the walls and ceiling of the machine room should be lined with sound-absorbing material.

Commendable ingenuity has been displayed in designing liftlevelling contacts which do not cause noise as the lift car passes them. A system which seems ideal from this point of view is that in which the lift car carries two parallel air-spaced coils connected in separate circuits, in one of which alternating current always flows. Alternating potentials are induced in the second coil except when the car approaches a landing, when an iron shield comes between the coils and interrupts the magnetic flux between them. Amplifiers and relays, actuated by the resulting change in the voltage induced in the second coil, control the lift motor. By using a series of coils,

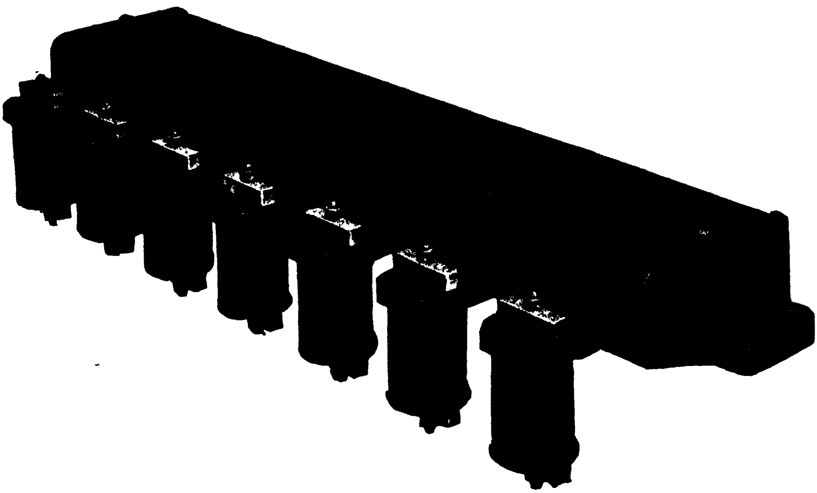


FIG. 25. SILENT-ACTING LIFT-CAR LEVELLING DEVICE
(*General Electric Co. Ltd.*)

gentle starting and stopping can be obtained. Induction switches used for accurate car levelling, based on this principle, are shown in Fig. 25. As there are no mechanical contacts to be made, the system can be very quiet.

Noise due to opening and closing the gates can be minimized by using rubber buffers between the vertical elements of sliding expanding gates. Gate locks can also be rubber cushioned.

Factories. Very little information appears to be available regarding any work that may have been done on the silencing of individual items of factory or workshop equipment, and in general it seems safe to say that with a few exceptions silent operation has not yet been seriously attempted by designers. It may be mentioned that circular saws have been quietened by providing two soft pads, one resting on each side of the saw,* and that

* Further details may be obtained from the Safety, Health and Welfare Museum, Ministry of Labour and National Service, Horseferry Road, S.W.1.

wood-planing machines are quieter if the plane irons are spiral instead of parallel with the centre line of the cutter block.*

Quiet Gearing. Advances have, however, been made in recent

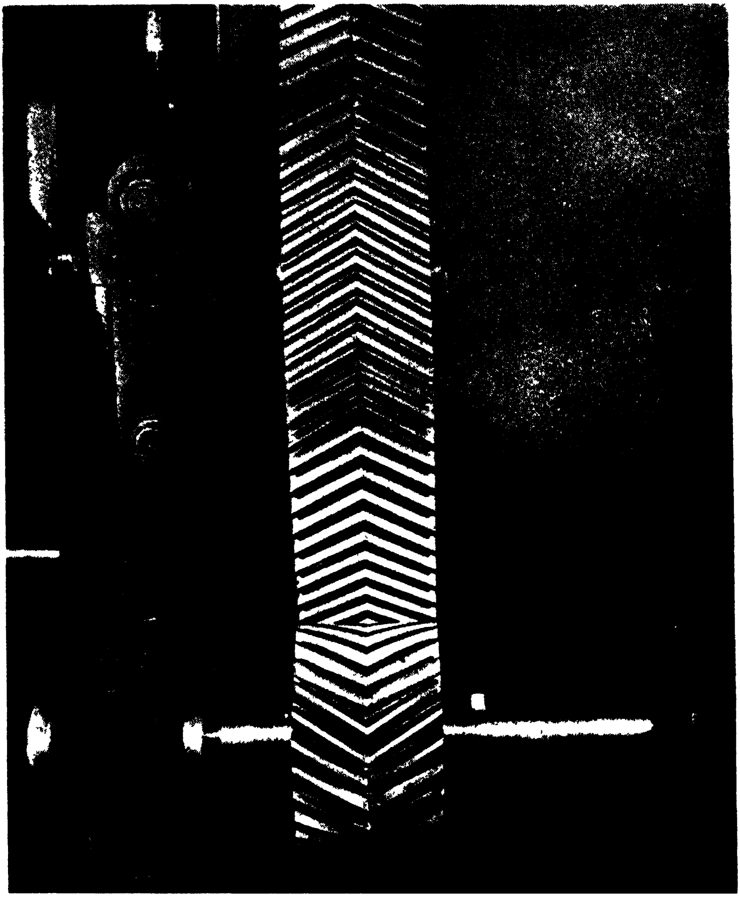


FIG. 26. A PAIR OF DOUBLE-HELICAL GEARS WITH PRECISION-GENERATED TEETH
These run silently when accurately mounted.
(*Farrel-Birmingham Co. Inc., N.Y.*)

years in the manufacture of quiet gearing—witness the modern car. The same principles which have been adopted in the motor-car have also been used on a larger scale, and single- or double-helical gearing is now used where quiet running is a necessity, and an example of such gearing is shown in Fig. 26. It is said that such

* K. W. WAGNER: *Zeits. für Techn. Physik*, 16, 12, p. 544, 1935.

gearing can run quietly at peripheral speeds of up to 18,000 ft./min. Quieter operation can, of course, be obtained from most gears if they are totally enclosed and immersed in oil.

A method of obtaining quiet gearing, which is useful for low

FIG. 27. GEARS DRIVING A HEAVY MACHINE, SHOWING THE USE OF A PINION MACHINED FROM BAKELITE SILENT GEAR MATERIAL AND MESHED WITH A STEEL WHEEL
(*Bakelite Ltd.*)

powers, is to make one of the gearwheels of raw hide. Laminated bakelite is another material which has been developed for gears, and satisfactory results have been claimed for it, both as regards durability and silence of operation. Investigations* on the cause of

* SEKIGUTI, YAEKITI, K. EBIHARA, AND T. NAKATA: *Trans. Soc. Mech. Eng. Japan*, Vol. 4, p. 144, 1938 (English summary).

noise in gears in which combinations of bakelite and hard and soft steel gearwheels were tested indicated that of these the quietest combination was that in which a bakelite gear is enmeshed with steel gears. (See Fig. 27.)

Modern practice of the individual motorization of machines formerly driven by shafting, belts and pulleys from a common prime mover, is a step in the right direction. Only a minimum of machinery is running at any one time, and the equipment is much more easily insulated from the building structure.

Building Operations. Noisy operations not usually performed inside a building, but which may cause disturbance to occupants of neighbouring buildings, include demolitions and certain building operations. The noise of riveting steel frames can be avoided by using electric welding, as was done in the Bank of England building. The use of electric welding in steel frames has received the approval of the Steel Structures Research Committee of the Department of Scientific and Industrial Research* in Great Britain, and is permitted in New York by the building code of New York City. Two other noisy building operations, namely cutting holes and chases, may be made less disturbing by the use of electric drills and grinding wheels respectively instead of the usual hammer and chisel. Pneumatic drills, used for demolitions, and road repairs, are a constant source of complaint, and though they can be silenced to some extent by fitting suitable silencers on the drills, there is some evidence that the quieter drills take a little longer to do a given job. A type of pneumatic drill has been demonstrated† which is claimed to be much quieter and also faster than the usual type. Pile-driving is another noise which can be heard over a wide area and which has been the subject of legal action. One system of piling may be mentioned for which several advantages are claimed, including the absence of noise and vibration. In this system a boring is made for each pile; subsoil water is then forced out by compressed air and concrete is forced in, suitable reinforcement having been placed in position in the shaft. This method has also been used to underpin existing buildings while in normal use.

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CHAPTER V

REDUCTION OF NOISE BY SOUND-ABSORBENT TREATMENT

MATERIALS specially designed to absorb sound were originally introduced in order to correct the acoustics of auditoria, and are still largely used for this purpose. Such materials, usually of a porous nature, e.g. felts, fibreboards, etc., are applied to the walls and ceiling of the auditorium in question in order to reduce excessive reverberation or to prevent unwanted reflection of sound at certain points. This aspect of the use of sound-absorbent materials has been dealt with in a number of textbooks,* and there is no need to go into it here. Nowadays, however, sound-absorbent materials are also used to reduce the noise level in rooms. Naturally, the more sound-absorbing are the surfaces of a room, the less is the amount of reflected or "reverberant" sound, and consequently a lower noise level is produced by any given source of sound.

Perhaps it is as well to make clear at this stage that a sound-absorbent has an entirely different function from that of a sound-insulator. A sound-insulator *transmits* only a fraction of the sound which falls upon it; a sound-absorbent *reflects* only a fraction of the sound which falls upon it, much as a piece of black velvet reflects only a fraction of the light which falls upon it.

A wide variety of materials is used for sound-absorbing purposes. Their efficacy is indicated by the sound-absorption coefficient, a figure which gives the fraction of the energy absorbed when a sound wave is reflected by the material concerned. To make this statement strictly accurate it should be added that the absorption coefficient varies with the angle at which sound falls on a material. The coefficient usually given applies (unless otherwise stated) to the absorption averaged for sound falling at all angles; this is strictly termed the "reverberation absorption coefficient," and is obviously the figure which is required when questions of noise reduction are being dealt with. The absorption coefficient also varies with frequency, but when dealing with noise-reduction it is usual to employ a figure obtained by averaging coefficients for low, medium, and high frequencies which, as explained later, is as a rule sufficient. The absorption coefficient of a completely reflecting surface is of course zero, and that of a completely absorbing surface (the usual example being an open window) is unity. Between these two values it varies with

* See for example: A. H. DAVIS AND G. W. C. KAYE: *Acoustics of Buildings*; C. W. GLOVER: *Practical Acoustics for the Constructor*; V. O. KNUDSEN: *Architectural Acoustics*; H. BAGENAL AND A. WOOD: *Planning for Good Acoustics*.

the material from 0·02 for a hard plaster to 0·80 or more for some specially effective absorbents (see Table V). To determine an absorption coefficient accurately requires special experience and equipment. For this reason manufacturers of acoustic materials often have measurements made by a standardizing laboratory (in Great Britain, usually the National Physical Laboratory) before marketing their product. For research and development purposes, however, relatively simple apparatus may be used which enables preliminary information on the sound-absorption of materials to be obtained.

It has, however, been pointed out* that absorption coefficients obtained by laboratory measurements vary slightly with the conditions of test as between one laboratory and another, although results from any one standardizing laboratory are self-consistent. Again, the absorption obtained when the materials are used on the job on a large scale may not correspond exactly with that computed from laboratory-determined coefficients. Too much importance should not, therefore, be attached to a small difference in coefficient of different materials when making a selection.

The quietening effect of an absorbent surface depends, in a way which will be described later, not only on its absorption coefficient but also on its area. The effect of the treatment is, in fact, determined by the product of these quantities, which is referred to as the *absorption* of the surface concerned. By summing the absorptions of the various surfaces in the room the *total obsorption* is obtained.

If the areas are in square feet, the total absorption is in *sabins*, a unit named after W. C. Sabine, a pioneer in architectural acoustics. For example, in a typical living-room having dimensions of 12 ft. by 18 ft. by 8 ft. 6 in. high, the total absorption might be calculated as in Table VI.

It will be noticed that if the ceiling and walls in the room referred to in this table were covered with an absorbing material such as fibreboard having an absorption coefficient of 0·3, the total absorption could be approximately doubled.

The reader may criticize the above calculation on the grounds that no mention has been made of the variation of absorption coefficient with frequency. Calculations of noise-reduction by the use of absorption coefficients averaged over a fairly wide range of frequency (say 200–2,000 c.p.s.) are usually sufficient for this purpose. There are special cases where the absorption at particular frequencies has to be taken into account, notably when the noise is confined to a definite frequency band; but these are the exception rather than the rule.

Effect of Absorption on the Noise Level in a Room. Before proceeding to discuss the effect of sound-absorbents upon the noise level in a room, the important distinction between direct and

* PAUL E. SABINE, *Journ. Acoust. Soc. Amer.*, Vol. 11, p. 41. 1939.

reverberant sound must first be made clear. (See Fig. 28.) The former is the sound received by the ear directly from the source,

TABLE V

ABSORPTION COEFFICIENTS OF VARIOUS MATERIALS

Material	Approximate Absorption Coefficients			
	Cycles per second			Average
	250	500	1,000–2,000	250–2,000
Ordinary wall and ceiling surfaces—				
Hard plaster	0·01	0·02	0·02	0·02
Unpainted brick	0·03	0·03	0·05	0·04
Porous breeze, 2 in. thick, unplastered	0·21	0·43	0·38	0·34
Wood panelling, ¾ in. thick . .	0·10	0·10	0·10	0·10
Curtains, cretonne . . .	—	0·15	—	0·15
,, medium-weight . .	—	0·30	—	0·30
,, heavy, in folds . .	—	0·75	—	0·75
Floor coverings—				
Wood-block floor laid in mastic .	0·03	0·06	0·10	0·06
Cork carpet, ¼ in. thick . .	0·03	0·07	0·20	0·10
Porous rubber sheet, ¼ in. thick .	0·05	0·05	0·20	0·10
Axminster carpet, ¼ in. thick .	0·05	0·10	0·35	0·17
Axminster carpet on ¼ in. felt underlay	0·15	0·40	0·65	0·40
Axminster carpet on ¼ in. rubber underlay	0·05	0·20	0·45	0·23
Turkey carpet, ½ in. thick . .	0·10	0·25	0·60	0·32
Turkey carpet on ½ in. felt underlay	0·30	0·50	0·65	0·48
*Special absorbents**—				
Acoustic plasters, ½–1 in. thick, on stone	0·15	0·25	0·30	0·23
Fibreboards, plain, ½ in. thick, on 1 in. battens	0·35	0·32	0·30	0·32
Medium-efficiency acoustic tiles, on battens	0·40	0·40	0·50	0·43
High-efficiency acoustic tiles with perforated surfaces, on battens .	0·50	0·80	0·85	0·72
Acoustic felts, 1 in. thick, perforated covers, on hard surface . .	0·30	0·70	0·80	0·60
Acoustic felts, ½ in. thick, on battens	0·25	0·45	0·70	0·47
Wood-wool cement board, 1 in. thick, on battens . . .	0·30	0·60	0·70	0·53
Sprayed asbestos, 1 in thick . .	0·60	0·65	0·60	0·62
Slag wool or glass silk, about 2 in. thick, on battens . . .	0·70	0·85	0·90	0·82
Slag wool faced with thin smooth cardboard	0·54	0·36	0·32	0·41

* The figures given for some of the special absorbents are only average for the class of material concerned, as different products vary a good deal.

and the latter is sound which has been reflected one or more times at the various surfaces in the room before reaching the ear. In the open air, which corresponds to completely absorbing walls, sound reaching the ear is, neglecting reflection from the ground, entirely direct sound. The intensity of the direct sound in a room is unaffected by the amount of absorbent; but the intensity of the reverberant

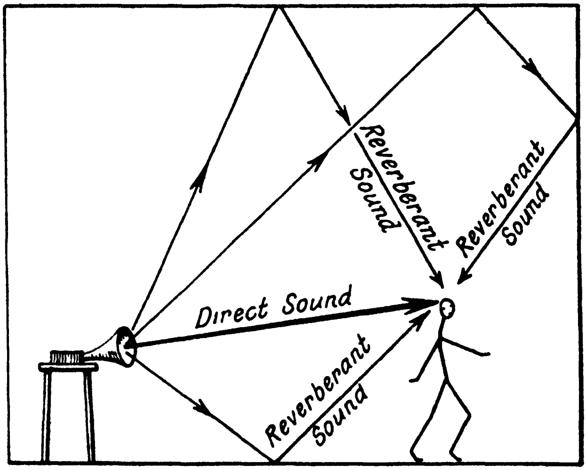


FIG. 28. ILLUSTRATING THE DISTINCTION BETWEEN DIRECT AND REVERBERANT SOUND

sound may be taken to be inversely proportional to the total absorption in the room, and can thus be reduced to any desired extent by installing suitable absorbent.

The point can be illustrated by an analogy. It is well known that

TABLE VI

ABSORPTION IN A TYPICAL LIVING-ROOM

Item	Area	Absorption Coefficient	Absorption of Item
	sq. ft.		sabins
Ceiling (hard plaster)	216	0·02	4
Walls (hard plaster)	450	0·02	9
Carpet	200	0·40	80
Curtains.	80	0·20	16
Wooden door	20	0·10	2
Large upholstered chairs and settee .	—	—	40
Miscellaneous furniture . . .	—	—	40
		Total:	191

the illumination in a room depends not only upon the lamps supplied, but also upon the character of the wall surfaces. If the walls are light in colour, the lamp appears to be much more effective than when it is used in a room in which the walls are dark-coloured. This is because in a room with light-coloured walls the light from the lamp is reflected many times backwards and forwards between the walls and builds up a degree of illumination greater than that which would be afforded by the lamp alone. For the purpose of our analogy we may say that the "reverberant" light renders the illumination greater than that which would be provided by direct light alone. Going to the other extreme, the illumination in the room could be considerably reduced by painting all the walls black (i.e. with a light-absorbing surface). Such treatment would of course never render the room completely dark, since the light coming directly from the lamp cannot possibly be affected.

In just the same way, applying sound-absorbent treatment to a room will reduce the reverberant sound level but cannot affect the sound proceeding directly from the source. The relative importance of the direct and reverberant sound determines the extent to which such treatment can profitably be applied, it being obviously useless to reduce the reverberant sound beyond the stage at which the direct sound becomes predominant. The position of the person concerned is of importance in deciding when this stage has been reached: if he is very near the source, the direct sound will very soon outweigh the reverberant sound. Assuming, as is at least approximately true, that the intensity of the direct sound is inversely proportional to the square of the distance from the source, it may be shown that the reverberant and direct sounds are of equal intensity at a distance L from the source given by

$$L = \frac{\sqrt{A}}{7\cdot2}$$

where A is the total absorption in the room.*

Thus in a room containing a total absorption of 100 sabins, the distance is about 18 in. In other words, the direct sound is of minor importance, and absorbent treatment could be profitably applied to the extent of, say, 1,000 sabins; the corresponding distance would then become about 4 ft. 6 in., and at most points in the room the direct sound would be less important than the reverberant sound. The above calculation is for illustration only, and the formula should not be regarded as being by any means exact. Its reliability decreases as the source of sound becomes greater in dimensions (since the inverse square law applies strictly only to point sources) and as the total absorption in the room increases.

There are various formulae available for calculating the intensity

* If A is given in sabins (i.e. square-foot units), the distance L is in feet. If A is in square metres, L is in metres.

of the reverberant sound in a room, but since they fail when considerable absorption is installed they should be used with caution, and are scarcely suitable for inclusion here. As mentioned before, it is usual to take the reverberant sound intensity as being inversely proportional to the total absorption in the room*—that is to say, the less the absorption in a room the higher the reverberant sound intensity. Quantitatively the relation means that the reverberant sound intensity can be halved (i.e. reduced by 3 db.) by doubling the amount of absorbent in a room. The reduction of loudness, measured in phons, which corresponds to this 3 db. reduction in intensity depends upon the frequency. (See page 11.) For sounds of medium pitch the loudness reduction is numerically about the same as the intensity reduction (i.e. 3 db. is equivalent to 3 phons); for low-pitched sounds the loudness reduction is numerically greater, and 3 db. may be equivalent to a loudness reduction of anything up to 5 or 6 phons. There is a compensation here for the decrease, which normally occurs in absorption coefficients at low frequencies.

Increasing the amount of absorbent treatment becomes progressively less effective as the total absorption in the room increases. There are three reasons for this—

1. The greater the total absorption, the less the importance of the reverberant sound in comparison with the direct sound.

2. The greater the initial absorption, the greater the amount of extra absorbent required to produce a given reduction of sound intensity.

3. Reference to the table relating loudness sensation units with noise level (Table IV, Chapter I) will show that the number of loudness sensation units corresponding to a given change in noise level is less as the loudness decreases, e.g. the first decrease of 3 phons is more effective than subsequent decreases. Hence the more absorbent (and therefore the quieter) a room, the smaller the reduction in loudness units produced by a given change in noise level.

Value of Absorbent in Different Classes of Rooms. In general, sound-absorbent treatment is probably only worth while where economic and practical considerations permit the total absorption to be at least doubled. Examples of such rooms will be mentioned later. Two important exceptions to the rule might conveniently be pointed out at this stage. Returning once again to the table relating loudness sensation and noise level, it is apparent that in a very noisy room quite a small change in the sound intensity—even as little as 1 phon—is valuable. In rooms such as these, for example in a printing pressroom, extra absorbent treatment should be valuable even if only a 25 per cent increase in absorption is feasible. The other special case is that in which a reflecting surface is near to the source of noise and to the occupants of the room. In this case, irrespective

* This is based upon Jaeger's formula, which is dealt with more fully in Chapter XV.

of whether the remainder of the room is absorbent, the sound intensity near the occupants will be increased by the presence of the reflecting surface, since the direct sound will be reinforced by reflected sound of similar intensity. An example of such a reflecting surface is the ceiling in a typing office. The floor may be fairly absorbent, and the walls may, if the office is large, be a considerable distance away. The room will probably contain considerable absorbent material such as the clothing of the occupants, carpets and linoleum, wooden furniture, and piles of paper. Thus, although the room contains considerable absorbent, each typist, besides the direct sound from her own and neighbouring machines, would receive sound of about the same intensity reflected via the ceiling. It will be seen, therefore, that in these cases a sound-absorbent ceiling would be of value. Such treatment is becoming increasingly used in modern typing offices.

The effect of similar treatment has been studied in factories in the United States. A recent paper* describes noise measurements and "public opinion" in 33 works in which the noise level ranges from 65 to 130 phons, 85 to 105 phons being common. Noise measurements alone are not always an infallible indication of the amount of annoyance; excessive reverberation is another important factor on account of the unnatural prolongation of the stimulus and the difficulty of understanding speech. Absorbent treatment is of little value when a number of closely spaced noisy machines fill a room, but if part only of the room is occupied by machines, absorbent treatment over the whole room benefits the operatives in other parts. Measurements show that in rooms whose smallest floor dimension is at least several times the ceiling height, and in which the ceiling is highly absorbent, the noise level due to a single source decreases at a constant rate in decibels per foot over the entire area of the room regardless of size. This rate varies with the ceiling height, attenuations of 0·4 db. per ft. being obtained for a 10 ft. ceiling, and 0·2 db. per ft. for a 20 ft. ceiling for material of absorption coefficient 0·7. The attenuation in the case of untreated ceilings is much less, being about 3 db. for each doubling of distance. Absorbent-treated ceilings are, therefore, recommended in suitable cases, the total absorption of the ceiling being increased if necessary by the addition of baffles.

As mentioned above, sound-absorbent treatment is most valuable in rooms in which there is little absorption. Typical values for the total absorption in different kinds of rooms are given in Table VII. It will be noted that bathrooms and kitchens contain little if any more absorption than empty rooms, so that absorbent treatment would prove valuable in reducing noise in rooms of this type.

Another typical noisy room which should benefit from absorbent

* Hale J. Sabine and R. Allen Wilson, *Journ. Acoust. Soc. Amer.* Vol. 15, p. 27, 1943.

treatment is a restaurant with marble walls, glass ceilings, stone floor, and marble- or glass-topped tables. It is very probable that a considerable improvement in the noise conditions would result if such restaurants received absorbent treatment; indeed, a number

TABLE VII

TOTAL ABSORPTION IN DIFFERENT TYPES OF ROOMS

Type of Room	*Total Absorption Averaged for a Number of Rooms of this Type**
Empty room	45 sabins
Bathroom	45 ,,
Kitchen	95 ,,
Office	160 ,,
Living-room	185 ,,
Bedroom	390 ,,

have already been treated, and the improvement is appreciable. Another example is the "modern" dining-room with its painted walls, metal furniture, and negligible upholstery. The possibility of quietening the nursery should also not be overlooked. In this case the treatment would probably have a double benefit in that not only would it absorb the sound, but also, by removing "bathroom" conditions, it would reduce the urge to be noisy. Indoor swimming-baths and gymnasia are also promising subjects for absorbent treatment.

Reverberation and hygiene often, unfortunately, go hand in hand, and in the modern hospital this may cause difficulties. Medical opinion appears to be opposed to the use of any porous material upon the walls and ceilings of the wards, and this, of course, rules out the majority of absorbents. There does not appear to be the same objection to treating the corridors, which often serve as ducts along which sound is conducted from other parts of the building, e.g. the staircase. In addition, owing to the traffic along them, considerable noise is generated in the corridors themselves. Several hospitals for this reason have now installed absorbent material on the corridor ceilings. The value of such absorbent treatment has been confirmed by measurement. As regards the use of absorbent materials in the wards, there appears to be only one method of combining absorption with a smooth non-porous surface. This is described on page 57.

Another position in which sound-absorbent treatment is valuable is on the inner faces of telephone booths in noisy situations, for instance, in workshops. Not only does its use render the booth quieter, but the reduced reverberation makes speaking conditions more comfortable. Sound-absorbent treatment can, in fact, be made so

* These figures are taken from a paper by A. Gastell (*Akustische Zeitschrift*, Vol. 1, p. 24, 1936).

Fig. 29. Absorbent-lined (Doorless) Telephone Cabinet
(*Burgess Products Co. Ltd.*)

effective that the door of the booth can be dispensed with (see Fig. 29), the conversation being still reasonably private, and the amount of noise entering from outside being unobjectionable.

Sound-absorbent material can be used to increase the sound-insulation of special constructions. The use of a sound-absorbent lining in a double partition (Chapter X) and in a ventilating duct (Chapter VIII) may be mentioned in this connexion. Another use is met with when, to increase the insulation provided by a door, a small anteroom is built in front of it. The effectiveness of this anteroom can be increased if it is rendered sound-absorbent either by special treatment (see Fig. 30) or by using it as a store for absorbent material such as bales of textiles.

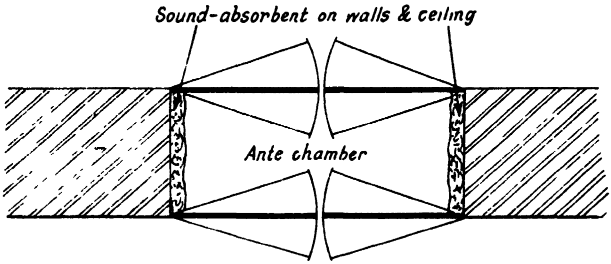


FIG. 30. USE OF SOUND-ABSORBENT TREATMENT TO INCREASE THE SOUND-INSULATING VALUE OF AN ANTECHAMBER

Most Economical Distribution of Sound-absorbent Material. When several rooms are to be treated with sound-absorbent, it is obviously desirable to distribute it in the most effective way.

The point may be appreciated in the simple case of two adjacent rooms, in the first of which is a source of sound and in the second of which quiet is desired. If the first room is very reverberant it will be very noisy, and considerable sound will in consequence be transmitted through the partition to the second. The conditions in the second room can be improved to a limited extent by introducing sound-absorbent into the first room and thus quietening it. On the other hand, if the second room is very reverberant, sound entering it from the first room will build up to a high level no matter how absorbent the first room is. In fact, if the second room contained no absorbent whatsoever, there are theoretical reasons (see Chapter XV) for expecting that the noise level in the two rooms would be the same however soundproof the partition between them. It follows from the above discussion that if a certain amount of absorbent treatment is permissible, it is unwise to put all of it in one of the rooms. Actually calculation shows* that the second room is quietest when the *total* available sound absorption (including an allowance for furniture, etc.) is distributed equally between the two rooms.

* J. E. R. CONSTABLE: *Journ. R.I.B.A.*, Vol. 45, p. 940, 1938.

It is not necessary to hold closely to this distribution, but an approximation to it should be aimed at. Similarly, if a row of similar rooms is served by the same corridor and it is desired to reduce the noise level in the rooms due either to sound originating in the corridor or to sound originating outside the building and passing through the corridor to the rooms, it can be shown that half the *total* available absorbent should be in the corridor, the remaining half being distributed equally between the rooms. Other examples of sets of rooms requiring absorbent treatment will no doubt occur to the reader. Calculation of the best distribution of absorbent material may be complicated if many rooms are involved. The above examples will, however, indicate the kind of solution likely to be most successful.

It should perhaps be pointed out that the calculations referred to deal only with the reduction of airborne sound, such as for example that emitted by a loudspeaker. The reduction of impact noises is another story. In the case of footsteps, for example, no amount of absorbent in the room above will prevent the transmission of the impact to the room beneath.

Materials Available for Sound-absorbent Treatment. The ways in which sound-absorbent treatments can be used have been discussed. It remains to describe the materials which are available for this purpose.

Generally sound-absorbents rely for their action upon the frictional losses which occur when the alternating pressure of the incident sound wave causes a to-and-fro movement of the air contained in the pores of the material. There is, however, a special type of absorbent which depends for its action upon resonance effects. This will be described later. Much time and trouble has been spent in calculating the absorption of porous materials, and a fair degree of success has been obtained.* Theory generally agrees that the acoustical behaviour of a porous type of absorbent is determined almost completely by—

1. The porosity, represented by the percentage volume of air contained by the material.
2. Resistance to air flow through the material, which depends upon the diameter of the pores.
3. The thickness of the material.

Generally, the greater these three factors, the greater the absorption coefficient of the material. The nature of the material itself appears to be unimportant compared with the structure of the air cells it contains.

The following are examples of materials which appear to rely upon porosity alone for their action—

Acoustic plasters

* See, for example: I. B. Crandall: *Theory of Vibrating Systems and Sound;* M. Rettinger: *Journ. Acoust. Soc. Amer.*, Vol. 6, p. 188, 1935; L. Cremer: *E.N.T.*, 12, p. 333, 1935; and others.

Acoustic felts
Slag wool and glass silk
Wood-wool slabs
Aerated concrete blocks
Sprayed asbestos
Acoustic stones
Wallboards (especially if perforated)

Photographs of some of these are reproduced in Fig. 31 (*a*)–(*l*).

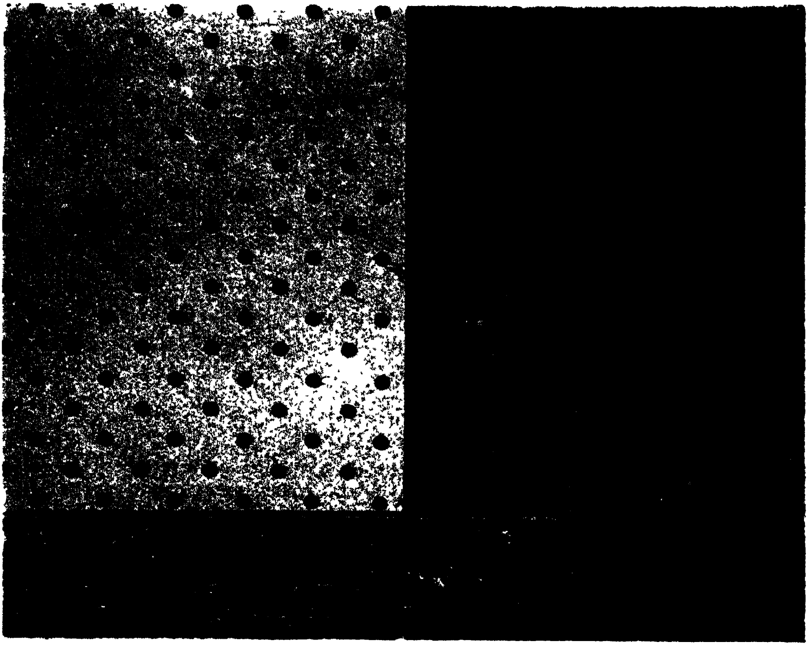
Resonant Type Absorbents. Wallboards, when mounted upon battens, as usually recommended, absorb in two ways. They absorb by reason of being porous, but they also absorb because of a resonance effect. Being very flexible, they are easily set into vibration by the incident sound, thus dissipating energy in another way. The effect of the resonance is to increase the absorption at low frequencies. This is illustrated in Fig. 32, obtained by Berg and Holtsmark* for "Treetex" at various distances from the wall.

The resonant type of absorbent finds particular application in forming an absorbent with a non-porous surface. This type of absorbent has been used by Oelsner in Denmark for correcting the acoustics of radio studios, churches, etc., and has been subjected to experimental investigation by Meyer† and Lauffer.‡ In its ordinary form it consists of a light wooden framework about 2 in. thick fixed to the wall and covered with a light impervious panel, such as aluminium sheet American cloth, thin plywood, or rubber sheeting. The space between the wall and the covering is rendered sound-absorbent by lining the wood frame with acoustical material having a high absorption coefficient. It should be mentioned that Meyer's experiments showed that it was sufficient to put the acoustic material upon the wood frame only, but Lauffer's experiments seem to indicate that the absorption obtained in this way can be increased by filling the air space with light absorbent material, such as wadding. The action of this construction, which is sketched in Fig. 33 (*a*), is, roughly speaking, to trap by absorption all the sound which is transmitted through the front surface. Reference to Chapter IX will show, however, that to obtain, say, 50 per cent transmission (i.e. at least half the sound falling on the panel passing through it) it would ordinarily be necessary to use an extremely light material, something of the order of thin paper. The resonant absorbent overcomes this difficulty by introducing resonance effects, whereby transmission through the panel is considerably increased. The resonance effects arise from the air imprisoned in the interspace, for at certain frequencies the combination of the mass of the covering

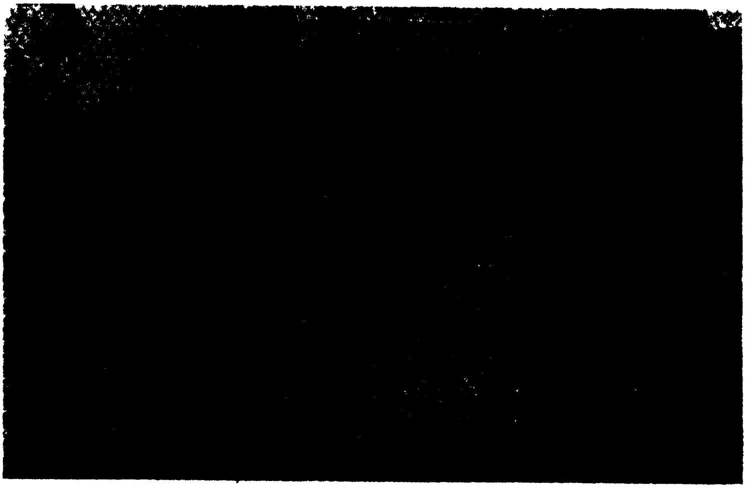
* R. Berg and J. Holtsmark: *Royal Norwegian Sci. Soc., Proc.*, Vol. 4, No. 23. (In Norwegian.)

† E. Meyer: *E.N.T.*, Vol. 13, p. 95, 1936, and *Acoust. Soc. Amer. J.* January, 1937.

‡ H. Lauffer: *Hochfrequenztechnik und Elektroakustik*, Vol. 49, p. 9, 1937.



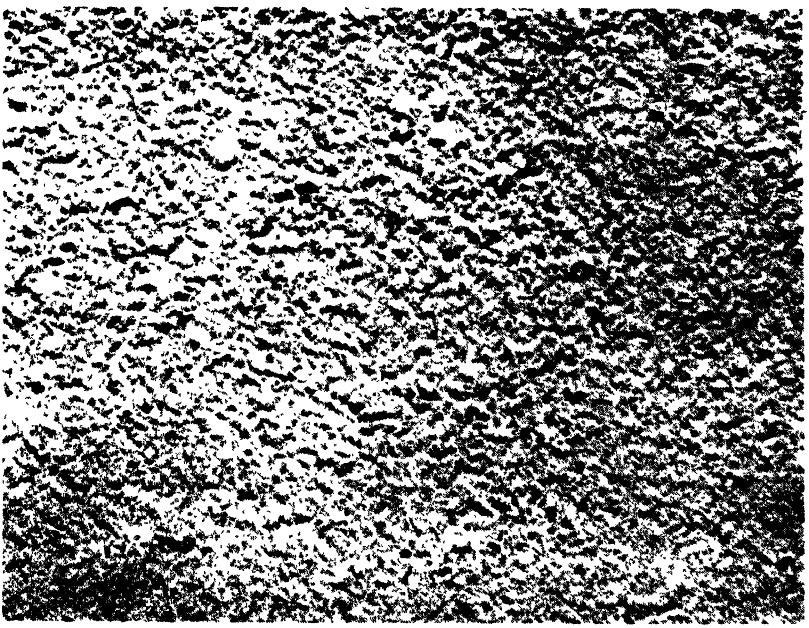
(*a*) Acoustic felt.
(*H. W. Cullum and Co. Ltd.*)



(*b*) Slag wool behind galvanized netting.
(*Frederick Jones and Co. Ltd.*)

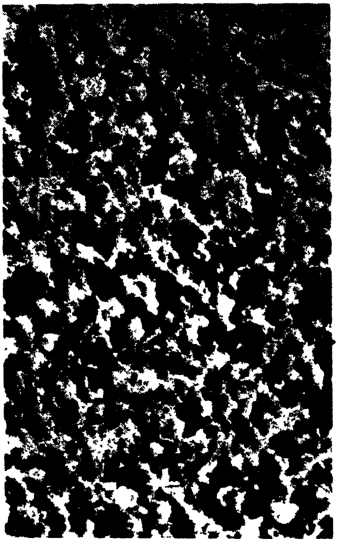
FIG. 31. SOUND-ABSORBING MATERIALS

(c) Fibre glass.
(*Fibreglass Ltd.*)

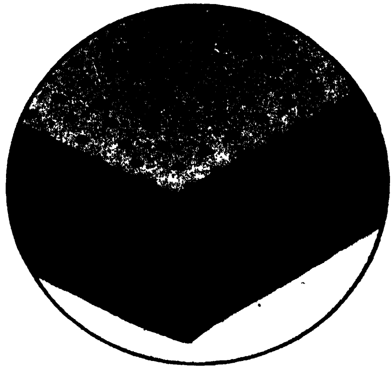


(*d*) **Fibrous wallboard.**
(***Patent Impermeable Millboard Co. Ltd.***)

FIG. 31—(*contd.*). SOUND-ABSORBING MATERIALS



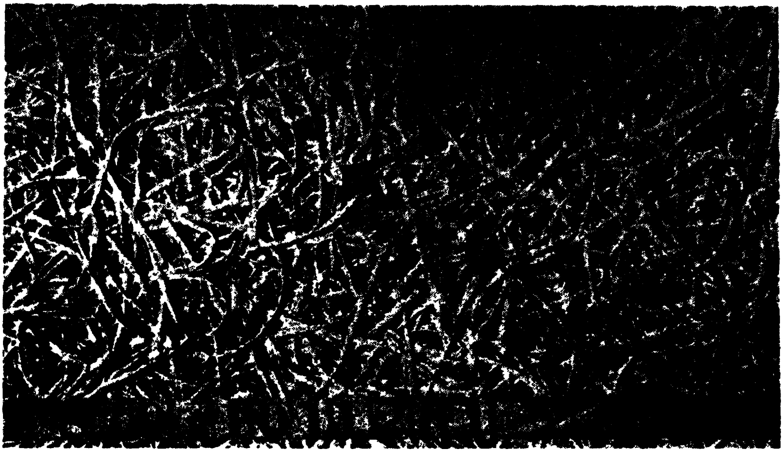
(*e*) Foamed slag block.
(*F. McNeill and Co. Ltd.*)



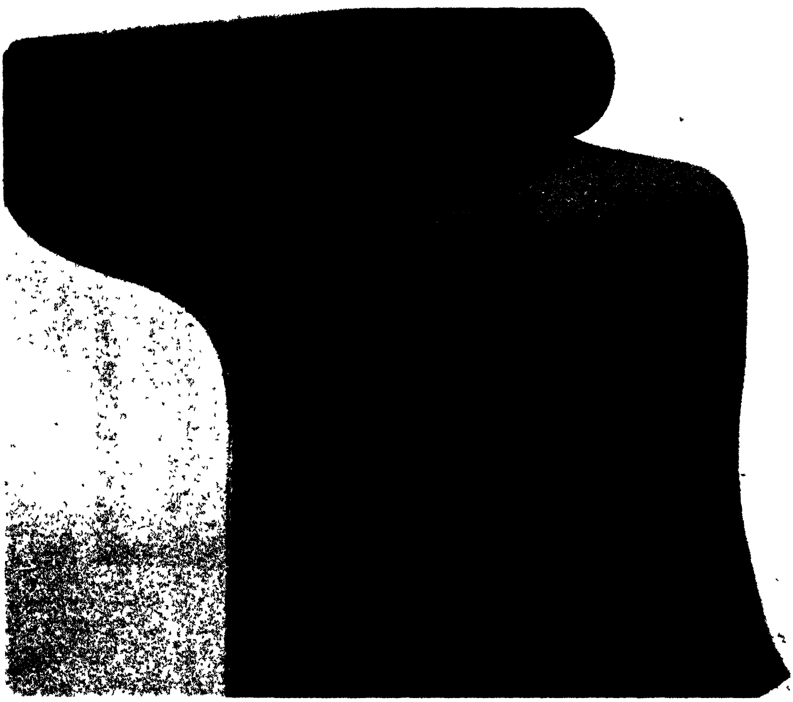
(*f*) Acousti-pad.
(*Burgess Products Co. Ltd*)

(*g*) Acoustic stone.
(*May Acoustics Ltd.*)

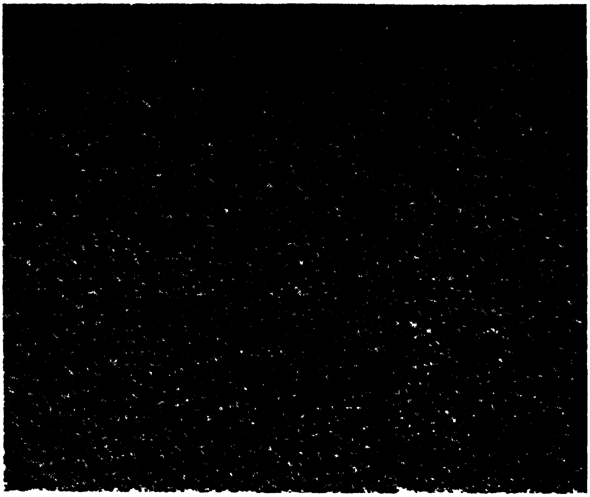
FIG. 31—(*contd.*). SOUND-ABSORBING MATERIALS



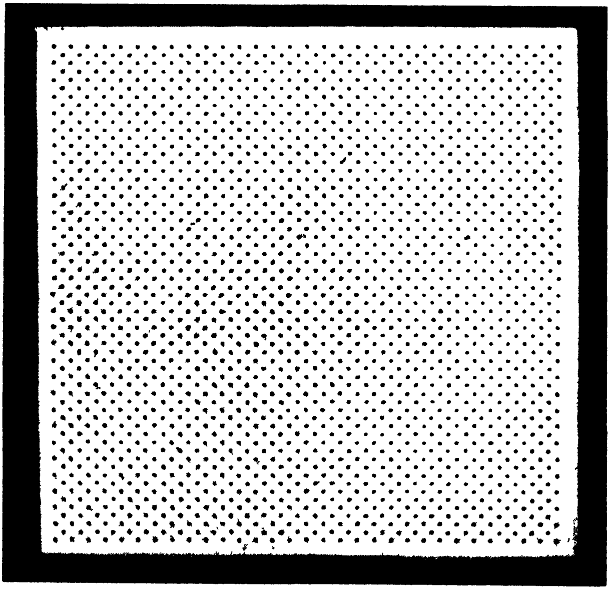
(*h*) Wood-wool bonded with cement; fine-grain slab as used for sound-absorption.
(*Thermacoust Products Ltd.*)



(*i*) Asbestos blanket.
(*Newalls Insulation Co.*)



(*j*) Sprayed asbestos.
(*Newalls Insulation Co.*)



(*k*) Asbestos fibre covered with washable plaster (perforated).
(*Newalls Insulation Co.*)

FIG. 31—(*contd.*). SOUND-ABSORBING MATERIALS

(*l*) A ceiling treated with "Celotex."
(*Celotex Ltd.*)

FIG. 31—(*contd.*). SOUND-ABSORBING MATERIALS

surface and the stiffness of the air layer comes into tune with the incident sound, which is consequently very easily transmittted. It might be feared that such a combination would be selective and absorb only certain frequencies, but Meyer and Lauffer have found that in practice the effect of the resonance spreads over a wide frequency range, giving considerable absorption for these frequencies. Some of Meyer's curves showing the manner in which the absorption of some of these absorbents varies with frequency are reproduced in Fig. 33 (*c*). The resonant character is well shown. When designing these absorbents the following formula can be used—

$$d = 29{,}900/n^2w$$

where d is the distance of the front covering from the wall,
w is the weight of the covering in pounds per square foot, and

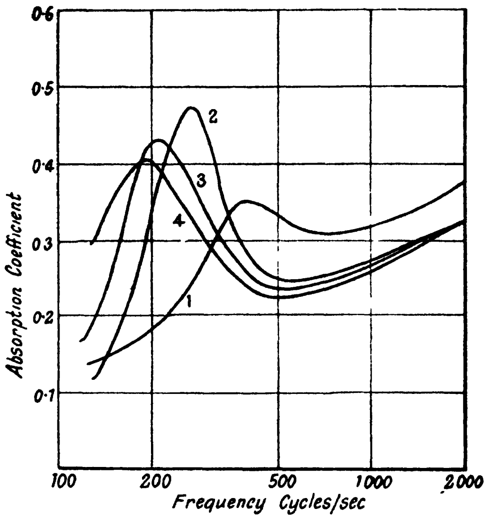


FIG. 32. ABSORPTION OF FIBREBOARD SPACED AT DIFFERENT DISTANCES FROM A WALL

Curve 1. Spacing 0 in.
„ 2. „ 1 in.
„ 3. „ 2 in.
„ 4. „ 4 in.

n is the frequency at which the system is giving its maximum absorption. This can be chosen from the character of the sound to be absorbed.

Meyer went further with the design of this type of absorbent and showed that if low frequencies were to be absorbed (this is of importance in radio studios) this could be achieved by using several layers of light material equally spaced as shown in Fig. 33 (*b*). This is the acoustical analogue of the resonant system known to electrical engineers as a low-pass filter.

Practical Considerations in the Choice of a Sound-absorbent Material. A number of considerations have to be taken into account when choosing a sound-absorbent material. A good appearance can be obtained with practically any absorbent material, though care

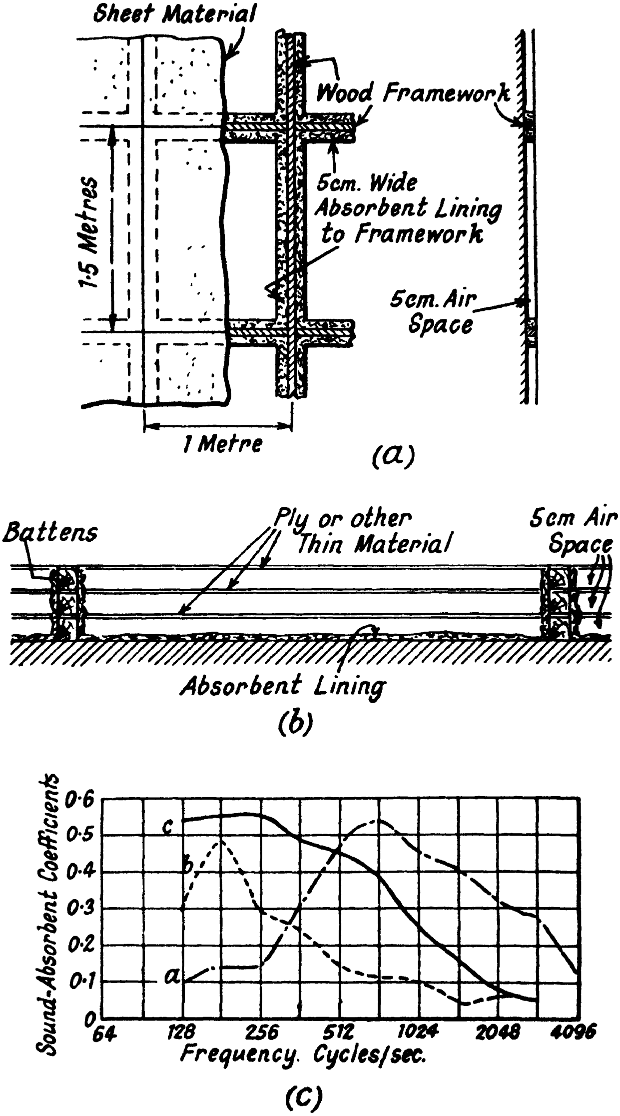


FIG. 33. RESONANT TYPE OF ABSORBENTS

(*a*) Construction of one design of resonant absorbent.

Absorption coefficients shown in curves *a* and *b* in Fig. 34(*c*) were obtained with covering material of aluminium sheet and thin plywood respectively.

(*b*) Resonant absorbent specially designed to absorb low frequencies. (See curve *c* in Fig 34 (*c*).

(*c*) Curves showing sound-absorption coefficients of resonant-type absorbents.

must be taken that the absorbent properties are not thereby sacrificed. There are, of course, situations in which appearance is of less importance; on the other hand, it is often necessary that the treatment should look as far as possible like an ordinary wall surface. Practically any soft absorbent material can be made to resemble an ordinary finish by covering with tightly stretched muslin or cribble cloth, which can be distempered if desired. Provided this covering is subsequently perforated (pinpricks are sufficient), an absorption not very inferior to that of the uncovered material can be obtained. Perforated metal or bakelite coverings are also used for covering soft absorbents.

Absorbent materials are, if possible, best left unpainted, as paint tends to cover up the pores. An investigation has been made by Chrisler* of the effect of paint on the absorption coefficient of a number of commonly used absorbent materials. These materials are described under the type number of the appropriate United States Federal Specification; reference should be made to the original paper for the detailed results, where the absorbents used are also illustrated by photographs. In general the reduction in average coefficient caused by brush painting with as many as 5, 6 or 7 coats never exceeds 35 per cent, and for some materials is much less than this. In one instance spray painting is found to reduce the average coefficient much less than brush painting In all cases the loss of absorption occurs at the higher frequencies (where a reduction of even as much as 50 per cent is often relatively unimportant). At low frequencies the absorption is generally unimpaired, and strangely enough, in some cases even shows a definite increase as a result of painting. The general deduction from this paper is that paint, even in repeated applications, is not as deleterious as might have been supposed, and that in cases in which painting of absorbent treatment is essential, it would be worth while to have measurements made of the effect upon the absorbents under consideration. There is obviously scope for further research in this subject, not only as regards decorative paints, but also as to the effect of paints and similar applications used for fireproofing.

Certain stains can be used without appreciably affecting the absorption, and by stencilling patterns on the material, decorative effects can be obtained. Information as to which stains can safely be used may as a rule be obtained from the manufacturers of absorbents. It is also possible to carve low reliefs on certain materials such as fibreboard and porous stones.

Ease of erection is another important consideration: certain materials, such as asbestos, are sprayed on with a gun; fibreboards are nailed on battens, and felts can be either nailed up or fixed with adhesive. Sound-absorbent plasters are applied in the usual way, but are said to be less easy to handle than ordinary plasters.

* *Nat. Bur. of Standards (Washington) J. of Research*, Vol. 24, p. 547, 1940.

As regards fireproof properties, a number of materials, such as asbestos and slag wool, are naturally incombustible and many others are non-inflammable or can be made so. Some, such as cotton wool, can be chemically treated; it has, however, been stated that impregnation with chemicals does not prevent the loose hairs on the surface from burning and spreading a flame across the surface of the material. In the lagged room of the Siemens — Halske A.G., Berlin,* precautions were taken to prevent a flame from spreading across the surface of the absorbent which lines the walls. The principle used was simply that of the miners' safety lamp; each wall was divided into sections by wire gauze, which projected above the surface of the absorbent. Any outbreak of fire would thus be localized to one of these sections. In this particular case the walls were divided into sections about a yard wide, each section extending from the floor to the ceiling, and the gauze strips used were folded parallel with their length, the edges being attached to the wall and the base of the loop projecting into the room a few inches above the surface of the absorbent.

One point should be borne in mind, namely the magnitude of the absorption coefficient. There will clearly be no point in using a material which is half as expensive if its absorption coefficient is only half as great, so that double the area would be required for the same quietening effect. The value of the absorption coefficient can usually be obtained from the manufacturer of the material.

It should also be noted that in the case of porous absorbents the absorption coefficient usually increases considerably with the thickness of the porous layer, particularly at low frequencies If low frequencies are the problem, it may well be more economical to use a greater thickness of treatment over a smaller area than a thin layer over all the available space.

The remaining important consideration is hygiene. In some circumstances it is essential that the treatment shall not harbour dust and must not gradually disintegrate or emit fine particles. The harbourage of bacteria by sound-absorbent materials is an important problem for hospital architects. Neergaard† experimented with a number of typical sound-absorbents. He applied *B. prodigiosus* in various ways and examined the absorbent materials at different depths during the following few days. On the twelfth day after applying the bacteria, tests were negative on all materials. It is concluded that, in general, acoustical materials do not favour the multiplication of bacteria more than do hard plaster, wood, and other materials commonly used in hospitals. The authors are not competent to judge, however, whether these results would be regarded by medical opinion as decisive. Even if acoustical materials

* W. Janovsky and F. Spandock: *Akustische Zeitschrift*, Vol. 2, p. 322, 1937.

† C. F. Neergaard: *Journ. Acoust. Soc. Amer.*, Vol. 2, p. 106, July, 1930.

are not breeding-grounds for germs, the need for easily cleansable hospital walls would rule out many materials.

In factories also the question of hygiene has to be borne in mind. In Great Britain the Factories Act, 1937* requires that, in general, parts of walls and ceilings at a height from the floor of less than 20 ft. should be whitewashed or colourwashed at least once every 14 months (unless the walls and ceilings have a smooth impervious surface, or are painted with oil paint or varnish or with washable water paint, when other requirements apply). The only exceptions are in favour of certain heavy and dirty industries. This means that any absorbent treatment applied at a height of less than 20 ft. must either be smooth and impervious, or such as to be unimpaired by periodic whitewashing or painting.

Choice of Position for Sound-absorbent Treatment. There are some positions in a room where sound-absorbent material would be unsuitable. To begin with, as the majority of these materials are soft, they should not be used on the lower parts of walls where they can be bruised by furniture. It is even doubtful whether they should ever be within reach of persons in the room, for soft absorbent surfaces seem to have an irresistible fascination for idle fingers.

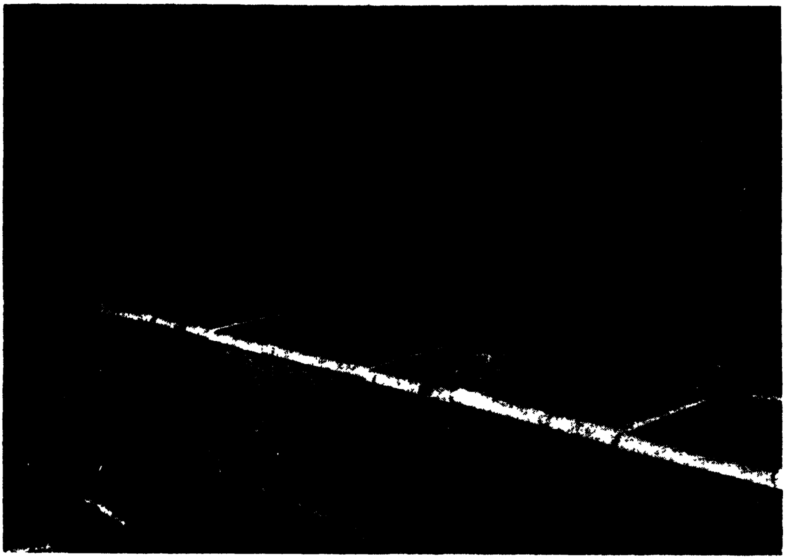
If the room is heated by covered ceiling panels, parts at least, of the ceiling will not as a rule be available for treatment, although acoustic plaster has been used over heating panels. The heating panels may occupy well-separated areas, in which case the ceiling space between them can be used for absorbent treatment. If the above suggestions cannot be adopted, the upper parts of the walls only can be treated; material having a high absorption coefficient should then be used on account of the limited area available. The floors can, of course, be carpeted in order to increase the absorption.

It may be difficult to find sufficient area to treat with absorbent. A possible solution of this difficulty is to divide large rooms by partitions reaching to the ceiling and to cover these with absorbent. The construction has the additional merit of screening sections of the room from each other. Failing this, the ceiling area may be increased by baffles.

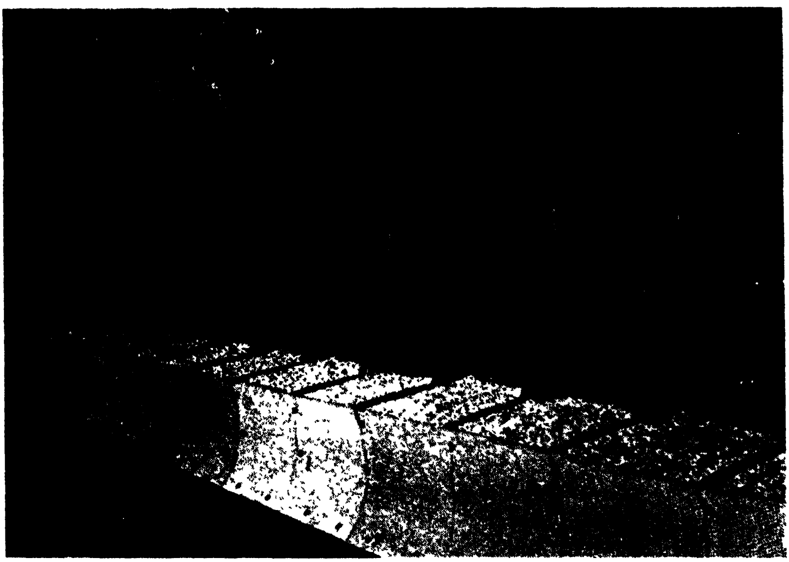
Value of Sound-absorbent Treatment Out of Doors. Courtyards and immediate surroundings of buildings can often with advantage be rendered more sound-absorbent by substituting areas of grass or freshly dug flower-beds for an unbroken expanse of paving or concrete. Direct sound entering the building is then not reinforced to such an extent by sound reflected from the ground.

An interesting example, from the engineering point of view, of the use of sound-absorbent material is in its application to the steel underground railway tunnels of the London Transport Executive.

* See Factories Act, 1937, Sect. I, and Statutory Rules and Orders, 1938, No. 487.



(*a*) Treatment in position.



(*b*) Treatment with cover removed, showing foamed slag.

FIG. 34. SOUND-ABSORBENT TREATMENT APPLIED TO AN UNDERGROUND RAILWAY TUNNEL

(*London Transport Executive*)

TABLE VIII

The Sound-absorption Coefficients of some Common Outdoor Materials

Material as tested (area of specimen 10 feet by 10 feet)	Thickness (inches)	Weight (lb. per cubic foot)	Reverberation absorption coefficients at frequencies/cycles per second					
			125	250	500	1000	2000	4000
Gravel soil, loose and moist	4	87	0·25	0·60	0·65	0·70	0·75	0·80
,, ,, ,,	8	,,	0·45	0·55	0·70	0·75	0·70	0·65
,, ,, ,,	12	,,	0·50	0·65	0·65	0·80	0·80	0·75
,, moist, pounded to give firm surface	12	101	0·10	0·10	0·15	0·25	0·40	0·45
Rough turf on 10 in. of compressed gravel	12–13	—	0·15	0·25	0·40	0·55	0·60	0·60
Sand (sharp), dry	4	108	0·15	0·35	0·40	0·50	0·55	0·80
,, ,, ,,	8	,,	0·15	0·30	0·45	0·50	0·55	0·75
,, ,, ,,	12	,,	0·20	0·30	0·40	0·50	0·60	0·75
,, wet (14 lb. water per cu. ft.)	4	122	0·05	0·05	0·05	0·05	0·05	0·15
,, ,, ,, ,, ,,	8	,,	0·05	0·05	0·10	0·10	0·10	0·15
,, ,, ,, ,, ,,	12	,,	0·05	0·10	0·15	0·20	0·20	0·30
Granite ballast (1500 stones per cu. ft.)	11	86	0·20	0·45	0·25	0·50	0·60	—
Limestone ballast (1500 stones per cu. ft.)	11	81	0·30	0·40	0·35	0·60	0·80	—
Slag ballast (900 stones per cu. ft.)	11	81	0·30	0·45	0·35	0·65	0·90	—
Foamed slag, graded between ¼ inch and ½ inch	11–12	26	0·65	0·70	0·75	0·80	0·80	0·80
Ashes, dry, loose (mainly fine cinders)	11	34	0·90	0·90	0·80	0·85	0·80	—
,, damped, loose (2·5 lb. water per cu. ft.)	11	36	0·90	0·90	0·75	0·80	0·80	—
,, ,, ,, ,, ,, ,,	6	,,	0·65	0·75	0·70	0·80	0·75	—
,, ,, ,, ,, ,, ,,	3	,,	0·25	0·55	0·65	0·80	0·80	—
,, ,, ,, ,, ,, ,,	1½	,,	0·15	0·25	0·35	0·55	0·75	—
,, ,, pounded and rolled	9½	42	0·75	0·70	0·75	0·80	0·80	—
Snow, freshly fallen	1	—	0·15	0·40	0·65	0·75	0·80	0·85
,, ,, ,,	4	—	0·45	0·75	0·90	0·95	0·95	0·95

These tunnels are, of course, markedly reverberant when untreated, and it has been found that a valuable reduction of the noise in the carriages is obtained by applying a sound-absorbent material to the lower part of the tunnel walls. A photograph of one of the experimental treatments (consisting of foamed slag behind a perforated asbestos-sheeting front) is shown in Fig. 34. Absorbent treatment at wheel level has been applied to the Stratford extension of the Central Line in London. There has also been a suggestion that the noise in carriages of surface railways might be reduced by the use of sound-absorbent track ballast. Incidentally, measurements made on the German railways have shown that, on an average, the upholstered second-class carriages are 5 phons quieter than the un-upholstered third-class carriages.*

The absorption coefficients of materials which commonly occur or which might be used out of doors have been measured† and are reproduced in Table VIII. It will be seen from the Table that the coefficients mostly increase considerably with frequency and with the thickness of the material concerned. Thick layers of ashes (wet or dry), loose gravel, and foamed slag are all valuable absorbents, particularly at low frequencies. Turf, while absorbing less at low frequencies, is also useful, but compressed gravel and wet sand are poor absorbents. Heavy freshly fallen snow has so high an absorption that it is recorded that during the construction of a shaft in the snow on the Jungfrau, those at the top of the shaft could not hear the shouts of men working at the bottom at a depth of 35 ft.

* *Zeits. für Techn. Physik*, 17, II, p. 60.

† G. W. C. Kaye and E. J. Evans, *Phys. Soc. Proc.*, Vol. 52, p. 371, 1940.

CHAPTER VI

INSULATION OF MACHINERY

MECHANICAL equipment is an important potential source of noise in the modern building. Any of this equipment may, either by poor design or by unskilful mounting, render abortive the careful planning which should otherwise have resulted in a quiet building. One can instance in this connexion lift machinery, ventilating plant, refrigerators, electricity generators, etc. The insulation and correct design of such equipment is an outstanding example of reducing noise at its source; the present chapter will deal with insulation.

Sometimes the contractors who supply the machinery include with it an insulating mounting, but cases frequently occur in which this has been omitted, and insulating treatment may be necessary. It is probably worth while, in buildings which are to be quiet, to insulate *all* machinery rather than risk having to insulate it after the building has been put into commission, since the expense involved is not usually great. In the case of large machines, insulation is a task for the specialist; insulation of light machinery can often be dealt with by non-specialists.

It should be pointed out that the subject to which this chapter is devoted is one upon which at least three books have been written;* there is also an extensive literature.† It will be appreciated therefore, that only a brief account can be attempted, and that recourse should be had to other works if detailed information is required.

Noise generated by machinery consists of two parts: the first is air-borne sound heard directly from the machine; the second is structure-borne sound which is communicated to the fabric of the building via the machine supports. This travels with relative ease through building materials, and may generate airborne sound of a disturbing intensity over a wide area.

Methods of dealing with air-borne sound will be dealt with first, leaving the prevention of noise due to structure-borne sound to later in the chapter.

Reduction of Sound arising Directly from Machinery. Machinery (other than factory plant) which is noisy in itself has become less common since makers have paid more attention to this point. We are, however, still far from the happy state of having no noisy machinery, and a few remarks on methods of dealing with it are necessary. The method adopted depends upon the aim. If the aim

* KIMBALL: *Vibration Prevention in Engineering;* EASON: *The Prevention of Vibration and Noise;* TIMOSHENKO: *Vibration Problems in Engineering.*

† See, for example, the bibliography given in *Handbuch der Experimental Physik*, 17, 3, p. 62.

is to reduce the sound transmitted out of the room containing the machinery to other rooms, the appropriate treatment is to reduce the noise in the machine-room and/or to increase the sound-insulation provided by the walls, doors, and windows of the room. The latter is dealt with in Chapters IX, X, XI, XII, and XIII. It is only necessary here to discuss methods of reducing the noise in the machine-room. The most effective treatment for this purpose is to build suitably constructed covers over the machines, either individually or in groups. Some benefit can, however, usually be obtained by rendering the room surfaces sound-absorbent, and this aspect is dealt with in Chapter V.

Sound-insulating covers often are a compromise between what is

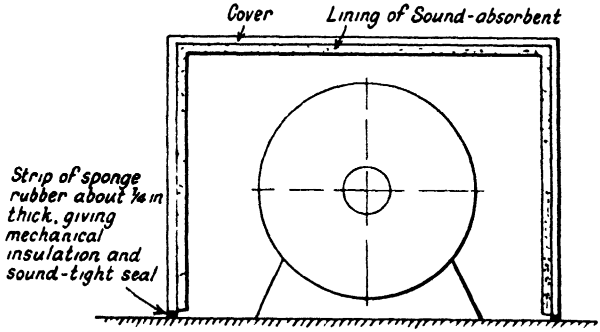


FIG. 35. ONE TYPE OF COVER FOR NOISY MACHINERY

acoustically desirable and what is practically possible. Frequently, as in the case of a calculating machine, the machinery cannot be completely covered, since there must be permanent access for an operator. In other cases heat dissipation becomes important (e.g. an internal combustion engine). A primary requirement is that there should be a minimum of structural connexion between the machine and its cover, otherwise this will in turn become a source of sound. The cover should not, therefore, stand upon the machine or the machine foundation. A useful construction shown in Fig. 35 is to stand the cover upon sponge rubber, a material which serves the double purpose of mechanically insulating the cover and making a sound-tight seal between the cover and the floor. Alternatively, the machine can, if possible, itself be mechanically insulated from the floor and hence from a cover standing directly on the floor.

Where complete enclosure can be effected the design of the cover should follow, as far as possible, the principles of sound-insulation described in Chapters IX and X. That is, speaking briefly—

(*a*) If single walls are provided, they should be as heavy as possible and should contain no gaps or pores through which sound can leak. Doors may be necessary, and if so should be of soundproof design (see Chapter XII).

(*b*) If the necessary weight for single walls is not practicable, a double structure should be used. A rough idea of the structure required can be obtained by measuring the noise level in the room made by the uncovered machinery and estimating the reduction of loudness (in phons) which is necessary to reduce the noise to the level permissible in the type of room concerned. (See Table XXIV, page 243.) As explained in Chapter XV this number of phons is roughly equal to the average sound-insulation (in decibels) of the structure required. The details of the structure can then be determined either by selecting a suitable material from Table XIV (page 139) or by deducing from Fig. 84 (page 143) the weight per square foot which the material should possess. If, to save weight, complex insulating constructions are aimed at, suggestions for their design can be obtained from Table XVI (page 165). In some cases a light framework covered with building board will be sufficient (this material has the practical advantage that it is also sound-absorbent); in other cases heavy plywood, or, for greater insulation, a steel plate or cast-iron cover may be more appropriate. In exceptional circumstances a brick or concrete construction may have to be built. If ventilation is necessary, it may be provided through sound-insulating ducts giving a suitable attenuation. (See Chapter VIII.)

The effect of enclosing electrical machinery has been studied by E. Lübcke.* Fig. 36, taken from this paper, shows a section of a cover of a large generator. In this case the cover is a double iron structure, the inner surfaces being lined with sound-absorbent. The noise level of the machine was reduced by this means by 20 phons.

If only a partial covering of the machine is possible, only a moderate reduction in loudness (which may, however, be very welcome) is possible. Figures do not seem to be available for the loudness reduction obtainable from a partial covering, but there is evidence of a general nature which indicates that the greatest loudness reduction will result if the interior surfaces of the cover are set as close as possible to the machine and are lined with a material having a high sound-absorption coefficient. (See Fig. 37.) Naturally, the enclosure should be as complete as practicable.

Where cooling of a completely enclosed machine is important something can be done by constructing the cover of metal with suitable cooling fins though this may involve danger of "drumming," if the metal is thin. (If this course is adopted, some part, but not all, of the metal cover should be lined with sound-absorbent material). Alternatively, some form of ventilation (probably forced) through

* *Zeits. für Techn. Physik*, Vol. 12, p. 576, 1935.

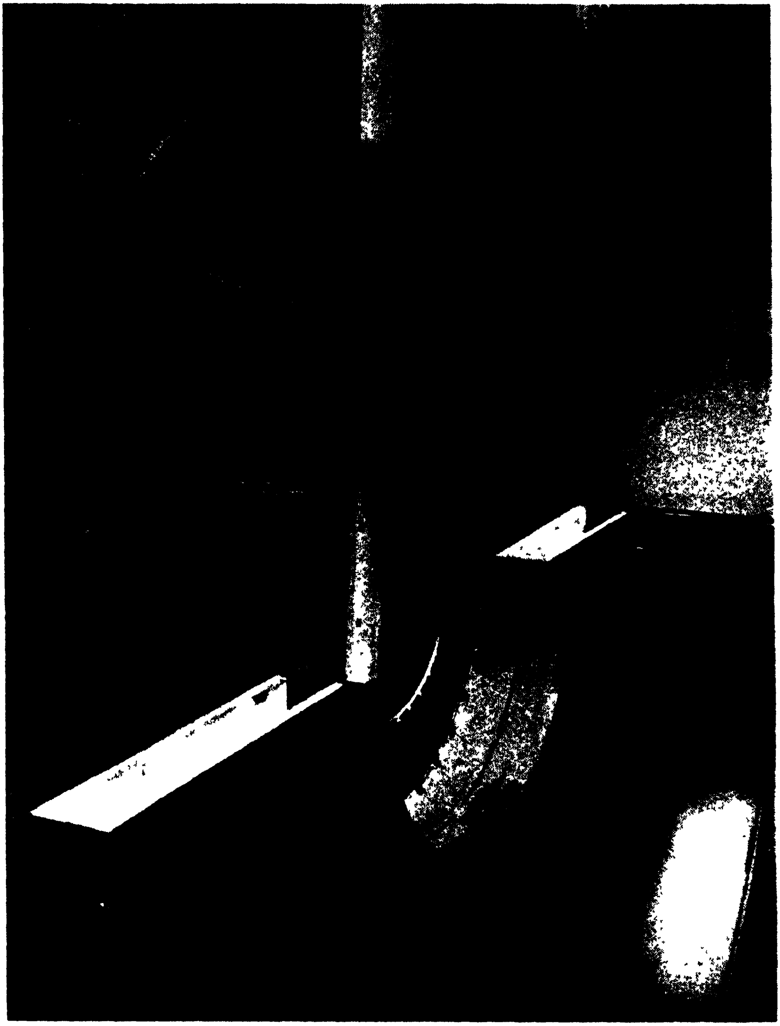


FIG. 36. COVER OF LARGE GENERATOR
(*Siemens & Halske A. G., Berlin*)

a sound-insulating duct will be necessary. Fig. 38 shows the application of this treatment to an electric motor.*

Insulation of Vibration. Mechanical insulation of machinery is necessary in the modern building for two reasons. The first is that undue vibration (and the reference is largely to sub-audible

* M. KRONDL, *Revue d'Acoustique*, Vol. 2, p. 358, 1933.

frequencies) may not only cause damage to a building, but can also, even in intensities which would be safe from the point of view of

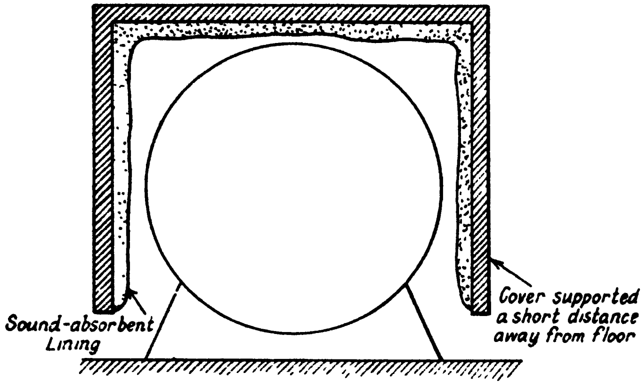


FIG. 37. A COVER WHICH COMBINES A DEGREE OF NOISE REDUCTION WITH VENTILATION

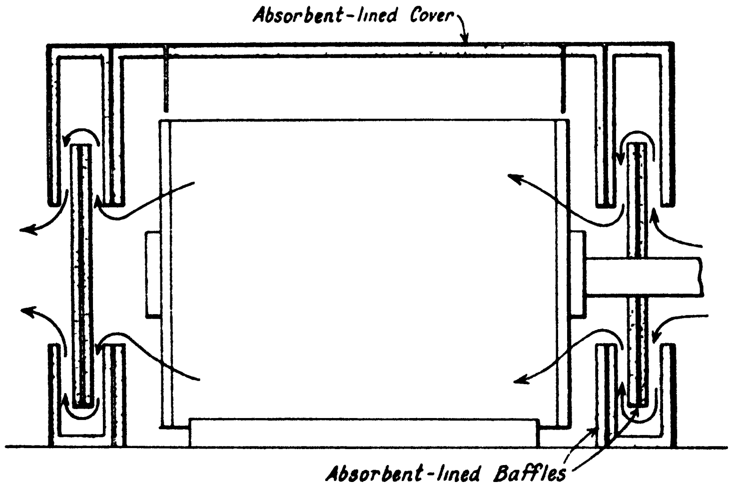


FIG. 38. SOUND-INSULATING MACHINE COVER DESIGNED TO ALLOW FOR VENTILATION

the structure, cause annoyance to the occupants of the building simply because no one likes to be in contact with a floor which can be felt to be vibrating.* The second reason, which seems to have

* See, for example, J. FRANCIS SMITH: *Journ. Inst. Chart. Surv.*, 1938. The human response to vibration has been studied by various authors, including F. J. MEISTER, *Akustische Zeits*, Vol. 1, p. 1, January, 1937; I. KATEL, *Revue d'acoustique*, Vol. 4, p. 86, 1935; H. M. JACKLIN: *Trans. S.A.E.*, 38–39, p. 401, 1936.

been recognized later but is probably tending to become the more important, is that machinery, particularly the high-speed motors which find so many uses in the modern building, can also cause audio-frequency vibration which is radiated from the structure as audible sound. Both aspects of mechanical insulation will be dealt with in this section, but the emphasis will be upon the second.

Machinery is usually insulated by standing it upon an elastic support proportioned so that the frequency of the free vibration of the machine on this support (natural frequency) is low compared to those of the vibrations generated by the machine.* It is scarcely appropriate to develop here the formula for the insulation afforded

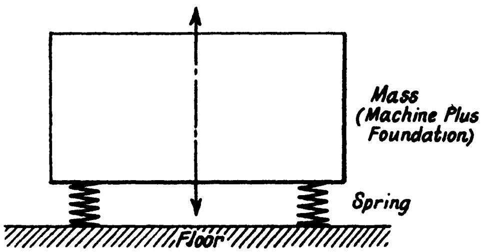


FIG. 39. MACHINE ON INSULATING SUPPORT (FRICTIONLESS)

by the elastic support—the calculation can be found in almost any standard textbook†—but the simple explanation given below may serve to show the essential truth of the above principle.

Noise and vibration generated by a machine are usually made more troublesome because the vibratory forces (due to unbalance, etc.) shake the floor or wall to which it is attached. The aim in insulating a machine is therefore to reduce the force transmitted to the floor or wall concerned. Fig. 39 represents a mass (machine plus foundation) supported on a spring which stands upon a floor. The vibratory forces generated by the machine will move the mass up and down with the same frequency (for simplicity only vertical forces and motion are considered). The up-and-down motion of the mass will cause simultaneous variations in the deflection of the spring, which will consequently exert alternating forces on the floor. It is these forces which we desire to reduce to a minimum. Their magnitude is determined by the stiffness of the spring (supposed for the

* The determination of the frequencies of the vibrations generated by any particular machine may require the services of a specialist; in simple cases such as a machine containing a single revolving part (e.g. an electric motor), the lowest frequency in cycles per second is numerically equal to the rate of rotation in revolutions per second. Another simple case is a reciprocating compressor, in which the chief vibration frequency is equal to the number of strokes per second.

† See, for example, KIMBALL: *Vibration Prevention in Engineering*; A. H. DAVIS: *Modern Acoustics*.

moment frictionless) and the amplitude of motion of the mass, being in fact proportional to each of them.

Before discussing methods of reducing these forces, we must look into the way in which the behaviour of the system depends upon the frequency of the vibratory force. If this force has a very low frequency, the mass is moved up and down slowly, and in these circumstances the force is resisted by the stiffness of the spring rather than by the inertia of the mass. That is to say, the amplitude of motion is determined largely by the stiffness of the spring. At high frequencies, however, the motion of the mass is rapid, and the amplitude is then determined by the inertia of the mass, the stiffness of the spring having little effect.

We can now again take up the question of reducing the forces exerted by the spring on the floor. When the vibratory forces are of high frequency, the forces exerted on the floor (which, as mentioned previously, are proportional to the stiffness of the spring and the amplitude of motion) can be reduced by making the stiffness as small as possible and the mass (which determines the amplitude) as large as possible. This may be expressed differently by remembering that the natural frequency of vibration of the mass on the spring is proportional to $\sqrt{(\text{stiffness}/\text{mass})}$ (see Chapter I); it then appears that the greatest insulation results when the natural frequency of the support is as low as possible. As regards low-frequency vibration, however, the position is not so simple. In this region the amplitude is determined chiefly by the stiffness of the spring. Hence, an attempt to reduce the forces exerted by the spring by reducing its stiffness might be nullified by the resulting increased amplitude. It is difficult, in fact, to say from this sort of argument what the effect of altering the stiffness will be in this case.

By mathematical analysis the insulation R obtainable from a support of this kind can be calculated. It is most conveniently expressed as—

$$\left(\frac{\text{Vibrating force due to machine}}{\text{Vibrating force transmitted to foundations}}\right)^2$$

which can be shown to equal

$$R = (1 - a^2)^2$$

where $$a = \frac{\text{Frequency of vibration due to machine}}{\text{Natural frequency of insulating support}}$$

This result is expressed graphically in Fig. 40, in which the insulation (expressed as usual in decibels, i.e. $10 \log_{10} R$) is shown for increasing values of a.

The curve shows that when the frequency of the driving force is very low, the insulation provided by the support is approximately 0 db.; as the frequency increases, the insulation becomes increasingly negative (i.e. the support becomes increasingly worse than useless), until the frequency is greater than the natural frequency. Thereafter, as the driving frequency increases, the insulation becomes less negative, and finally becomes positive once the frequency exceeds $\sqrt{2}$ times the natural frequency.

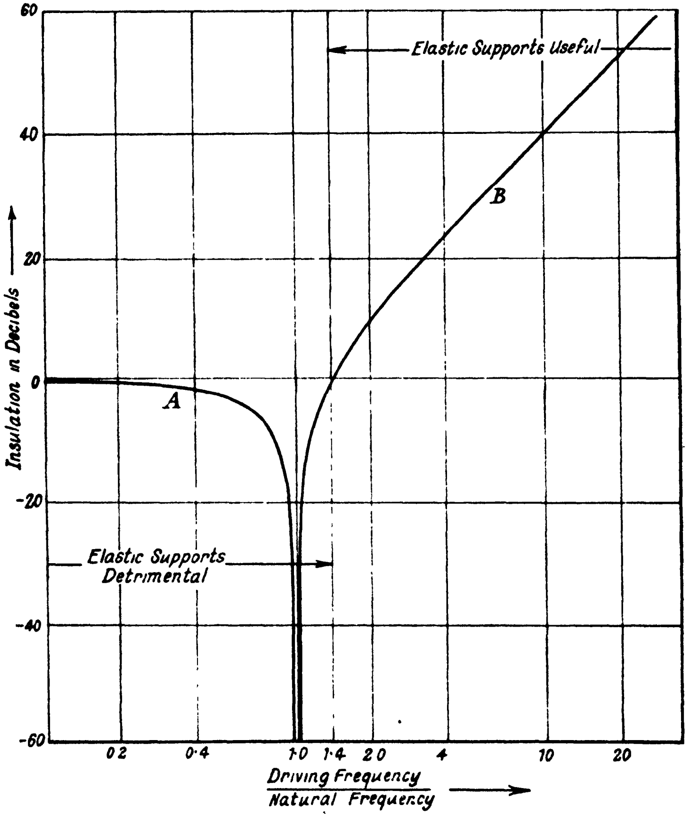


FIG. 40. INSULATION AFFORDED BY UNDAMPED MACHINE SUPPORT FOR DIFFERENT RATIOS OF DRIVING FREQUENCY/NATURAL FREQUENCY

The aim should be, therefore, to arrange that the insulator is working as represented by the region *B* on the graph, i.e. the frequency of vibration of the insulating support should be as small as possible compared to the frequency to be insulated against, and in order to be worth while should be less than about one-third of this frequency.

Methods of Obtaining a Support having a Sufficiently Low Frequency of Vibration. Discussion of methods of obtaining a support having a low frequency of vibration is much assisted by the use of a very simple formula, which is derived below. The frequency of

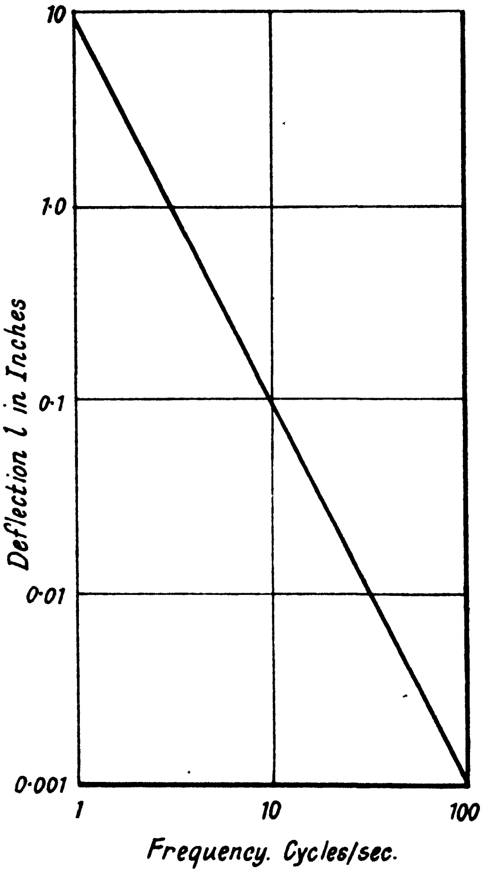


FIG. 41. GRAPH SHOWING DEFLECTION l OF INSULATING SUPPORT REQUIRED TO GIVE THE LOADED SYSTEM A NATURAL FREQUENCY n. ($n = \sqrt{10/l}$)

Note. For insulating supports other than springs, namely most elastic materials, the deflection obtained from the above graph or formula should be corrected by a multiplying factor K, values of which are given in Table IX. (K is the ratio of the dynamic to the static elasticity of the material, and varies with the load.)

vibration of a mass supported on a spring is shown in textbooks to be given by the formula—

$$n = 3{\cdot}17 \sqrt{(S/m)} \quad . \quad . \quad . \quad . \quad (1)$$

where n is the frequency of vibration in cycles per second,
m is the mass in pounds,
S is the stiffness of the spring in pounds per inch, i.e. the weight (in pounds) which will compress or extend the spring by 1 in.

Now, the amount by which the spring is compressed when the mass is put upon it is obviously $m/S = l$ in., say.

We may therefore rewrite formula (1) as—

$$n = 3{\cdot}17/\sqrt{l} = \sqrt{(10/l)} \text{ with sufficient accuracy.}$$

Thus the greater the amount by which the spring deflects when the machine and foundation are put upon it, the lower will be the frequency of vibration of the machine on the support.

It will be noted that the frequency and hence the insulation are determined by l, and l only.

The formula provides a convenient way of calculating the strength of the elastic material required for insulating a given machine, and is accordingly shown graphically in Fig. 41. By use of this graph it is possible, once the vibration frequency of the support has been decided, to specify the insulating material in terms of the amount by which it should compress under load. Caution is required when using this graph for insulating materials other than springs, since, as is well known, the elasticity of materials such as rubber, cork, and felt is greater for a steady load than for an alternating force, sometimes by as much as a factor of 10. Thus a static compression test can be misleading as regards the effective elasticity when the material is subjected to a vibratory force. For this reason, when using a graph of the type shown in Fig. 41, it is usual to employ a factor appropriate to the material under consideration. Factors deduced from available published information are given in Table IX*; this is only a rough method of taking account of the peculiar elastic properties of these materials, but it is probably sufficient for ordinary purposes. The factors given are the figures by which the compression under load deduced from Fig. 41 should be multiplied to deduce the compression required to give the system a certain natural frequency.

An important point emerges from Fig. 41. It will be seen that low vibration frequencies are obtainable only by arranging that the insulating material is deflected by a considerable amount under load; thus, a frequency of 1 c.p.s. requires that the deflection under load should be 10 in. Compressions of the order of several inches are very difficult to arrange, since the uncompressed thickness of the insulating material will need to be at least two or three times

* A. J. King: *Engineering*, Vol. 144, p. 296, 1937; also Vol. 146, pp. 124 and 198, 1938. See also B. E. Eisenhour and F. G. Tyzzer: *Journ. Franklin Inst.*, p. 691, 1932; and C. Costadoni, *Zeits. für Techn. Physik*, Vol. 17, p. 108, 1936.

TABLE IX

MULTIPLYING FACTORS (K) FOR THE DEFLECTION UNDER LOAD OF ELASTIC MATERIALS

Material	Load (lb./sq. in.)	K
Soft rubber sheet	10	1·3–1·8
	50	1·4–2·1
	100	1·6–2·3
Felt	10	16·5
	20	11·8
	50	9·0
Cork material	10	1·8
	50	3·3
	100	5·0
Felt with cork laminae bonded with latex	10	28·1
	20	20·2
	50	14·8
	100	11·7

this thickness; a simple practicable method of achieving this deflection would be to *suspend* the machinery by steel springs, since insulating materials under a compression of this magnitude would tend to make the system top-heavy. Considerable deflections can be obtained in this way from a moderate length of spring. Insulating suspensions of this type are sometimes used for special purposes, but apart from the practical difficulty of constructing them, they tend to bounce so much that there are only a few purposes for which their use is possible. It appears, in fact, that supports having these very low frequencies of vibration are ordinarily impracticable, and hence that insulation against frequencies of the order of 3–5 c.p.s. (180–300 per minute) is difficult to obtain. In these circumstances it is best not to attempt insulation by an elastic support, since it is liable to magnify the transmitted vibration if the support frequency cannot be made low enough. It is fortunate that these frequencies are sub-audible, and hence will not cause a noise nuisance directly. It should not be forgotten, however, that, if sufficiently intense, vibration at sub-audible frequencies can lead to noise by rattling objects such as windows and even crockery.

Insulation against the lower audible frequencies of 20–25 c.p.s. (1,200–1,500 per minute) necessitates a support frequency of no greater than 5–8 c.p.s., i.e. materials which deflect under load by about ½ in. (provided the dynamic and static elasticities are nearly enough equal; more if they are not). Deflections of this order are probably most easily obtained in practice by springs of steel, or rubber-like materials in compression, and these appear, therefore, to have a good deal to commend them when insulation against these low frequencies is required.

It should be remembered, however, that frequencies of the order discussed above only just come into the audible range, and hence can have a relatively high intensity without being heard. Often, however, when vibrations of this frequency occur, they are accompanied by higher frequencies which though less intense are more audible. In such cases the more important consideration would be to provide insulation against the higher frequency, and, if practical considerations demanded it, supports of materials other than those mentioned above could be fitted and would probably prove very satisfactory.

Insulation against frequencies greater than 30 c.p.s. requires only relatively small deflections of the insulator, and the range of insulating materials which can be used is accordingly widened. Practical considerations, such as those of durability and load-bearing properties, can then be given the place of primary importance.

Effect of Weight of Machine. Having decided upon the deflection of the spring under load, i.e. the ratio of the mass of the machine to the stiffness of the spring, which will provide the required insulation, it is possible to vary either of these quantities without altering their ratio, and the question is whether it is advantageous to do this, or to let circumstances, in the form of the weight of the machine, settle the matter without further thought.

Theoretically, as explained earlier, the insulation provided by a given support is determined only by the relation between the driving frequency and the support frequency. Accordingly there appears to be no acoustical reason for adding to the weight of the machine before mounting upon the elastic support, although there may be practical considerations, such as the need for a foundation block with holding-down bolts, which will necessarily increase the weight. Increasing the weight of the foundations does not, in fact, result in a lower support frequency, since the springs will need to be strengthened proportionately. As mentioned later, however, there may be practical reasons for adding to the weight of the support, e.g. to increase stability.

Effect of Damping or Resistive Forces. We must now consider the effect of damping or resistive forces (which must not be confused with the elastic forces hitherto discussed). Damping or resistive forces are commonly present in insulating supports, either on account of dampers used to limit the motion of the support or because of internal friction in the elastic materials used; felt, for example, has a marked internal friction, while a steel spring has very little.

Fig. 42 shows diagrammatically an insulating support similar to that shown in Fig. 39, but with the addition of a dashpot to represent damping either by external dampers or internal friction. The dashpot acts as a brake upon the motion of the mass. Since this motion tends to be large at a resonance, damping is valuable there. If this were the only consideration, damping would be a useful feature of an insulating support. It will be noticed, however, that the dashpot provides an additional link between the mass and the floor, and hence to some extent short-circuits the insulation. Except, therefore, when it is necessary to limit the amplitude at a resonance, damping is inadvisable. The effects of damping are discussed in greater detail in the following paragraph.

Fluid Friction and Solid Friction. A dashpot was chosen to represent damping in Fig. 42. While this is the conventional way of representing damping, it may not exactly represent the dissipative force in an elastic material.

The characteristic of damping afforded by a dashpot is that the damping force increases with the rapidity of movement, since it is

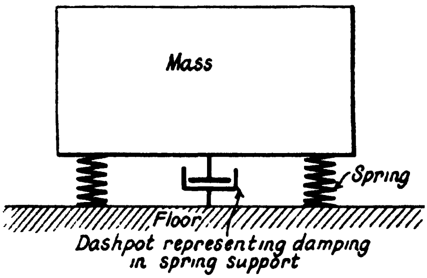


FIG. 42. MACHINE ON INSULATING SUPPORT

Case in which there is internal friction in the support, or an external damper is fitted

produced by the viscous flow of a liquid (compare hydraulic dampers used in automobiles). This type of friction is termed *fluid friction*, but experiment indicates that internal fricton in the elastic materials used for insulating machinery is not entirely of the fluid-friction type.* It appears that there is also a type of internal friction which is independent of the rapidity of motion. This type of friction is termed *solid friction* on account of its being a characteristic of friction between solid surfaces (compare the friction type of damper used on automobiles). A simple explanation of this behaviour could be that the internal friction is caused by different parts of the material rubbing together during distortion. Both types of friction are probably always present, but their relative amounts vary with the material.†

* A. L. KIMBALL: *Physical Review*, December 1927; E. SCHMIDT: *Gesund. Ing.*, Vol. 46, p. 61, 1923; E. WINTERGERST: *Schalltechnik*, Vol. 4, p. 85, 1931; C. COSTADONI: *Zeits. für Techn. Physik*, Vol. 17, p. 108, 1936; E. MEYER AND L. KEIDEL: *ibid.*, Vol. 18, p. 299, 1937; H. NEUBERT: *Akustische Zeits.*, Vol. 2, p. 34, 1937.

† To the physicist the difference between the two types of friction is that in the case of fluid friction the coefficient of the velocity in the equation of motion is constant, but in the case of solid friction it is inversely proportional to the frequency.

The importance of the distinction can now be seen. If the internal friction in a material is of the fluid-friction type, then the amount by which the insulation is spoiled by the friction will clearly increase as the frequency of vibration rises, since the velocity corresponding to a given amplitude of motion increases with the frequency. If however, it has the characteristic of solid friction, the deleterious effect will not change as the frequency rises.

The difference between the effects of the two types of friction is shown in Figs. 43 and 44, which are drawn from the appropriate formulae.* In Fig. 43 the insulation to be expected is shown for several different degrees of *fluid friction* damping. It will be noted that as the damping is increased the loss of insulation at resonance is reduced, but at the same time the insulation at greater frequencies decreases, the effect being greater for high frequencies than for low. On the other hand, in the case of solid friction (Fig. 44) a damping which is sufficient almost to obliterate the resonance decreases the insulation at the higher frequencies by only a comparatively small amount, which does not vary with the frequency.

It will be seen that it is important to decide which type of friction is predominant in an insulating material. Not much information has been published on this point, but it seems that, at least in the case of homogeneous materials such as rubber or cork, the dissipative forces are characteristic of solid rather than fluid friction. It follows that, where materials of this type are used, their internal friction (which in some cases may, to prevent bounce, make them preferable to springs), is not necessarily so harmful as is sometimes supposed.

Necessity for Damping Resonance of Support in Certain Cases. As explained earlier, the greatest insulation results if the elastic support is undamped, and this is the ideal to aim at ordinarily. There are circumstances, however, in which a degree of damping is advisable. The most commonly encountered example is the case of a machine of variable speed. If the speed of the machine is ever likely to be in the neighbourhood of the support resonance frequency

* The formulae are—

(1) *For fluid friction:*

$$\text{Insulation in decibels} = 10 \log_{10} \frac{a^2b^2 + (1 - a^2)^2}{1 + a^2b^2}$$

where $b = R\sqrt{(MF)}$; R, M, and F being the coefficients in the usual equation of motion $\frac{Md^2x}{dt^2} + \frac{Rdx}{dt} + Fx = 0$.

Note. b is proportional to the logarithmic decrement of the system; a = driving frequency/natural frequency.

(2) *For solid friction:*

$$\text{Insulation in decibels} = 10 \log_{10} \frac{c^2 + (1 - a^2)^2}{1 + c^2}$$

where $c = ab$; but in this case b is no longer constant, but is inversely proportional to the frequency; c is therefore a constant.

for an appreciable time, dangerous vibration may occur unless damping is introduced. A reciprocating engine which takes a perceptible time to run up to full speed would be another special example of this. In these circumstances springs would be contra-indicated unless

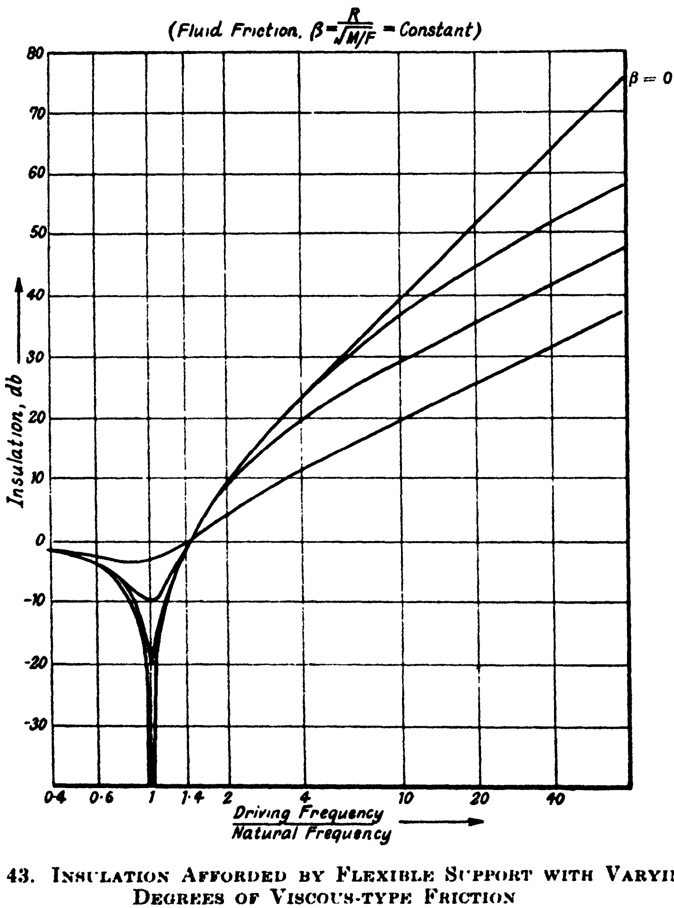


FIG. 43. INSULATION AFFORDED BY FLEXIBLE SUPPORT WITH VARYING DEGREES OF VISCOUS-TYPE FRICTION

special dampers, similar in action to automobile spring dampers, were fitted, and a material such as cork would be more suitable. The ordinary small electric motor runs up to full speed so quickly that resonance effects are unlikely to arise and damping is unnecessary.

A method of incorporating a degree of damping in a steel spring is shown in Fig. 45.* The spring is precompressed to such an

* G. LINDENAU: *Die Schalltechnik*, Vol. 7, p. 15, 1935.

extent that the load to be carried would just "float" on it; the spring is then embedded in a suitable rubber compound which acts as a damper.

Since damping may decrease the insulation obtainable, no greater

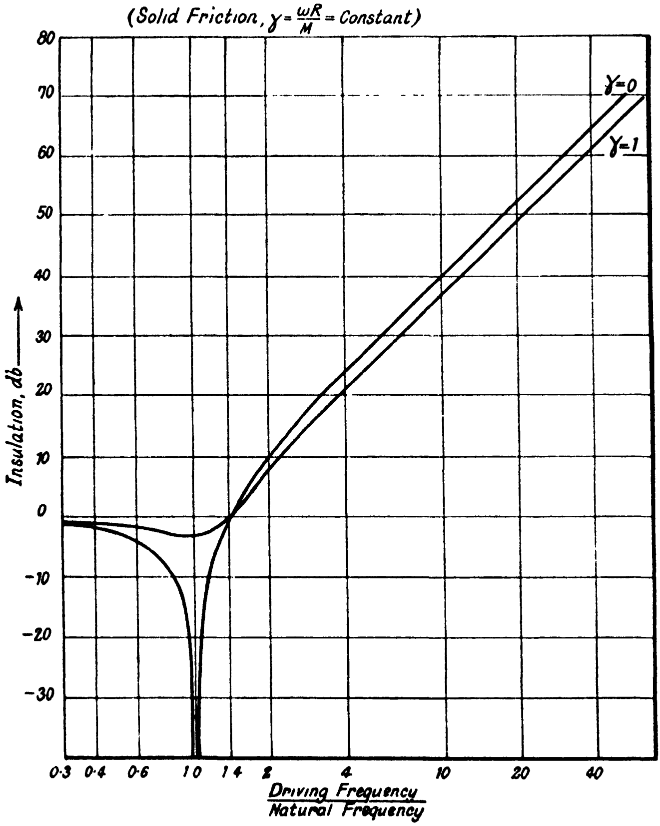


FIG. 44. INSULATION AFFORDED BY FLEXIBLE SUPPORT WITH VARYING DEGREES OF SOLID-TYPE FRICTION

damping should be employed than is absolutely necessary. Such matters are probably best determined by experiment.

Effect of More than One Mode of Vibration. We have assumed so far that the insulating support can vibrate vertically only, and that the machinery to be insulated produces only a vertical driving force. Actually, this is scarcely ever true. Supports can almost always vibrate in other ways also, and machinery may generate horizontal vibrating forces and also torsional forces. In fact, an elastic support normally has six modes of vibration, four of which are shown diagrammatically in Fig. 46. (The remaining two are: sideways, similar to (*b*), but in the other direction; and tilting, similar to (*c*), but in the other direction.) To each mode of vibration corresponds a natural frequency. The support thus has six possible frequencies of vibration. The relative importance of the different forms of

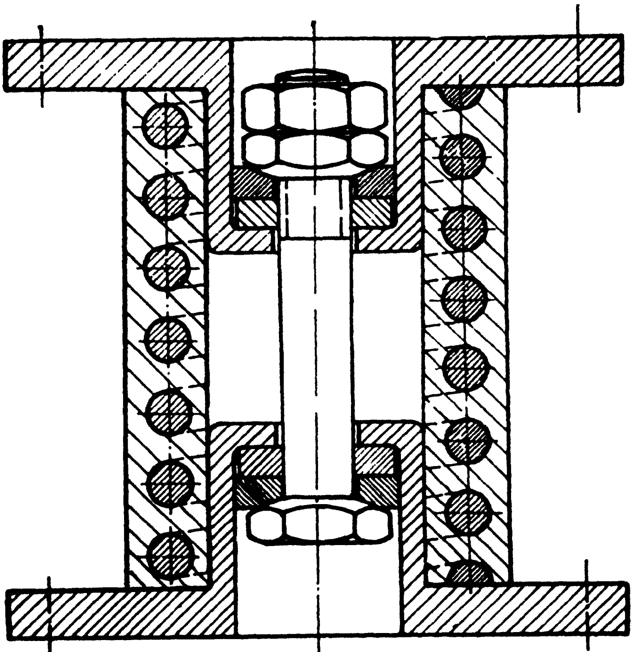


FIG. 45. DAMPING INCORPORATED IN A SPRING INSULATOR
(*Emil Zorn A. G., Berlin-Heinersdorf*)

vibration of the support depends upon the character of the vibrating force generated by the machine. For example, if the machine generated a pure vertical vibration, the horizontal mode of vibration of the support would be relatively unimportant. There are very few machines for which this is true, but more commonly, as stated above, vibratory forces are likely to occur in all directions. All modes of vibration of the support are then important, and for effective insulation all the six natural frequencies should, in accordance with our rule (page 79), be less than about one-third of the driving frequency.

Calculation of the natural frequencies in any particular case is complicated,* and is best performed by specialists, but will, however,

* Formulae for this purpose have been given by E. H. HULL: *Journal of Applied Mechanics*, Vol. 4, A.109, 1937.

probably be required only when the support frequencies cannot be very much lower than the driving frequency. This follows, speaking quite roughly, from the fact that the frequencies corresponding to the various modes of vibration are usually much the same, so that if one is markedly lower than the driving frequency, the others probably will be also. If, however, the frequency of vertical vibration (the form of vibration ordinarily considered) is, say, only about a third of the driving frequency, it might happen that the frequency

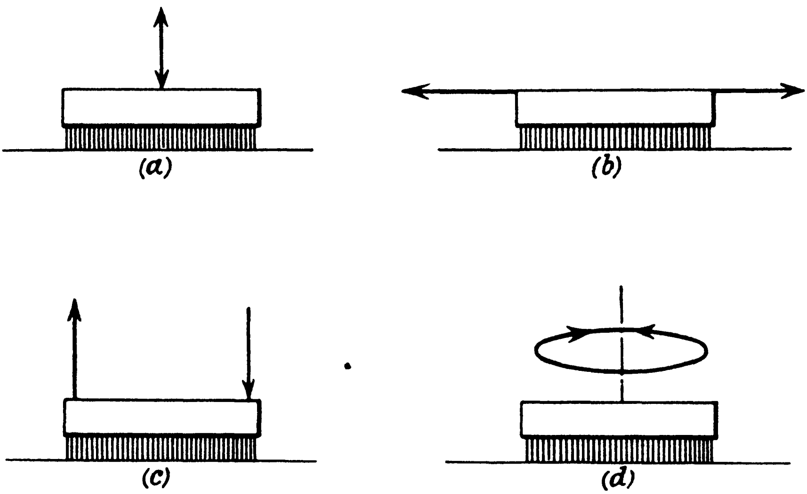


FIG. 46. ILLUSTRATING FOUR OF THE DEGREES OF FREEDOM OF AN INSULATING SUPPORT

(*a*) Vertical, compressing insulating material.
(*b*) Sideways, shearing insulating material.
(*c*) Tilting, compressing insulating material.
(*d*) Twisting, shearing insulating material.

of one of the other modes of vibration was so much nearer the driving frequency that the insulation would be spoilt. In such cases the frequency corresponding to each mode of vibration should be calculated and the insulation proportioned so that the corresponding resonances are not injurious. Ordinarily, it would be sufficient to design the support so that the frequency of vertical vibration is amply low compared to the driving frequency and to assume that the other frequencies will thereby be dealt with. It is inadvisable, of course, to impose a rigid restraint upon these other modes of vibration, even if the vertical vibration is thereby unaffected. A case in point is a machine mounted on rubber blocks; these should be "jelly-like," and attempts, such as are sometimes seen, to restrict the sideways wobble are ill-advised. There is, of course, no objection to providing cushions (proportioned in accordance with the principles discussed here) to take, for instance the pull of a belt. The above discussion applies, of course, equally to a machine mounted on springs.

Effect of Resonances in Insulating Material. In addition to the fact that elastic supports have several resonance frequencies, corre-

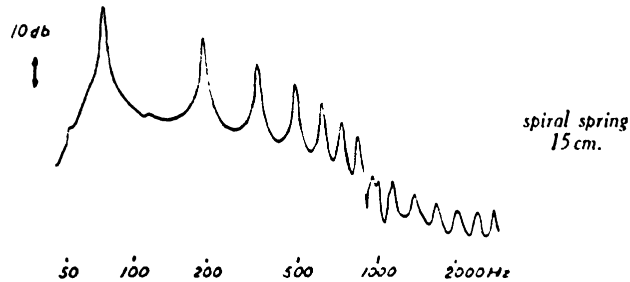


FIG. 47. EFFECT OF RESONANCES ON TRANSMISSION OF A SPRING INSULATOR

sponding to different modes of vibration, there is a further complication which requires attention, namely the fact that additional resonances may occur within the insulating material. This is particularly liable to occur in the case of helical springs, since the

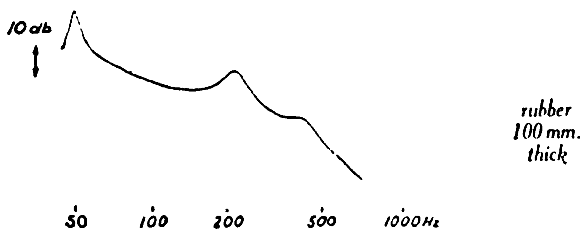


FIG. 48. EFFECT OF RESONANCES ON TRANSMISSION OF A RUBBER INSULATOR

velocity with which a compression in the helix is transmitted is very low. It will readily be seen that if a weight is supported upon a spring there will be, in addition to the up-and-down motion of the mass on the spring, other vibrations in which, while the weight remains relatively still, the centre part of the spring, by virtue of the inertia of the coils, vibrates up and down, The spring can, in fact, perform many variants upon this type of vibration*, and hence has numerous resonances. An insulating support mounted upon helical springs is therefore liable to have a large number of resonances in addition to the fundamental one, which is given by the ordinary

* One sees this when steel springs are used as gongs in clocks.

calculation on page 81. At any one of these resonances the insulation provided can fall very low. The phenomenon is exhibited in Fig. 47 taken from a paper by Meyer and Keidel,* which shows the results of measurements made of the transmission (note, *not* the insulation) provided by a weight supported upon a spring. In Fig. 48 similar measurements made upon a 4-in. thick block of rubber are shown. This shows one resonance in addition to the fundamental. The upper resonances in rubber are not so important as they are in the case of steel springs. The above facts would be a strong argument against the use of helical springs were it not possible, by simple means, to remedy the defect. The cure is to use, in addition to the springs, a subsidiary insulator which will insulate against the harmonics of the spring, although it will probably be ineffective against the low frequencies, for the insulation of which a steel spring is particularly well suited. Such an insulator is provided by a pad of felt or rubber laid between the spring and its bearings at each end.

Effect of a Resonant Floor Beneath a Machine. The floor upon which the insulating support stands has its resonance frequencies also, and a mention of the effect of these resonances is necessary. The theory has been worked out by various authors,† and readers interested should consult one or other of the references given. The chief conclusions are that the compound mechanical system formed by the support and the resonant floor has two resonance frequencies, one of which is usually much higher than the other, which are not the same as the individual resonance frequencies of the support and the floor. If either of these frequencies coincides with the frequency of the driving vibration, marked transmission will result. The actual amount of the vibration introduced in this way is limited by the comparative stiffness and mass of the floor; resonance of the floor is therefore only likely to be important when a heavy vibrating machine is concerned.

Other Methods of Insulating against Vibration. In this section will be described a few methods of insulating against vibration which differ from the simple mass and elastic support treatment discussed so far.

(*a*) *Low-pass Mechanical Filter.* Instead of using a single mass on an elastic support, a combination of a number of insulating elements can act as what is known as a low-pass mechanical filter. A typical system is shown in Fig. 49, in which four elements have been combined. Such a system differs from the simple insulating support in that, instead of the insulation passing through a minimum value in the neighbourhood of the resonance and thereafter continually

* E. Meyer and L. Keidel: *Zeits. für Techn. Physik*, Vol. 18, p. 299, 1937.

† R. Berger: *Ges. Ingr.*, Vol. 36, p. 433, 1913. See also A. B. Eason: *The Prevention of Vibration and Noise* (Oxford Technical Publication); and A. L. Kimball: *Vibration Prevention in Engineering* (John Wiley & Sons).

increasing (above the resonance) as the frequency rises, it is low up to a certain frequency and thereafter rises sharply to a value which is steadily maintained as the frequency is increased. The frequency at which the insulation commences to rise is given approximately by the formula—

$$\text{Cut-off frequency} = 3{\cdot}17\ \sqrt{(S/m)}$$

where S is the stiffness of the individual springs or resilient layer in

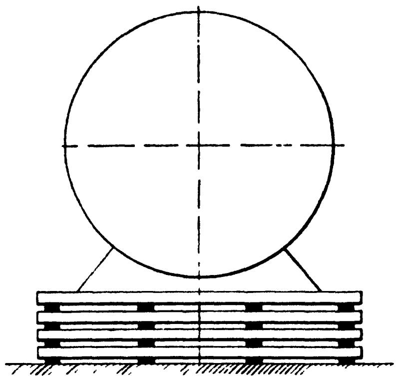


FIG. 49. MACHINE SUPPORT USED TO GIVE GOOD INSULATION AT MEDIUM AND HIGH FREQUENCIES

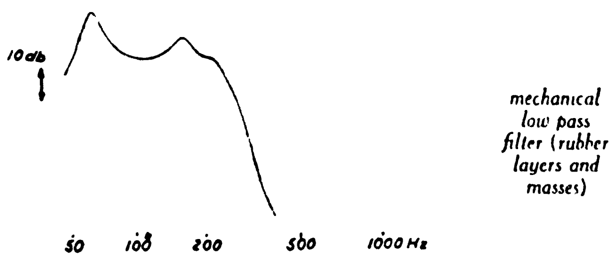


FIG. 50. TRANSMISSION OF SUPPORT OF ABOVE TYPE

pounds per inch compression and m is the weight in pounds of the individual masses.

Meyer has tested a filter of this type in which rubber layers were used, and has obtained a transmission (see Fig. 50) corresponding to what has been stated above.* This type of machine mounting is not often used, but it has value where exceptionally good insulation is required at medium and high frequencies.

* E. MEYER AND L. KEIDEL: *Zeits. für Techn. Physik*, Vol. 18, p. 299, 1937.

(*b*) *Dynamic Vibration Absorber.* Where the disturbing vibration has a very constant frequency, it is possible to reduce the effects of the vibration very considerably by using dynamic vibration absorbers. These do not insulate; rather they automatically balance the machine. They consist, in principle, of a mass attached to a spring which is fixed to the machine. The spring and mass are proportioned so that the frequency of vibration of the mass on the spring is exactly equal to the frequency of the disturbing vibration. Naturally, a pronounced resonance effect occurs, and the mass

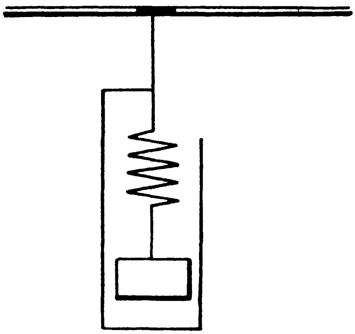


FIG. 51. THE HOLST DAMPER

Damper attached to electric transmission line to reduce vibration caused by wind. Sometimes the tube contains a viscous fluid.

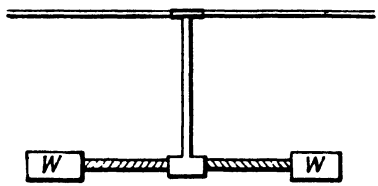


FIG. 52. THE STOCKBRIDGE DAMPER

Two masses of steel *w* are attached to the line through a piece of stranded cable which acts as a spring and which at the same time has sufficient friction between the individual wires of the cable to ensure energy dissipation.

vibrates with a considerable amplitude. It happens, however, that the phase relationships automatically adjust themselves, so that forces which arise from the periodic tensioning of the spring as the weight vibrates tend to balance the disturbing vibration forces, and, indeed, a powerful opposing force is produced. This form of vibration absorber finds frequent application; sometimes it consists of a weight sliding in a tube and attached to a spiral spring (the Holst damper, Fig. 51), and sometimes of a cantilever spring supported at the middle and having a weight at each end (the Stockbridge damper, Fig. 52).

Various dampers for reducing torsional vibration, for instance of crankshafts of Diesel engines, have been described.* The principle is in general the same as that of the simple dampers mentioned above, but modifications in design are necessary if the damper is to be effective over more than a limited range of engine speed. A type which will operate at practically all speeds is shown schematically in Fig. 53. A disk A is keyed solidly to the end of the shaft B, while C is a mass rotating freely on a bearing D, which is attached to A.

* J. P. DEN HARTOG: *Journal of Applied Physics*, Vol. 8, p. 76, 1937.

A non-uniform rotation of A will set C into resonant vibration, thus absorbing the energy of the torsional vibration of the shaft.

PRACTICAL CONSIDERATIONS IN MACHINE INSULATION

The insulators available may be divided into three classes, those using metallic springs, those using specially designed rubber insulators, and those using layers or pads of other elastic materials. Metallic springs have largely held the field so far for heavy loads, and also have the advantage that they can be designed to receive big deflections and are accordingly useful for insulating against very low frequencies. The others have certain advantages on the score of cheapness, and also because their use is very simple.

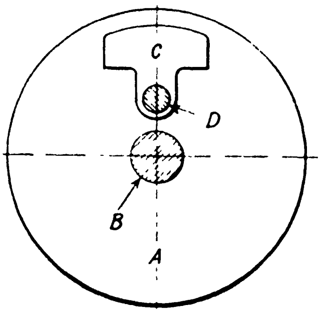


FIG. 53. PRINCIPLE OF ONE TYPE OF DAMPER FOR REDUCING TORSIONAL VIBRATION

There are one or two practical considerations which apply to the design of all vibration insulators. Where impacts have to be insulated against, these are particularly likely to excite resonances, and hence it is advisable that the motion of the insulators should be damped though this may mean some loss of insulation at other frequencies. If the machine to be insulated has a high acceleration, steps should be taken to check the "kick," which the insulator will receive when the machine is started. This can be secured by attaching the machine to a base having considerable inertia, the springs being underneath this base. (See Fig. 54.) In this way, not only is the initial momentum due to the machine starting reduced, but the actual motion is also reduced on account of the greater stiffness of the springs which the greater weight has necessitated. An alternative is to fit suitably disposed buffers of sponge or solid rubber. In the case of tall machines, such as vertical reciprocating engines, a massive base also gives greater stability.

When the machine in question is used to drive other machinery, problems of transmitting the drive may arise. The ideal solution to this problem is to mount the entire equipment upon an insulated foundation. (See Fig. 55.) If this is not possible, the insulated machinery must be installed so as to provide an effective resistance to the pull of the belt or the torque of the shaft, whichever method is used for transmitting the power. The use of elastic buffers for this purpose has already been referred to.

It may be worth while to remind the reader that the insulation provided by an elastic support will suffer if rigid connexions are

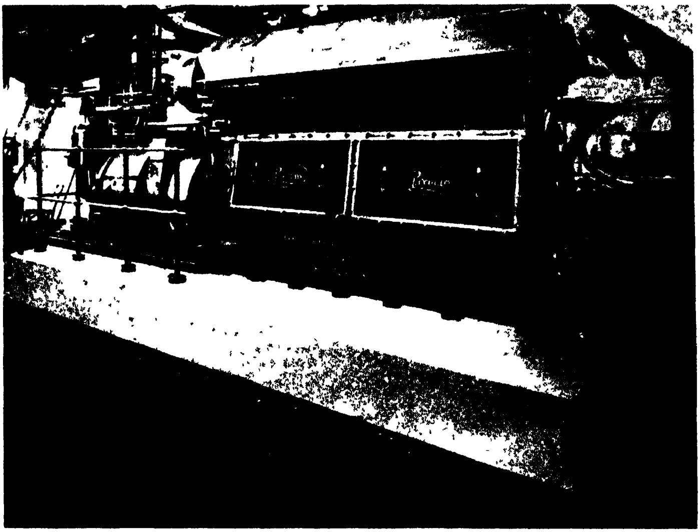


FIG. 54. SPRING-MOUNTED DIESEL-DRIVEN GENERATOR
Note the massive foundation block.
(*W. Christie & Grey Ltd.*)

provided, e.g. by electric conduits or air pipes. These connexions also must, obviously, be made flexible. (See Chapter VII.) The flexible pipe connexions to the compressor in Fig. 55 will be noted.

In this connexion it should be remarked that it sometimes happens that loose cover plates, provided to keep dirt, etc., away from insulation below a sunk foundation, bridge the essential air gap round the sides of the foundation. A design consisting effectively of two overlapping, but not touching, pieces of angle iron (see Fig. 56) has been suggested by W. Hausler.*

Use of Metal Springs. Metal springs can carry heavy loads, and with reasonable care will last practically indefinitely. Their chief merit, from the insulation point of view, is that they can easily be designed for big deflections, and hence are suitable for insulating against very low frequencies. Helical springs should, as explained on

* *Heizung und Lüftung* (Swiss), January, 1936, p. 9.

page 91, be supplemented with a layer of elastic material such as felt or rubber on each bearing surface, to deal with the high frequencies which are liable to be transmitted along springs. The box type of spring (Fig. 57) has an interesting construction in that the spring is pre-compressed by the bolt shown at the top, and is adjusted so that when the load is applied, the load-bearing plate rests just clear of the side members of the box. The box construction assists the spring to withstand the sideways pull of a belt, and the felt lining to the outer shell should be noted. Springs of this type have been used for loads of between 40 and 10,000 lb. per insulator.

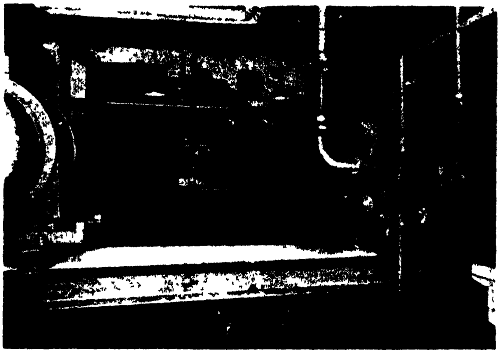


FIG. 55. INSULATION OF BELT-DRIVEN AIR COMPRESSOR INSTALLED IN A BANK
(*W. Christie & Grey Ltd.*)

Heavier loads may be supported upon laminated springs of various types.

Use of Rubber Insulators. When rubber is used for vibration insulation it is scarcely ever used as a continuous sheet as are the majority of elastic materials; instead it is used in the form of small blocks, which often have special shapes and almost always have carefully calculated proportions. It is presumably for this reason that rubber insulators are referred to, particularly in the United States, as "rubber springs," a term which is so convenient that it is employed here. Rubber has one peculiarity which distinguishes it from other insulating materials, namely, it derives its elasticity, not from an ability to be compressed, but from its ability to flow. Actually rubber is very incompressible (its bulk modulus of elasticity is about the same as that of water), very great forces being required to make appreciable changes in its *volume*. It follows that if rubber is to be elastic, room must be left for it to expand in one direction when it is compressed in the other. Continuous sheets of rubber should not, therefore, be used for insulating purposes, considerably greater compression and hence insulation being obtainable

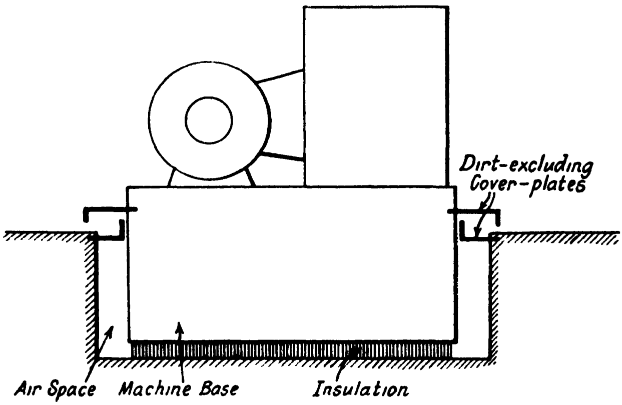


FIG. 56. COVER PLATES DESIGNED TO AVOID RIGID CONNEXION BETWEEN INSULATED MACHINE AND FLOOR

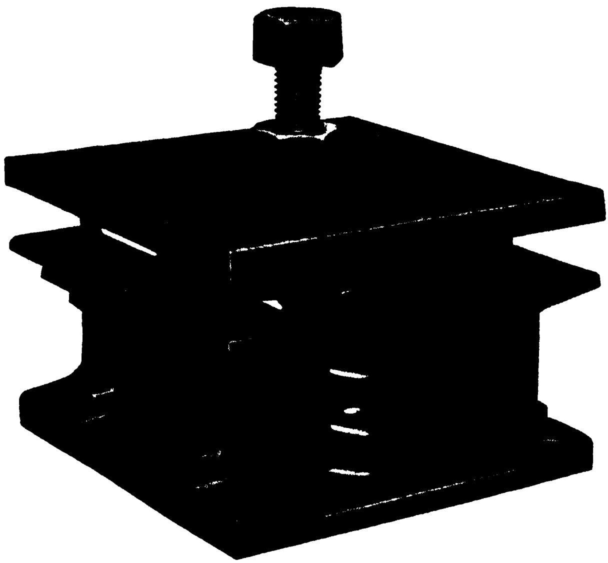


FIG. 57. BOX-TYPE SPRING INSULATOR
(The Cementation Co. Ltd.)

by using a number of small pads, leaving space between them to allow for expansion.

The fact that the apparent elasticity of a rubber pad depends upon its general proportions is disconcerting when an attempt is

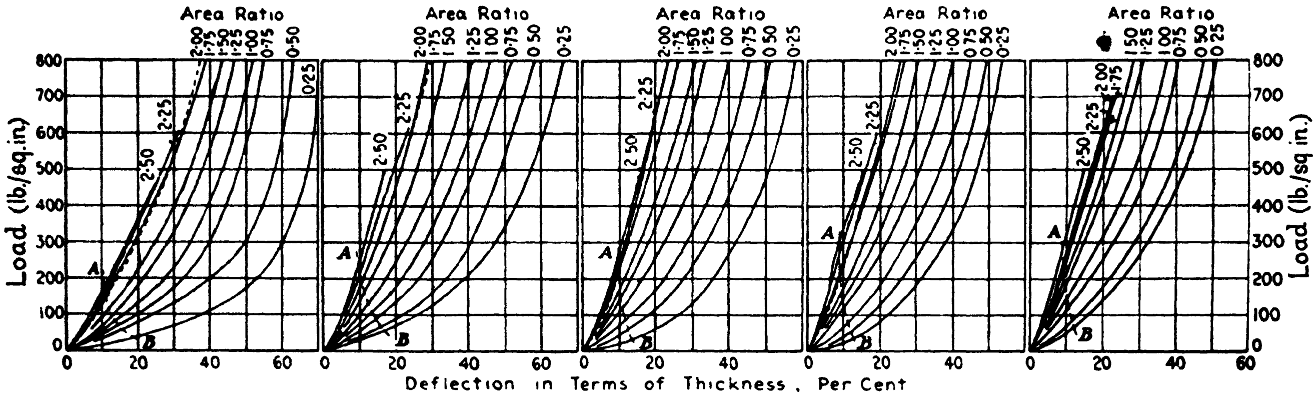


Fig. 58. Load/Deflection Curves for Five Typical Rubber Compounds

Deflections to the left of the line A–B on each set of curves are considered safe practice.

made to give a figure representing the elastic properties of a particular rubber. The difficulty has been overcome* by using a unifying factor termed the *area ratio.* This is the ratio of the total load-bearing area to the area of the unconfined edges. It has been shown that, for the same quality of rubber, blocks having the same area ratio will deflect by the same amount when subjected to the same load per unit area. Thus a 1 in. cube of a given rubber (area ratio, 2 : 4) would have the same elasticity as a 2 in. cube (area ratio, 8 : 16) or a pad 4 in. by 2 in. by 2 in. thick (area ratio, 16 : 32). Curves which relate the deflection for a given pressure with the area ratio have been given by Keys for five typical good-quality rubbers, and these are reproduced in Fig. 58. Certain apparent inconsistencies which may be seen in these curves are attributed by Keys to slipping between the rubber and the metal bearing plates. Physical data for these rubbers are given in Table X.

TABLE X

APPROXIMATE PHYSICAL PROPERTIES OF VARIOUS RUBBER COMPOUNDS

Rubber Compound	A	B	C	D	E
Nominal hardness:					
Shore durometer	30	40	50	60	70
Pusey & Jones plastometer	175	145	117	92	70
Specific gravity	1·01	1·06	1·11	1·17	1·24
Tensile strength of original cross-section, lb./sq. in.	2,000	2,800	3,500	3,500	3,000
Elongation at rupture, per cent	580	750	700	600	700
Shear modulus, lb./sq. in.	48	65	84	108	166
Average tension modulus for 0–10 per cent elongation, lb./sq. in.	128	190	240	—	—
Vibration data at 77° F.:					
Energy loss per cycle, per cent	16·1	18·4	38·9	60·6	77·3
Decrease in amplitude, per cent	8·5	9·6	21·8	37·3	52·4

These figures are given as being representative of good-quality rubbers. Unfortunately they are not sufficient to define the rubber exactly, but probably the figures given are near enough for ordinary design purposes, which do not usually demand very great accuracy.

The process of selecting a suitable rubber pad would be to decide upon what load it can safely bear, and then from Fig. 41 and Table IX to decide how far it should deflect under load to give the appropriate support frequency. It remains then to decide to what extent the total required area of rubber can be split into separate pads. Finally, a thickness is chosen for the pads which by giving the appropriate area ratio will provide the required elasticity. The

* W. C. KEYS: *Mechanical Engineering*, May 1937, p. 345.

extent to which the total area can be cut up will probably be decided chiefly by questions of stability. If the rubber is in compression, it is probably unwise, on this account, to use a base having dimensions less than the thickness. Something between a cubical pad and one which is almost twice as wide as it is thick seems to work very well in practice.

Rubber can be used stressed in compression, extension, or shear. Rubber stressed in compression carries heavier loads with smaller deflections than rubber stressed in shear. Rubber in shear has important applications where a support having a low natural

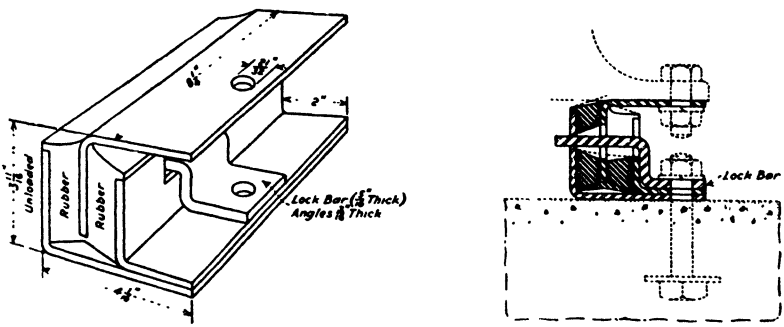


FIG. 59. MACHINE MOUNTING USING RUBBER IN SHEAR

frequency is required. For using rubber in this way what is known as a "sandwich" is made, by bonding or *adhering* plates of steel or certain other metals to both sides of a rubber slab. The advantages claimed for this type of mounting are—

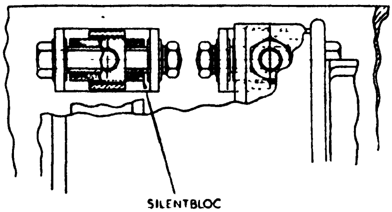
1. Large deflections are permitted.
2. No slippage occurs, thus eliminating abrasion and wear.
3. The support can be cushioned vertically, while it is restrained horizontally.

Rubber can be made to adhere very strongly to metals, some manufacturers guaranteeing a bond strength of 200–250 lb./sq. in.; usually, however, the bond between the rubber and the metal is stressed at only 25–50 lb./sq. in. Good practice requires the thickness of rubber used in shear to be not more than one-quarter of the smaller of the other two dimensions. Practical considerations appear to limit the thickness of rubber used in this way to not more than 2 in. Accordingly, when springs of greater thicknesses are required, they are made from two or more sandwiches bolted together. Fig. 59 illustrates a typical rubber spring designed for large deflections in the shear plane.

Rubber in shear is also used in the type of machine insulation shown in Fig. 60.

A rubber spring designed for a load of the order of a ton and intended for use on a street car is shown in Fig. 61.

While purpose-made machine insulators such as those described



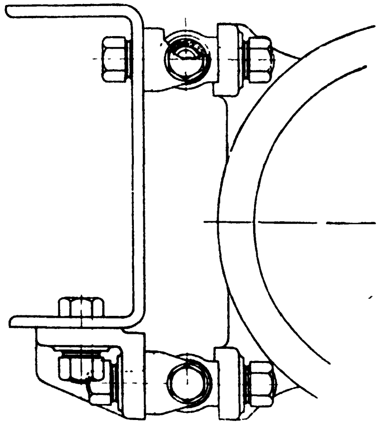


FIG. 60. RUBBER INSULATORS USED IN TROLLEY-BUS COMPRESSOR AND GENERATOR MOUNTING (*Silentbloc Ltd.*)

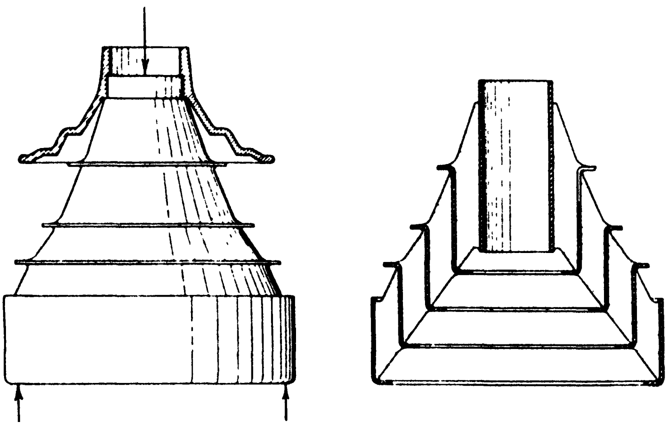


FIG. 61. RUBBER STREET-CAR SPRING

above are very useful and often essential, quite satisfactory insulation can often be obtained merely by standing the machine concerned upon appropriately proportioned rubber blocks. For rough design it may be taken that good-quality flexible rubber about an inch thick and loaded to about 40 lb./sq. in. gives very satisfactory insulation, provided individual pads do not have a greater area than two or three square inches.

In some cases special rubber is required, e.g. if it has to withstand oil or high temperature. Oil-resisting synthetic rubbers are obtainable; sometimes oilproofing is achieved by varnishing the rubber.*

Drift of Rubber. One property of rubber which requires mention is its drift under load. This subject has been investigated by several authors.† The conclusion seems to be that the drift of good-quality rubber 1 in. thick, under safe working loads is small, being not more than about 0·01 in. per year.

Those interested in the subject of rubber as a vibration insulator may be referred to a book by Thum and Oeser‡, in which the design of rubber supports and machine beds is discussed in detail.

Use of Insulating Materials Other than Rubber. Certain materials other than rubber are used for insulating machinery. Among these can be mentioned cork (natural and granulated), felt, and

FIG. 62. CORK INSULATION, SHOWING IRON BAND USED TO BOND IT TOGETHER

Note that the iron band does not cover the whole depth of the cork.

(*W. Christie & Grey Ltd.*)

proprietary materials consisting of alternate layers of cork and felt. Natural cork is often used in the form of a number of strips bound together by an iron band round the edge (Fig. 62). These materials are commonly used as layers having the full area of the machine foundation. A typical method of construction is to place the insulating material on the floor and to cast a concrete foundation block directly on to it, taking care that wet concrete does not drip down and short-circuit the insulation.

There is some reason for believing that in general materials of this type are not so useful for insulating against very low-frequency vibration as are properly designed springs of rubber or metal. Some test results which have been obtained for representative materials are given in Table XI. It will be noted that the dynamic elasticity (i.e. the elasticity under an alternating force) of these materials usually increases as the load increases, a phenomenon which distinguishes them from metal springs.

* E. H. HULL (*Journal of Applied Mechanics*, Vol. 4, p. 109, 1937), describes the use of coverings of flexible glyptal lacquer and plasticized shellac for this purpose.

† C. F. HIRSHFELD AND E. H. PIRON: *Trans. Amer. Soc. Mech. Eng.*, Vol. 59, p. 471, 1937; E. H. HULL: *Journal of Applied Mechanics*, Vol. 4, p .109, 1937; A. J. KING: *Engineering*, Vol. 144, p. 296, 1937.

‡ *Gummifederungen fur ortfeste Maschinen* (*V.D.I.*—Verlag, 1937).

TABLE XI

DYNAMIC ELASTICITIES OF VARIOUS INSULATING MATERIALS

Material	Area of Specimen (sq. in.)	Thickness of Specimen (in.)	Load (lb./sq. in.)	Dynamic Elasticity (lb./sq. in.)
Hair felt* . . .	9	1	100	6,000
			50	5,515
			10	3,400
Ordinary compressed cork† . . .	49	0·8	100	5,000
			50	4,500
			15	4,000
Specially soft cork† .	47	0·8	40	780
			15	500
Cork-felt-cork† . .	49	0·8	20	2,100
			10	1,600

In Table XII are given some results obtained for various insulating materials by Eisenhour and Tyzzer‡ which are expressed in a different way. They show the measured natural frequency of various loads supported upon the material. This method of presenting the results is useful, since it is by making this frequency less than that of the vibration generated by the machinery in question that adequate insulation is obtained. The results apply to materials 1 in. thick; but, roughly speaking, the frequency for other thicknesses of material could be calculated by dividing the frequency shown in the table by the square root of the thickness.

Safe Loads for Insulating Materials. The information available regarding safe loads for insulating materials is sketchy, and the figures given vary over a wide range. Figures for proprietary materials can usually be obtained from the manufacturers. Rubber can be safely stressed up to 40 and 50 lb./sq. in., loads of 80 and 90 lb./sq. in. having been recommended.§ This is not inconsistent with the data in Fig. 58, which indicate safe loads increasing with the area ratio up to 200 lb./sq. in. A safe load for cork seems to be 50 lb./sq. in., and probably this figure would be safe for felts.

Life of Insulating Materials. Very little reliable data are available on the life of insulating materials, as so much depends on the quality of the sample and the conditions of use. Experience of rubber

* A. J. KING: *Engineering*, Vol. 144, p. 296, 1937; Vol. 146, pp. 124 and 198, 1938.

† C. COSTADONI: *Zeits. für Techn. Physik*, Vol. 17, p. 108, 1936.

‡ B. E. EISENHOUR AND F. G. TYZZER: *Journ. Franklin Inst.*, p. 691, 1932. These investigators concluded that the elasticity of cork and felt did not depend appreciably upon the area of the specimen (compare rubber).

§ E. H. HULL: *Journal of Applied Mechanics*, Vol. 4, p. 109, 1937.

TABLE XII

NATURAL FREQUENCIES OF VARIOUS LOADS UPON ELASTIC MATERIALS

Dimensions of samples, 30–144 sq. in. by 1 in. thick

Material	Frequency (c.p.s.) under loads (lb./sq. in.)				
	1	5	20	50	100
Natural cork	74	54	35	24	18
Compressed cork (light)	83	50	33	26	—
,, ,, (medium)	99	58	36	26	24
,, ,, (heavy)	—	63	39	26	25
Fibreboard	61	42	28	22	22
Felts—					
Hair	31	24	21	21	24
Asbestos	56	38	26	21	21
Wool	33	25	22	21	25
Jute	36	30	30	26	21

engine mountings in the relatively hard conditions of service found on road vehicles indicates at least 10 years as a reasonable expectation of life. There is some indication that a routine replacement of rubber springs every 5 years may be desirable if a very high standard of insulation is to be maintained under arduous service conditions, but periodic inspection usually shows signs of deterioration. As far as cork is concerned, it was thought advisable to replace the cork insulation under the experimental rooms at the National Physical Laboratory (Acoustics Department) after about 7 years' service.

CHAPTER VII

NOISE DUE TO WATER SYSTEMS

NOISE arising from water services can be treated in three ways. Firstly, and best of all, the noise can be avoided by preventing its generation, for example, by using quiet fittings, such as silent W.C. flushes and silent taps. Secondly, steps, which will be described later, can be taken to prevent the sound arising in fittings from being transmitted to the water pipes. Thirdly, if the above steps are not possible, treatment designed to prevent the radiation of sound from pipes must be used. The three lines of attack will be dealt with in the following pages.

Methods of Preventing Noise from being Generated in a Water System. The following are common sources of noise in a water system—

1. Equipment associated with the water system, e.g. pumps.
2. Vibration of the water system as a whole, viz. water-hammer.
3. Turbulence in water flowing in the system.
4. Falling water (e.g. bath wastes, W.C. flushing).

1. *Noise from Equipment Associated with the Water System.* Boilers, pumps, and water taps are a few examples of potential sources of noise. The first named may give rise to noise when the furnace is raked or stoked, so probably mechanical stoking would be less likely to offend in this connexion than hand stoking, though even in this case a little care can make the equipment quieter. For example, the mechanical stoker can be mounted upon insulating material to prevent the transmission of vibration to the building structure. Similarly, it may be advisable to insulate the compressor unit of oil-fired boilers. Incidentally, oil-fired boilers have given noise trouble on account of flame roar, though this can be overcome by careful design.

Where it is particularly necessary that noise should not pass from a boiler room into the rooms above, the ceiling should be rendered sound-insulating in accordance with the principles described in Chapter XIII. The doors and windows and, if necessary, the walls of the boiler room should be soundproofed (Chapters IX–XII), artificial ventilation being provided if required (Chapter VIII). The piping should be supported from the floor of the boiler house rather than from the ceiling.

As regards noises caused by circulating pumps, centrifugal pumps are as reasonably quiet, provided they are of the low-speed type (below 1,000 r.p.m. has been recommended). It is usual to find the driving motor directly coupled to the pump, with the result that noise from the motor may be transmitted to the water system and thence about the building. To avoid this trouble, the pump may have a belt drive, the motor being mounted on insulating supports above the pump casing.

The design of silent taps should, strictly speaking, also be dealt with in this section, but for convenience this has been left till later (page 110). Kitchen machinery, such as dish-washing machines and potato-peelers, should be insulated from the structure as described in Chapter VI, and flexible water and electricity connexions provided.

It is not possible to detail all the quiet equipment which is available. The important point is to insist on quiet operation when specifying equipment. For the most part the manufacturer must be relied upon for the production of quiet equipment, although there are certain expedients, largely the product of the inspiration of the moment, available for the builder. One such is the insertion of an elastic pad of felt or rubber beneath the arm of water-waste preventers to reduce the clank due to its operation.

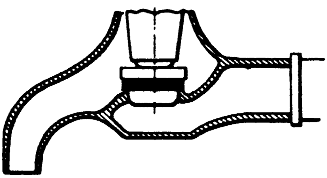


FIG. 63. TAP DESIGNED TO PREVENT WATER-HAMMER BY SHUTTING OFF FLOW GRADUALLY

2. *Noise due to Water-hammer.* Vibration of the water system as a whole gives rise to the well-known water-hammer, and also to hum in pipes. Water-hammer, it is perhaps unnecessary to say, consists of a series of metallic-sounding blows which occur on opening or closing taps. These blows are often very loud and are readily transmitted by the water system about the building.

Water-hammer can be the result either of a sudden release or a sudden rise of water pressure. The former can occur, for example, when a flush valve fed through unduly narrow piping is suddenly opened. Water-hammer is, however, most frequently the result of a sudden pressure rise caused, for example, by quickly closing a tap; this can produce very high transient pressures (up to 600 lb./sq. in. has been recorded). A pressure wave is formed which returns along the pipe and may be reflected back again at the end of the pipe, thus giving a series of blows of gradually decreasing loudness as the energy of the wave is slowly dissipated. The control of water-hammer is a matter of limiting the flow velocity and the suddenness of the cut-off. The former can be accomplished by fitting larger pipes and so ensuring a lower rate of flow, though this is liable to be expensive. A cheaper method of attack, and one which is claimed to be very effective, is to modify the tap design so as to shut off the flow gradually. A simple device which has been recommended* for this purpose is illustrated in Fig. 63. It consists of replacing the nut

* BAESE AND LÜNING: *Gas- und Wasserfach*, Vol. 79, 11th April, 1936.

which holds the washer in place by a cone which fits into the washer seating. In effect this is a step towards a streamlined tap, the merits of which are discussed later. The same problem arises with press button taps, and has been solved by introducing a control to slow up the action of the spring-return device. One type of tap in which this has been done is shown in Fig. 64; on depressing the button a

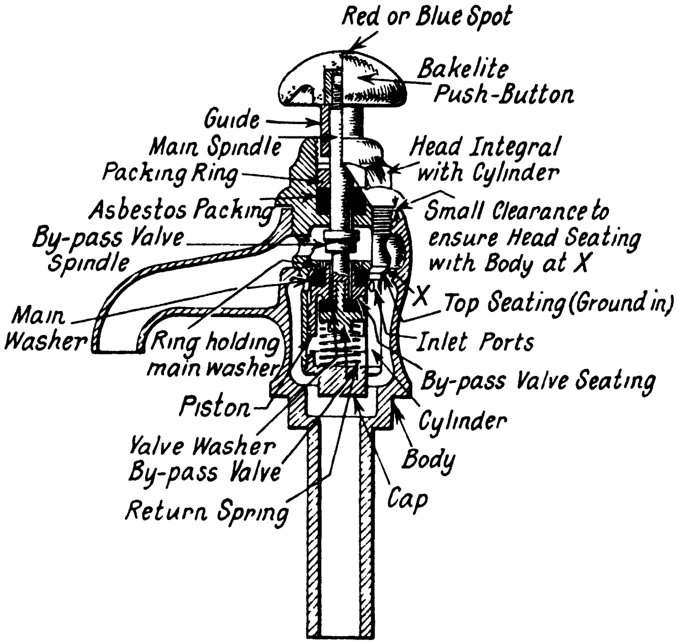


FIG. 64. TAP OF PRESS-BUTTON TYPE, SHOWING DEVICE FOR GRADUALLY SHUTTING OFF THE FLOW

(Peglers Ltd)

by-pass valve is unseated, allowing water to escape from the cylinder and the main valve on the piston to become unseated. When pressure is taken off the button, the spring immediately closes the by-pass valve and forces the piston up, the rate of closing being governed by the percolation of water to the bottom of the cylinder through the small gap between the piston and the cylinder: as the piston is a close fit in the cylinder, the main valve closes slowly.

Failing either of these methods, water-hammer can be dealt with by fitting an air chamber in the supply main on the house side of the meter (if any). The chamber, in its simplest form, consists of a vertical pipe capped at the top leading from a tee in the main pipe. A pipe 6 ft. long and 1½ in. in diameter has been recommended as suitable for domestic use.* Owing to the gradual absorption of the

* *American Architect*, p. 88, July 1936.

air in such chambers, cocks should be fitted at the top and the bottom to permit of drainage. (See Fig. 65.) The air in the chamber, owing to its compressibility and low elasticity, acts as a shock absorber. The investigations of Lohmann* indicate that the "ironing-out" effects depend upon the volume of the air chamber. Baese and Lüning have suggested that an air pressure chamber is better than the simple type described above, and is specially suitable for large buildings and high water pressures. A relatively large air buffer which fills about two-thirds of the chamber is kept at the average pipe pressure by means of a compressor.

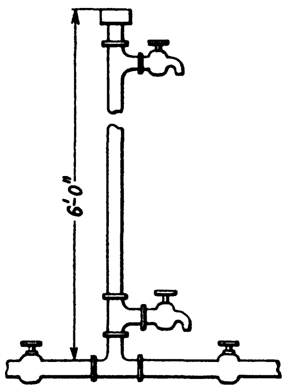


FIG. 65. SIMPLE FORM OF AIR CHAMBER ATTACHED TO SUPPLY MAIN TO REDUCE WATER-HAMMER

An associated noise is that arising from a loose washer or "jumper." The actual conditions which produce the noise do not appear to have been much studied, and the information available is rather the result of practical experience. A loose washer can in certain conditions of pressure, etc., generate a noise which can be anything between a series of sharp taps and a loud hum. Probably the action is similar to that taking place in a reed instrument such as a clarinet, in which the passage of air past the reed causes it to vibrate at a frequency determined by the air column in the instrument. The remedy for this type of noise is, of course, to make sure that the washers are firmly held and that the "jumper" is held by a set screw. Reducing the supply pressure may also be effective.

It is a matter of common observation that steam heating systems are often much noisier than hot water systems, due to "steam hammer" and also to the escape of steam at traps and safety valves. Some types of steam trap are much quieter than others, and in any case the system should be so designed that traps do not have to be inserted near rooms where quiet is required.

A loud noise sometimes occurs within steam heating systems. Faber and Kell† state that where absence of noise is important in such systems, the flow in steam risers must be limited. The limit is set by the velocity at which globules of condensation are carried up with the steam. These authors have given figures for the approximate maximum discharges for upward risers.

3. *Noise due to Water Flow.* Turbulence in the water flow is a common source of noise, particularly in high buildings where the

* H. LOHMANN: *Gas- und Wasserfach*, Vol. 78, p. 648, 1935.

† OSCAR FABER AND J. R. KELL: *Heating and Air Conditioning of Buildings* (The Architectural Press).

water pressure is high on account of the reservoir being at the top of the building.

A fluid can flow in two ways, namely in a state of "laminar flow," in which layers of fluid slide smoothly past each other, or in a state of "turbulent flow," in which the flow consists of irregular eddying motions. Other conditions being the same, turbulent flow takes place at higher speeds than laminar flow.

It has been established that water noise, a familiar example of which is the hiss which occurs at a partly open tap, is associated with turbulence. The exact process by which the noise is caused is not

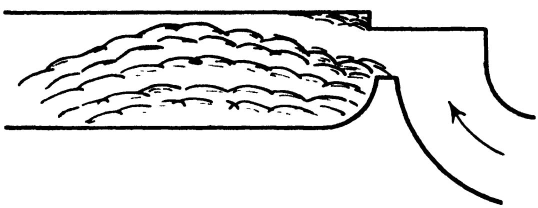


FIG. 66. TURBULENCE IN WATER FLOWING THROUGH A MODEL SECTION OF A TAP

known. It has been suggested* that the noise originates in the collapse of the water-vapour bubbles which are formed in the eddies. In support of this may be mentioned an experiment by Wintergerst,† who showed that the hiss could be suppressed if the formation of bubbles was prevented by increasing the absolute pressure on the water while maintaining the pressure difference constant. Of interest in this connexion is Fig. 66, due to Föttinger, which shows turbulence and bubbles produced in water flowing through a model section of a tap.

Osborne Reynolds showed theoretically that the behaviour in smooth tubes of different widths can be correlated by the fact that in any tube the transition from laminar to turbulent flow should take place for a certain value of the quantity dvr/q, where d = fluid density, v = average velocity, r = tube radius, and q = viscosity. This quantity is termed the Reynolds number. Substituting numerical values for the constants of water at normal temperature, the Reynolds number becomes 88 vr, where v is measured in centimetres per second and r in centimetres. Thus high velocities are possible in small tubes without turbulence occurring. The actual value of the critical Reynolds number depends upon circumstances: thus, if a tube is joined to a smooth-walled vessel by a sharp edge, the critical value would be about 1,400; while if the outlet is

* Das Lärmfreie Wohnhaus (V.D.I.—Verlag, Berlin, 1934).

† *Gesund. Ing.*, Vol. 54, p. 129, 1931.

carefully rounded, the value may rise to as high as 20,000 or more.* It follows that to prevent water hiss, great care should be taken to round off all corners.

Turbulence does not normally occur in smooth pipes except possibly at joints and bends, as Kreuger and Sager† showed, but rather in fittings such as taps, ball valves, etc. These usually contain many sharp edges and also constrictions. Some progress has been made towards overcoming these difficulties, and various designs for silent taps suggested. Careful shaping to avoid sharp edges, and insertion of throttling devices just in front of the tap are usually the important features of the design. The reasons for avoiding sharp edges have already been explained; the value of throttling lies in the reduction in flow velocity, which it effects at the tap, thereby decreasing the noise. The principle of a tap designed by Kreuger and Sager, embodying streamlining and throttling is shown in Fig. 67.

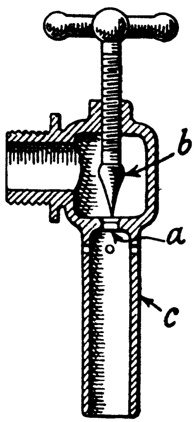


FIG. 67. DESIGN FOR A QUIET TAP

a = Short throttling tube below valve seating.
b = Streamlined valve
c = Delivery tubes with small air holes.

For general use Mengeringhausen‡ has recommended a throttle consisting of a coil of metal foil slipped inside the pipe leading to the tap or ball valve, and has published measurements which indicate that marked improvement can be obtained in this way.

Another type of ball-valve silencer has been developed which simply acts as a throttle in the feed pipe near the valve to reduce the speed of

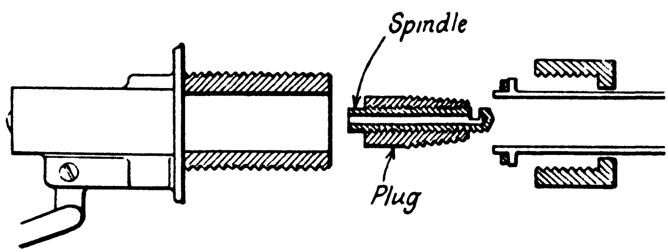


FIG. 68. BALL-VALVE SILENCER
(*Fordham Pressings Ltd.*)

* For further information regarding turbulent flow, reference may be made to textbooks dealing with the subject such as *The Physics of Solids and Fluids*, by Ewald, Pösche, and Prandtl, published in an English translation by Blackie & Son Ltd.

† KREUGER AND SAGER: *Proc. Roy. Swedish Inst. for Eng. Res.*, No. 132, 1934.

‡ *Zeits. Verein. Deut. Ing.*, Vol. 75, p. 357, 1931.

water through the valve itself. The expense and trouble of installing a special stop-tap for this purpose is thereby avoided, and the device, which is shown in Fig. 68, is very simply installed. It consists of a screwed tapered plug threaded internally to receive a hollow screwed spindle. This spindle is not drilled right through, but is closed at one end, a slot being cut in it at right angles to the bore. By unscrewing the spindle from the plug the slot is gradually covered, thus reducing the aperture through which the water flows. The plug is forced into the open end of the pipe, cutting its own thread in the pipe material; the aperture is adjusted by trial until quiet operation combined with a not-too-slow rate of cistern fill is obtained.

To get the best out of a "quiet" tap or, indeed, any tap, it should work under the least possible pressure consistent with a reasonable discharge. In a high building this can be achieved by arranging that taps on the lower floors are fed from intermediate cisterns rather than from the roof cistern; if the taps are fed directly from the street mains, it has been recommended* that they should be fed from a descending main rather than from a rising main, as shown in Fig. 69. The fall in pressure due to the narrow pipe then offsets to some extent the increased pressure due to gravity, making it possible by the selection of suitable diameter piping to ensure that taps on all floors work at more nearly the same pressure than they would if the usual arrangement were employed. This pressure can then be regulated to a suitable value by a single valve.

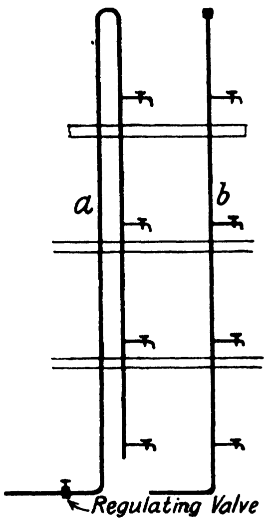


FIG. 69. ARRANGEMENT FOR REGULATING THE PRESSURE AT TAPS FED DIRECTLY FROM STREET MAINS

(*a*) Taps on all floors of a high building, working at about the same pressure.
(*b*) Taps working at widely different pressures.

4. *Noise due to Falling Water.* Noise arising from falling water is a common cause of complaint, and modern sanitary fittings are still capable of a good deal of improvement in this respect. The chief offenders are probably W.C. flushes and bath wastes. Some results obtained by Kreuger and Sager in a hotel are given in Table XIII, and show that the noise levels due to this equipment can be quite high; but the annoyance due to these noises is probably even greater than the measurements suggest. It will be noticed that the noise due to some W.C. flushes is as much as 15 phons louder than that due to the quietest.

Though no corresponding measurements appear to have been made in England, ordinary observation indicates that W.CS. of the

* P. KULA: *La technique sanitaire et municipale*, April, 1937, p. 79.

low-flush type are usually considerably quieter than those in which the cistern is mounted several feet above the pan. The chief factors contributing to the quiet operation probably are the smaller height of fall of the water, the reduced mechanical noise, and the auxiliary siphon which prevents the loud sucking noise which would otherwise occur when the main cistern siphon emptied. These features are illustrated in Figs. 70 and 71. The flushing of the low-flush type of w.c. appears to be quite as effective as that of the older type, provided the closet is of the siphonic type.

Flushing valves have the obvious advantage that the cistern noise is eliminated, and according to Kreuger and Sager's measurements can be 5–10 phons quieter than the ordinary cistern equipment.

FIG. 70. SILENT SIPHONIC-ACTION W.C. SUITE
(*Shanks & Co., Ltd.*)

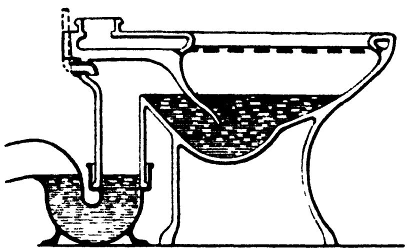


FIG. 71. SECTION SHOWING ACTION OF SIPHON OF W.C. SUITE ILLUSTRATED IN FIG. 70
(*Shanks & Co Ltd.*)

TABLE XIII

NOISE CAUSED BY SANITARY INSTALLATIONS

		Phons
W.C. flush cistern, various makes . . .	flushing	50–70
,, ,, ,, ,, ,, . . .	filling	35–55
W.C. flush valve, various makes . . .	flushing	60–65
Noise level in lobby outside lavatory when flush valves were used		30–42
Noise due to filling bath in same room as noise meter. .		75-80
,, ,, ,, ,, ,, in room above		65
,, ,, ,, ,, ,, two rooms above.		55
,, ,, ,, ,, ,, three rooms above		50
,, ,, ,, ,, ,, in adjoining room		68
,, ,, ,, ,, hand basin in same room		55
,, ,, ,, ,, hand basin in adjoining room . .		55
,, ,, ,, w.c. outflow, one floor below lavatory . .		35–40
,, ,, ,, w.c. outflow, two floors below lavatory . .		35–40
,, ,, ,, w.c. outflow, three floors below lavatory .		35–40

One method of preventing the transmission of noise from w.c. suites will be mentioned, although it is obviously more satisfactory to install quiet equipment wherever possible. The method consists of mounting the pan on rubber insulators and insulating the cistern support brackets and flushing pipe clips.

As regards noise due to water flowing from taps, the old but effective anti-splash tap fitting should not be overlooked. This is so well known that no more need be said about it except to lament that it is usually only applied to scullery taps: bath taps can also be prime offenders in this connexion. It has been suggested that the noise from bath taps could be reduced by adopting the method used in low-flush w.c. cisterns, viz. filling the bath from inlets as near the bottom as possible. There are, however, objections to this, owing to danger of contamination of the supply. Incidentally, emptying the bath can be as noisy as filling it. Very little appears to have been done regarding this source of noise, however, and possibly enclosing the waste pipes in properly designed service ducts is the only solution.

The filling of main water tanks in the roof often causes considerable noise in the room below. This difficulty can be met by mounting the tank on suitably proportioned cork or rubber strips (see Chapter VI) and by filling the tank from below the water level, if permitted by the water supply undertaking. Alternatively, the room below can be planned to be a store or other unoccupied space.

Prevention of Transmission of Sound along Water Pipes. If the measures described in the previous pages for quietening the equipment attached to the water system have failed or cannot be used, noise will, unless appropriate measures are taken, be conveyed along the water pipes to distant rooms and cause disturbance there. The small attenuation of sound in metals has been demonstrated experimentally by Meyer,* and is, indeed, almost a matter of common observation.

When discussing methods of reducing such transmission, one point must be considered. The water column contained in water pipes is probably as good a conductor of sound as are the metal walls themselves. It may be thought, therefore, that preventing transmission through the metal would be of no avail unless the water column were dealt with at the same time. Experimental investigation† indicates, however, that transmission through the water column is not of great importance. This is probably due to the fact that before sound energy travelling in the water can be heard it has first of all to be transmitted through the pipe wall, and marked reflection losses will then occur due to the change of medium. (See Chapter I.)

In any event, however, it happens that there is a simple method of reducing transmission through the pipe walls which also has a

* E. MEYER: *Zeits. Verein Deut. Ing.*, Vol. 78, p. 957, 1934.

† J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 50, p. 360, 1938; *Engineering*, Vol. 144, p. 612, 1937.

value for reducing transmission through the water column. The method in question is to replace a part of the metal pipe near the source of noise with a flexible pipe (usually of reinforced rubber). The difference between the acoustical constants of rubber and metal causes transmission losses (see Chapter I) which can be considerable. It also happens that the velocity of sound in water contained in a rubber tube is markedly less than that contained in a metal tube,* and consequently transmission losses occur in the water column also.

The insulation obtainable in this way has been investigated experimentally by Constable,† who tried the effect of varying the length of the rubber hose and also of varying the quality of the rubber. The results are shown graphically in Fig. 72 (*a*) and (*b*). It is found that—

1. The insulation obtainable increases with the frequency of the sound.
2. The insulation increases with the length of the rubber.
3. Canvas-reinforced rubber is less effective than plain rubber.
4. The insulation does not depend upon whether the pipe is empty or full of water.

It follows that insulation against high-frequency sounds such as water hiss can be obtained with short lengths of rubber hose; a length of 4 – 6 in. fitted as near to the water tap or valve as possible has been found effective in practice. Canvas-reinforced hose fixed with hose clips appears to be satisfactory in practice. Insulation against low-frequency sounds, such as the hum from a circulating pump, requires greater lengths of flexible piping: lengths of approximately 18 in. were used in the heating systems of the Acoustics Laboratory at the National Physical Laboratory and were found sufficient to render a noticeable hum inaudible. The insulating value was found by measurement to be about -13 db.,‡ a figure which will be seen to agree with the laboratory measurements described above. Insulating connexions of this length are probably most successfully constructed with moulded-on flanges which can be bolted to corresponding flanges on the piping.

The life of rubber insulating connexions is unknown, but it appears that they will certainly last several years, even on hot-water systems. They should, of course, be subjected to periodical inspection, and for this reason shut-off cocks should be provided.

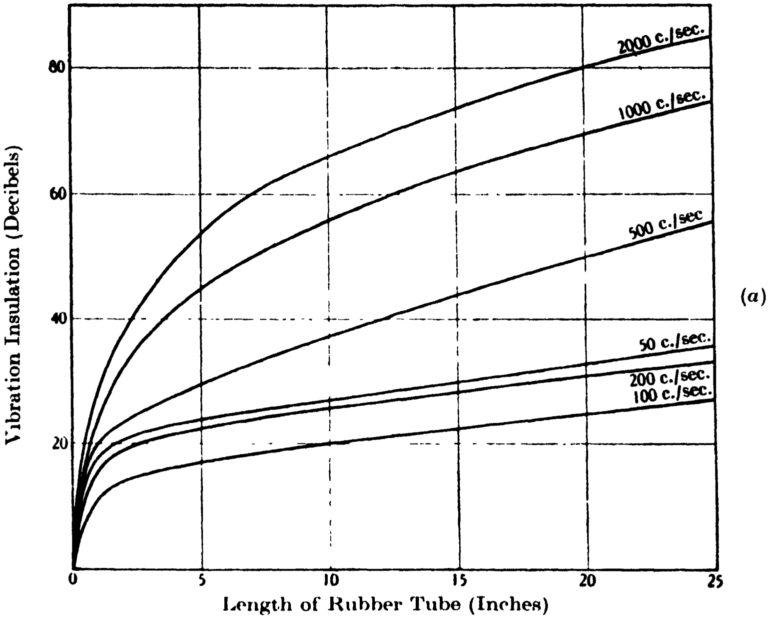
It may be mentioned that experiments have also been made§

* The mathematics of this phenomenon have been studied by D. J. KORTEWEG (*Wied. Ann d. Phys. u. Chem.*, V. 525, 1878), and are complicated. The reason is, roughly speaking, that the flexibility of the rubber makes the water behave as if it were more compressible than it really is, and consequently the velocity of sound in the water is decreased.

† J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 50, p. 360, 1938.

‡ J. E. R. CONSTABLE: *Engineering*, Vol. 144, p. 612, 1937.

§ For a complete account of this investigation reference should be made to Technical Publication No. 108 of the Lead Industries Development Council.



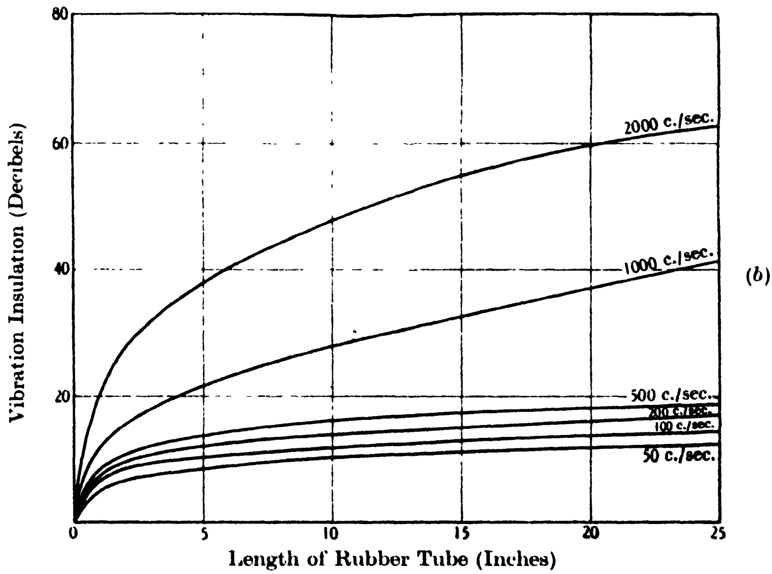


FIG. 72. INSULATION PROVIDED BY FLEXIBLE INSERTS AGAINST THE TRANSMISSION OF SOUND THROUGH WATER PIPES

(a) Insulation provided by soft red rubber hose.
(b) Insulation provided by canvas-reinforced rubber hose.

on the insulation provided by a flanged joint which had a rubber washer between the flanges and rubber bushes round the bolts. This construction was found to have no insulating value at low frequencies no measurements were made at other frequencies.

There is also the possibility that the material of which the pipe is made may affect the attenuation of sound by the pipe. Comparative measurements have been made at the National Physical Laboratory upon the transmission of sound along pipes of lead, steel, and copper, under various conditions of use, and it appears that sound is attenuated more rapidly in a lead pipe than in a copper or steel pipe under corresponding conditions, the difference being most marked in the case of pipes suspended freely. The effects are much the same for empty as for full pipes.*

There is a further method of reducing the amount of sound conducted by a pipe. This relies upon dissipating the sound energy during its travel, and is particularly applicable to water hiss. If a pipe is in good contact with masonry (e.g. is cemented in a chase in brickwork) sound can easily pass from the one to the other. Hence as sound passes along the pipe it loses energy, owing to leakage out into the brickwork. That this effect is real has been shown by Kreuger and Sager. They tried the effect of burying various lengths of a pipe in brickwork, and found that the water hiss audible in the pipe could be attenuated by about 13 db. even by passing through a 16 in. wall, provided it was well cemented in. The insulation against blows was not, however, so efficient.

If this method of attenuating water hiss is used, it should be remembered that its basis is that sound is conducted by the wall, which will therefore itself radiate sound. The wall should accordingly be an unimportant one and should not adjoin, for instance, a living-room or bedroom.

Prevention of Radiation of Sound by Water Pipes. If the precautions described in the previous pages are not possible and sound is conducted to the pipes, steps must be taken to prevent the sound being heard in rooms through which the pipes pass. Sometimes the sound intensity in the pipe is very high, as may be realized by listening with an ear in contact with the pipe. The sound radiated by the pipe itself is then sufficiently loud to be disturbing. It may, however, happen that even if the noise radiated by the pipe is not very great, the plumber by rigidly fixing the pipe to a light wall has provided it with an excellent sounding board, and a noise sufficiently loud to be disturbing may then come from the wall.

To obviate the above troubles it is necessary to enclose the pipe so as to cut off the sound it generates or to insulate it from the wall to avoid the sounding-board effect. The former can be achieved by leading the pipes through service ducts or burying them in properly

*For a complete account of this investigation reference should be made to Technical Publication No. 108 of the Lead Industries Development Council.

designed chases: if chases are used, insulating material such as felt or insulating blanket should be wrapped round the pipe at points at which it would otherwise come in contact with the building structure. When service ducts are specified, the walls which divide them from adjoining rooms should be reasonably sound-insulating.

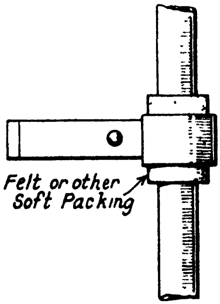


FIG. 73. PIPE IN INSULATED CLIP

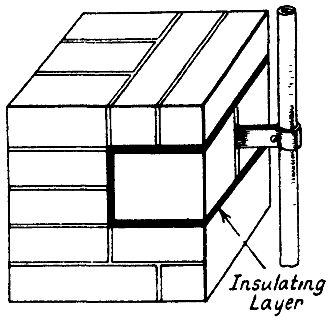


FIG. 74. PIPE SUPPORTED BY INSULATED WALL BLOCK

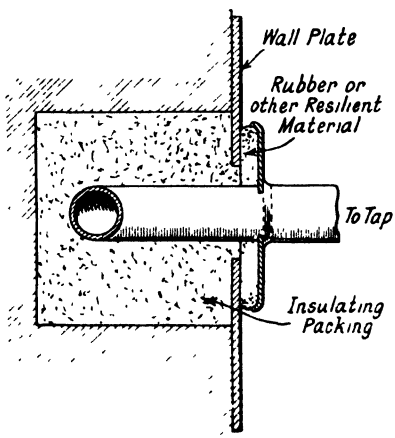


FIG. 75. A METHOD OF INSULATING TAPS

Probably the equivalent of 4½ in. brickwork would be suitable. Table XIV (page 139) may be consulted in this connexion.

Insulation of Piping from Walls. It is a little difficult to make positive recommendations as to insulating pipes from walls which are likely to act as sounding boards, as sufficient measurements have not been made to determine how the sounding-board effect varies with the material. It is a matter of common observation, however, that water hiss can be heard from a 9 in. wall in which a pipe is buried, and it is therefore probable that the majority of walls can be a nuisance in this respect. It is suggested, therefore, that noisy pipes should always be insulated from the wall, particularly if they are fixed to the walls of service ducts which pass between sets of flats.

Insulated clips and insulated wall blocks have been used for insulating piping from walls, the insulating medium being felt, cork, or rubber. Two designs are shown in Figs. 73 and 74. Measurements have been made* which show that insulating a water pipe from a brick wall by cork or felt decreases the transmission from the pipe to the wall by 15 db.

It is, of course, of no use to insulate one section of the water system only: if the pipes are insulated, for instance, the taps should be also (see Fig. 75). There would be value also, as mentioned above, in supporting cisterns upon insulating material to avoid the transmission to the building structure of the noise due to filling.

A general consideration should also be mentioned in this section, viz. that the frame of a steel-framed building is to be expected to conduct sound as easily as metal piping. It is advisable, therefore, to make sure that there is no immediate rigid connexion between the water system and the steel frame.

* *Die Schalltechnik*, 4 Jahrgang, p. 100, December 1931.

CHAPTER VIII

NOISE IN VENTILATING AND AIR-CONDITIONING SYSTEMS

THE sealed building with its system of internal ventilation, whether by units or by a central plant, is the modern defence against extremes of temperature, dirt, and noise. It can happen, however, if the ventilating system is not carefully designed, that it can create nearly as much disturbance as the traffic and other noise which has been excluded. That noise in occupied rooms due to ventilating systems is not inconsiderable may be illustrated by the fact that Parkinson has observed noise levels due to ventilating systems of as high as 90 phons, a representative range being 55–75 phons.* Reference to the table of permissible noise levels in Chapter XVI (Table XXIV) is illuminating in this connexion. On the other hand, in installations in which every effort has been made to keep the noise level low, e.g. in radio studios, very satisfactory conditions have been achieved.

By no means as much investigation has been made of methods of suppressing noise due to ventilating systems as of, for instance, sound-insulating walls; a good deal of useful information is available, however, and it is hoped that most of this has been included in the present chapter. The responsibility for designing and installing quiet ventilating equipment falls mainly on the manufacturer and the heating and ventilating engineer, to whom this chapter is offered as a convenient summary of research results. In so far, however, as the architect is the final arbiter in all matters of equipment, a grasp of the problems with which his sub-contractor has to deal may enable him to select the best type of proposed installation, or to obtain more effective co-operation in the actual job. It is hoped that the data given here will be of assistance in this connexion, or at least will convince architects and others that noise in ventilating systems is not a problem which may be safely left to take care of itself.

The necessity for some kind of restriction on noise caused by ventilating and air-conditioning systems has become apparent in the United States, where a standard has been proposed to the effect that "No noise resulting from the operation of an air-conditioning system shall exceed the loudness level of the noise in the room when normal activities are in progress and no part of the air-conditioning system is operating. The appropriate noise measurements shall be made in no less than ten different positions at a height of 5 ft. from

* PARKINSON: *Heating, Piping, and Air Conditioning*, Vol. 9, p. 183, March 1937.

the floor, and no reading shall be taken closer than 5 ft. from any wall, register face, window, or ventilation equipment." (Chicago Standards, October, 1936.)

In Germany it had been recommended* that the noise made by ventilating systems in different buildings should not exceed the following levels—

	Phons
Concert halls, theatres, cinemas (good-class)	20
Lecture halls, cinemas (ordinary)	25
Public assembly rooms, offices	30
Hotels (good-class)	35
Hotels (ordinary)	40

The noise level is to be measured at a distance of 10 ft. from the ventilating opening, at a height above the ground of an average person when seated. It is considered that these standards are easily attainable. It has, however, been pointed out that total loudness measurements may not be sufficient to determine whether the noise made by the system is unobjectionable, as there may be some outstanding note, such as the whine of a fan, which would be annoying even against a high background of noise.

There are three lines of approach towards solving the acoustical problem of an air-conditioning system, namely—

1. To reduce the noise at its source.
2. To prevent amplification of the noise by resonance effects.
3. To impede its transmission through the system.

These will be dealt with in the following pages.

REDUCTION OF NOISE AT ITS SOURCE

Noise can be generated in an air-conditioning system by the fans, the driving motor, water sprays and associated pumps, refrigerator compressor and associated motor, and the ozonizer, if any.

Noise Due to Fan. The question of reducing the noise due to propeller type fans has received a good deal of attention from manufacturers, and fans specially designed to be quiet are now on the market. K. D. McMahan, working in the research laboratories of the American General Electric Company, has shown that fan noise consists of unpitched noise together with a series of musical tones, due to the blade frequency and its overtones, which constitute the familiar "whine."† The total noise emitted by a fan depends largely upon its peripheral speed, as is the case with aeroplane propellers. In fact, according to McMahan's measurements, the noise of most fans, measured in phons, is proportional to the common logarithm of the peripheral speed. This is confirmed by the measurements of E. Lübcke.‡ As, by working with larger fans, the same air flow can

* V.D.I.: *Lüftungsregeln*, p. 3 (V.D.I.—Verlag, Berlin, 1937).

† *G.E.C. Review*, p. 82, February 1934; *Journ. Acoust. Soc. Amer.*, p. 204, 7th January, 1936.

‡ *Gesundheits--ingenieur*, vol. 60, p. 577, 1937.

be obtained with a reduced speed, a large slow fan is preferable to a small high-speed fan. Some manufacturers specify fan speeds which should not be exceeded for reasonably quiet operation. Other points which require attention are the provision of ample clearance between the blade tips and the housing and the avoidance of roughness or obstructions in the interior surface. It is perhaps unnecessary to add that the fan should be in other respects well constructed. The above principles also apply to centrifugal fans, which are the only type suitable for use with any considerable length of ducting.

Noise Due to Motor. The prevention of noise due to motors has already been dealt with in Chapter IV. It is sufficient here to say that low-speed motors are advisable.

Noise Due to Water Sprays. The noise produced by sprays depends on the water speed, type and number of nozzles, etc., and no universally applicable instructions for quietening these can be given. Very little information on this point has been published, and probably the best that can be done at this stage is to rely upon manufacturers' experience. It has been suggested, however, that if the water sprays are intended for washing the air only (frequently they are used for controlling its humidity), they might well be replaced by viscous or fabric air filters.* The pumps associated with the water sprays should be of good construction and low speed, and should be insulated from the building structure.

Noise Due to Refrigerator Compressors. Probably, at least in smaller installations, overall efficiency of a refrigerating plant is not so important as quietness of operation. It is advisable to mount compressors on insulated foundations.

Noise Due to Ozonizers. Ozonizers emit a high-pitched discharge hiss. A note of this character is comparatively easily dealt with by suitable sound-absorbent duct linings.

PREVENTION OF AMPLIFICATION OF NOISE BY RESONANCE EFFECTS

An ordinary ventilating system with sheet metal ducts will have a number of resonance frequencies. Just as pressed-steel car bodywork will "drum" at a particular engine speed, so the metallic parts of a ventilating system will vibrate in response to certain fan or motor speeds. Similarly, the air column within the duct has also a series of resonance frequencies just like an organ pipe. As it is very doubtful whether even by trial and error adjustments the fan speed can be arranged so as to excite no resonance, the best procedure is, following the treatment adopted against "drumming" in cars, either to make all parts connected with the fan non-resonant or to insulate them from the fan, or both. Fan casings themselves cannot well be insulated, but probably the use of heavy-gauge material,

* G. W. PENNEY: *Journ. Elect.*, Vol. 34, p. 313, August, 1937.

or laminated metal, consisting of two sheets of steel with a layer of felt between, would be of value.

Sheet-metal ducts of circular section are said to be fairly free from drumming problems; rectangular ducts are usually stiffened to avoid drumming either by attaching stiffeners to the outside or by punching suitable stiffening grooves. As an example may be mentioned the ducting in the Chicago N.B.C. studios,* which was stiffened at 4 ft. intervals with angle iron carried completely round the duct (see Fig. 76 (*d*)), in addition to diagonal creasing of the duct sections. In addition to stiffening, it is sometimes recommended that to prevent drumming, the duct walls should be wrapped round with blanketing, or anti-drum material of some kind should be applied. While this treatment should be useful, it would probably be more valuable applied to the interior surfaces of the duct, since the sound-absorption thus introduced would reduce the resonances of the air column within the duct besides reducing the transmission of sound along the duct. (Ducts are, of course, frequently wrapped with blanketing of some kind to act as a thermal insulator when warmed or cooled air is being conveyed about the building.)

Mention may be made at this stage of the hum which can arise if the fan is directly coupled to the motor. Vibration can be transmitted from the motor via the shaft to the fan blades from which the hum is radiated. Probably the best way of avoiding or curing this trouble is to insulate the fan from the motor shaft by a suitable coupling, or to use a belt drive.

TRANSMISSION OF NOISE

Prevention of Transmission of Noise from Ventilating and Air-conditioning Equipment. In spite of careful choice of equipment and precautions against the amplification of noise by resonance, there probably will still remain noise and vibration in the fan room which can be transmitted by various paths to other parts of the building. Transmission of sound to rooms near the fan room can be minimized by suitable planning. Obviously, if a basement is available, that will be, from a noise standpoint, the best place for the plant, for the solid foundations and massive walls should afford satisfactory insulation against sound originating in the air—always provided care is taken to block up unused flues and shafts, and to provide doors and windows having adequate insulation. (See Chapters XI and XII.) The possibility of sound from the fan room being transmitted through the air intake or outlet should be borne in mind. These should be placed where noise emerging from them cannot cause disturbance. The installation of a separate ventilating plant for the fan room and other noisy rooms may have to be considered as a precaution against introducing noise into the main duct system.

* V. J. Gilcher: *Heating and Ventilation*, p. 19, November 1933.

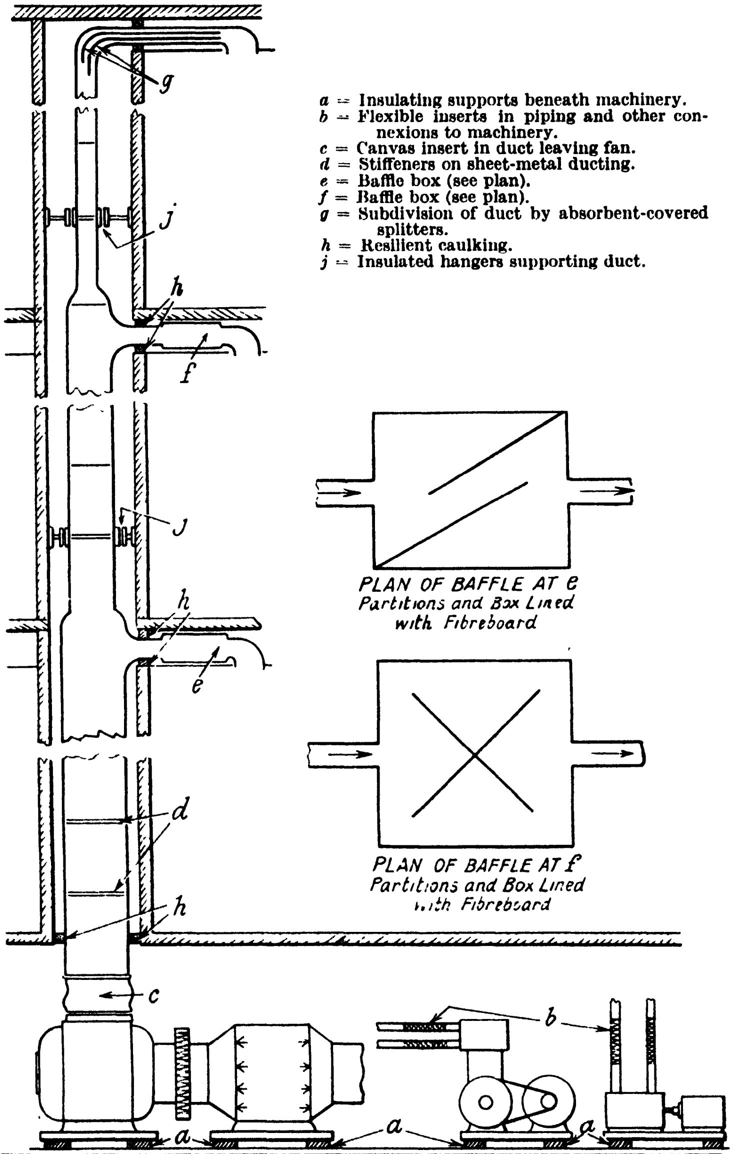


FIG. 76. PART OF AIR-CONDITIONING SYSTEM, SHOWING NOISE-REDUCING TREATMENT

Clearly the first step towards reducing disturbance from the fan room is to reduce the noise level in the room itself. To this end quiet equipment should be used, and the walls and ceiling of the room may be lined with sound-absorbent (see Chapter V). The

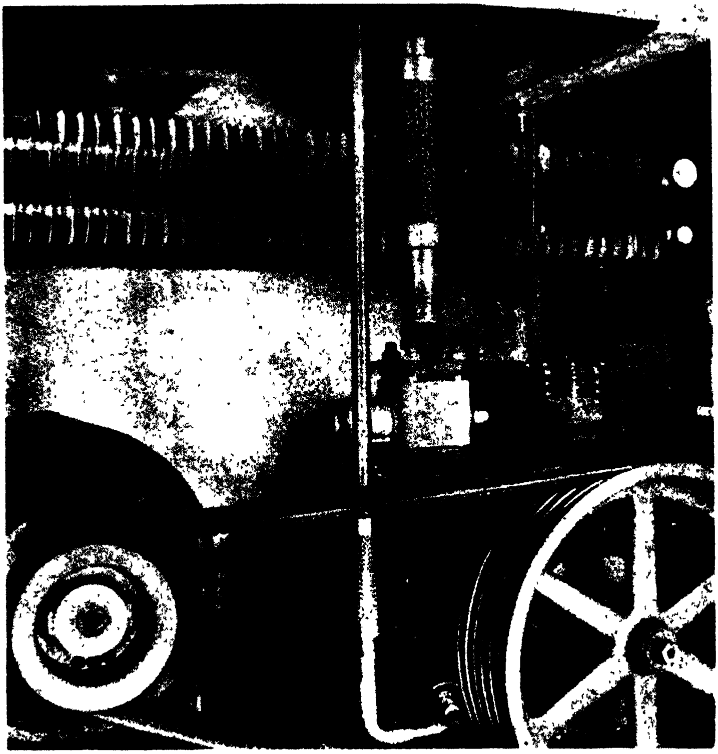


FIG. 77. FLEXIBLE METAL CONNEXION USED IN REFRIGERATOR COMPRESSOR PIPING
(*Chicago Metal Hose Corporation*)

walls of the room should also be sound-insulating; if an existing room has to be used, it may be necessary to increase the insulation provided by the walls by using one of the treatments suggested in Chapter X.

Insulation of the building structure and duct system from vibrations caused by the equipment is also important, even if the machinery is in the basement. Suitable methods of insulation are discussed in Chapter VI. It may be useful, however, to recall here that insulation requires flexible supports beneath the machinery in question (see Fig. 76 (*a*)) and the provision of flexible connexions to ducting, piping, or electrical conduit (Fig. 76 (*b*)). The flexible connexions are necessary to avoid impairing the insulation below the machinery and to prevent fractures arising from the continual vibration. An illustration of a flexible metal connexion used on a refrigerator compressor is given in Fig. 77.

Fig. 76 (*c*) illustrates a common method of insulating the ducting from the fan housing, i.e. by the insertion of a short length of canvas or leather near the fan. Such connexions should be fireproof, and should of course be airtight. The flexible insert should not be tightly stretched.

Transmission of Sound through the Duct System. An untreated sheet-metal duct such as is often used acts as a speaking-tube, and can convey sound to considerable distances. The subject of sound transmission via ducts is in its infancy. Most of the recommendations here given are accordingly only of a general nature and will be subject to revision when more information is available. It seems worth while, however, to collate such progress as has already been made and to draw at least some conclusions for immediate use, as it will probably be some time before the subject is finally thrashed out.

There are various types of noise to be dealt with. These are—

1. Noise entering the air stream in the duct at definite apertures, e.g. from the plant room or from rooms which the duct serves.

2. Noise transmitted into the duct by vibration of the structure to which the duct is attached, or by reason of passage of the duct through a noisy room (even if there are no apertures in the duct in the noisy room).

3. Wind noises due to the motion of the air through the duct, which may be generated throughout the length of the duct, especially at sharp edges and bends.

All three can be dealt with by impeding the transmission of sound along the duct. General methods of achieving this are accordingly described first of all. Other methods of quietening the noises referred to in items 2 and 3, are, however, given later, and it may be that in some circumstances these will prove the most economical.

Methods of Impeding the Transmission of Sound along Ducts. The two common methods of preventing sound transmission in a ventilating system are to line parts of the duct with sound-absorbent material and to introduce absorbent-lined baffle boxes into the system.

Of these, the first named is probably the more widely used; the second can, however, be valuable, and some space has accordingly been devoted to this as well. A number of practical questions arise when sound-absorbent treatment is proposed for a ventilating system. Possibly the most important are: How much lining is required for a given attenuation? What is the effect of the duct dimensions? Where is the material best placed? What characteristics should be looked for in a duct lining, and what frictional losses will it cause?

What is, probably, to the majority of readers, the most important of all considerations, i.e. cost, is not suitable for discussion in a book of this type. It should be pointed out, however, that against the cost of the treatment can be offset various savings which result from its use, e.g. higher air speeds are then possible, so that it may prove possible to use smaller ducts.

Prevention of Sound Transmission by Lining Ducts with Sound-absorbent. There has been up to date little systematic investigation of the attenuation of sound by duct linings. The measurements of Sivian,* who has discussed the theoretical aspects of the question, should be mentioned. Parkinson has given an approximate theory of the effect of absorbent linings,† and on it has based an empirical formula to represent his own and other experimental data. The following are the factors which chiefly influence the attenuation of sound in ducts—

(*a*) The length l of absorbent lining. (Straight lengths only are considered.)

(*b*) The shape and size of the duct. These are included in the formula by what is termed a "shape factor," defined as the square root of the ratio of the perimeter of the duct p to its area A.

(*c*) The sound-absorption coefficient α of the lining.

Parkinson's formula, which embodies these three factors, states that the sound-attenuation in decibels equals—

$$R = -\ 2{\cdot}84 l \sqrt{\frac{p}{A}} \log_{10}(1 - \alpha)$$

the various lengths being in feet.

Hale J. Sabine has published‡ a slightly different formula of the same type, namely—

$$R = 12{\cdot}6\, l\, \frac{p}{A}\, \alpha^{1{\cdot}4}$$

This formula is claimed to be accurate to ± 10 per cent for absorption coefficients in the range 0·20 — 0·80.

It should be mentioned that for the purposes of these formulae the sound is supposed to be generated at one end of the absorbent-lined duct and heard at the other. For the absorption coefficient α the value is taken corresponding to the particular frequency for which the attenuation is measured. If the overall reduction for a sound containing several frequencies is required, probably the best course is to make analysis of the sound. Failing this, it may be taken that the lowest important frequency is that of the tips of the fan blades passing the casing, and that the major amount of the noise is usually in the frequency range 100 – 500 ~, as pointed out

* *Journ. Acoust. Soc. Amer.*, Vol. 9, p. 135, 1937.

† *Heating, Piping, and Air Conditioning*, Vol. 9, p. 183, March 1937.

‡ *Journ. Acoust. Soc. Amer.*, Vol. 12, p. 53, 1943.

by A. J. King.* As the absorption coefficients of a number of materials are considerably lower at these frequencies than the average value (see Table V, Chapter V), this point should be borne in mind in selecting the type of absorbent.

Effect of Length of Lining. It is generally agreed that, as is stated by the formulae, the sound-attenuation in decibels produced by an absorbent is approximately proportional to the length of duct so treated, though there is some evidence that the attenuation per foot is greater very near the source of sound.

Effect of Shape Factor p/A. The shape factor is equal to $2/r$ in the case of a circular section duct of radius r, and to $2/b + 2/c$ in the case of a rectangular duct of sides b and c. Thus the larger the radius or the sides of the duct, the less is the attenuation. In the case of rectangular ducts, the attenuation is least in ducts of square section.

The Effect of Absorption Coefficient. It was at one time thought that the attenuation R was directly proportional to the absorption coefficient of the lining. Both the above formulae agree, however, that the increase of attenuation with absorption is rather more rapid than this. The value of using material of high coefficient is at once apparent. The greater the attenuation per unit length obtained, the smaller the length of absorbent treatment necessary, with consequent saving in expense.

Types of Material used for Sound-absorbent Lining in Ducts. Only certain sound-absorbent materials are suitable for duct lining. Among the properties which an absorbent should possess, in addition to an absorption coefficient which is high at low frequencies, may be included a low surface coefficient of friction, high resistance to moisture absorption, and fire and vermin resistance. Incidentally, most sound-absorbents are also heat insulators, a distinct advantage in a material designed to line ducts carrying warmed or refrigerated air about a building. Among materials in common use may be mentioned fibreboard, asbestos, mineral wool, glass silk, and balsa wool, the loose-fibre materials being usually covered with perforated metal sheeting.

The panel-type absorbent which has already been described in Chapter V probably has a future in ventilating-duct lining. It may be recalled that essentially this consists of a number of flat, thin air cells containing absorbent, the front being a sheet of sound-transmitting material such as thin sheet metal or oilcloth, the back being the rigid wall to which the absorbent structure is applied. If the depth of the cells is properly related to the stiffness of the covering material, the cell acts as a resonating system with a very wide response, absorption coefficients of the order of 0·5 being obtainable over a selected frequency range. This range could if, necessary, be widened by using cells of different depths. This type

* *Engineering*, June, 30th, 1944.

of absorbent has two merits from the ventilating engineer's point of view: it can be adjusted to absorb low frequencies, which are a nuisance in ventilating systems, since ordinary porous-type absorbents are liable to be less effective at these frequencies, and it also has a smooth impervious surface.

The choice of a sound-absorbent for a particular system will depend on the individual case. Acoustically, the criterion for a duct lining is the absorption coefficient when it is attached to the duct wall in the manner in which it will be used in the duct. It will be recalled in this connexion that some wallboards absorb less when they are attached to a rigid backing than when they are attached to battens.

Suitable Positions for Absorbent Treatment. If expense were no object and quiet imperative, one would advise that all the ducts should be lined with sound-absorbent material. Some discrimination as to the ducts to be lined is, however, usually necessary. Probably the positions in which treatment is most necessary are—

1. The short ducts leading from supply ducts to rooms (to prevent cross-talk between rooms supplied by the same trunk and to reduce wind noise).
2. The main duct leading from the fan (to reduce fan and equipment noise).
3. In ducts which ventilate noisy rooms, e.g. kitchens.

As great a length of duct should be treated as is practicable. If insufficient attenuation is obtainable from treatment in the above positions, the treated sections should be subdivided by absorbent covered splitters.

As regards the treatment of ducting in general, there is evidence that absorbent is most effective when used on bends.* Bends should not, however, be introduced for the sake of the increased attenuation thus obtained, since they may add to the wind noise as well as to the power required. Measurements indicate that the extra insulation afforded by a bend may on this account be nullified.

Perhaps this is a suitable stage for disposing of a fallacy, viz. that it is unnecessary to line ducts if the sound is travelling, as sometimes occurs, against the air stream. The air speeds used are so much less than the velocity of sound (1,100 ft./sec.) that sound travels as easily against the stream as with it. This has been confirmed by experiments of Sivian,† who showed that the attenuation in a lined duct was unaltered by air speeds of up to 2,000 ft./min.

Insulation between Two Rooms Connected by Ducting. The following is an approximate method of calculating the treatment of the ventilating system required to attain a specified sound-insulation between two rooms—

* Kreuger and Sagar: *Proc. Roy. Swedish Inst. for Eng. Res.* No. 132, 1934. Author's translation (*Building*, July 1937).

† *Journ. Acoust. Soc. Amer.*, Vol. 9, p. 135, 1937.

Let the rooms 1 and 2 be connected by a duct of cross-sectional area E. Suppose there is a source of sound in room 1 and that the total absorption (see Chapter V) in room 2 is A. Then once a steady noise level is built up, the amount of sound energy entering room 2 will equal the amount of energy leaving it plus the amount absorbed in it.

Using a method of calculation explained in Chapter XV, and assuming there are no energy losses in the duct (supposed untreated) and that the energy density (or, loosely speaking, the sound intensity) in rooms 1 and 2 is I_1 and I_2 respectively—

$$\frac{I_1}{I_2} = 1 + A/E$$

As an example, we may take average rooms with a total absorption of 100 sabins, the duct area being $\frac{1}{4}$ sq. ft. The ratio of intensities would then be approximately 400, i.e. the sound-insulation between the rooms would be 26 db., which is low. If conversation in the one room is not to cause a nuisance in the second room, an insulation of 50–55 db. would be advisable. Accordingly sufficient acoustical treatment of the duct would be required to give an additional attenuation of 24–30 db. A suitable lining for the length available for treatment could be determined by reference to the data given above.

The above method of calculation is rough, as various factors have been neglected. As a matter of fact, it tends to overestimate the treatment required, and on this account the calculated requirement may possibly be reduced by 5 db.

Power Losses Due to Absorbent Linings in Duct. As might be expected, absorbent linings, unless specially treated (see later), increase the resistance to air flow along a duct. There are, however, very few data to show the extent of this resistance. Parkinson* mentions that a certain absorbent increased the air resistance by 19 per cent. Other figures are given by Larson and Norris,† who found that the resistance in their 30 ft. long experimental duct was practically abolished by covering the duct lining with thin perforated metal sheeting. This treatment has been developed as a commercial article, the covered lining being as efficient a sound-absorber as the uncovered material, though it is necessarily more expensive. The expense of the perforated metal can, however, be offset against the cost of the power saved. A perforated metal covering has the additional advantage of minimizing the detachment of loose particles of absorbent material into the air stream.

Apart from frictional losses at the surface of the absorbent, linings increase power losses owing to the reduction of the effective duct area, a factor which may be considerable in small ducts. If it is

* *Heating, Piping, and Air Conditioning*, Vol. 9, p. 183, March 1937.
† *Ibid.*, Vol. 3, p. 59, January 1931.

not possible to compensate for this by installing larger ducts, increased power must be allowed to maintain the same air flow.

Duct Material. The choice of the material of the duct walls themselves is important from the acoustical point of view. The usual alternatives appear to be brick or concrete, depending on the construction of the building as a whole, or sheet metal. The latter has several obvious advantages: cheapness, ease of installation in existing buildings, a certain saving of space, and so on. Against these must be offset distinct acoustical disadvantages such as its tendency to drum and its low sound-insulating properties. When planning a new building, if economy is not an overriding consideration, there is a great deal to be said for the use of brick or other massive material for the ducts—at least for the main ducts. In a large building in which service shafts and galleries are required for other purposes, economy of space may be effected by using these as trunks for the ventilating supply network. This was actually done in the Bank of England building, where a brick 8 ft. by 8 ft. service tunnel in the basement communicates the main fresh air supply to risers which go to all parts of the building.

Brick, incidentally, has the advantage of a somewhat higher absorption coefficient than ordinary concrete or sheet metal.

Acoustic Filters. If low-frequency noise is particularly troublesome and sufficient sound-absorbent treatment is for some reason not practicable, a device may be tried based upon the fact mentioned in Chapter I that transmission losses occur when a conduit or duct changes its area. The device consists of replacing a length l of the duct by a length having considerably greater cross-sectional area. Calculation shows that a band of frequencies ranging about a value f are then attenuated, where $f = 280/l$, l being measured in feet. The attenuation depends on the width of the inserted section, values of 15 db. being quoted for an increase in width by a factor of 10. Greater attenuation over a wider frequency range can be obtained by using two consecutive inserts of this kind, of different length. Such a device is known as a high-pass acoustic filter, and is fully dealt with in textbooks on acoustics.* It can, of course, only be used in ventilating systems if there is sufficient space available, and care would have to be taken to see that the enlarged section is well braced, and also lined with anti-drum material, to prevent vibration. A necessary feature of the construction also seems to be that the changes of area should be *sudden*.

Baffle Boxes. Baffle boxes appear to have received little attention, either as regards their properties or as regards their practical application. The baffle box contains, as its name implies, one or more sound-absorbent-covered baffles, which are placed so that the air stream is tortuous, the sound in this way suffering a number of reflections at absorbent surfaces. Some care is needed

* STEWART AND LINDSAY: *Acoustics*, (Van Nostrand Co., 1930).

in the design to ensure that excessive power losses are not introduced. The use of such boxes concentrates the acoustical treatment in a comparatively small space, a system which has some practical advantages over the lined-duct system.

Lindner* carried out considerable work on this subject, giving a theory for the action of baffle boxes. Measurements upon a number of different types gave results which agreed fairly well with the calculated values. The attenuation of the boxes ranged from 16 to 24 db. The most successful construction is illustrated in Fig. 76 (*e*) and afforded an attenuation of 24 db. It will be noted that the obstruction to the air stream is low. Lindner recommends

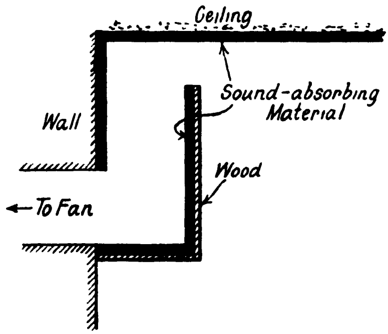


FIG. 78. BAFFLE BOX CONSISTING OF ABSORBENT-LINED BOX BUILT OVER ROOM OUTLET

a length of flexible connexion inserted in the duct immediately following the baffle box.

A rather more complicated type of baffle installed in the A.V.R.O. studios in Hilversum has been described by Zwickker and Costen,† and is shown in Fig. 76 (*f*). The absorbing material was "Insulwood" (which has an average coefficient about 0·25), and the measured attenuation of the baffle in the range 500–2,500 c.p.s. varied from 33 to 42 db.

Before leaving this section, mention should be made of a somewhat different type of baffle box which is valuable for soundproofing existing ventilating systems, but which can also form a part of a new installation. This consists simply of an absorbent-lined box built over the grille and arranged as shown in Fig. 78. The sound suffers at least one reflection at an absorbent surface before entering the room. If more attenuation is required, one or more lined baffle boards can be built into the box.

Noise Entering a Duct through its Walls. As well as entering

* *Zeits. für Techn. Physik*, No. 6, p. 290, 1932.
† *Revue d'acoustique*, January-March 1935, p. 1.

through apertures, sound can enter a duct either by reason of the duct being in direct contact with a vibrating surface or by transmission of sound through the duct walls as may occur, for instance, if the duct passes through a very noisy room, even though there are no actual openings from the duct into that particular room.

As regards the first, it is a worth-while precaution to suspend the duct by insulated hangers (Fig. 76 (*j*)) from any wall or ceiling which can be heard or felt to be in a state of vibration. As regards noise entering a duct by transmission through the duct walls, this will almost certainly occur at least once in the course of every supply trunk, viz. where it passes through the equipment room on its way out. The logical treatment in this and similar cases is to increase the sound-insulation of the walls of the duct. This is most simply done by increasing the weight, e.g. by using heavy-gauge metal, or by constructing a wooden covering. Alternatively, the duct walls may be made composite by covering with building board on battens. Wrapping the duct round with material such as rock wool or hair felt is frequently done, but no figures are available as to the efficacy of this treatment. Probably a great deal of its usefulness arises from the damping of the resonances of the duct walls which it causes. The treatment which is most certain to be effective is to brick in the duct, first wrapping it round with a building blanket, which will serve the double purpose of insulating the duct from structure-borne vibration and of damping its resonances.

Wind Noises. (*a*) *Wind Noise Arising in Ducts.* So far, this chapter has been concerned with sound entering a duct from without. Noise due to the passage of air along the duct is different in that it is generated continuously along the length of the duct, as was shown, for example, by Parkinson.*

Prevention of disturbance due to wind noise can be achieved by measures dealt with earlier, designed to reduce the sound emerging from the ventilation outlets, oı preferably by reducing the occurrence of wind noise. There is no doubt that high air speeds lead to high wind noise levels, accompanied in some cases by vibration of the duct. In this connexion measurements have been made which indicate that the noise level produced in unlined sheet-metal ducts of average construction arising from the combined fan and wind noise, increases by about 1 phon per 100 ft. per min. increase in air speed. This figure applies to speeds greater than 1,000 ft./min.; the rate of increase of noise is rather more rapid for lower speeds. If there are obstructions such as valves and grilles, these figures may be exceeded. It is extremely difficult to recommend maximum air speeds for silent operation, as authorities differ so widely. Air speeds in the United States appear in general to be considerably greater than on this side of the Atlantic. In the United States the

* J. S. Parkinson: *Heating, Piping, and Air Conditioning*, Vol. 9, p. 183, March 1937.

following air speeds are considered standard for public buildings—

	ft./min.
Through the outside air intakes	1,000
Through connexions to and from heating unit . .	1,000 – 1,200
Through main discharge duct.	1,200 – 1,600
In branch ducts	600 – 1,000
In vertical flues	400 – 800
In registers or grilles	200 – 400

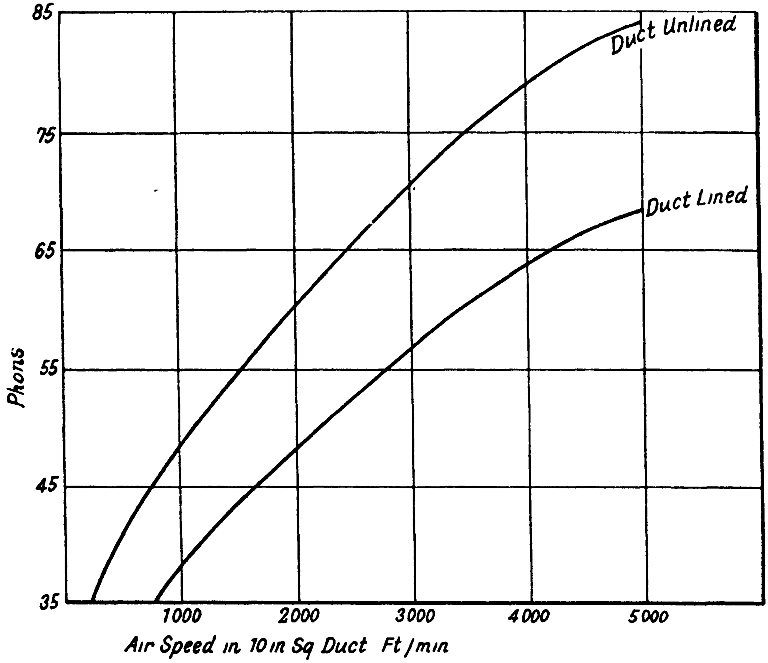


FIG. 79. RELATION BETWEEN NOISE LEVEL AND AIR SPEED IN DUCTS WITH AND WITHOUT ABSORBENT LINING

These velocities may be increased by 20 per cent if first-class duct construction is used to prevent any buckling, or vibration; for industrial buildings, where noise is seldom considered, main-duct velocities as high as 3,000 ft./min. may be used; for department stores and similar buildings, maximum velocities may, with good construction and design, be as high as 2,000 ft./min.

Certain details of design need attention; an obvious precaution is to avoid anything which can cause eddies in the wind stream, e.g. sharp edges and roughnesses on the interior of the ducts. Any pipes or other obstructions passing through the air stream should be streamlined by means of a suitable "easement" placed round the pipe. Also proper streamlining of elbows is usually stated to be necessary, and for this purpose splitters are often inserted to distribute the air more uniformly over the duct section. In this connexion, methods of controlling air speeds which rely upon a sudden constriction are likely to cause noise. The curves in Fig. 79, which are due to Larson and Norris, show the relation between noise level and air speed in lined and unlined ducts. Comparing curves 1 and 2, it will be noticed that the air speed can as a rule be doubled

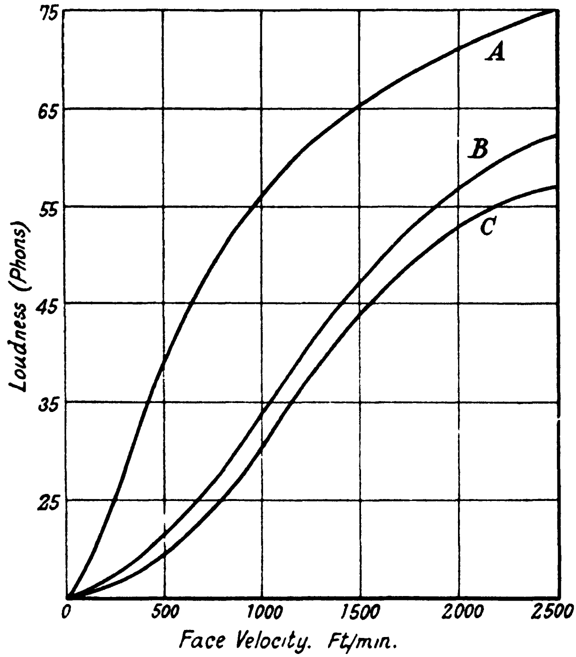


FIG. 80. NOISE CAUSED BY DIFFERENT TYPES OF GRILLES, *A*, *B*, AND *C*, AT VARIOUS AIR SPEEDS

Data applicable to rooms containing 100 units of absorption, e.g. the average living-room.

without increasing the noise level provided the duct is lined with absorbent. (The absorbent used in these experiments was wood-fibre blanket covered with perforated metal.) It may thus sometimes be economically worth while to increase the air speed, keeping the noise level at the same or even a lower level by introducing absorbent material.

(*b*) *Wind Noise Arising at Ventilation Outlets.* It is the custom to furnish the ventilation outlet with a grille, more or less ornamental. These can cause considerable noise unless attention is paid to their design. One function of a grille is, of course, to direct the air stream, being designed to give either a wide spread or a "long throw" according to requirements. Return or exhaust openings are unlikely to be noisy, since these are usually plain apertures and as a rule take only low air speeds. Air-regulating valves in the inlets can also produce wind noises.

The variations in the amount of noise caused by different types of grille are shown in Fig. 80, due to Geiger.

The above remarks are inserted only for the purpose of drawing attention to the need for consideration of this point. Grille designs are so numerous that it would not be possible to give any recommendations regarding the type to use.

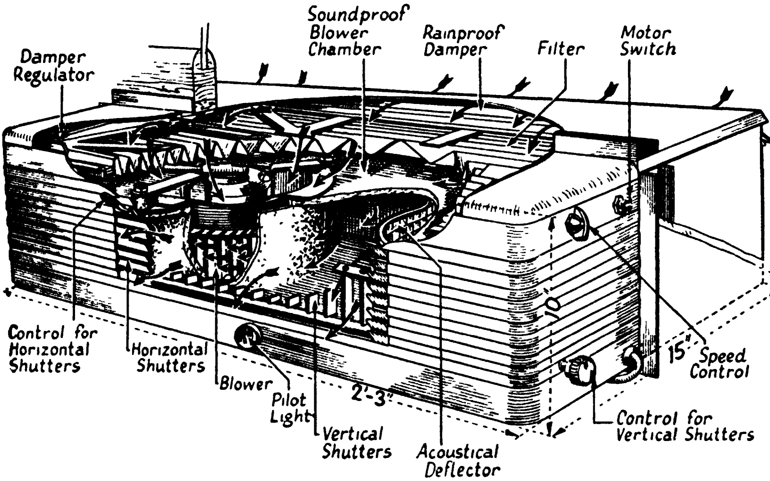


FIG. 81. UNIT VENTILATOR
(*Filteraire Ltd.*)

Unit Ventilating and Air-conditioning Equipment. A wide range of installations is now available for dealing with the air of a single room only. They range from the humble extractor fan which removes the kitchen smells, to the comprehensive air-conditioning cabinet which graces the stockbroker's office. There is probably a future for self-contained unit air-conditioning equipment owing to the considerable structural alterations involved in providing existing buildings with a central plant and duct system. Quiet operation is essential, since the equipment itself is in the room. In the case of rooms which overlook noisy streets, the equipment should also prevent the ingress of street noise. A stage intermediate between the provision of unit conditioning equipment for each room and installing a central system consists of a separate conditioning plant for each group of rooms or flat. A few short lengths of small ducting supply the different rooms. Although the initial cost of plant may be higher, there are various advantages to offset against this, including the acoustical advantage that noise cannot be conducted from flat to flat as is possible when a central system is used.

Unit ventilators which draw air in from the street, filter it, and blow it into the room can be quiet in operation provided the fan and motor are silent and properly mounted, and that acoustical baffles are provided to prevent transmission of street noises. An example is shown in Fig. 81.

CHAPTER IX

THE TRANSMISSION OF SOUND THROUGH WALLS
PART I—SOLID PARTITIONS

SCIENTIFIC study of the transmission of sound through walls has been practically confined to the last quarter of a century, though from 1900 onwards investigators were toying with the subject and studying such matters as the transmission of sound through porous fabrics.* The subject is thus considerably younger than the related subject of auditorium acoustics, which Sabine began to study in 1895.

Probably the first to make reliable measurements of the sound transmission through walls was R. Berger in Munich, and the general results which he obtained are accepted at the present day.† He was closely followed by other investigators, including W. C. Sabine, and the subject rapidly assumed sufficient importance for national laboratories in various countries to erect test chambers for its study and to issue reports upon the sound-transmission of building constructions submitted to them for examination. A great deal of information is now available, and the principles which should be followed in designing a sound-insulating wall are now clear; difficulties are, however, liable to arise in putting these principles into practice.

Sound energy falling upon a wall pursues several paths, which are illustrated in Fig. 82. A great deal of it is usually reflected (90–99 per cent) unless the wall is faced with a specially absorbing material. It may be asked why, if most of the sound falling on a wall is reflected, the transmitted sound should be of importance. The answer lies in the great range of sensitivity of the ear. (See Chapter I.) The remainder of the sound is either absorbed at the surface or in the material, being converted into minute amounts of heat, or is transmitted. This transmission may be (*a*) by direct transmission through the pores of the wall if it is of porous material, (*b*) to the other side by re-radiation due to the wall vibration, (*c*) to other rooms by travelling as structure-borne sound along the length of the wall. The relative importance of the different paths depends upon circumstances: (*c*) is discussed in Chapter XIV, and its effect is ignored in the present chapter.

The *sound-reduction factor* of the wall is defined as the ratio of the sound energy falling upon a wall to the amount transmitted to the

* F. L. TUFTS: *Amer. Journ. Science*, Vol. 11, p. 357, 1901; SIEVEKING AND BEHM: *Ann. d. Physik*, Vol. 15, p. 808, 1904; R. OTTENSTEIN: *E.T.Z.*, Vol. 38, p. 410, 1917.

† R. BERGER: *Dissertation*, Munich, 1911.

other side of the wall. This figure can be anything between a small number (for a sheet of paper) and a hundred or so millions (for a brick wall). These figures are inconveniently large, and sound-reduction factors are accordingly usually expressed in decibels. (See Chapter I.)

In the laboratory, measurements of the sound-insulation provided by a wall are usually made by building it into an aperture which connects two otherwise soundproof rooms and determining the

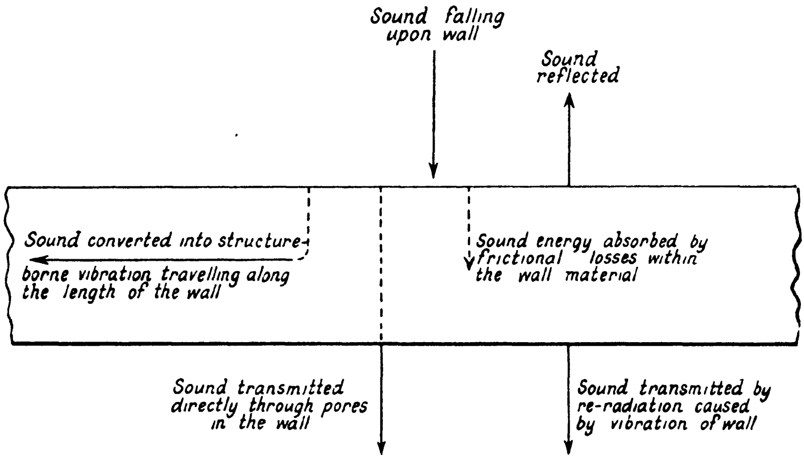


FIG. 82. PATHS TRAVERSED BY SOUND FALLING UPON A WALL

sound-intensity in one room when a loudspeaker is sounded in the other. In this way the wall is tested as an isolated unit, and the results are not complicated by other factors such as the transmission of sound through the building structure mentioned in (c) above. The relation between the insulation determined in the laboratory and the insulation obtainable in practice is discussed in Chapter XV.

The question of whether laboratory tests, which are usually made upon freshly built partitions, apply to partitions which have been erected for some time has been studied in various laboratories.* It appears that the insulation of masonry partitions may decrease a little during the first week or so, but that afterwards the insulation remains constant.

Sound-insulation of Solid Non-porous Partitions. Solid non-porous partitions (or, as they are often termed in scientific papers, single homogeneous non-porous partitions) fall into a special class acoustically, since the two faces of the partition, being rigidly connected,

* C. FECK: *Dissertation*, Brunswick, 1936; V. L. CHRISLER: *Scientific Papers of the Bureau of Standards*, Vol. 11, p. 231, 1927.

move together. The properties of this type of partition are discussed in this chapter, those of complex partitions being dealt with in the following chapter.

In Table XIV are collected a number of measurements made at the National Physical Laboratory* upon solid partitions ranging in weight from about ½ lb./sq. ft. to 95 lb./sq. ft. It will be observed that the insulation is tabulated for six frequency ranges, namely 100 and 150; 200 and 300; 500, 700, 1,000; 1,600 and 2,000; 3,000 and 4,000 c.p.s., and finally the average for the frequency range 200–2,000 c.p.s. The average for this frequency range is useful for roughly comparing partitions. The figures for the separate ranges are of importance when selecting a partition to exclude a given type of noise. The significance of the figures in brackets is referred to below.

The Mass Relation. All laboratories agree that the sound-insulation provided by single solid non-porous partitions against airborne sound of a given frequency depends almost entirely upon their weight per square foot. This general result is known as the "mass relation." This does not mean, however, that walls of equal weight are acoustically similar in other respects. For example, a 1-in. sheet of iron and a 4½-in. brick wall have approximately the same airborne sound insulation. They would probably differ considerably in behaviour as regards impact sound. In Fig. 83 are shown curves based upon National Physical Laboratory measurements which show how well the mass relation is obeyed for partitions ranging in weight from ½ lb./sq. ft. to 100 lb./sq. ft. Fig. 83 (*a*)–(*e*), and Fig. 84, were obtained by averaging results for the same frequencies as in Table XIV. The curves represent the sound-insulation which the average single solid partition of a given weight may be expected to have when tested under the above-described conditions of measurement. The curves are also very useful in assessing the effectiveness of any partitions other than single partitions, for a complex type of partition is of special value for sound-insulation only in so far as it has an insulation appreciably greater than that of the average single partition of the same weight. For this reason the figures in Table XIV for the insulation of partitions are in each case followed by a figure (in brackets) for the insulation which the *average* single solid non-porous partition of the same weight would be expected to have.

As shown by the "scatter" of the points through which the curves are drawn, the mass relation cannot be dignified by the term of "mass law." Partitions may be expected to show divergencies of average insulation of up to 2 or 3 db. from that shown in Fig. 84. Differences of this amount have, however, little practical significance.

It is unfortunate that different methods of test give slightly different figures for the insulation of apparently identical partitions;

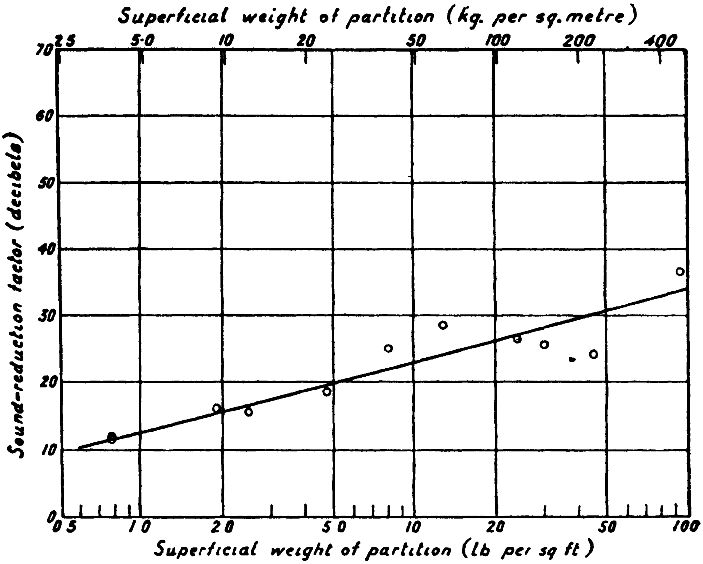
* G. H. Aston: *The Sound Insulation of Partitions.* (Department of Scientific and Industrial Research, 1948.)

TABLE XIV

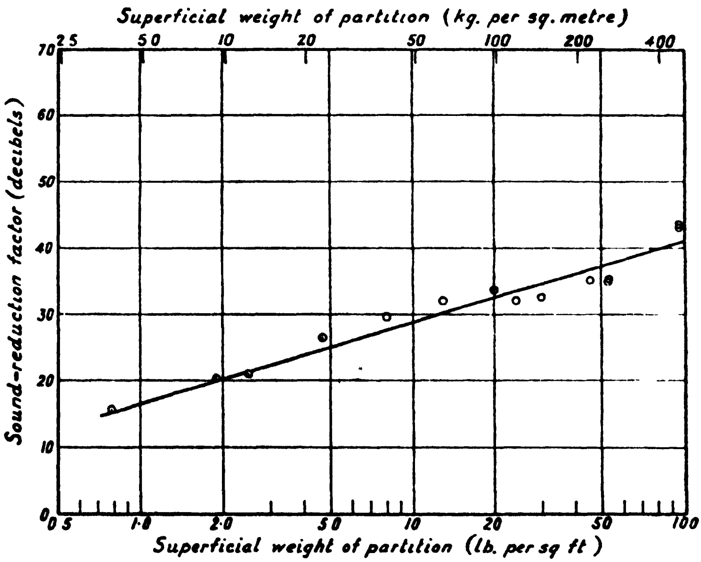
Sound-insulation of Solid Walls and Partitions

Partition No.	Description of Test Partition: Construction	Weight (lb./sq. ft.)	Thickness (in.)	Mean Sound-reduction Factor (db) for Frequencies (c.p.s.): 100 and 150	200 and 300	500, 700, and 1000	1600 and 2000	3000 and 4000	200 to 2000
	SINGLE SHEETS								
	(*Approximately homogeneous*)								
1	⅜ in. laminated building board on wood frame	0·78*	⅜	12 (12)	16 (15)	22 (23)	28 (26)	30 (30)	22 (22)
2	½ in. fibre board on wood frame	0·78*	½	12 (12)	15 (15)	22 (23)	28 (26)	29 (30)	22 (22)
3	¼ in. asbestos cement board in steel frame (10 panels with cover strips)	1·7*	¼	12 (15)	18 (20)	27 (26)	33 (30)	36 (34)	26 (26)
4	⅜ in. plasterboard on wood frame	1·9*	⅜	16 (15)	20 (20)	27 (26)	34 (30)	31 (35)	27 (26)
5	16G. steel plates in steel frame (3 panels with cover strips)	2·5*	1/16	16 (17)	21 (21)	30 (28)	37 (32)	43 (37)	29 (27)
6	⅜ in. plate glass in wood and steel frame	4·7*	⅜	19 (20)	27 (25)	31 (30)	30 (36)	41 (41)	30 (30)
7	Board formed of waste materials bonded with plastic resins (3 panels with cover strips in wood frame)	4·9*	1¼	20 (20)	28 (25)	37 (31)	39 (36)	36 (41)	35 (31)
8	Laminated plasterboard (5 layers each ⅜ in. thick)	8	1⅞	25 (23)	30 (28)	32 (33)	34 (40)	39 (45)	32 (33)
9	¾ in. plasterboard, plastered both faces to thickness of ⅝ in.	13	2	29 (25)	32 (30)	31 (36)	42 (44)	50 (49)	34 (36)
	SINGLE MASONRY AND BLOCK PARTITIONS								
10	Hollow clay blocks, plastered on one face to thickness of ½ in. (Three partitions of nominally the same construction.)	14	3½	28 (25)	30 (31)	33 (36)	37 (44)	40 (49)	33 (36)
				30	34	33	37	42	34
				27	33	37	37	45	36
11	3 in. clinker concrete slabs, unplastered	17	3	17 (26)	18 (32)	22 (37)	30 (46)	40 (51)	23 (38)
12	2 in. clinker concrete slabs with 1 in. ribs at 9 in. centres on one face, other face plastered to thickness of ½ in.	19·5	2½	28 (26)	36 (32)	38 (38)	51 (48)	56 (52)	41 (39)
13	2 in. clinker concrete slabs, plastered on both faces to thickness of ½ in.	20	3	26‡	34 (33)	35 (38)	45 (48)	57§	38 (39)
14	As No. 13, but with ½ in. cork insulation around edges (no plaster on cork)	20	3	37‡	33 (33)	35 (38)	43 (48)	55§	36 (39)
15	As No. 11, but with one face plastered to thickness of ½ in.	24	3½	27 (27)	32 (33)	40 (39)	52 (49)	58 (54)	41 (40)
16	As No. 11, but with both faces plastered to a thickness of ½ in	30	4	26 (28)	33 (35)	44 (41)	56 (52)	57 (56)	44 (42)
17	Cellular concrete blocks, one face plastered to thickness of ¾ in	45	8¾	24 (30)	35 (37)	47 (44)	56 (55)	55 (60)	46 (45)
18	4½ in. brick, plastered on both faces to thickness of ½ in.	53	5½	30‡	35 (38)	45 (45)	54 (57)	61§	45 (46)
19	9 in. brick, plastered on both faces to thickness of ½ in.	95	10	45‡	44 (41)	49 (49)	65 (63)	70§	52 (51)
	Same wall after 5 months			48‡	43	48	63	68§	51 (51)
20	Another wall similar to No. 19	95	10	37 (34)	43 (41)	51 (49)	61 (63)	69 (67)	52 (51)

* Superficial weight of sheet (i.e. excluding frame). ‡ For 100 c.p.s. only § For 4000 c.p.s. only.

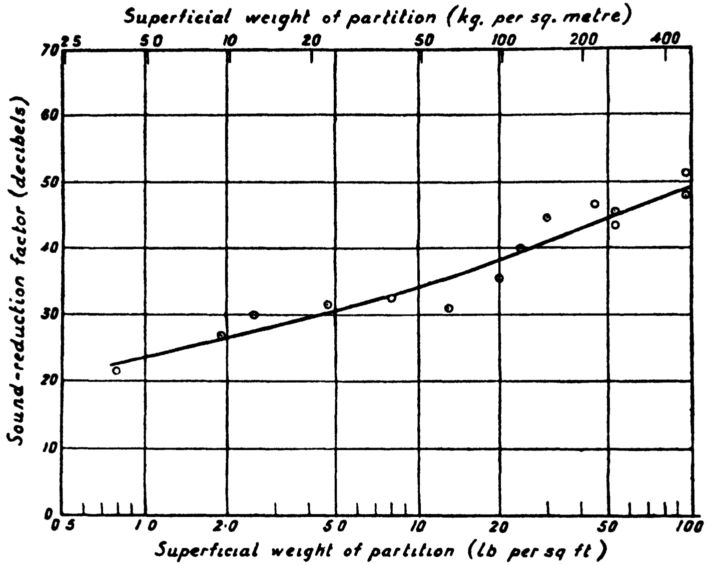


(*a*) *For frequencies* 100 *and* 150 *c.p.s.*

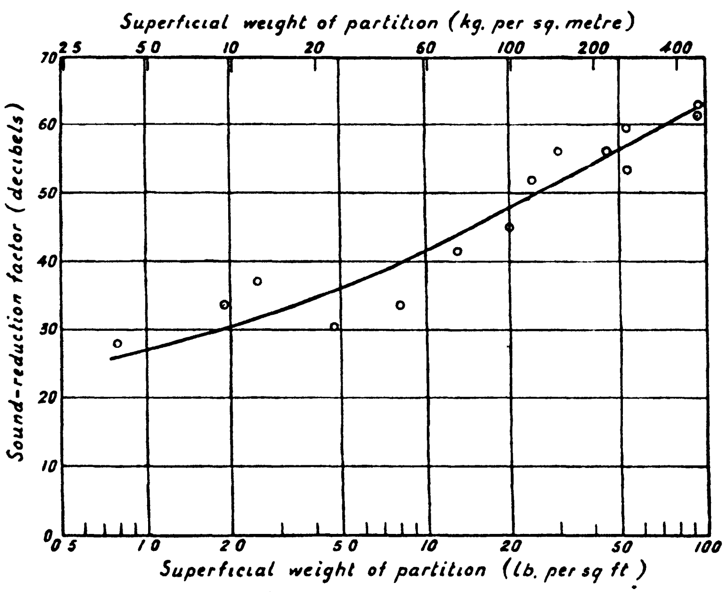


(*b*) *For frequencies* 200 *and* 300 *c.p.s.*

FIG. 83. RELATION BETWEEN MEAN SOUND-REDUCTION FACTOR AND SUPERFICIAL WEIGHT OF SINGLE SOLID PARTITIONS

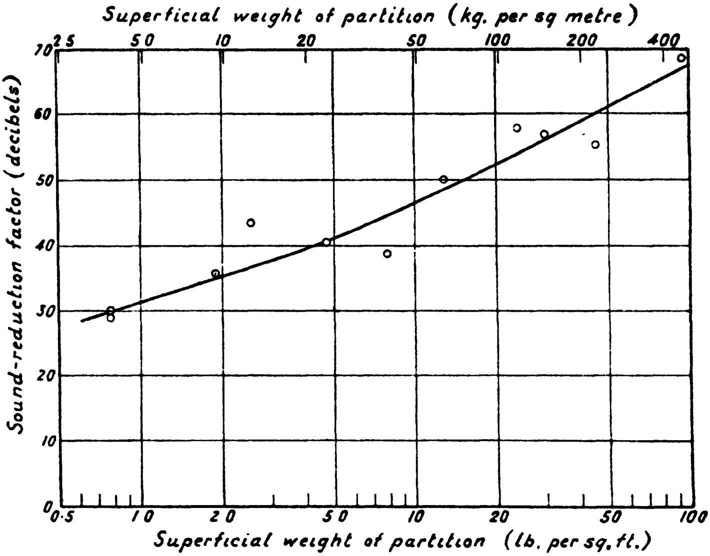


(c) *For frequencies 500, 700, and 1,000 c.p.s.*



(d) *For frequencies 1,600 and 2,000 c.p.s.*

FIG. 83—(*contd.*). RELATION BETWEEN MEAN SOUND-REDUCTION FACTOR AND SUPERFICIAL WEIGHT OF SINGLE SOLID PARTITIONS



(e) *For frequencies* 3,000 *and* 4,000 *c.p.s.*

FIG. 83—(*contd.*). RELATION BETWEEN MEAN SOUND-REDUCTION FACTOR AND SUPERFICIAL WEIGHT OF SINGLE SOLID PARTITIONS

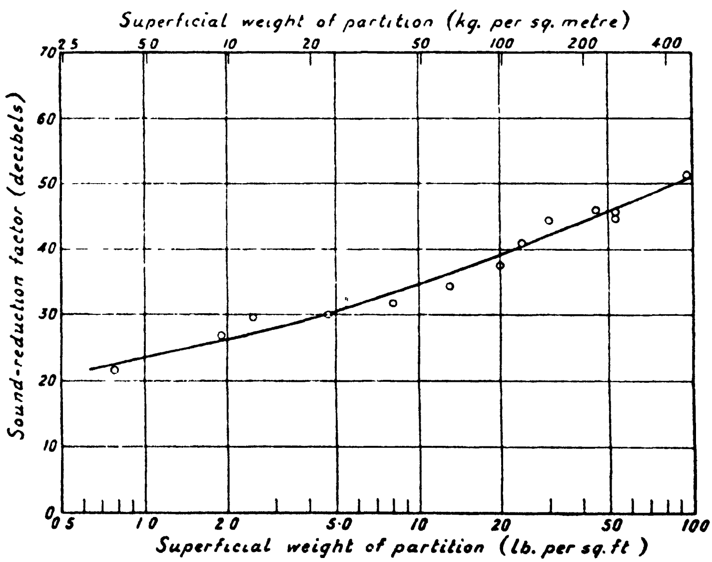


FIG. 84. RELATION BETWEEN MEAN SOUND-REDUCTION FACTOR FOR FREQUENCY RANGE 200–2,000 C.P.S. AND SUPERFICIAL WEIGHT OF SINGLE SOLID PARTITIONS

the results are of course self-consistent, that is to say that generally each testing station puts partitions in the same order of effectiveness, but the mass curves based on each testing station's measurements vary slightly from each other, by about 2 or 3 db.

It will have been noted that the insulation of a partition depends upon the frequency of the sound. As a rough rule it may be taken

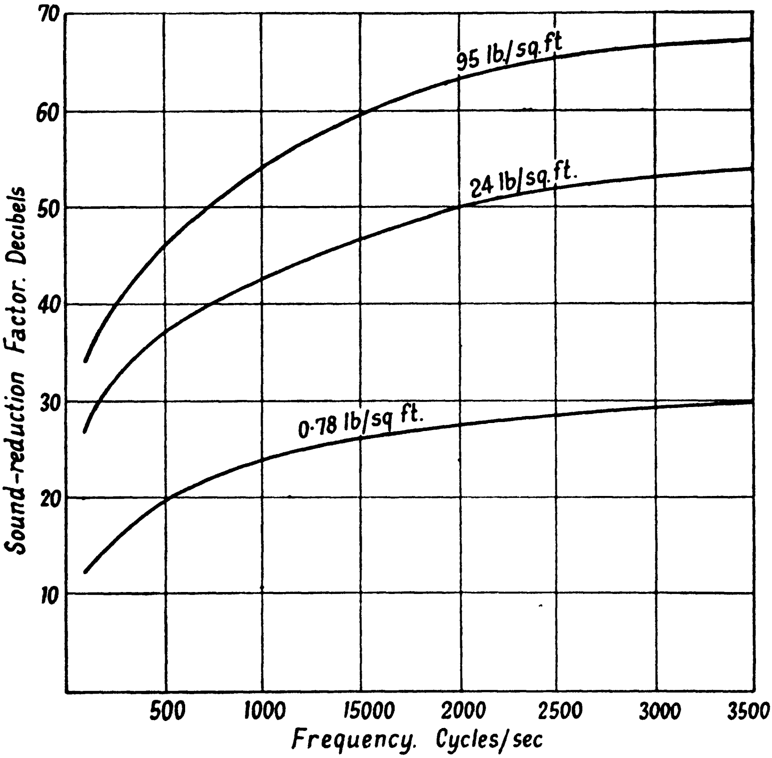


FIG. 85. VARIATION OF SOUND-INSULATION OF SOLID PARTITIONS WITH FREQUENCY FOR PARTITIONS OF THREE DIFFERENT WEIGHTS

that the insulation increases by about 5 db. each time the frequency is doubled (that is, for each octave rise in pitch). Fig. 85 shows the increase of insulation with frequency for three partitions (the figures being taken from Table XIV). The increase is slightly more than 5 db. for light partitions and less for heavy partitions. At any frequency, doubling the weight of a partition increases the insulation by about 5 db., as may be seen from Fig. 83 (*a*)–(*e*).

The mass relation clearly demands an explanation. This is not the place to discuss in detail the theories which have been put forward;

those interested may refer to the original papers.* The simplest explanation of the result is that usually, so far as sound-transmission is concerned, a wall may be regarded as having no stiffness. It reduces, then, to a solid plate which is free to move to and fro under the action of the alternating pressures in the sound wave which falls on it. (Lest it be thought that these pressures are too small to affect a wall, it may be remarked that the acoustical forces on a wall of a room in which a radio set is in operation may easily reach a total of several pounds.) Sound is re-radiated by both sides of the wall, just as it would be from a loudspeaker diaphragm. That radiated on one side is a part of the reflected sound; that on the other is the transmitted sound. The higher the frequency of the sound, the less will be the motion of the wall, as the reader may easily demonstrate for himself by trying to move a weight held in the hand first slowly then quickly. Clearly, also, the heavier the wall, the more difficult it will be to set into vibration. Also changing the material (say from wood to brick) would not be expected to affect the amplitude of vibration, provided the weight is the same.

The mass relation can thus be quite easily explained in a general way. There are, however, difficulties in giving an exact explanation: for example, calculations based upon the above simple assumptions require the insulation to increase 6 db. per octave rise in pitch, whereas the experimentally determined change is 5 db. The commonly accepted explanation of this difference is that a wall does not behave exactly as the solid plate assumed in the above explanation, since it has a number of resonances having frequencies ranging from a few cycles to thousands of cycles per second. At each of these resonances sound is transmitted very freely. (See Chapter I.) The combined effect of these resonances will clearly be to reduce the sound-insulation of the wall. The resonances are very numerous: in the case of a glass window, which has been studied at the National Physical Laboratory,† 95 well-marked resonances were observed between the fundamental frequency of 17 c.p.s. and the limit of the measurements at 3,000 c.p.s.

Their effect may be seen in another way. Those who are familiar with the Chladni sand figures,‡ will know that with each of the large number of resonances possessed by a metal plate is associated a definite vibration pattern; these patterns consist of lines called nodal lines, along which the plate is stationary, separated by areas

* R. Berger: *Dissertation*, Munich, 1911; P. E. Sabine: *Journ. Acoust. Soc. Amer.*, Vol. 4, p. 38, 1932; A. H. Davis: *Philosophical Magazine*, Vol. 15, p. 309, 1933; A. Schoch: *Akustische Zeits.*, Vol. 3, p. 113, 1937.

Berger treated the wall as having no flexural resonances; Sabine and Davis allowed for a single resonance; Schoch allowed for the full range of resonances to be expected.

† J. E. R. Constable: *Proc. Phys. Soc.*, Vol. 48, p. 914, 1936.

‡ See, for example, J. Tyndall: *Sound*, p. 172, 1876, or A. T. Jones: *Sound*, p. 174, 1937.

which are in a state of vibration. These patterns can be made visible by sprinkling sand upon the vibrating plates, the sand being driven by the vibration to the nodal lines, along which it can lie at rest (see Fig. 14).

By using a different technique it can be shown that walls behave in a similar way. Fig. 86 shows the results of measurement made at the National Physical Laboratory* of the vibration of a 9 in. brick wall. The areas of greatest vibration are shown in black and the areas of least vibration in white. The patterns have not the symmetry of Chladni's sand figures, but show the analogy. As in the case of Chladni's figures, the complexity of the pattern increases with the frequency.

A point of practical interest which is suggested by these figures is that since walls can flex in this way, we must not expect to increase the insulation of a wall merely by loading it at a series of points or stiffening it along a few lines; for the vibration of the wall would be expected to be reduced only at or near those points, the remainder of the partition vibrating as before. A practical example is a stud partition faced on one side only with building-board (see partitions Nos. 1–5, Table XVI, page 165), which is no more insulating than building-board by itself. The experiment has also been tried of loading a sheet of plywood at a series of points,† and in this way increasing its weight from about ½ lb./sq. ft. up to 2½ lb./sq. ft. The sound-insulation was unaffected by the loading while it was distributed at a number of points (from 1 up to 25 weights were used) but an increase of weight obtained by a continuous loading (sand or water was used for the experiments) does give the increase in sound-insulation which would be expected from the mass relation.

Another point of practical interest concerns highly resonant partitions such as metal partitions, which possess very little internal damping, especially if supported on metal surrounds rather than wooden surrounds. There is some evidence that the insulation may be increased by applying some kind of anti-drum treatment such as sprayed fibrous material.‡ Increases in insulation of 3 db. at high frequencies and rather larger increases at frequencies near the fundamental resonance frequency of the partition are reported. This result is, of course, of particular interest in connexion with vehicle bodies.

Deviations from the Mass Relation. It occasionally happens, as mentioned above, that the insulation of a specimen wall deviates by one or two decibels from the insulation which would have been predicted for it from the curve in Fig. 84. These deviations do not usually have any practical significance, and are usually attributed to

* J. E. R. Constable and G. H. Aston: *Proc. Phys. Soc.*, Vol. 48, p. 919, 1936.

† *Handbuch der technische Physik*, Vol. 17, part 3, p. 33, 1934.

‡ P. Baron and L. Renault: *Travaux*, June 1938.

the effect of resonances. As has been explained earlier, the insulation of a resonant partition is somewhat less than that of the idealized non-resonant partition. If, when a partition is tested, an average number of its resonance frequencies coincide with test frequencies, its insulation would be expected to lie on the experimental mass-relation curve. If fewer than usual coincide, the insulation would be high; if more than usual coincide, it would be low. Partition resonances are fairly sensitive to the details of construction, and it is often found that two partitions ostensibly of the same construction have slightly different insulation. Probably the only way to establish that a building material has special properties which make the insulation of a wall built from it greater than that of an average solid partition of the same weight would be to test a dozen or so specimen walls made of the material in question.

Effect of Porosity. The above-described mass relation holds only if the partitions are not porous. Pores (such as occur, for example, in an unplastered breeze wall) can transmit sound to an appreciable extent.* See also Table XIV, Nos. 11 and 13.

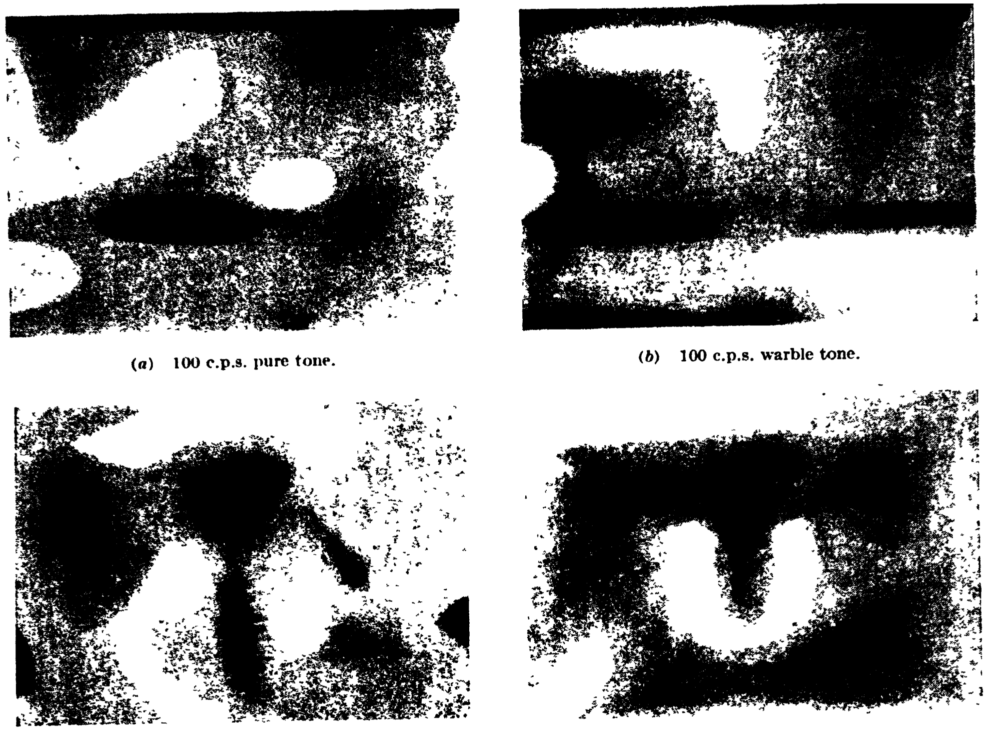
Experimental studies have been made of the transmission through small holes (somewhat larger than pores) by Wintergerst and Knecht. An account of their experiments appears in Chapter XI.

Effect of Hair Cracks. Solid walls can lose insulation if hair cracks develop in them, owing to shrinkage, vibration, or settlement. Lübcke has investigated this point and shown that the insulation of a 2½ in. wall having a 10 in. long hair crack was 6 db. lower than it should have been. The insulation of another wall, 5 in. thick but with many fine cracks in it, was 10 db. low. Similarly, a single fine crack in a 4½ in. brick wall reduced its insulation by 5 db. It is evident that such cracks must be avoided if good sound-insulation is desired.

Partitions which contain joints in their construction such as square edged or tongued and grooved boards have been shown to be markedly less insulating than an equally heavy jointless partition. Sealing the joints by fixing a non-porous layer on the boards, e.g. linoleum, has been tried with some success, but it is better to use a jointless partition.

Another way in which cracks likely to impair the sound-insulation can occur in partitions is round pipes passing through the partition. Cracks are particularly likely to occur round hot-water pipes, which are constantly expanding and contracting. One method of overcoming this is to build into the partition a sleeve through which the pipe can pass with ample clearance; this gap is then caulked

* Rayleigh: *Philosophical Magazine*, Vol. 16, p. 181, 1883; R. Berger: *Dissertation*, Munich, 1911; E. Wintergerst and W. Knecht: *Zeits. d. Ver. Deutsche Ing.*, Vol. 76, p. 777, 1932; L. J. Sivian: *Journ. Acoust. Soc. Amer.*, Vol. 7, p. 95, 1935; A. Gigli and G. Sacerdote: *Alta Frequenza*, Vols. 4–5, p. 229, 1936; M. Rettinger: *Journ. Acoust. Soc. Amer.*, Vol. 8, p. 172, 1937.



(*a*) 100 c.p.s. pure tone.

(*b*) 100 c.p.s. warble tone.

(*c*) 500 c.p.s. pure tone.

(*d*) 500 c.p.s. warble tone.

FIG. 86. VIBRATION PATTERN OF PLASTERED 9 IN. BRICK WALL
(Areas of greatest vibration are shown black.)

(e) 1,600 c.p.s. pure tone.

(f) 1,600 c.p.s. warble tone.

(g) 4,000 c.p.s. pure tone.

(h) 4,000 c.p.s warble tone.

FIG. 86—(*contd.*). VIBRATION PATTERN OF PLASTERED 9 IN. BRICK WALL
(Areas of greatest vibration are shown black.)

with tow or asbestos. It is essential that the clearance should be sufficient to allow the whole space to be filled with the caulking material, for if it is only applied on the surface it will soon work out as the pipe expands and contracts.

Movable Partitions. The question of avoiding small apertures in the construction of a partition also arises in connexion with movable partitions. These are required when it is necessary to be able easily to throw two rooms into one, etc., but considerable difficulties arise if these partitions, when in place, are to afford a reasonable degree of sound-insulation. Sliding partitions, for example, usually have to be made in a number of sections to permit of storage; the gaps between these sections, added to the almost inevitable gaps beneath the partition, render abortive any special sound-insulating construction of the partitions themselves. In cases of this kind, if other circumstances permit, the balanced door described in Chapter XII may be useful. This door can be made in single spans of up to 120 ft., and its action is such that a tight closure against a rebate could probably be arranged for. The transmission through gaps would probably then not be serious, and an insulation more nearly corresponding to the weight per square foot of the door could be obtained.

Effect of Character of Wall Surface. It is often stated that the character of the wall surface affects the insulation obtainable. Except for the fact that the porosity is affected by plastering (and also the weight per square foot), there does not seem to be any foundation for this statement. There does not, therefore, seem to be any point in providing a reflecting surface on the noisy side of the wall as is sometimes recommended or, on the other hand, in the application of a layer of sound-absorbent material to one or both faces of a wall. There appears to be no evidence in support of the latter, and it is probable that any effect is due to the increase in total absorption in the room (see page 224).

Practical Importance of the Mass Relation. The mass relation shows that if solid partitions are to be used an appreciable increase in the sound-insulation can be obtained only by increasing the weight considerably, and, in the case of heavy partitions, prohibitively. This result also extends to partitions built from hollow bricks (see Table XIV), which instead of having special sound-insulating properties (as was at one time supposed) are actually slightly less insulating than a solid wall of equal thickness on account of being lighter. It follows, therefore, that if the architect has decided to use a solid wall, he can please himself as to what material he uses for it and as to whether he uses solid or hollow bricks. He must, however, aim at a sufficiently heavy wall and must design the partition so that cracks do not develop and so that all pores are sealed with plaster or other material. The question of what insulation is necessary in given circumstances is dealt with in Chapter XVI.

As already mentioned, it is doubtful whether in practice a change of anything less than 3 db. in the insulation of a partition has any significance. Put in terms of weight, this means that changing the weight of a wall by anything less than a factor of 2 has little acoustical significance. For example, to make a noticeable improvement in the insulation of a 9 in. brick wall, it should be converted into an 18 in. wall if solid construction is to be used. There is a limit even to this process. As the wall is thickened, resonances due to compression waves in the thickness of the wall, as distinct from the flexural vibrations considered previously, become possible. It may be shown that the insulation of a solid wall is limited on this account (whatever its weight) to about 75 db. In the following chapter methods of attaining good insulation without excessive weight will be described.

CHAPTER X

THE TRANSMISSION OF SOUND THROUGH WALLS
PART II—COMPLEX PARTITIONS

IN the last chapter single solid partitions were discussed, and it will be recalled that the chief factor affecting the insulation obtainable from such a partition is its weight per square foot; in other words, a single partition can only be made sound-insulating by making it sufficiently heavy. It nearly always happens, however, that weight is the last thing the designer is prepared to allow, and it is accordingly often necessary to look to non-solid partitions to provide sound-insulating constructions.

It has been found that non-solid or, as they will be termed in this chapter, complex partitions can, if properly designed, combine insulation of a high order with a comparatively low weight, and this chapter will be devoted to discussing the principles which should be adopted in the design of such partitions. Incidentally, it should be stated that the remarks made regarding these principles apply with some generality to constructions which would not ordinarily be regarded as partitions, e.g. double windows and composite doors.

Before commencing this discussion we must be clear as to what is meant by a complex partition. It is easier to mention examples as, for instance, stud partitions or double-leaved partitions, than to give a comprehensive definition. Probably the best definition is that a complex partition is one which, unlike a single partition, is so constructed that one face can vibrate differently from the other. It may be taken as a general rule that the more complete the disconnexion between the two faces, the greater will be the insulation of the partition.

The fundamental acoustical difference between solid and complex partitions is, therefore, that whereas the insulation provided by the former is almost completely determined by its weight, the insulation provided by the latter, although it is affected by its weight, also depends upon several other factors. Consequently, while two solid partitions having the same weight will have nearly enough the same insulation, two equally heavy complex partitions may differ very considerably in their insulating properties.

The faces of a complex partition are connected in two ways. One is by the air between the leaves (this linkage is termed *acoustical coupling*), and the other is by the connexion provided by the structure to which they are attached (this linkage is termed *mechanical coupling*).

The position may be illustrated by the example of a stud partition in which the two panels are attached to opposite sides of the same set of studs. Sound falling on one face of such a partition causes vibrations, which are communicated to the second face partly through the air interspace and partly via the studding. In a general way it can be seen that the linkage due to air coupling will depend upon the stiffness of the air in the interspace and upon the weight of the panels, while the mechanical linkage will depend upon the mass and stiffness of the panels and the mass and stiffness of the studding.

The aim in designing a complex partition is to minimize the importance of both forms of coupling. Generally speaking, the air path is the more easily controlled but there are certain devices, described later in this chapter, by which the mechanical coupling can also be reduced. It is well, perhaps, to point out that there is an overriding limit to this process. If the mechanical coupling could be completely abolished and acoustical coupling reduced to its minimum, i.e. a sound wave travelling from the first leaf to the second, the overall sound reduction (in decibels) would be the sum of the reductions of the separate leaves. The factors which affect air coupling will be dealt with first, mechanical coupling being discussed later.

Linkage Caused by Air Coupling. The air contained between the two leaves of a double partition acts almost exactly as if it were a spring connecting them. When sound falls upon the first face (Fig. 87), the pressure variations in the sound waves force the face backwards and forwards. This movement creates pressure variations in the interspace, and in consequence the second face is moved backwards and forwards and radiates sound on the other side of the partition. The movement of the second leaf is usually considerably less than it would have been had the sound wave acted directly upon it. Increasing the separation between the leaves of the partition will decrease the pressure difference in the interspace and, by decreasing the motion of the second leaf, accordingly increase the insulation. Generally speaking, the insulation obtainable from a double partition increases continuously as the separation between the leaves increases, but there is a secondary effect which disturbs the continuity of this increase, especially at low frequencies. The origin of this effect, which is due to a resonance, is discussed in the original papers,* and reference should be made to these if detailed information is required on this point. That the resonance is worthy of attention will appear from the following section. We do not wish, however, to overrate its importance: the most important point in designing a complex partition is to reduce the air coupling at all frequencies, and this can be done

* E. WINTERGERST: *Schalltechnik*, 4–5, 1931; J. E. R. CONSTABLE: *Philosophical Magazine*, Vol. 18, p. 321, 1934; D. HURST: *Canadian Journ. of Res.*, Vol. 12, p. 398, 1935; A. L. KIMBALL: *Journ. Acoust. Soc. Amer.*, Vol. 7, p. 222, 1936; L. RENAULT: *Revue d'acoustique*, Vol. 6, p. 69, 1937; J. E. R. CONSTABLE: *Philosophical Magazine*, Vol. 26, p. 253, 1938.

by making the separation as big as possible; attention to the resonance effect mentioned above is of the nature of a refinement in that it affects the lower-pitched tones only.

Double Partitions Constructed from Two Similar Components. The behaviour of double partitions constructed from components of equal weight is illustrated in Fig. 88, which is based on measurements made at the National Physical Laboratory upon the sound-insulation of a double window glazed with 21 oz. glass.* It will be

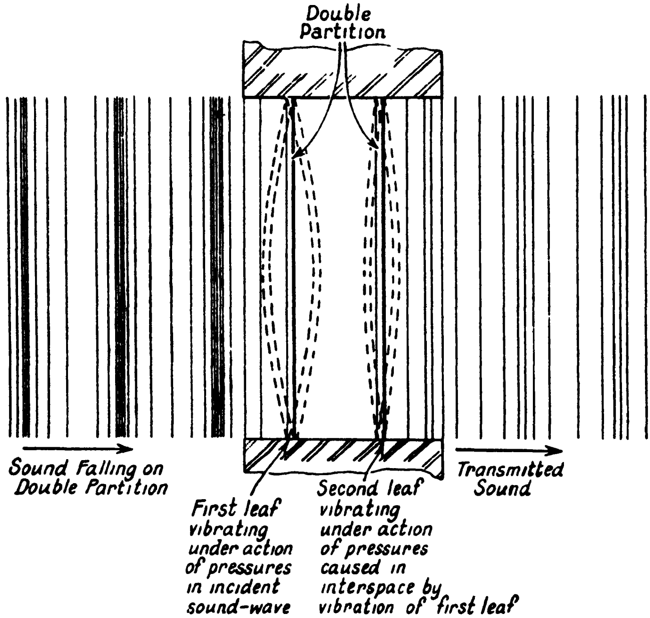


FIG. 87. ILLUSTRATING THE WAY IN WHICH THE AIR IN THE INTERSPACE BETWEEN THE TWO LEAVES OF A DOUBLE PARTITION PROVIDES AN ACOUSTICAL CONNEXION BETWEEN THEM

seen that, particularly at low frequencies, increase of the separation between the panes of glass decreases the insulation at first but afterwards increases it. (Similar results have been obtained by Renault for double sheet-steel panels.) This behaviour arises from the air-coupling effect referred to above, the minimum in the insulation occurring, of course, when the separation is such that the frequency of the air-coupling resonance is about equal to the frequency of the sound concerned. It will be noticed, incidentally, that (particularly at the lower frequencies) the insulation of the double window at its minimum can be less than that of one pane alone. The spacing at

* J. E. R. Constable: *Philosophical Magazine*, Vol. 18, p. 321, 1934.

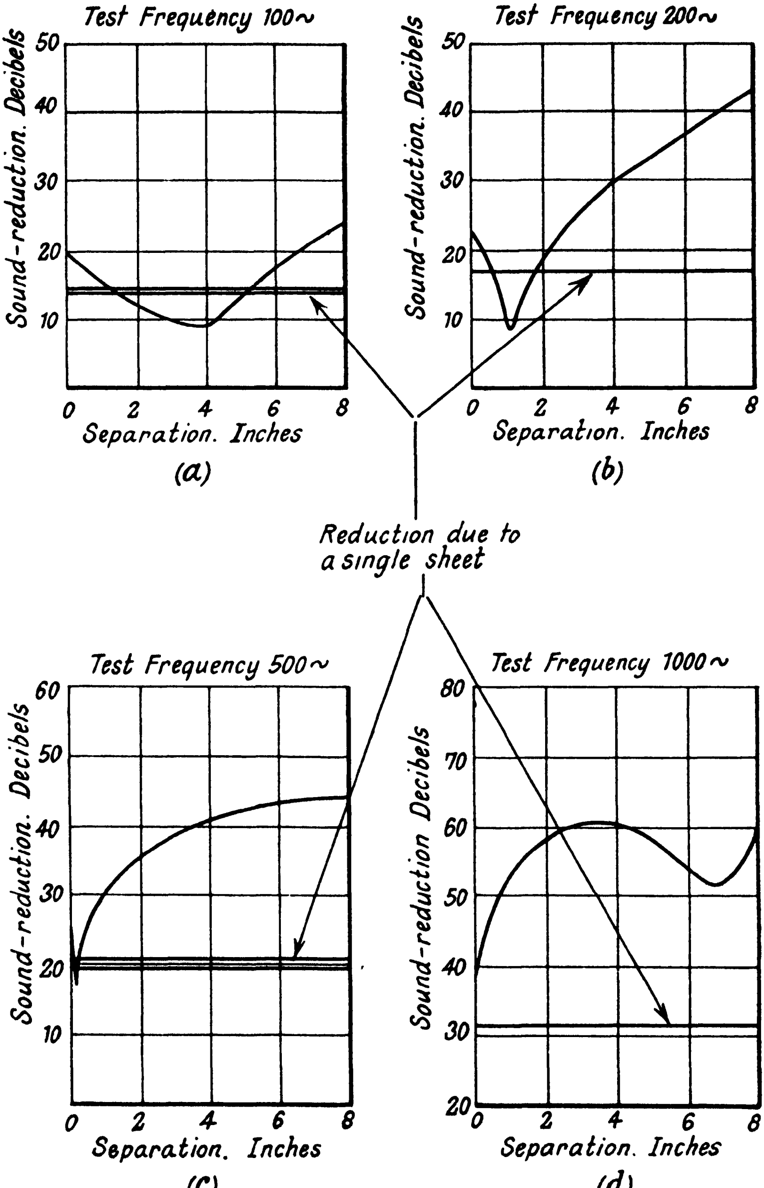


FIG. 88. VARIATION WITH SPACING OF THE SOUND-INSULATION OF TWO SHEETS OF 21 OZ. GLASS

which the minimum occurs decreases as the test frequency increases, as is shown in the figures, being 4 in. at 100 c.p.s. but only about $\frac{1}{20}$ in. at 1,000 c.p.s. when 21 oz. glass is used.

Formulae have been given in the various papers referred to for the sound-insulation of double partitions idealized in various respects. These formulae are unlikely to be strictly applicable in practice, so only the following general conclusions will be given. (These are, of course, based upon the assumption that air-coupling is predominant over mechanical coupling.)

The sound-insulation of a double partition constructed from similar components which have ordinary thicknesses and spans, so that their fundamental resonance frequencies are low, is a minimum for a separation given approximately by the following formula—

$$d = 60{,}000/n^2w \text{ in.} \qquad \qquad (1)$$

where w = weight of each component in lb./sq. ft.,

n = frequency in cycles per second,

d = separation between components in inches.

This formula shows that increasing the spacing decreases the frequency at which the sound-insulation minimum occurs and that increase of the weight of the components has a similar effect.

For separations greater than those which give the minimum sound-insulation, increase of the separation increases the insulation continuously, until the spacing is about equal to a quarter of the wavelength of the sound considered; further increase of the separation causes a decrease of the insulation to a second minimum at a spacing of about a half-wavelength. This point is not likely to be reached at low frequencies (the wavelength corresponding to 100 c.p.s. is of the order of 10 ft.) but may occur at higher frequencies; see, for example, Fig. 88 (*d*), in which the second minimum at 1,000 c.p.s. is shown. After this second minimum, other sound-insulation minima occur at successive increases of a half-wavelength in the separation. It is doubtful, however, whether they are as important as the first minimum discussed above. *For practical purposes, it is sufficient to assume that after the first minimum the insulation steadily increases as the spacing is increased up to about a quarter-wavelength of the sound concerned, but that thereafter any further increase in spacing causes only minor variations in the insulation.*

Increasing the weight of the components, besides decreasing the frequency at which the minimum occurs, also increases the insulation of the individual components in accordance with the mass relation, thereby increasing the insulation of the double partition. Using heavy leaves is particularly important when insulating against low notes, since double partitions tend to be defective at these frequencies.

It follows from what has been said above that any decrease in the weight of a double partition has to be compensated for by an increase in its thickness if the insulation is to be unaffected. That is to say, that to provide anything more than moderate insulation, a double partition must be either thick or heavy; a thin, light sound-insulating partition seems, at any rate for the present, impossible to construct.

Double Partitions Constructed from Dissimilar Components. It is often claimed that there is an advantage in constructing a double partition of components of unequal weight. The theory of the sound transmission through double partitions of this type has been discussed by various authors,* and it has been shown that they behave similarly to those having similar leaves except that the minimum in the insulation caused by the resonance is less important. Calculation indicates that this latter point is the sole advantage of dissimilarity between the leaves, and that even this is of minor significance. In fact, for most frequencies the insulation obtainable from a double partition of given weight and thickness is greatest when the leaves have equal weight. It is accordingly to be concluded that ordinarily there is no advantage in making the leaves dissimilar.

One other point may be dealt with here. It has been urged in favour of partitions constructed from dissimilar components that the disadvantage of the leaves having identical resonance frequencies is obviated. It is doubtful, however, whether this has much practical significance, at least as regards insulation against airborne sound, since the resonances of partitions appear to be so sensitive to the conditions at the edges and other factors that it is unlikely that in the case of similar components the two resonances would be sufficiently near together to have a marked effect upon the sound-transmission.

Effect of a Sound-absorbent Lining upon Air Coupling in a Double Partition. Building acoustics is scarcely ever subject to exact theory (possibly the one exception is reverberation). The difficulties arise because the dimensions of the objects concerned are so often about the same as the wavelength of the sound. Were they very different one way or the other, an exact theory might become possible. As it is, one can only proceed by a process which consists practically of doing the theory twice, first assuming the objects are small compared to the wavelength, and then again, assuming they are large compared to the wavelength.

An example of this process is seen in double partitions. We have so far regarded them as for the most part small (in thickness), and have obtained the resonance effects described above. If instead we regard them as large, we are enabled to investigate another factor

* A. L. KIMBALL: *Journ. Acoust. Soc. Amer.*, Vol. 7, p. 222, 1936; L. RENAULT: *Revue d'acoustique*, Vol. 6, p. 69, 1937; J. E. R. CONSTABLE: *Philosophical Magazine*, Vol. 26, p. 253, 1938.

which influences their sound-insulation, namely the sound-absorbent conditions of their inner surfaces.

We may in imagination follow the course of a ray of sound which falls upon one leaf of a double partition (Fig. 89). Part of the ray is transmitted into the interior of the partition, within which it will be reflected to and fro between the various surfaces. Every time the ray strikes the second leaf some of it will be transmitted out into the room on the other side. (Similarly, of course, for the first leaf; but we are not concerned with that.) This we can imagine to be the process by which sound is transmitted through the partition. Clearly the more absorbent the interior surfaces are, the more rapidly will the ray be attenuated during its to-and-fro movements and the less will ultimately emerge through the second leaf. This effect of an absorbent lining has been studied,* and a formula has been obtained which was confirmed by experiment. This formula does not seem to be appropriate to a book of this type, since it is somewhat complicated; if it is required, reference should be made to the original paper. The point of practical importance which emerges is that many double partitions have what may be termed "reverberant" interiors and that their insulation should be capable of improvement by lining their inner surfaces with sound-absorbent material. The greater the area of sound-absorbent and the higher its absorption coefficient, the greater will be the improvement. It should be remembered, however that, roughly speaking, as when using absorbent for reducing the noise level in a room (Chapter V), it is necessary to double the total absorption to produce a worth-while effect. The reader should perhaps be reminded at this stage that for the purposes of discussing the air linkage we are neglecting mechanical linkage. The insulation of a double partition with considerable mechanical linkage between the leaves would not be affected by the amount of absorbent in the interspace.

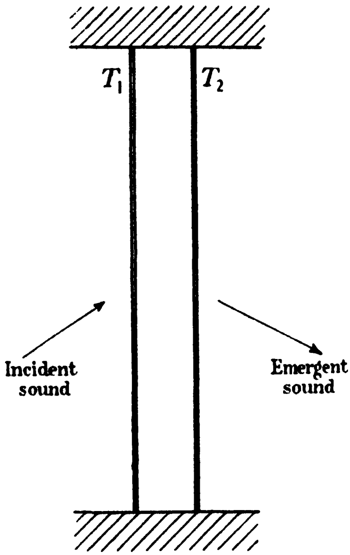


FIG. 89. RAY OF SOUND PASSING THROUGH A DOUBLE PARTITION

Measurements have been made upon a double partition* constructed of sheet iron weighing 21 oz./sq. ft., which was sealed into a brick aperture; the separation between the components was about

* J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 48, p. 690, 1936.

8 in. The effect of covering the comparatively non-absorbent brick surfaces with sound-absorbent felt (average coefficient of absorption, 0·7) was to increase the insulation of the partition by about 8 db.—a worth-while improvement. A lining of ½ in. fibreboard gave a smaller improvement, as was to be expected from its lower absorption coefficient.

It should be noted that a sound-absorbent lining is of most value in partitions which are constructed from non-absorbent materials, e.g. metal, glass, or even plywood (double partitions of which have been examined by Meyer).* It seems accordingly that little improvement is to be expected from putting sound-absorbent into a double partition which is constructed from absorbent material, e.g. fibreboard.

There has been some discussion as to the best position, acoustically, in which to install the absorbent. Meyer has argued that it should be fixed round the edges of the partition as shown in Fig. 101 in the chapter dealing with windows. This is, of course, the natural position in double windows. The evidence on this point is inconclusive, however, and no doubt the position of the absorbent will most often be determined by practical considerations.

A practice frequently adopted is that of filling the cavity in a double partition with a loose material. There does not appear to be any evidence in favour of this course, and, indeed, it seems that fillers can only provide an unwanted connexion between the two faces. Constable and Aston† have tested the effect of light fillers in double aluminium partitions and have found no effect. P. E. Sabine‡ tried fillers of various types in double masonry partitions, and concluded that they have no value beyond the fact that the resulting increase in weight led to an increase in insulation. On the other hand, hanging an absorbent blanket in the interspace between two light-weight panels (see Nos. 15, 18, 22, in Table XVI) affords an improvement in insulation, as might be expected.

Partitions Nos. 6, 8, 9, and 10 illustrate the effect of sand and other filling materials in the interior channels in a plastic sheeting partition formed of two sheets joined at 2 in. intervals with ½ in. webs. The insulation of the unfilled partition is distinctly below that predicted by the mass curve, while the fillings bring the insulation up to the "mass curve value."

Effect of Evacuating the Interspace. From time to time the suggestion is made that evacuating the interspace would get rid of the air-coupling effects. This is correct theoretically, but up to the present efforts at constructing such a partition have failed because the forces due to atmospheric pressure are so great. Constructions stiff enough

* E. Meyer: *Electrische Nachrichten-Technik*, Vol. 12, p. 393, 1935.

† J. E. R. Constable and G. H. Aston: *Philosophical Magazine*, Vol. 23, p. 161, 1937.

‡ P. E. Sabine: *Journ. Acoust. Soc. Amer.*, p. xx, January 1930, 197.

to withstand this pressure would render the partition too heavy, and thus would also tend to make mechanical linkage too great. Meyer* has tried putting a number of iron supports between two sheets of an evacuated double sheet-iron partition to overcome this difficulty, but has found only a loss in insulation.

Reduction of Air Linkage—Summary. 1. The leaves should be similar, and the separation between them should be made as large as possible. In any event the separation should be so large that the resonance caused by air coupling occurs at a low frequency. On this basis may be calculated minimum values of the separation to be used if satisfactory insulation is to be obtained at low frequencies. Representative values are given in Table XV.

TABLE XV

MINIMUM SPACING BETWEEN THE LEAVES OF DOUBLE PARTITIONS

Weight of Leaf (*lb./sq. ft.*)	*Minimum Spacing between Leaves* (inches)
1·0	6
1·3	4
2·0	2¼
3·8	1½
7·5	¾

(The above weights of leaf are those of commonly-used window glass.)

It should be emphasized that the above separations are the least which should be used. Using a greater separation should be advantageous, up to a quarter of the wavelength of the most important frequency concerned.

2. The interior of the interspace should be rendered sound-absorbent either by using sound-absorbing materials for the construction, e.g. fibreboard, or by lining the interior surfaces of the partition with absorbent. The absorbent treatment must not provide a mechanical linkage between the two leaves; for this reason fillers such as sawdust, broken clinker, slag, wool, etc., are inadvisable or, at the least, valueless.

Linkage Caused by Mechanical Coupling. The relative importance of mechanical and air coupling in a double partition depends upon circumstances, and the interplay of these two effects has not yet been studied in detail. There are, however, a number of general observations which can be made and based on these, and on certain experimental results useful methods of reducing mechanical coupling can be developed. The greatest difficulty seems to be to decide whether, in any particular case, air coupling or mechanical coupling is likely to predominate: clearly there is no point in reducing the one linkage if the other is already of overwhelming importance. Since no complete theory is available, the subject may perhaps be best discussed by means of a few examples.

* E. MEYER: *Akutische Zeits.*, Vol. 2, p. 72, 1937.

(*a*) **Double Partitions with Leaves connected only at their Edges.** The simplest example of mechanical linkage is found in a double partition the leaves of which are connected only at their edges. Such partitions can consist either of two leaves attached to a common framework, e.g. a double window or a hollow door (Fig. 90 (*a*)), or two leaves built up to a common building structure, e.g. a double masonry partition (Fig. 90 (*b*)). In the former, vibrations of the first face of the partition will cause pressure variations in the inter-space with consequent motion of the second face (air linkage), and will also cause vibration of the connecting frame with consequent

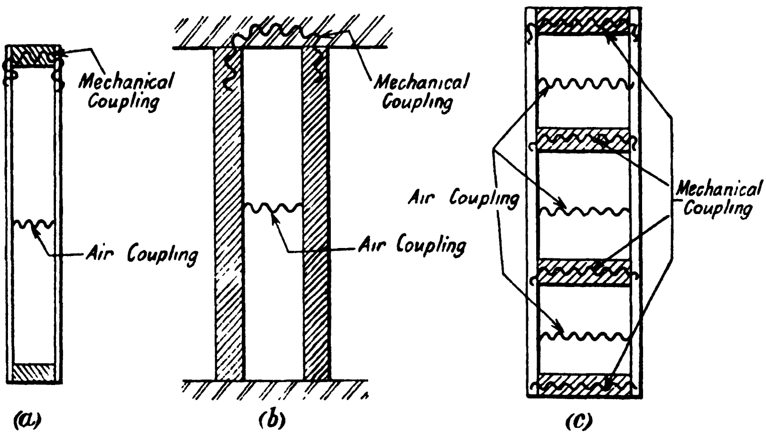


FIG. 90. MECHANICAL COUPLING IN DIFFERENT TYPES OF DOUBLE PARTITION

motion of the second face (mechanical linkage). If the frame is held firmly (e.g. attached, as in the case of a window, to a brick surround) the motion of the connecting frame will be reduced and mechanical linkage lessened. When the frame is free to vibrate (e.g. a door frame) mechanical linkage is likely to be greater. These statements are confirmed by the experimental observation that the insulation of a hollow, plywood-faced door is no better than that of an equally heavy solid door (in fact, mechanical linkage is evidently more important than air linkage in this case), whereas a double window, in which the window frames are attached to a common massive structure, can provide insulation of a high order. In the latter case, the fact that the insulation varies with the separation is evidence that air linkage predominates over mechanical linkage.

A second point can be made regarding this form of double partition, namely that the less the weight and stiffness of the leaves, the less will be the mechanical coupling. For example, if the partition consisted of two sheets of paper attached to a wood frame, one would expect the frame to be practically unaffected by the motion of the paper, and the linkage would probably be almost entirely via the air. If the leaves were heavier, e.g. of ¼ in. glass, the mechanical coupling would probably be markedly greater and might become more important than the air coupling.

In a double masonry partition (Fig. 90 (*b*)) the experimental evidence indicates that normally mechanical coupling via the edges is of overwhelming importance, presumably on account of the great weight of the partition. This is shown clearly by Nos. 33 and 36, Table XVI; in the former case the two leaves were mounted on a single wall forming one side of the gap separating the two structurally-isolated test-rooms, while in the latter the leaves were erected on opposite sides of this gap; the average insulation was thereby increased from 49 to 71 db. The vibration of the leaf upon which the sound falls causes vibration in the building structure to which the leaf is attached and consequent movement of the second leaf, which radiates sound on the other side of the partition. The predominance of mechanical coupling in masonry partitions leads to the following conclusions—

1. Varying the separation between the leaves has little effect upon the insulation.

2. There is no point in putting sound-absorbent material in the interspace: there is experimental evidence, for example, that hanging eel-grass quilt in the interspace of a double masonry partition has no value.

3. For the greatest insulation, the leaves should be insulated at the edges with a layer of elastic material so as to impede the transmission of vibration to the building structure which would otherwise connect the two leaves. That edge insulation is valuable has been shown by experiment at the National Physical Laboratory,* where the effect of insulating the edges of the leaves of a double breeze partition with a continuous layer of ½ in. compressed cork has been tested. It appears that the insulation can be increased by this treatment by 5 db. or more, and in this way a double partition of 2 in. breeze blocks, separated by 2 in., can be built to have an insulation as great as that of a 9 in. brick wall which is about three times as heavy. The construction, which appears to be quite practicable and has been used in various buildings in Great Britain, is shown in Fig. 91. An important point to notice is that the insulation must not be bridged, and for this reason the plaster must not be carried over it. A suitable finish is distemper or a covering of cloth or paper. It is of interest to note that the insulation of a *single* masonry partition is not increased, but rather the reverse, by marginal insulation of this kind. (See No. 14, Table XIV.) This observation confirms the view that the cork layer has the sole

* Ministry of Health Departmental Committee on the Construction of Flats for the Working Classes, 1937 (H.M. Stationery Office).

function of reducing the mechanical linkage between the leaves and the supporting structure.

Another way of insulating the second leaf of a double partition

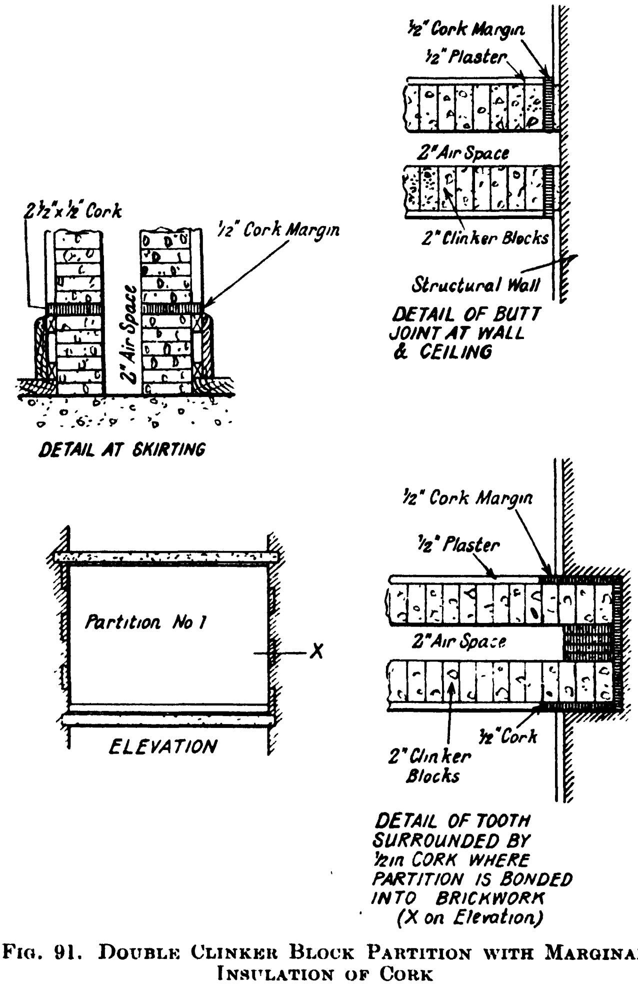


FIG. 91. DOUBLE CLINKER BLOCK PARTITION WITH MARGINAL INSULATION OF CORK

(*H.M. Stationery Office*)

was used in the National Broadcasting Company's studios, New York, and is shown in Fig. 144. A somewhat similar method of insulating the inner leaf was used in the Berlin radio studios, and has been described by von Braunmuhl.*

* H. J. V. BRAUNMUHL: *Zeits. fur Techn. Physik*, Vol. 16, p. 571, 1935.

Effect of Wall Ties in Double Masonry Partitions. This has been studied by G. H. Aston* for double partitions with no other mechanical linkage, i.e. each leaf was mounted on the opposite side of the gap separating the test rooms at the National Physical Laboratory. Hollow clay-block partitions were used, giving an insulation of 12–15 db. above the mass curve value when so mounted. Butterfly-shaped wire ties between the leaves reduce the insulation by 6–9 db. at low frequencies and practically not at all at high frequencies, while iron bar ties bring the insulation down to

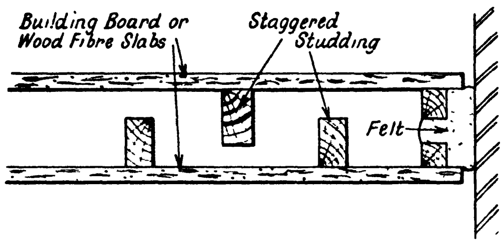


FIG. 92. METHOD OF INSULATING EDGES OF STUD PARTITION

the mass curve value, unless the bar tie tips are covered with $\frac{3}{16}$ in. rubber, in which case there is no appreciable reduction in insulation.

In the case of lighter double partitions, e.g. staggered stud partitions (which must be distinguished from stud partitions in which the studding is common to the two faces), it is possible to insulate the edges with felt. The two faces of the partitions are then wedged into a felt lining laid against the walls, floor, and ceiling between which the partition stands (Fig. 92). The important point to observe with this construction is that the felt insulation must not be short-circuited by driving nails or screws through it.

(*b*) **Partitions with Common Studding.** The type of partition shown in Fig. 90 (*a*) is usually suitable for moderate spans only; in the case of the average partition it is necessary to introduce additional supports at intervals as shown in Fig. 90 (*c*). That the mechanical coupling is only moderate in partitions consisting of plasterboard attached to wood studding has been shown by measurement at the National Physical Laboratory (partitions 25–28, Table XVI), which have shown that the average insulation provided by stud partitions is greater than that of an equally heavy solid partition.

One point must be considered here, as it is connected with the question of the relative flexibility of the facing material and of the framing which supports it. It arises in connexion with partitions,

* G. H. ASTON: *The Sound-insulation of Partitions.* Department of Scientific and Industrial Research, 1948.

TABLE XVI

Sound-insulation of Complex Partitions*

The figures in brackets give the insulation which the average solid non-porous partition of the same weight would be expected to have. The extent to which the measured insulation exceeds this figure is a measure of the extent to which the linkage between the two faces has been reduced.

Partition No.	Description of Test Partition: Construction	Weight (lb./sq. ft.)	Thickness (in.)	Mean Sound-reduction Factor (db.) for Frequencies (c.p.s.): 100 and 150	200 and 300	500, 700, and 1000	1600 and 2000	3000 and 4000	200 to 2000
	SINGLE SHEETS ON STUDDING								
1	1 in. board of foamed phenolic resin on 2 in. by 1 in. studding at 2 ft. centres	0·5†	1	7 (10)	11 (13)	17 (21)	24 (25)	25 (27)	17 (20)
2	3/8 in. plasterboard on 4 in. by 2 in. studding at 16 in. centres	1·9†	3/8	14 (15)	20 (20)	26 (26)	32 (30)	30 (35)	26 (26)
3	As No. 2, but with felt between plasterboard and studding	1·9†	3/8	11 (15)	20 (20)	26 (26)	35 (30)	33 (35)	27 (26)
4	7/8 in. T. and G. boarding on 3 in. by 2 in. studding at 19 in. centres (Boards tightly cramped)	2·8†	7/8	13 (17)	14 (22)	21 (28)	26 (32)	31 (37)	21 (28)
5	As No. 4, but with junctions of boards and other cracks sealed	2·8†	7/8	20 (17)	17 (22)	24 (28)	30 (32)	34 (37)	24 (28)
	SINGLE PANELS (*Composite construction*)								
6	Two 1/8 in. sheets of plastic material joined at 2 in. intervals by 1/8 in. webs	2·4	1	15 (16)	19 (21)	22 (27)	26 (32)	27 (36)	22 (27)
7	Paper pulp between sheets of 1/16 in. plywood	2·9	2	13 (17)	19 (22)	28 (28)	25 (33)	28 (37)	25 (28)
8	As No. 6, but with channels filled with foamed slag sand	5·2	1	21 (20)	25 (25)	35 (31)	38 (36)	39 (41)	33 (31)
9	As No. 6, but with alternate channels filled with sand	5·6	1	21 (20)	25 (26)	34 (31)	36 (37)	31 (42)	32 (31)
10	As No. 6, but with channels filled with sawdust cement	5·9	1	23 (21)	26 (26)	33 (31)	31 (37)	38 (42)	31 (32)
11	Wood wool cement between 3/16 in. asbestos cement boards (3 panels in wood frames)	7·5	1¼	21 (22)	26 (27)	30 (33)	33 (39)	37 (44)	30 (33)
12	Asbestos board between sheets of 18 G. steel (8 panels in steel frame with cover strips)	7·6‡	½	22 (22)	27 (27)	30 (33)	36 (39)	45 (44)	31 (33)
13	As No. 11 in general construction	8·3	1¾	21 (22)	27 (28)	28 (33)	31 (40)	34 (45)	28 (33)
14	As No. 6, but with channels filled with sand	8·7	1	25 (23)	28 (28)	40 (34)	46 (40)	46 (45)	38 (34)

* G. H. Aston: *The Sound Insulation of Partitions*. Department of Scientific and Industrial Research, 1948 (selection of data).

† Superficial weight of sheet (i.e. excluding frame). ‡ Superficial weight of sheet (i.e. excluding studding).

TABLE XVI—(*contd.*)

Partition No.	Description of Test Partition: Construction	Weight (lb./sq. ft.)	Thickness (in.)	Mean Sound-reduction Factor (db) for Frequencies (c.p.s.): 100 and 150	200 and 300	500, 700, and 1000	1600 and 2000	3000 and 4000	200 to 2000
	DOUBLE PARTITIONS OF LIGHT-WEIGHT PANELS								
15	Two sheets of ¼ in. plywood with two layers of glass silk blanket hung between them	2·5	4½	13 (17)	25 (21)	38 (28)	48 (32)	46 (37)	37 (27)
16	Two leaves, each of two ⅛ in. sheets of plastic material joined at 2 in. intervals by ⅛ in. continuous webs; spacing between leaves 2½ in.	4·8	4½	16 (20)	20 (25)	31 (30)	40 (36)	45 (41)	31 (30)
17	As No. 16, but with spacing between leaves 5 in.	4·8	7	19 (20)	24 (25)	33 (30)	40 (36)	45 (41)	33 (30)
18	As No. 16, but with glass silk blanket hung between leaves	5·2	4½	21 (20)	32 (25)	38 (31)	46 (36)	51 (41)	38 (31)
19	Two leaves, each of two ¼ in. asbestos boards spaced 1½ in. apart by wood frames; spacing between leaves 8 in.	6·6	12	21 (21)	34 (27)	46 (32)	58 (38)	65 (43)	46 (32)
20	As No. 19, but with spacing between leaves 2 in.	6·6	6	15 (21)	30 (27)	45 (32)	57 (38)	62 (43)	44 (32)
21	As No. 19, but with strips of ¼ in. fibre board between asbestos board and frame on outer sides; fixing nails passing through fibre board	7·4	12½	24 (22)	38 (27)	48 (33)	62 (39)	66 (44)	49 (33)
22	As No. 21, but with glass silk blanket between the asbestos boards in each leaf	8·0	12½	27 (22)	43 (28)	52 (33)	62 (40)	66 (45)	52 (33)
23	As No. 22, but with spacing between leaves 2 in.	8·0	6½	21 (22)	41 (28)	51 (33)	61 (40)	65 (45)	51 (33)
24	As No. 18, but with channels of both leaves filled with sand	17·8	4½	36 (26)	48 (32)	58 (37)	65 (47)	70 (51)	57 (38)
	STUD PARTITIONS								
25	¼ in. plywood on both sides of 2½ in. by 1½ in. wood studs at 14 in. centres; 2 layers of glass quilt in interspace	3·3	3	13 (18)	16 (23)	36 (29)	42 (33)	39 (38)	32 (29)
	Partitions No. 26 to 32 on 4 in. by 2 in. wood studs at 16 in. centres								
26	⅜ in. plasterboard on both sides of studs	5·1*	4¾	13 (20)	27 (25)	35 (31)	44 (36)	42 (36)	35 (31)
27	⅜ in. plasterboard on both sides of studs, felt between board and studs; fixing nails passing through board and felt	5·1*	5¼	11 (20)	27 (25)	36 (31)	49 (36)	49 (36)	37 (31)
28	⅜ in. plasterboard (baseboard) on both sides of studs; both faces plastered to thickness of ½ in.	12·5*	5¾	24 (24)	28 (30)	41 (35)	42 (43)	53 (48)	38 (36)
29	⅜ in. plaster lath on both sides of studs, nails fitted with expanded metal lath pads round their heads and driven into studs between edges of laths; both faces plastered to thickness of ½ in.	15*	5¾	23 (25)	32 (31)	45 (36)	47 (45)	59 (50)	42 (37)
30	As No. 29, but with felt between laths and studs; nails passing between edges of laths and through felt	15*	6¼	23 (25)	34 (31)	49 (36)	59 (45)	60 (50)	47 (37)
31	Three-coat plaster on metal lath on both sides of studs	12·5*	5	29 (24)	29 (30)	38 (35)	38 (43)	51 (48)	35 (36)
32	Three-coat plaster on wood laths on both sides of studs	15·5*	5⅝	27 (25)	26 (31)	38 (37)	42 (45)	57 (50)	35 (37)

* Including superficial weight of studding, 1·3 lb./sq. ft. averaged over whole area. The variations in weight of partitions Nos. 28–32 are mainly du to unintentional variations in the thickness of plastering.

TABLE XVI—(*contd.*)

Partition No.	Description of Test Partition: Construction	Weight (lb./sq. ft.)	Thickness (in.)	Mean Sound-reduction Factor (db.) for Frequencies (c.p.s.): 100 and 150	200 and 300	500, 700, and 1000	1600 and 2000	3000 and 4000	200 to 2000
	DOUBLE BLOCK PARTITIONS								
33	Two leaves, each of 2 in. clinker concrete slabs plastered on outer faces to thickness of ½ in.; spacing between leaves 2 in.	33	7	39*	45 (35)	46 (42)	56 (53)	65†	49 (43)
34	As No. 33, but with ½ in. cork insulation around edges of each leaf (no plaster on cork)	33	7	40*	48 (35)	52 (42)	64 (53)	76†	54 (43)
35	As No. 34, but with plaster over cork	33	7	44*	46 (35)	44 (42)	58 (53)	75†	48 (43)
36	Two leaves, each of 2 in. clinker concrete slabs, separated by 14 in. cavity and built on opposite sides of gap separating rooms, outer faces plastered to thickness of ½ in.	33	19	66*	68 (35)	67 (42)	82 (53)	98†	71 (43)
37	Two leaves, each of 3 in. clinker concrete slabs, plastered on outer faces to thickness of ½ in.; spacing between 2 in.	40	9	40*	44 (36)	49 (43)	60 (56)	69†	51 (44)
	TRIPLE BLOCK PARTITIONS								
38	Three leaves, each of 2 in. clinker concrete slabs, plastered on outer faces and on one face of middle leaf; spacing between adjacent leaves 2 in.	50	11½	44*	45 (37)	46 (44)	57 (58)	69†	49 (46)
	BOARDS ON BATTENS ON BRICKWORK								
39	⅜ in. plasterboard on 1 in. by 2 in. battens at 16 in. centres on one side of 4½ in. brick plastered on both faces to thickness of ½ in.	55	7	29*	34 (38)	47 (45)	57 (60)	58†	46 (46)
40	As No. 39, but with plasterboard plastered to thickness of ½ in.	60	7½	30*	32 (38)	48 (46)	57 (61)	60†	46 (47)
41	½ in. fibre board on 1 in. by 2 in. battens at 16 in. centres on one side of 4½ in. brick plastered on both faces to thickness of ½ in.	54	7	30*	32 (38)	47 (45)	58 (59)	66†	46 (46)
42	As No. 41, but with fibreboard plastered to thickness of ½ in.	59	7½	28*	35 (38)	48 (46)	60 (60)	66†	48 (47)
43	⅜ in. plasterboard on 1½ in. by 2 in. battens at 17 in. centres, held in clips incorporating asbestos insulation, on one side of 9 in. brick plastered on both faces to thickness of ½ in.	97	12½	49*	44 (41)	54 (49)	70 (66)	72†	56 (51)

* For 100 c.p.s. only. † For 4000 c.p.s. only.

and also windows. A partition constructed as shown in Fig. 93 and consisting of a single sheet of building-board attached to studding is occasionally used where the finish on one side is of no importance. It might be expected that the studding would restrict the motion of the facing material and thus increase its insulation. Actually, however, measurements (partitions 1–5, Table XVI) show that, at least when the facing material is building-board, the insulation of the partition is no greater than would be provided if the studding were omitted. That is to say that the fibreboard vibrates somewhat as shown in Fig. 93 (*b*), the studding remaining relatively stationary. This observation, incidentally, confirms the statements made earlier regarding the small mechanical linkage caused by studding used under these conditions. A similar observation has been made in the case of metal-framed windows, in which it appears that the weight and stiffness of the glazing bars do not add to the insulating power of the glazing.

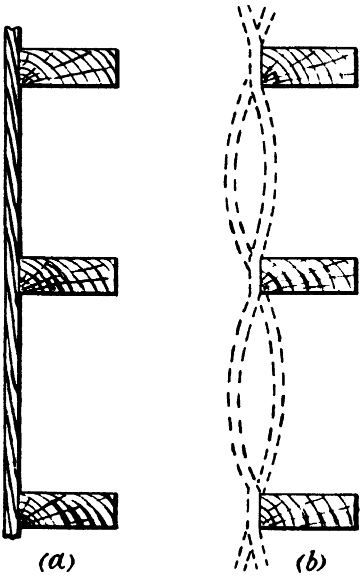


FIG. 93. SHOWING THAT THE INSULATION OF A SINGLE SHEET OF THIN MATERIAL IS NOT INCREASED BY ATTACHING IT TO HEAVY STUDDING

It should be pointed out that stud partitions with light facing materials have the usual defect of light double partitions, namely that the insulation they provide at low frequencies is usually low (see Nos. 26 and 27). As shown by the results obtained with partitions 28–32 (Table XVI), however, heavy stud partitions can be satisfactory in this respect. The lighter constructions are useful where high-pitched sound, e.g. typing noise, is to be insulated cheaply.

(*c*) **Insulating Treatment Supported on Battens.** Another common type of complex partition in which mechanical coupling is important consists of a masonry partition faced on one or both sides with a layer of light material supported on battens attached to the wall. The partition is sketched in Fig 94 (*a*). The light facing usually consists of wallboard, and can be plastered. In practice it is found that only small improvements result from this treatment unless the battens are insulated from the wall as shown in Fig. 94 (*b*). The insulation afforded by a 9 in. wall can be increased by 5 db. by applying this treatment to one face only (partition 43, Table XVI);

the treatment probably finds its greatest value as a method of improving the insulation of already existing walls, particularly light ones. No doubt the architect can devise methods of insulating the battens to suit his particular needs; one satisfactory method is to use insulated floor clips for this purpose (Fig. 121).

Incidentally, measurements have shown that attaching building-board directly to the face of a masonry partition does not increase the insulation.

(*d*) **Multiple Partitions.** The chapter must not be concluded without a reference to multiple partitions, i.e. partitions constructed with

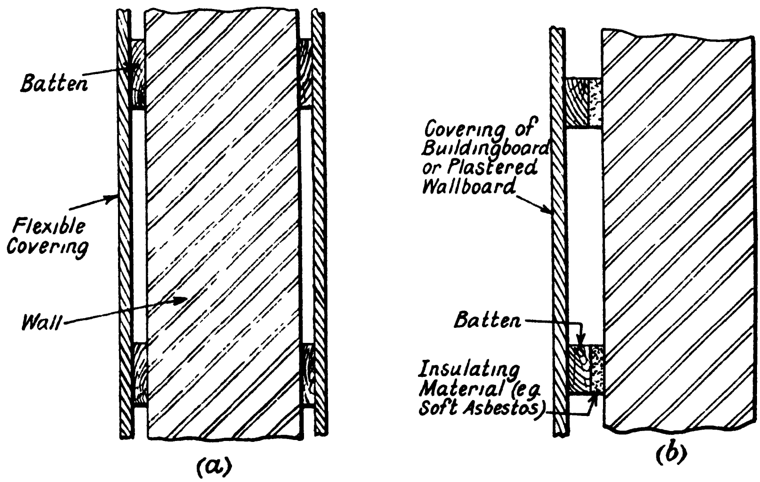


FIG. 94. INSULATING TREATMENT ATTACHED TO A WALL BY BATTENS

more than two leaves. These are not yet very common, probably the sole example being the treble windows sometimes used for sound-insulation. This type of partition probably has a future, however, but can only be used advantageously provided the mechanical coupling between the leaves can be controlled, since obviously, if sound can pass by mechanical coupling easily between the first and the last leaves, the intermediate leaves will not contribute to the insulation. This is conspicuously shown in No. 38, Table XVI, in which the average insulation of three leaves of clinker concrete is only 3 db. above the mass curve value, where all three leaves are mounted on one continuous structure. Taking into account only the air coupling a multiple partition can be regarded as a series of weights connected by springs. Such a system constitutes what is known as a *low-pass filter*, i.e. a system which will transmit sound having a frequency below a certain limit but attenuates considerably frequencies above this limit. The magnitude of this limit depends upon the relative weights and stiffnesses. It is given approximately by the formula—

$$\text{Limiting frequency} = 280/\sqrt{(md)}$$

where d is the spacing between neighbouring components in inches and m is the mass of each leaf in pounds per square foot. Such

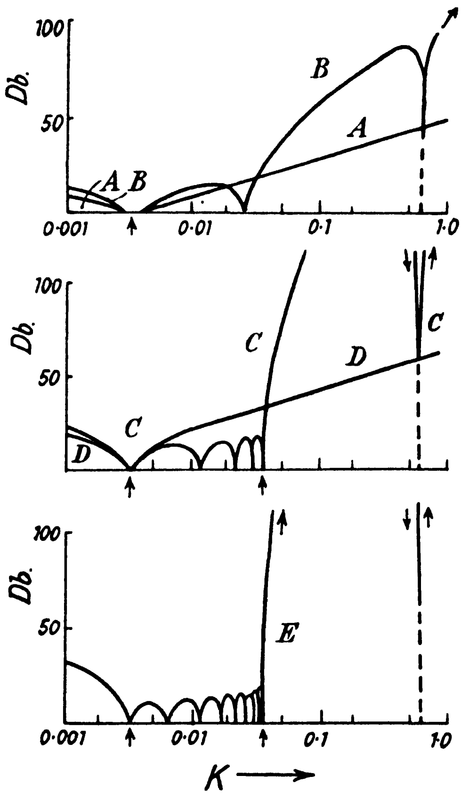


FIG. 95. SOUND-INSULATION OF MULTIPLE PARTITIONS OF GLASS

The figures show the calculated reductions in intensity levels (measured in decibels) due to various numbers of partitions, plotted against a logarithmic scale of $K = (2\pi/c) \times$ frequency in cycles per second. The standard partition (A) is taken as glass, having a mass per unit area 1·4 lb./sq. ft. and natural frequency 18·3 c.p.s. The spacing between the partitions is 2 inches.

The curves are: A, one partition; B, two partitions; C, five partitions; D, one partition having a mass per unit area five times that of partition A, and a natural frequency of 18·3 c.p.s.; E, 10 partitions.

partitions transmit low-pitched sound readily (this corresponds to the resonance effect discussed in connexion with double partitions), but there is a sharp rise in the insulation to a very much greater value as the limiting frequency is exceeded.

Curves based upon calculation* of the insulation to be obtained from two, five, and ten sheets of 21 oz. glass are shown in Fig. 95, which illustrates the low-pass filter effect very well. Meyer, who has made measurements upon plywood multiple partitions,† has

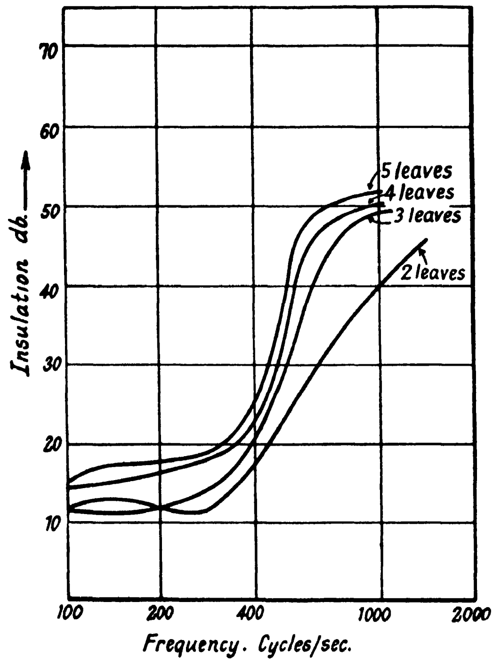


FIG. 96. SOUND-INSULATION OF MULTIPLE PARTITIONS OF PLYWOOD

Curves 2, 3, 4 and 5 show the insulation at various frequencies of multiple partitions composed of 2, 3, 4 and 5 sheets of plywood respectively.

been able to observe these effects provided there was a sound-absorbent lining round the edges to destroy wave motion parallel with the leaves. Some of his results are shown in Fig. 96.

It is possible that such partitions would find a use where a very light partition was required to insulate against a noise which contained little low-frequency sound.

* D. HURST: *Canadian Journ. Res.*, Vol. 12, p. 398, 1935.

† E. MEYER: *Elektrische Nachrichten-Technik*, Vol. 12, p. 393, 1935.

CHAPTER XI

SOUND-INSULATING WINDOWS

GLASS, as a structural material, is coming more and more into use, both in this country and abroad. Not only are windows used as a means of admitting light and air, but they also play an increasingly important part in modern exterior design. Indeed, in factories, department stores, and hospitals, it is not unusual to find that a large part of the exterior surface consists of glass. The vogue for glass is not confined to the outside of buildings: glass interior partitions in offices, factories, and schools are in common use. This use of glass brings problems of heat- and sound-insulation, but it fortunately happens that these go hand in hand, the soundproof window constructions described later affording also considerable heat-insulation. There are many situations where heat-insulation is desirable, but sound-insulation is imperative.

There are other positions, not perhaps quite so obvious as the city hotel, where soundproofing is practically a necessity. Interior partitions in offices, schools, and in certain cases in factories should be "soundproof," i.e. their sound-insulation should be sufficient to render the transmitted noise inaudible against the average noise level due to activities in the room where quiet is required. An even more stringent specification than this is needed in the case of windows in radio studios, gramophone recording and audition rooms, and so on.

Although not actually an architectural problem, the exclusion of noise from railway carriages, particularly in underground railways, has received attention and the importance of providing soundproof windows in the rolling stock may be pointed out.

The average window with single glazing, even if shut, does not afford satisfactory sound-insulation if "excessive noise" is present or if "absolute quiet" is required, as can easily be verified by actual observation. To give a few figures: 30 db. represents the average sound-reduction of a well-constructed single window glazed with ¼ in. glass and having a reasonably tight closure (this figure can be seriously reduced by gaps between windows and frame, of which more later), a figure which may be contrasted with that of the average 9 in. wall, which will usually have an insulation of about 52 db. Thus the low sound-insulation of windows is the overriding factor influencing the sound-insulating value of a building, a point discussed more fully in Chapter XV.

Such experiments as have been made indicate that it is probably not possible to produce a singly glazed opening window of insulation (when shut) greater than 30 db., presumably since any improvement in the insulation provided by the glazing is masked by the sound transmitted through the gaps round the edge of the frame. This transmission is one of the reasons for double glazing in a common frame being unsuccessful for sound-insulation purposes. By using a double window with the glazing in separate frames, not only is the insulation increased but the loss due to the gaps is decreased, since there are now two to be traversed.

The value of double windows in sound-insulation as well as in heat-insulation has been known for some time, but the principles underlying their action have not been fully understood until recently. Calculation, amply confirmed by experiment, has shown that, neglecting for the moment the effect of gaps, two sheets of window glass separated by an air layer can by suitable design afford an average insulation of the order of 50 db. Not many walls possess an average insulation greater than this, so that a double window can, on the whole, be adequate to its task. Double windows are actually being used with success in several large London buildings, and at least two manufacturers market standard double windows in this country. On the Continent and in America double windows are more often used than in England—largely, however, because of their heat-insulating properties.

In the following pages the various factors which affect the sound-insulation of windows are discussed. These are, for single windows: (*a*) weight of glazing, (*b*) closure, and (*c*) effect of opening. For double windows the various factors are: (*a*) the separation between the components, (*b*) the weight of the glazing, (*c*) the sound-absorbent character of the space between the components, (*d*) the mechanical linkage between the components arising from their fixing at the edges, (*e*) the closure, and (*f*) the angle of opening.

I. SINGLE WINDOWS

(*a*) **Effect of Weight of Glazing.** As with all single partitions, the sound-insulation of a single window increases with the weight of the glazing. It is therefore preferable to use heavy glass ¼ in. or ⅜ in. thick in noisy situations where single windows are installed. For reference purposes, the sound-insulation to be expected from different weights of glass is given in Table XVII.

The possibility of affecting the sound-insulation of a single window by subdividing the panes with glazing bars has been investigated by P. E. Sabine, and his measurements do, in fact, show a small improvement (2 db.) as the result of quartering a ¼ in. glass window. It is probable, however, that this was of the order of the experimental error, and in any case the improvement recorded is too small to be of practical importance.

Other measurements made upon a window having dimensions of approximately 5 ft. by 4 ft., subdivided to consist of two opening frames and one fixed frame, showed that its sound-reduction factor

TABLE XVII

SOUND-INSULATION OF SINGLE WINDOWS WITH GLASS OF DIFFERENT WEIGHT

Thickness of Glass (in.)	Weight (lb./sq. ft.)	Average Sound-reduction for Frequencies (cycles per second)			
		200 and 300	500, 700, and 1,000	1,600 and 2,000	200, 300, 500, 700, 1,000, 1,600, and 2,000
		db.	db.	db.	db.
0·1	1·3 (21 oz.)	19	25	35	26
0·12	1·6 (26 oz.)	21	26	36	27
0·25	3·8	28	32	40	32
0·5	7·6	33	36	44	37

was that corresponding to the weight of the glazing (3½ lb./sq. ft.). The complete window had a heavy metal frame, so that the average weight was more than four times the weight of the glazing. It can be concluded that a heavy frame affords no advantage on account of its weight.

(*b*) **The Effect of Closure.** The closure of any window is a matter of importance. Manufacturers are fully alive to the need for keeping in heat and excluding draughts, but the importance of tight closure for sound-insulation is not always realized. Considering for the moment only single windows, it is not unusual to find, e.g. between the two sashes of a sash window, a gap which may appreciably impair the insulation. It may be shown by simple calculation that, say, a 40 in. by ¼ in. gap may be expected to reduce the insulation of a window of area 50 in. by 40 in. and glazed with 21 oz. glass by at least 5 db. The method of calculation is given in Chapter XV.

The important effect of gaps justifies a little closer consideration being paid to their sound-transmitting properties. Wintergerst and Knecht* are of the few who have made an experimental study of this point. Some of their results are given graphically in Fig. 97, in which the variation of a factor q equal to

$$\frac{\text{effective area of aperture}}{\text{actual area}}$$

with frequency of the test sound is plotted. The results apply for circular apertures in a material of thickness 0·04 in. having diameters between roughly 0·1 and 0·5 in. Similar results were obtained for slits, except that the values of q were even greater than those shown

* *Zeits. Verein Deut. Ing.*, Vol. 76, p. 777, 1932.

for circular apertures. The results show that, particularly at low frequencies, apertures transmit far more sound than would be expected from their area: they "draw" sound energy into themselves, in fact. At 100 c.p.s., for instance, a $\frac{1}{16}$ in. hole behaves as

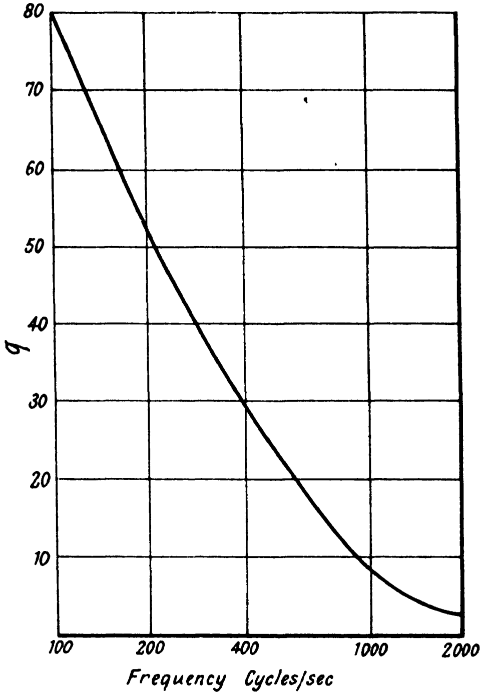


FIG. 97. EFFECTIVE AREA OF CIRCULAR APERTURES AT DIFFERENT FREQUENCIES

Actual diameters were 0·12 in. to 0 48 in.

$\left(q = \frac{\text{Effective area}}{\text{Actual area}}\right)$

if it were about 1 in. in diameter. It is not until quite high frequencies are used that the sound transmitted through a hole becomes of the same order as that calculated from its area. This is attributed to diffraction effects, which were discussed in Chapter I.

These experiments, being made with holes in comparatively thin sheets, are not directly applicable to our present problem. The gaps which occur in ordinary window construction are deeper, and hence are likely to transmit less sound than holes in thin sheets. It is to be presumed, however, that similar effects will occur. Measurements made at the National Physical Laboratory have shown that in the case of even a good-quality metal-framed casement window, glazed with ¼ in. glass, the loss due to transmission through the gap was about 5 db.

Clearly the ideal at which to aim is an airtight seal. This could be obtained by using a soft lining such as chamois leather, felt, or soft rubber on the rebates of the window frame and fitting latches

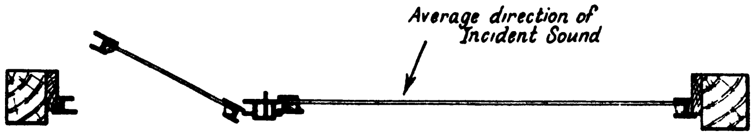


FIG. 98. WINDOW TESTED FOR SOUND-INSULATION WITH ONE SECTION OPEN

with a wedge action. If lining is not practicable, the gaps should have the greatest possible depth, as well as being as narrow as possible.

(c) **The Effect of Opening.** In view of the above, it is surprising to find that opening a section of a window does not necessarily entirely destroy the insulating effect of the window. This has

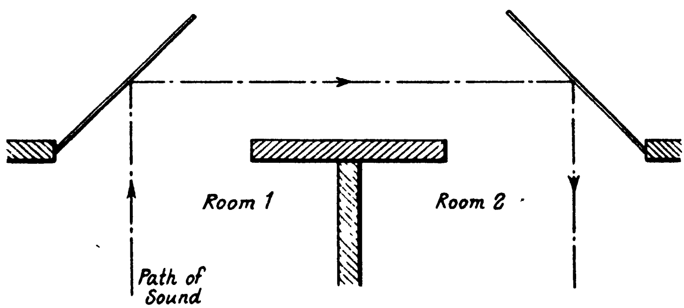


FIG. 99. SOUND REFLECTED FROM ROOM TO ROOM BY OPEN WINDOWS

been shown by measurements at the National Physical Laboratory, in which the average sound-reduction factor of the window shown in Fig. 98 was found to be 16 db. with a section open as shown, as compared with 28 db. when the window was closed. The amount of sound transmitted into a room where a window is open depends upon a number of factors, e.g. the direction from which the sound is coming, the area of the opening section, the extent to which the window is opened, and the absorbent condition of the wall surfaces upon which the sound falls. No comprehensive experiments appear to have been made to examine these points, but some remarks of a general nature may be made.

Firstly, windows opening about a vertical axis form excellent sound reflectors, and when installing them in a building their direction of opening should be arranged so that it is not possible for sound to be reflected from room to room via the opening windows as shown in Fig. 99.

As regards ventilating flaps, it should be remembered that the majority of street noises come from below and can be reflected into the room by the flap as shown in Fig. 100 (*a*). To reduce this reflection, absorbent material may be applied as shown in Fig. 100 (*b*).

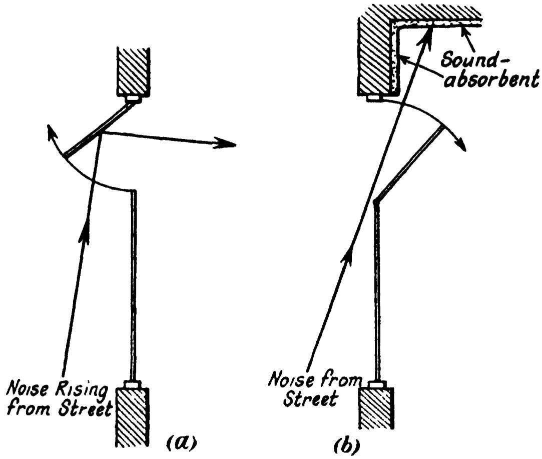


FIG. 100. SOUND FROM BUSY STREET REFLECTED INTO ROOM BY OPEN WINDOWS

(*a*) Sound rising from the street is reflected into the room by the top-hung ventilating flap.
(*b*) The bottom-hung ventilating flap reflects little sound into the room. The ceiling and soffits near the window are treated with absorbent.

The principle underlying this design is that sound coming from below strikes against the absorbent material before reaching the occupants of the room. There are no figures available for the effectiveness of this design.

II. DOUBLE WINDOWS

(*a*) **The Value of Spacing between the Components of a Double Window.** The value of the spacing between the components of a double partition has already been discussed in Chapter X. It will be recalled that it was shown that the sound-insulation obtainable from a double partition of which the leaves are comparatively light depends to a marked extent upon the spacing between the components. For each frequency there is a critical spacing at which a resonance occurs arising from the stiffness of the air between the components. At this resonance the sound-insulation is a minimum.

Increasing the spacing beyond this point increases the insulation again. The practical rule is therefore to make the separation sufficiently large, so that the resonance occurs at a low frequency. An approximate formula which can be used for this purpose is given in Chapter X, but for convenience it is repeated here. It is that a resonance will occur if—

$$d = \frac{60{,}000}{n^2 w} \text{ in.}$$

where w = weight of each component in pounds per square foot,
n = frequency in cycles per second,
d = separation between components in inches.

On this basis may be calculated minimum values of the separation to be used if satisfactory insulation is to be obtained at low frequencies. Representative values are given in Table XV.

(*b*) **The Effect of the Weight of the Glass used in a Double Window.** The weight of the glass used in a double window has two effects: (*a*) upon the frequency of the resonance due to air coupling, and (*b*) upon overall insulation of the window. With regard to the former, the formula given above shows that increasing the weight of the glass decreases the spacing at which the resonance at any particular frequency occurs. Thus if ¼ in. glass weighing about 3·8 lb./sq. ft. is used, the window may be expected to resonate to 100 c.p.s. when the separation is about 1½ in. This compares with the 4 in. spacing which would obtain were 21 oz. glass used. It follows that if space is limited, heavy glass is valuable in that it enables good low-frequency insulation to be achieved with a moderate separation between the components. As regards the effect of the weight upon the overall insulation of the window, it will be recalled that in the case of a single partition increase of weight increases its insulation. The same holds in a general way with a double partition, except that the effect is complicated by the resonance discussed above. However, as was shown when discussing partitions in Chapter X, increasing the weight of the components will increase the average insulation of a double partition, other factors remaining the same. (See items 1 and 2, Table XVIII.)

While dealing with the effect of weight, another question has to be discussed, viz. whether there is any advantage in glazing the components with glass of different weight. This recommendation has often been made and has some theoretical backing, for equal areas of glass having the same thickness will individually have equal resonance frequencies. (The resonances referred to are those of each sheet by itself, not those arising from the air coupling.). Hence, if sound of a frequency equal to one of these resonances falls upon one component of the window it would be expected to be readily transmitted by both components. By using glass of differing weights this

TABLE XVIII

SOUND-INSULATION OF DOUBLE WINDOWS

Construction of Window	Weight (lb./sq. ft.)	Average Sound-reduction for Frequencies (cycles per second)			
		200 and 300	500, 700, and 1,000	1,600 and 2,000	200, 300 500, 700, 1,000, 1,600 and 2,000
1. Double window consisting of two sheets of 21 oz. glass sealed into aperture in brick wall. All gaps sealed. Separation between sheets as follows—					
8 in.	26	40	52	66	53
7 in. . . .		36	47	62	48
6 in.		36	50	67	51
5 in.		35	49	64	49
3 in. . .		28	52	64	49
2 in. . .		23	49	64	46
1 in. .		20	42	65	42
¾ in. . . .		18	41	64	41
½ in. . . .		22	36	56	38
¼ in. . .		23	32	52	35
⅛ in.		24	27	50	33
2. Double window consisting of two sheets of ¼ in. glass sealed into aperture in brick wall. All gaps sealed. Separation between sheets, 5¾ in.		43	57	70	56
3. Double window consisting of two metal frames attached to a common wood frame and containing opening hinged windows. Separation between frames, 6¾ in.; one glazed with ¼ in. glass and the other with 26 oz. glass. Opening windows closed but not sealed. Interior surfaces of window lined with absorbent tiles . .	21	42	47	62	50

effect could be avoided. The point has been tested by Krueger and Sager, who also tested the effect of subdividing one of the components and found that while alterations in spacing have a considerable effect no significant effect is observable from either method of rendering the components dissimilar.

It must be concluded that there is no practical point in using dissimilar glazing, at least for the separations which Kreuger used. A possible explanation lies in the fact that as shown by one of the authors,* the resonances of a glass sheet are very sharp. For, since no two sheets can be exactly alike, their resonance frequencies will not be exactly the same; hence, owing to their sharpness, they may not overlap sufficiently to have an appreciable effect. A general theory of sound-transmission through double partitions (including, of course, double windows) has been worked out† and is briefly summarized in Chapter X.

* J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 48, p. 914, 1936.

† J. E. R. CONSTABLE: *Philosophical Magazine*, Vol. 26, p. 253, 1938.

(*c*) **The Effect of the Sound-absorbent Character of the Wall Space between the Components of a Double Window.** The effect of the sound-absorbent character of the space between the two components of a double partition was discussed in Chapter X, and it will be recalled that the results were quoted there of experiments made with a light double metal partition having leaves weighing about 21 oz./sq. ft. This partition should be very approximately the same as one constructed from two sheets of 21 oz. glass, owing to the workings of the mass relation, and also to the fact that glass and metal are so alike in being good reflectors of sound. The results obtained should, in fact, be equally applicable to double windows.

Double windows are often constructed with bare brick or plaster on the walls between the two components. The results quoted above

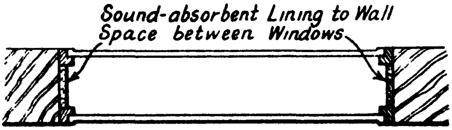


FIG. 101. INCREASING THE SOUND-INSULATION OF DOUBLE WINDOWS BY SOUND-ABSORBENT TREATMENT

show that the sound-insulation of such windows can be considerably increased by the simple expedient of covering the jambs, cill, and lintel between the components with a sound-absorbent material. (See Fig. 101.) The effect increases with the absorbing power of the material used. In the case of the double partition referred to above the distance between the components was about 8 in., and an increase in the average insulation of about 8 db. was obtained by covering the masonry surfaces with an absorbent felt having an average absorption coefficient of 0·6. It will be agreed that for the expense involved such an improvement is well worth having. The treatment can present quite a good appearance if the felt is covered with distempered muslin which is afterwards pinpricked. The felt could also be covered with perforated metal or asbestos cement sheeting instead of muslin. If a perfectly hygienic and fairly weatherproof surface is required for the absorbent used in this position, a panel-type absorbent might be used. (See Chapter V.) Another absorbent possessing several obvious advantages is curtain material. If provision is made for hanging curtains between the components of a double window, the curtains when drawn back (preferably into recesses in the jambs to avoid obstruction of light) will provide a useful amount of absorption without the expense of special absorbent lining.

(*d*) **The Effect of Mechanical Linkage between the Components of a Double Window.** A question that is often asked is whether it is necessary to have the two components of a double window in separate frames. Many windows, intended to be soundproof, have double glazing in the same frame. An answer to this question is supplied in part by the fact that, as explained earlier, a considerable separation is required between the components, and this would be impracticable in a single frame. A further consideration arises from the effect of gaps around the edges of a casement window, as discussed in the next section.

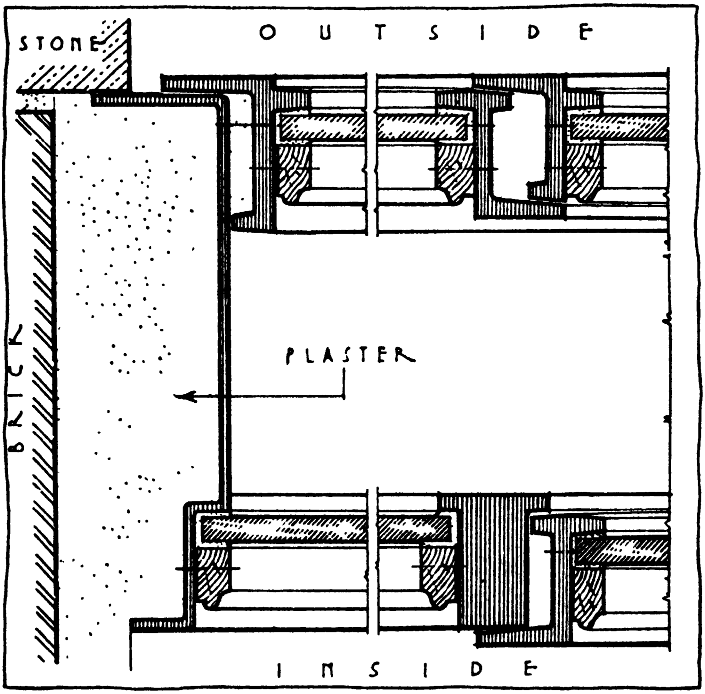


Fig. 102. Section of Double Window Consisting of Two Components in Separate Frames
(*Vitrea Drawn Sheet Glass Co. Ltd.*)

The point has been tested by both Kreuger and P. E. Sabine.* Kreuger measured the sound-insulation of a quartered window glazed with double panes of $\frac{1}{8}$ in. glass, the separation between the panes being $\frac{3}{8}$ in. For comparison he measured the insulation of a window glazed with a single sheet of $\frac{1}{4}$ in. glass. P. E. Sabine compared the insulation of a window glazed with a single sheet of $\frac{3}{16}$ in. glass with that of a similar window double glazed with the same thickness glass. The latter was 2 db. better than the former, a difference which can be accounted for by the increase in weight. In both cases the insulation should have been noticeably better than a single

* P. E. Sabine: *American Architect*, 28th July, 1920.

sheet if only air coupling were operating. (See Fig. 90.) It must be concluded that mechanical coupling is in these cases of overwhelming importance: this point is discussed in Chapter X.

It must be deduced that double glazing in the same frame is of no value. The explanation is that the weight and stiffness of the average window frame are comparable to that of its glazing. Hence when the glass vibrates under the influence of the incident sound, the frame moves with it and so drives the second sheet of glass. The two sheets are, in fact, subjected to strong mechanical coupling at their edges.

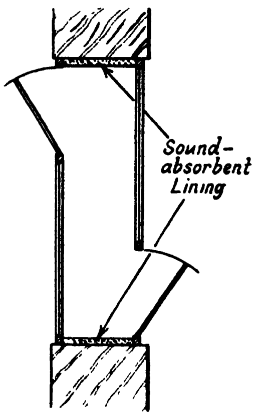


FIG. 103. DOUBLE WINDOW DESIGNED TO PROVIDE SOUND-INSULATION TOGETHER WITH VENTILATION

When a double window consists of two separate frames fixed in an aperture in a brick wall, the weight and stiffness of the wall are very much greater than that of the glass. The glass does not drive the wall to an appreciable extent, and there is consequently little mechanical linkage between the edges of the windows. This is proved by the experiments, quoted earlier,* in which the effect of spacing was tested. If there had been a considerable coupling due to the brick wall in which the specimens were mounted, the effect of spacing would have been masked.

It thus comes about that a double window consisting of two components in separate frames can have an insulation comparable to

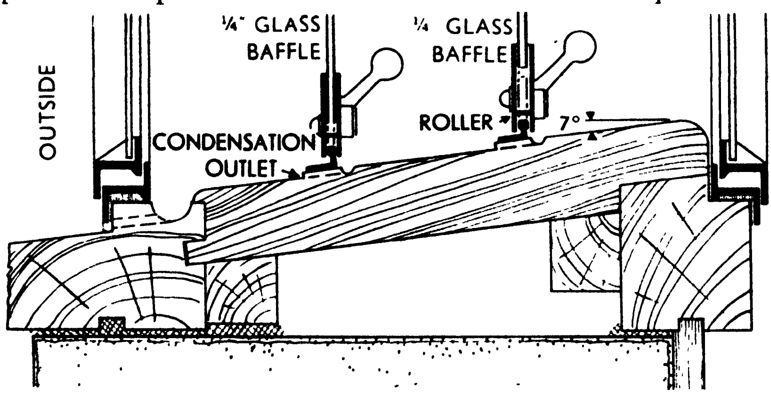


FIG. 104. A MORE ELABORATE DESIGN OF SOUND-INSULATING WINDOW

The window has two steel-frame casements and two sliding sheets of plate glass. (*Crittall Manufacturing Co. Ltd.*)

* J. E. R. CONSTABLE: *Philosophical Magazine*, Vol. 18, p. 321, 1934.

that of the wall in which it is built. A section through a window built on these lines and taken from Dr. Hepburn's book *Glass as a Structural Material* is shown in Fig. 102.

(*e*) **The Effect of Closure.** The effect of closure has already been

FIG. 105. A MORE ELABORATE DESIGN OF SOUND-INSULATING WINDOW

This shows the general appearance of the window illustrated in Fig. 104.

(*Crittall Manufacturing Co. Ltd.*)

discussed when dealing with single windows. It has a special significance in connexion with double windows, since these have greater insulation and hence are more sensitive to a leakage round the edges. The possibility of a defective closure is an additional argument against double glazing in the same frame, since if this is adopted there will be only one gap for sound to leak through. If the glazing is in separate frames, sound must pass through two gaps one after the other. The overall leakage via the gaps is then much less (particularly if the wall surface between the frames is rendered sound-absorbent), and the glazing is then being used efficiently. Reiher and Sippell* have in fact shown that while a double window, using separate frames, is rendered less insulating by poor closure, it is still a better insulator than a single window, even if the latter is tightly closed. For the greatest insulation, however, an airtight closure is required: in the case of opening windows this could be achieved by lining the rebates. If the windows are to be permanently closed, or, rather, will not be required to be opened for ventilation, an airtight construction is comparatively easily obtained. It is as well to arrange that the windows can be occasionally opened so that the inside surfaces may be cleaned, for no closure will be so perfectly airtight that "breathing" will not occur. Occasional opening can easily be allowed for, for instance by fitting the glass into frames which bed on to a rebate faced with felt or sponge rubber, the frames being held in place by removable screws. Windows inside buildings in which an efficient air-filtering plant is in constant operation would presumably not accumulate so much dirt on their inner faces, and it might be possible to dispense with facilities for opening, particularly if the double window is provided with a small breather fitted with an air filter, as was done in the National Broadcasting Company's studios in New York.

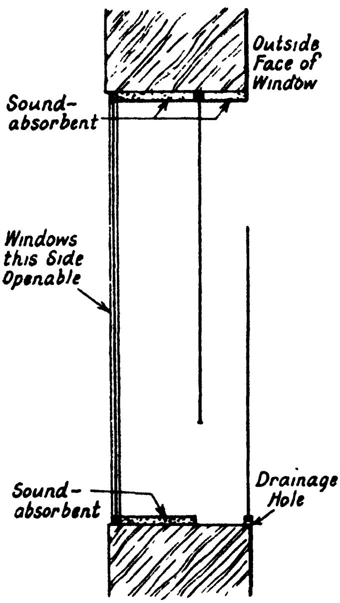


FIG. 106. ANOTHER DESIGN OF SOUND-INSULATING WINDOW

(*f*) **The Effect of Opening.** This point, again, has already been discussed when dealing with single windows. It may be mentioned that the remarks regarding direction of opening have been taken account of in a double window tested by the National Physical Laboratory. This is shown in section in Fig. 103. Such a construction provides quite good insulation, together with some ventilation. Test results show that when the windows are open as shown the insulation obtainable is about 25 db. on the average, i.e. about the equivalent of a tightly closed single window. A development of this design is shown in Figs. 104 and 105. Yet another type is shown in Fig. 106.

(*g*) **Provision of Ventilation.** If only one or two rooms in a building are to be soundproofed, and if the degree of soundproofing necessitates the installation of double windows which are to remain

* H. REIHER: *Gesundheitsingenieur*, Vol. 2, p. 12, 1932; K. T. SIPPELL: *ibid.*, 55/45, p. 535, 1932.

permanently closed, the expense of installing a central internal ventilating system to provide the necessary ventilation for these rooms only may well be deemed prohibitive. Individual or unit ventilation for these rooms then deserves consideration. (See Chapter VIII.) One proprietary unit ventilator equipped with an air filter is shown in Fig. 81. No figures are available for the sound-insulating effect of this construction, but it will be noted that some attention has been paid to this point.

CHAPTER XII

SOUND-INSULATING DOORS

THIS chapter is mainly concerned with the prevention of sound-transmission through doors, but a section devoted to means of reducing the noise made by doors themselves in opening and closing is also included.

The noise made by door-slamming is one of the most disturbing which occur in buildings. Quiet-operating doors are specially important in residential buildings, but are also much appreciated in business premises. The remarks made below are based upon common observation and the comments which have been made from time to time in the literature of noise-reduction.*

The noise heard when a door is closed depends on the type of door, its furniture, and the way in which it is closed. Noise may arise from impact between the door and the frame and from the functioning of the latch mechanism, the noise due to the latter being amplified to some extent by reason of the door acting as a sounding board. In the case of sliding doors there is another possible source of noise, namely the track mechanism.

(*a*) **Noise due to Impact of Door upon the Frame.** A simple method of preventing noise due to impact between the door and its frame is to use one of the many check actions available which (and this appears to be important) control the motion of the door over a considerable distance before it closes. When properly adjusted, these devices considerably diminish the speed of the door over the last few inches of its travel, the latch being operated by the spring rather than by the momentum of the door. Cheaper devices such as rubber buffers, which only begin to operate when the door is nearly closed, are probably not so good, since they cannot retard the door sufficiently gradually to prevent noise occuring. An additional defect of these buffers is that they are liable to prevent the latch from engaging, and as a result the single noise due to the slam of the door may be exchanged for an irritating series of clicks as currents of air repeatedly bring the latch of the nearly closed door up against the striking plate.

The problem of reducing the noise due to door-slamming is particularly important in the case of all-metal office partitions. It has been suggested that this noise could be reduced by fixing a continuous strip of rubber round the frame (see Fig. 107) and by applying an "anti-drum" treatment to the door. This latter treatment takes the form either of a suitable non-resonant filling such as slag wool, glass

* See, for example, Noise Abatement League leaflet No. 10, "The Silencing of Doors"; K. W. WAGNER: *Das Larmfreie Wohnhaus;* and others.

silk, sawdust, and glue, or of an "anti-drum" paint or felt applied to the inner faces of the metal sheets (as is done on automobile bodies). When choosing doors for a residential building, preference should be given to those which are likely to make least noise when slammed, particularly if anti-slam devices are not desired. Lack of actual measurements on slamming noise made by different types of

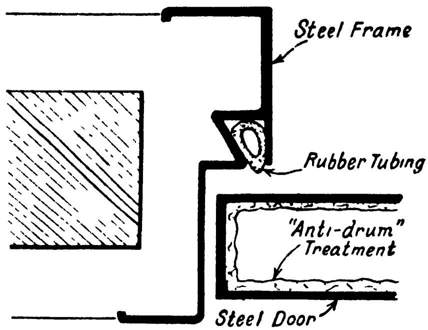


FIG. 107. STEEL DOOR-FRAME WITH RUBBER TUBING DESIGNED TO REDUCE THE NOISE OF DOOR-SLAMMING

The steel door has "anti-drum" treatment applied to the interior.

door is a handicap, but it seems likely that, weight for weight, solid doors should be less resonant than hollow doors and should therefore cause less noise when slammed. If hollow doors are to be used, the possibility of using a non-resonant filling should be considered. It may not be out of place to suggest that in cheaper buildings, where check actions cannot be provided, hooks or door stops which will keep the doors from slamming in the wind should be provided.

(*b*) **Noise Arising from the Latch Mechanism.** Very little attention appears to have been paid to designing silent latches. Improvements have been made in individual cases by altering the angles of the latch and striking-plate. The value of periodic oiling is, of course, obvious. Noise arising from inside the lock has been dealt with by suitably disposed rubber buffers or spring-controlled latch bolts (Fig. 108). Mortise locks are said to be less noisy than rim locks, particularly if they are fitted to a solidly constructed door. Spring ball catches are inherently noisy, and are, presumably, best avoided.

A particular type of latch which appears to be always noisy and for which treatment is difficult is the panic bolt. It sometimes happens that the only means of access to a particular part of a building is through doors which must be fitted with panic bolts. In this case a supplementary quiet-acting entrance door may be provided.

(*c*) **Noise due to Other Door Mechanism.** Sliding-door gear is often noisy, but quietening devices such as fibre wheels or tubular

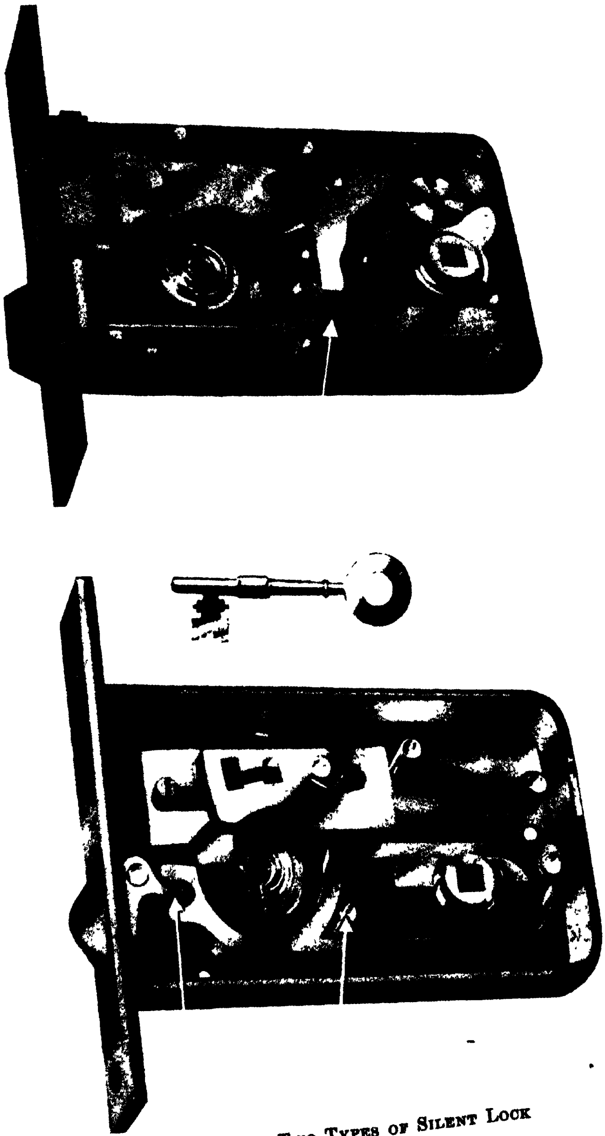


FIG. 108. TWO TYPES OF SILENT LOCK
(*James Gibbons Ltd.*)

slides may be used. A rubber track which has been used for the bottom runners of a sliding door is shown in Fig. 109.

In the case of garage or other large doors, sliding doors can be very noisy in operation, since the door acts as a kind of sounding board,

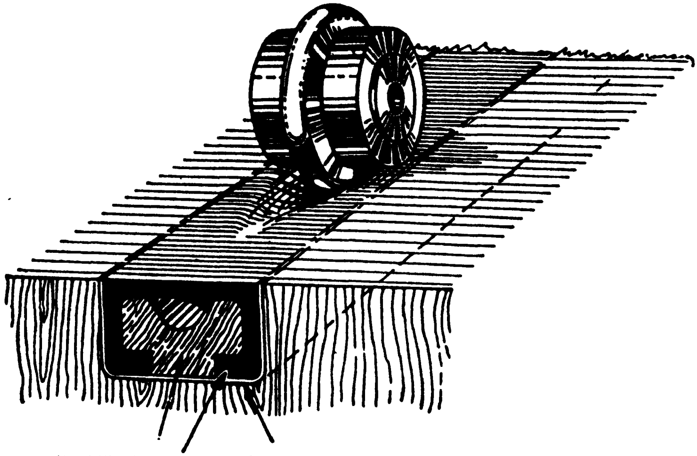


FIG. 109. A TYPE OF SLIDING DOOR TRACK

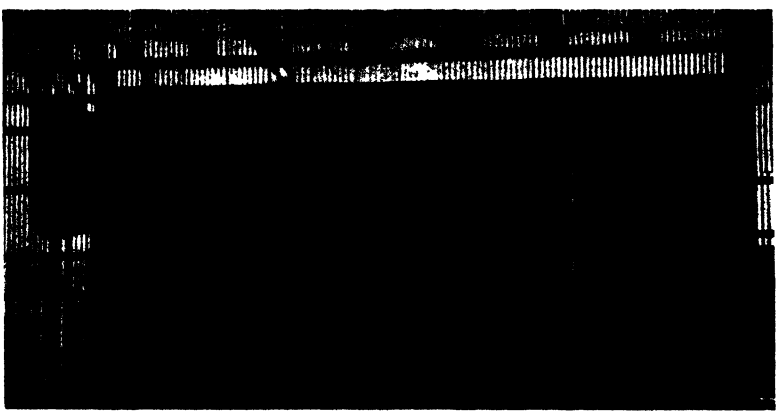


FIG. 110. BALANCED DOOR SUITABLE FOR GARAGE OR OTHER LARGE DOORS WHERE QUIET OPERATION IS DESIRABLE
(*Eclair Doors Ltd.*)

amplifying the noise produced by the wheels or other door gear. Balanced doors, one make of which is shown in Fig. 110, can, however, be comparatively noiseless, the only sound being that of the motion of the cable carrying the counterweight over the pulley.

SOUND-INSULATING DOOR CONSTRUCTIONS

No sound-insulation scheme is complete without sound-insulating doors, though the number required depends upon the skill with which the building has been planned. In residential buildings the doors of noisy rooms such as kitchens, laundries, and machine-rooms should be sound-insulating. The entrance doors to individual flats or suites of rooms should also be reasonably soundproof. In offices, rooms opening off a noisy corridor or dividing an executive's room from a typing office should be soundproof. Each building will present its own problem, and it is for the architect to decide where soundproof doors will be most needed.

Doors often form a weak link in an otherwise well-conceived design, but soundproof doors are not easy to provide. As was explained in Chapter IX, good sound-insulation can be obtained by a solid construction if sufficiently heavy, or a complex construction if sufficiently thick. As weight and thickness are normally both restricted in the case of doors, it follows on this account that the insulation obtainable from one door alone is limited by practical considerations. At the Acoustics Laboratory, National Physical Laboratory, where extreme silence is required, one room is fitted with solid steel doors weighing between 2 and 3 tons. Doors of this type are not practicable for other than specialized buildings of this type.

Closure also sets a limit to the insulation obtainable, as was explained when dealing with windows in Chapter XI. Normally there is a gap between a door and its frame, particularly at the bottom. Calculation and measurement show that the transmission (see Chapter XV) of the normal gap limits the insulation obtainable from any door to between 20 and 25 db. unless special devices for sealing the gap are used. This aspect of sound-insulating door construction will be returned to later. In the discussion given in the following few pages of the insulation afforded by different constructions, a perfect sound-tight seal is assumed.

When dealing with doors, three grades of sound-insulation may be recognized—

1. 25–30 db., which is afforded by ordinary doors for which no special sound-insulating properties are claimed.

2. 30–35 db., afforded by some commercially available doors which though not specially sound-insulating are nevertheless appreciably better than ordinary doors.

3. 35 db. upwards, afforded by purpose-made doors of special design which are intended for use when a high degree of sound-insulation is required.

The first class consists of panelled doors or ordinary flush plywood-faced doors; the second consists of heavy solid doors and complex doors; the third of very heavy doors or thick complex doors. Unless a sound-tight seal is to be provided, there is no point in using doors other than of the first class.

In residential buildings, doors of the first class will probably be used in most rooms, doors of the second class being used as entrance doors to flats or suites and possibly to service rooms. In offices, doors of the first class will probably be used in most positions, doors of the second class being provided to rooms containing noisy machines and to offices in which quiet is specially desired. Doors of the third class are relatively rarely required. Probably their chief application is found in industrial buildings, e.g. in noise-test rooms, for shutting in noisy machinery, or in radio studios.

The acoustical considerations which govern the design of solid and complex doors are discussed below.

(*a*) **Solid Doors.** Solid doors of uniform thickness are the simplest to discuss from the acoustical point of view. As in the corresponding case of single homogeneous partitions, their insulation is determined almost entirely by their weight, and it can be predicted with sufficient accuracy from the curves given in Figs. 83 and 84, or from Table XIX.

The following table gives the approximate insulation in decibels thus predicted for solid doors of uniform thickness.

TABLE XIX

SOUND-INSULATION OF SOLID DOORS

Weight (lb./sq. ft.)	Approximate Sound-reduction Factor (db.) averaged for Frequencies of 200–2,000 c.p.s.
1	25
2	30
5	35
10	40
20	45

It will be seen that a solid door weighing 5 lb./sq. ft. (corresponding to a total weight of about 1 cwt. for a door of average size) gives an insulation of only 35 db. This is still 15 db. less than the insulation provided by a 4½ in. brick wall, and such a door would be a weak point if used in anything except a light wall. To be as insulating as a 4½ in. wall a solid door would need to have the same weight per square foot as the wall, and would weigh about half a ton.

It may be pointed out that the sound-insulation of the common panelled door is likely to be less than that of a solid uniformly thick one of the same weight, since the effective insulation is determined largely by that of the lightest part, namely the panels.

(*b*) **Complex Doors.** Many types of complex door, including those commercially available, have been tested in Professor Kreuger's laboratory in Sweden. The results published by Kreuger and Sager* are given in Tables XX and XXA which give the insulation obtainable from a number of constructions.

* KREUGER AND SAGER: *Proc. Roy. Swedish Inst. Eng. Res.*, No. 132, 1934 (in Swedish). See also an abbreviated translation by J. E. R. CONSTABLE and K. M. CONSTABLE: *Building*, March 1937.

TABLE XX

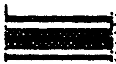
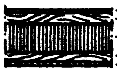
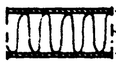
Sound-insulation of Complex Doors (Test Size 5 ft. by 5 ft.)

No.	Description of Door			Weight (lb. per sq. ft.)	Insulation against airborne sound (decibels)			
					100–300~	300–1000~	1000–3000~	100–3000~
1	— blockboard		1·65"	4·4	27	28	33	29·6
2	blockboard airspace blockboard		1·65" 0·04" 1·65"	8·8	34	32	40	36·5
3	blockboard airspace blockboard		1·65" 1·96" 1·65"	8·8	38	36	50	41·3
4	blockboard airspace blockboard		1·65" 3·92" 1·65"	8·8	41	38	46	42·0
5	blockboard airspace blockboard		1·65" 5 92" 1·65"	8 8	43	47	52	44·7
6	each inner side covered with	fibreboard	0 51"	10·2	47	48	59	51·7
7		cocoafibre mat	0 79"	9 4	44	44	55	48·1
8		hairfelt	0·24"	9 2	42	45	56	47·7
9		"	0·35"	9 4	42	44	57	48·0
10		"	0 47"	9 6	44	45	57	48·9
11		wadding	0 40"	9 0	44	45	58	49·0
12		"	0 80"	9 0	45	46	58	50·0
13		"	1 20"	9 2	45	46	58	49·8
14	As No. 13, but with 0·01" pegamoid nailed over wadding			9 4	46	47	59	51·0
15	1 sheet of fibreboard			0 7	17	21	30	22·8
16	2 sheets of fibreboard, spaced 0·4"			1 4	20	26	48	31·1
17	3 " " " " "			2 1	21	33	60	37·9

18	4 " " " " "			2 8	24	39	60	42·9
19	5 " " " " "			3·5	27	44	68	46·5
20	blockboard 1·65" wadding 0·40" airspace 0·80" wadding 0·40" plywood 0·40"			5 7	35	39	49	40·9
21	sheet iron 0·08" sheet iron 0·08"	fibreboard	0·51"	7·0	33	49	66	49·0
22		hairfelt	0·47"	6·7	28	52	65	48·6
23		kapok	2·36"	6·7	44	59	67	56·1
24		cocoafibre mat	0 79"	6 6	34	50	64	49·3
25		eelgrass	0·79"	6 9	34	55	67	52·1
26		wadding	0·79"	6 5	33	57	68	52·6
27	plywood 0·24" plywood 0·24"	fibreboard	0 51"	2 1	24	28	45	32·3
28		hairfelt	0 47"	1 8	20	25	47	30·6
29		kapok	2 36"	1 7	19	41	63	41·0
30		cocoafibre mat	0 79"	1 7	17	28	46	30·4
31		eelgrass	0 79"	2 0	19	31	49	33·0
32		wadding	0 79"	1 5	16	33	53	34·3
33	fibreboard 0·51" fibreboard 0·51"	fibreboard	0 51"	2 1	22	32	56	37 0
34		hairfelt	0 47"	1 8	18	32	55	35·0
35		kapok	2 36"	1 8	25	44	67	45·3
36		cocoafibre mat	0 79"	1 7	18	33	56	35·7
37		eelgrass	0 79"	2 0	19	35	56	36·9
38		wadding	0 79"	1 6	17	37	59	38·0
39	panelled door 1·77" lead 0·02" fibreboard 0·51" plywood C·24"			6 1	30	40	55	41·9
40	plywood 0·24" plywood 0·24"	kieselguhr	2 0"	5 7	22	24	41	29·2
41		wadding, loose	2 0"	1·9	23	42	56	40·1
42		wadding, compressed	2 0"	2 1	23	42	56	40·2
43		slag wool	2·0"	2 0	20	41	58	39·6
44		eelgrass	2 0"	2 0	24	42	57	40·9
45		corrugated paper	2 0"	3 0	17	36	52	35·3

TABLE XX—(*contd.*)

Sound-insulation of Complex Doors (Test Size 5 ft. by 5 ft.)

No.	Description of Door		Weight (lb. per sq. ft.)	Insulation against airborne sound (decibels) 100-300 ~	300-1000 ~	1000-3000 ~	100-3000 ~
46 47		plywood 0·24" airspace 0·40" fibreboard 0·51" [sheet iron 0·12" fibreboard 0·51" [eternit 0·20" airspace 0·40" plywood 0·24"	7·8 4·9	26 24	41 39	61 59	43·0 40·9
48		plywood 0·24" wadding 0·40" blockboard 1·65" wadding 0·40" plywood 0·24"	5·9	21	36	61	39·6
49		plywood 0·24" airspace 0·40" blockboard 1·65" airspace 0·40" plywood 0·24"	5·7	24	23	46	31·3
50		plywood 0·24" solomit 2·20" plywood 0·24"	3·9	21	37	59	39·5
51		plywood 0·24" sheet iron 0·08" kapok 2·36" sheet iron 0·08" plywood 0·24"	8·1	49	62	51	50·5
52		plywood 0·24" eternit 0·20" airspace 0·12" fibreboard 0·51" airspace 0·12" eternit 0·20" plywood 0·24"	6·2	29	36	51	38·5

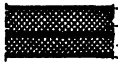
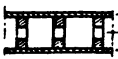
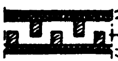
53		plywood 0·24" eternit 0·20" airspace 0·12" fibreboard 0·51" airspace 0·12" eternit 0·20" airspace 0·12" fibreboard 0·51" airspace 0·21" eternit 0·20" plywood 0·24"		9·0	32	43	57	44·5
54		rubber 0·16" fibreboard 1·50" fibreboard 1·00" rubber 0·16"	lead 0·02"	8·2	36	44	64	48·3
55			sheet iron 0·08"	10 0	37	50	69	52·3
56		sheet iron 0·08" sheet iron 0·08"	corkdust 1·50"	6·1	34	40	51	41 5
57			fibreboard 1·50"	6·1	34	36	48	39 4
58		plywood 0·24" blockboard 1 06" plywood 0 24"		4 1	30	28	34	30 6
59		plywood 0·20" fillets 1·80" plywood 0·20"		4 2	29	26	31	28·2
60		fibreboard, hard 0 20" " , porous 0 31" hairfelt 0·31" fibreboard, porous 0 31" fibreboard, hard 0·20"		5 3	32	33	37	33 6
61		linoleum 0·14" fibreboard 0·31" airspace 1·10" fibreboard 0·31" linoleum 0·14"		4 7	30	38	44	36 9
62		plywood 0·20" fibreboard 0·31" dry sand 1·02" fibreboard 0·31" plywood 0·20"		7·1	34	35	36	34·7

TABLE XX—(*contd.*)

Sound-insulation of Complex Doors (Test Size 5 ft. by 5 ft.)

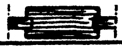
No.	Description of Door	Weight (lb. per sq. ft.)	Insulation against airborne sound (decibels) 100–300~	300–1000~	1000–3000~	100–3000~
63	 sheet iron 0·06"; solid filling 1·45"; sheet iron 0·06"	11·6	39	41	50	43·6
64	 panelled door 1·77"	3·1	28	28	31	29·2

TABLE XXA

Sound-insulation of Complex Doors (Test Constructions of Standard Door Size)

No.	Description of Door	Weight (lb. per sq. ft.)	Insulation against airborne sound (decibels) 100–300~	300–1000~	1000–3000~	100–3000~
65	 plywood 0·20"; fillets 0·20"; battens 1·0"; fillets 0·20"; plywood 0·20"	3·6	24	29	33	29·0
66	 sheet iron 0·06"; kapok 1·42"; sheet iron 0·06"	5·7	32	46	56	44·4
67		5·1	30	46	58	44·9
68	 sheet iron 0·05"; kapok 1·42"; sheet iron 0·05"	5·9	35	47	57	46·2
69		5·3	30	46	57	43·9
70	 sheet iron 0·05"; fibreboard 1·54"; sheet iron 0·05"	6·7	32	42	56	43·0
71		6·7	33	44	59	46·5
72	 fibreboard 0·47"; kapok 0·79"; fibreboard 0·47"	3·0	16	36	57	36·6
73		2·8	16	35	54	35·3
74	 plywood panelling 0·87"	3·6	25	29	32	28·8
75		3.6	24	28	32	28·2

These results show the relative efficacy of the different constructions tested, but the numerical values of the insulation relate with accuracy only to the particular conditions of test obtaining. Systematic variations of a few decibels are usually found between the insulation of apparently similar constructions when tested in different laboratories. The general principles described in Chapters X and XI governing the insulation of complex partitions show up again, as might be expected, in the case of complex door constructions.

It will be seen from Table XVI, dealing with partitions, that a door consisting of two flexible layers separated by an air space can combine reasonable thickness (2 in.) with an insulation which is somewhat greater (by up to 10 db.) than that of an equally thick (though considerably heavier) solid door. Of all common building materials, wallboard is probably from the acoustical point of view most suitable for forming the flexible layer, particularly since it also has sound-absorbent properties. If untreated, the surface may have practical disadvantages, though possibly a flexible hard-wearing covering such as linoleum or oilcloth might overcome this criticism.

It should be noted that the advantage in using a complex door is mainly confined to medium and high frequencies; indeed, at low frequencies there may be an actual loss of up to 5 db.

Complex doors may also be used for obtaining high sound-insulations, but will be either thick or heavy. Some of the most successful doors tested by Kreuger and Sager gave average insulations of more than 40 db. For example, four layers of ½ in. fibreboard spaced about ½ in. from each other provided a door weighing only a few pounds per square foot, and yet having an insulation of 40 db. Five layers provided an insulation of over 45 db. Sheet iron doors gave similar insulation without being unduly thick (about 1½ in.). These were constructed from sheets having a thickness of about 0·05 in., and had an absorbent filling of either kapok or fibreboard. Their weight was of the order of 5–7 lb./sq. ft. The value of using sheet iron probably arises from the fact that the two faces of the door are heavy (which increases the insulation of the individual leaves) and flexible (which decreases the mechanical coupling between the leaves.)

Pairs of Doors. The use of special door designs can often be avoided and more satisfactory insulation obtained if two or more doors are used instead of one. The system has the advantage that it minimizes the effect of leakage due to defective closure of the doors. The doors should be as far apart as possible. (The space between, if large enough, can form an anteroom or "sound lock.")

The interspace should be rendered sound-absorbent by suitable treatment of the walls and ceiling with an acoustic felt or even with a wallboard. If the doors have to be near together, it may be advisable to cover their inner surfaces with a sound-absorbent material in order to get sufficient absorption in the interspace. (See Fig. 111.) This treatment is analogous to the use of sound-absorbent in double windows. Its effect has been measured by Berg and Holtsmark in the case of two doors, the one panelled and the other a flush door.* The doors were about 18 in. apart and individually had sound-reduction factors of about 20 db.; the insulation of the combination was about 25 db. before special absorbent treatment was installed; erecting absorbent material in the interspace

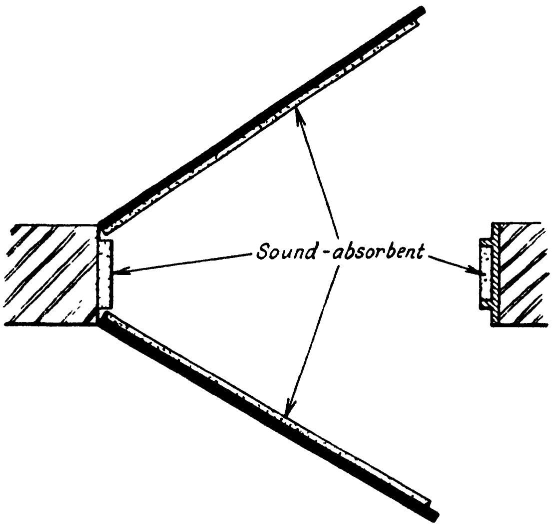


FIG. 111. SOUND-ABSORBENT APPLIED TO INTERIOR SURFACES OF DOUBLE DOORS, ALSO TO JAMBS AND SOFFIT

increased the insulation to about 35 db., representing a worth-while gain. As there is no mention of special sealing arrangements, the above measurements presumably refer to doors as ordinarily hung, with the usual gaps at each edge.

METHODS OF ENSURING A SOUND-TIGHT CLOSURE

As mentioned above, the gaps which ordinarily exist round the edge of a door limit the insulation obtainable to 20–25 db. If the best is to be obtained from the special door constructions discussed above, special means for ensuring a sound-tight closure are necessary.

There are two general methods of obtaining a sound-tight closure. The most frequently used relies upon making the closure as nearly

* R. BERG AND J. HOLTSMARK: *Det Kongelige Norske Videnskabers Selskab, Forhandlinger*, Vol. 8, No. 35.

as possible airtight. There is an alternative, however; though its value has not, apparently, been determined experimentally. This second method makes the gaps as small as is practicably possible, but instead of trying to make them airtight it aims at reducing their transmittance by lining the interior surfaces with sound-absorbent. Examples of both methods are given below.

1. Use of an Approximately Airtight Closure. To obtain an approximately airtight closure, the rebates of the frame or the edges of the door must be faced with a soft material (such as sponge rubber, rubber tubing, or felt) which is slightly compressed when the door is closed. A design based on this principle is described by Knudsen*

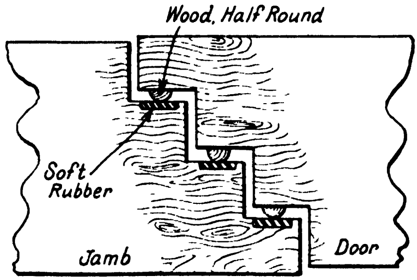


FIG. 112. A METHOD OF OBTAINING AN AIRTIGHT SEAL

which is said to be suitable for large doors such as those used in sound-recording film studios. Large mechanical locks force the door tightly against a rubber-lined jamb, the construction of which is shown in Fig. 112. Three wood half-rounds, nailed to the edge of the door, 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 lb. per running foot, the insulation of the seal is said to be about 40 db. The same principle has been used in the sound-insulating doors of the National Broadcasting Corporation's radio studios, shown in Fig. 113. Here a specially contoured door edge presses against two rubber gaskets. (An automatic felt plunger is provided to seal the bottom edge of the door.) The latches are provided with a wedge action to enable the door to be drawn tightly against the sealing strip. In the case of a large door or where sound-insulation is specially important, it may be advisable to fit more than one latch to avoid possible warping of the door and to make sure that the door is pulled down on to the sealing material all round its edges. Difficulties may arise at the hinge edge of the door, since the movement of the door is small in this region; the use of a soft sealing material should assist in preventing leakage at this point. A "crane" hinge as used on strong-room doors overcomes the difficulty.

* V. O. KNUDSEN: *Architectural Acoustics*, p. 577.

Obtaining an airtight seal along the bottom edge of the door also presents difficulties. Further, this is usually the most important section to treat, since the gap is nearly always wider and less deep at the bottom, where there is no rebate. To give an example of measurements made in a building of the effect of blocking only the gap at the bottom of a door, Douglas and Himsworth found that the insulation of 50 db. between a room containing a door and a position outside the door was increased by 4 db. on blocking the gap below the door.* If there is no objection to a low cill, the treatment can be the same as along the other edge of the door. (See Fig. 114.) If, for example, as in an industrial test room, trucks are to be taken into

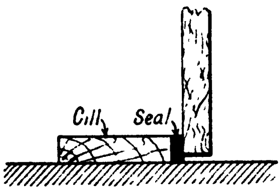


FIG. 114. RAISED DOOR-CILL FACED WITH SEAL OF COMPRESSIBLE MATERIAL

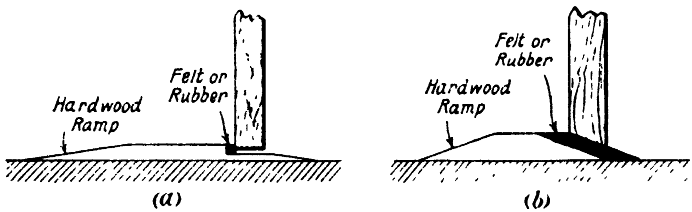


FIG. 115. TWO DIFFERENT TYPES OF RAMP FACED WITH FELT OR RUBBER

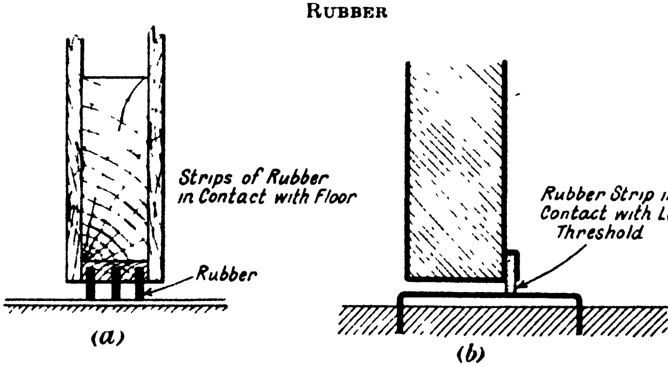


FIG. 116. DRAUGHT-EXCLUDING DEVICES ATTACHED TO BOTTOM OF DOOR

the room, temporary ramps can then be provided to help them over the cill. The alternatives are—

(*a*) To use a low ramp, as shown in Fig. 115, the bottom edge of

* A. H. DOUGLAS AND F. R. HIMSWORTH: the *Structural Engineer*, March 1938.

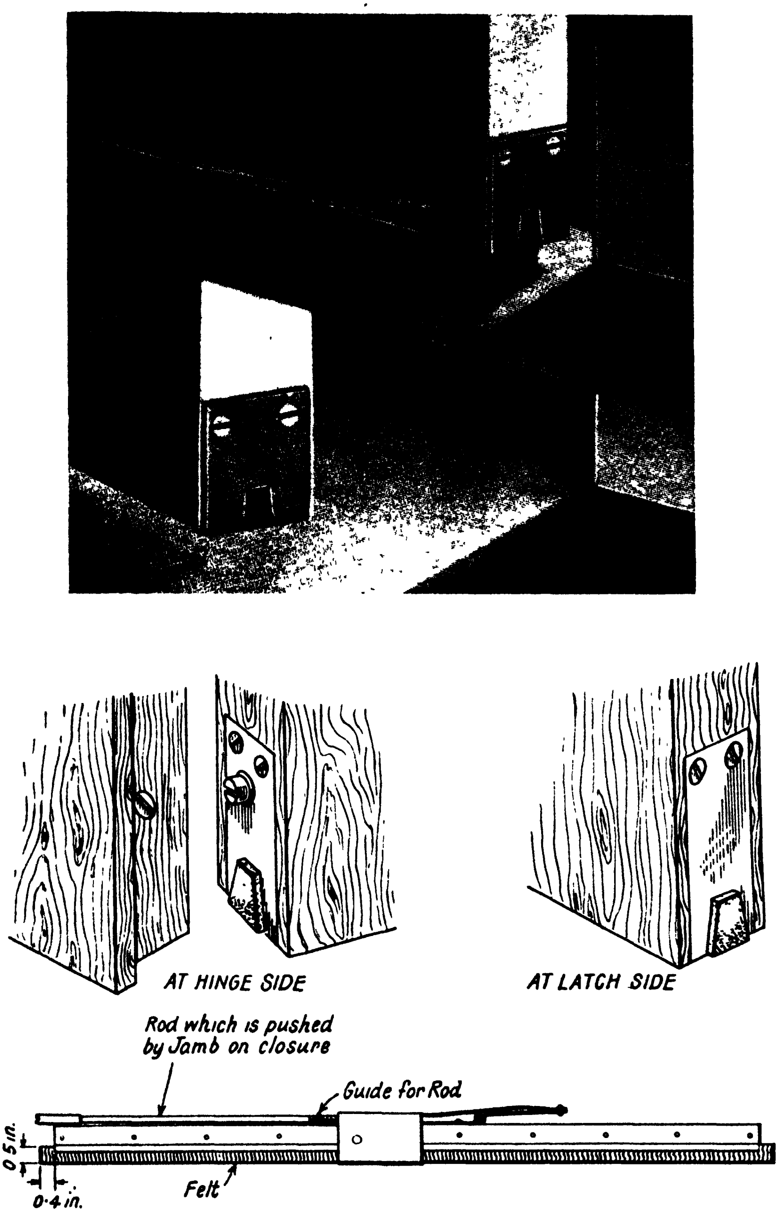


Fig. 117. An Automatic Felt Plunger which Acts as a Draught- and Sound-excluder beneath a Door

(Toft-Nielsen & Vallö, Copenhagen)

the door (which is shaped to fit the ramp) being faced with a soft material such as felt or sponge rubber with a view to obtaining an approximately airtight seal.

(*b*) To attach a draught-excluding device to the bottom of the door. Two types are shown in Fig. 116. These have been advocated for factory use, but may mark the floor. That shown in Fig. 117 has applications in domestic work. The device lifts automatically when the door opens.

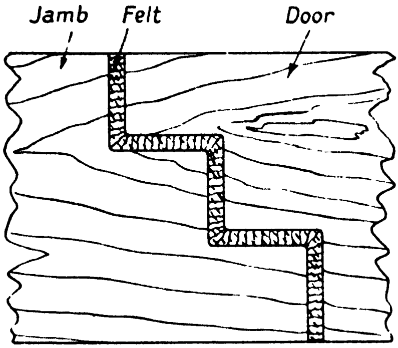


FIG. 118. USE OF SOUND-ABSORBENT TO REDUCE THE TRANSMISSION OF SOUND THROUGH GAPS - DOOR WITH MULTIPLE FELT-COVERED REBATES

2. Use of Sound-absorbent to Reduce Transmission of Gaps. Where it is not possible to provide a wedge-action latch and a rebate against which a tight closure can be made, the alternative of rendering the interior of the gaps sound-absorbent can be used, though this may not be so effective as an airtight closure. One possible design, which should prove fairly effective, is shown in Fig. 118; the feature of this is the provision of multiple felt-covered rebates with a view to making the sound path as long as possible. The felt should be as thick as is practicable. No doubt there will be other designs, based upon this principle, which will suggest themselves to the reader.

Gaps due to imperfect closure are not the only means by which leakage can reduce the effective sound-insulation of doors. Other small holes such as keyholes can seriously reduce the insulation of otherwise well-insulating doors (classes 2 and 3 above) but are not of importance in doors of ordinary insulation (class 1). For example, a simple calculation of the transmittance of a door of area 20 sq. ft. and sound-reduction factor 45 db. shows that the sound-reduction factor is reduced to 40 db. by a keyhole measuring 0·9 in. by 0·2 in. Attention to points such as well-fitting keyhole covers is worth while when designing doors which will be required to give a high degree of insulation.

General. Soundproof doors obviously lose their effect if left open: an automatic closing device should overcome this difficulty, however. Another method of dealing with the problem is met with in the revolving doors commonly fitted in the entrances to hotels and shops. These doors give ready admittance, but if properly designed never allow the full intensity of the street noise to enter the building. It is possible that they could be used for a similar purpose in other positions, e.g. between a factory and offices.

CHAPTER XIII

SOUND-INSULATING FLOORS

PROBABLY the earliest measurements were those made by Chrisler and Snyder at the Bureau of Standards in America. Since then, several other investigators have taken up the task in Scandinavia, Germany, Austria, Switzerland, and England, to name only a few countries.* In England the work has been largely carried out by the National Physical Laboratory working in collaboration with the Building Research Station.

More is required of a sound-insulating floor than of a sound-insulating wall. In addition to insulating against airborne sound such as that of conversation, music, etc., a floor must also insulate against impact sound, such as that due to footsteps. The latter is usually the more difficult requirement to fulfil.

Insulation provided by Floors against Airborne Sound. It may be taken that the insulation provided by solid floors against airborne sound is normally that which would be expected from their weight as discussed in Chapter X.

Measurements made at the Bureau of Standards† indicate that the average insulation of a wood-joist floor is about the same as that of an equally heavy solid partition, e.g. in the case of a floor having a lath and plaster ceiling, about the same as that of a plastered 2 in. clinker concrete partition. Measurement of the effect of small apertures in partitions suggests that if the construction were airtight the insulation would be rather greater. Laying felt below the floorboards or covering the floor closely with linoleum are among the simpler ways of achieving this. It should be noted, incidentally, that the weight of the plaster is usually a good proportion of the total weight of the floor, and hence that a floor having an unplastered wallboard ceiling is likely to be less insulating than one having a heavy plastered ceiling.

It will be seen that the insulation provided against airborne sound by untreated floors, particularly wooden ones, is not usually of a high order. However, as will appear in the next section, a floor usually requires treatment to prevent noise due to impacts, and it is found that treatment used for this purpose in most cases also increases the insulation against airborne sound. For example,

* V. L. CHRISLER AND W. F. SNYDER: *Journ. Res. Nat. Bur. Standards*, Vol. 14, p. 749, 1935; K. W. WAGNER: *Zeits. für Techn. Physik*, 16, 12, p. 544, 1935; G. HOFBAUER: *Gesundheits In*, Vol. 42, p. 562, 1934; R. R. BERG, F. BERNER, E. HARBOE AND J. HOLTSMARK: *Byggekunst*, 7, 1934. H. KREUGER AND J. H. SAGER: *Proc. Roy. Swedish Inst. Eng. Res.* No. 132, 1934; A. GASTELL: *Akutische Zeits.*, Vol. 1, p. 24, 1936; F. M. OSSWALD: *Journ. Acoust. Soc. Amer.*, Vol. 7, p. 261, 1936.

† See V. L. CHRISLER AND W. F. SNYDER, *loc. cit.*

adding a floating wood-raft floor to a wood-joist floor increases the average airborne sound-insulation by nearly 10 db.; adding a similar floating floor to a concrete floor increases the insulation by about 6 db.* Provided, therefore, that a floor is reasonably satisfactory as regards footstep noise and is free from cracks or gaps, it is unlikely that trouble will be experienced on account of defective airborne sound-insulation. When floors are required to be specially good in this latter respect they should be designed in accordance with the principles set out in Chapters IX and X. An example of a floor in which high airborne sound-insulation was aimed at is the construction used in the National Broadcasting Corporation's studios in New York. (See Fig. 142.)

Insulation provided by Floors against Impact Sounds. It is commonly agreed that whereas, in the case of partitions, insulation against airborne sound is particularly required, in the case of floors, insulation against impact sound such as that due to footsteps, is more important.

Generally, the impact insulation of floors is tested by subjecting the upper surface of the test floor to a series of blows which represent footsteps and measuring the noise produced below. In Great Britain the insulation provided by a floor is given by the extent (expressed in phons†) to which it is quieter than some floor chosen as standard. In some laboratories this procedure is slightly varied by expressing the insulation of a floor as the amount by which the noise below it, when it is beaten with the standard blows, is quieter than some standard noise such as the noise of beating a sheet of plywood. It will be seen, however, that this is scarcely different in principle from the British method. Another method is used by the Bureau of Standards, where the insulation of a floor is expressed as the difference between the noise levels above and below the floor when it is subjected to standard blows. In this book the British method of expressing the insulating effect of a floor construction is used, the improvement (in phons) in noise conditions below a standard structural floor when the treatment referred to is used upon it being spoken of as the *insulation gain* of the treatment. The methods of measurement adopted by the different laboratories vary so much that it is extremely difficult to correlate their results numerically. Accordingly in this chapter, for the sake of simplicity, only figures obtained by the National Physical

* CHRISLER AND SNYDER: *Journ. Res. Nat. Bur. Standards*, Vol. 2, p. 541, 1929: see also KREUGER AND SAGER, *loc. cit.*

† It will be noted that phons are the units in which impact insulation is measured, and not decibels, as is the case where insulation against airborne sound is referred to. The difference arises because insulation against airborne sound is measured using comparatively pure notes, whereas insulation against impacts involves measurement of a noise consisting of an undefined mixture of notes.

Laboratory are used, the results of other laboratories being used only to obtain qualitative conclusions.

Impact-insulation measurements do not seem to be capable of the accuracy that can be obtained when measuring airborne sound-insulation, and they suffice only to group floors into classes. Generally speaking, it appears that unless the difference between the impact-insulating values of two floors is 5 phons or more they may be taken, for practical purposes, to be equally effective.

All untreated solid concrete and hollow-tile floors which have been tested up to the present appear to be about equally noisy when subjected to impacts, whatever their weight, thickness, or construction. This is an important result upon which there is fairly general agreement.

Methods of Increasing Insulation against Impact Sounds. The methods which have been shown to be successful for increasing the insulation of floors against impact sounds are as follows—

1. Adding one or more layers insulated from the structural floor, e.g. laying an insulated floating floor on the structural floor or fixing an independent ceiling below it.

2. Putting a soft covering on the floor, e.g. a heavy pile carpet on underfelt, or rubber with a sponge-rubber backing. This treatment is not so effective as treatments mentioned under (1) and is best regarded as supplementary to them.

3. In the case of wood-joist floors, filling the space between the joists with a loose material (pugging). This treatment gives only moderate improvement, but is useful when employed in conjunction with others.

The above treatments, which will be discussed below in detail, may be used alone or in combination, and their effects appear to be approximately additive.

LAYERS INSULATED FROM THE STRUCTURAL FLOOR

If a floor could be constructed of two totally unconnected layers, the problem of preventing footstep noise would be solved. Unfortunately, however, mechanical and acoustical connexion is inevitable and research has had to devote itself to minimizing the effect of these connexions as far as is consistent with other requirements such as economy or strength. Two types of treatment have been evolved: the floating floor, in which an auxiliary floor is supported on insulating material above the structural floor; and the independent or insulated ceiling, which is fixed below the structural floor. The first of these is probably the most effective single treatment available for reducing transmission of impact noise. The two treatments can, of course, be used in combination where high insulation is required.

It is not easy to enumerate the principles which should be used when designing floors of this type, for the problem has not yet been investigated systematically and fully. The following points appear to have been established—

1. The insulation is likely to be greater the more resilient the insulating material used to support the auxiliary layer, though there is a limit to this imposed by the stiffness of the air interspace. (See below.)

2. The smaller the area of insulating material, the greater is the insulation likely to be; although a limit to the extent to which the area can be reduced is set by the strength of the material.

3. Loading a floating floor merely by standing weights upon it has very little effect upon the insulation.

4. Increasing the thickness of a floating floor increases the insulation. (This may at first sight appear to contradict (3), but probably the improvement is due to the resulting increase of stiffness of the floating floor rather than of its weight.)*

5. Decrease of the air space between the two layers reduces the insulation.

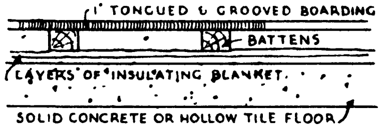


Fig. 119. Wood Floating Floor

The last mentioned is an interesting effect described by Davis and Knowler,† and it bears some analogy to the effect of varying the air space in a double partition. (See Chapter X.) As in that case, the elasticity of the air in the interspace is important, and there comes a stage, as the thickness of the air space is decreased, at which the stiffness of the air becomes greater than that of the insulating material upon which the floating floor is supported. Thereafter, as the space decreases, the insulation also decreases. In the case of the concrete floor studied there was a marked increase of insulation (about 13 phons) as the air space was increased from $\frac{1}{2}$ in. to 2 in. The separation between floating and structural floors should accordingly be made as great as possible.

Practical Examples of Floating-floor Treatments. A number of floating-floor treatments are in common use, and the insulation gain to be expected from some of them is given in Table XXI (page 216). The treatment consists, generally, of a concrete slab or wooden raft floor laid upon an insulating blanket or upon pads of insulating material. Concrete and wood floating floors are suitable for use upon solid- and hollow-tile structural floors; strength considerations normally prohibit anything other than a wood floating floor being used upon a wood structural floor.

Wood Floating Floors. Wood floating floors (usually made of

* A. H. Davis and C. J. Morreau: *The Reduction of Noise in Buildings* (Building Research Station Special Report, No. 26).

† A. H. Davis and A. E. Knowler: *Philosophical Magazine*, Vol. 23, p. 154, 1937.

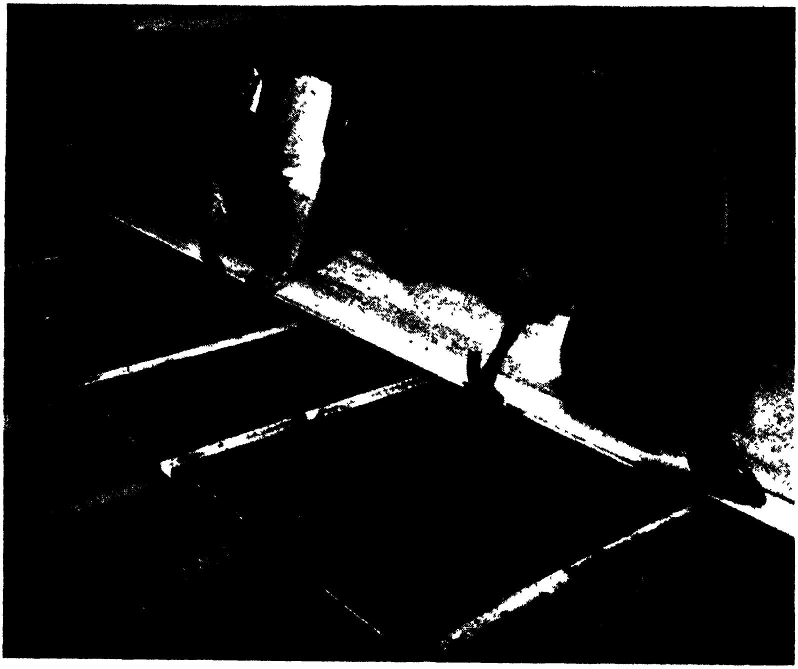


FIG. 120. WOOD FLOATING FLOOR BEING LAID ON FIBREGLASS QUILT
(*Fibreglass Ltd.*)

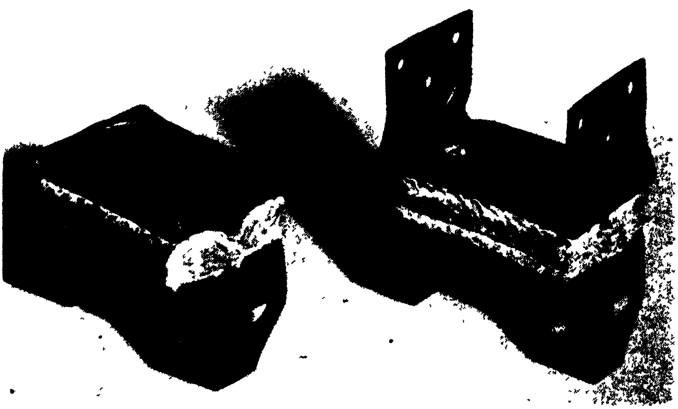


FIG. 121. INSULATED FLOOR CLIP
(*Adamite Co. Ltd.*)

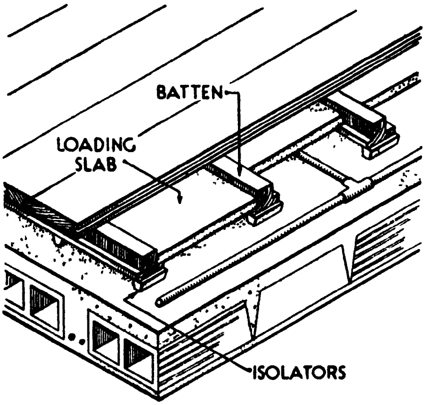


FIG. 122. A SPECIALLY DESIGNED WOOD FLOATING FLOOR
(*H. W. Cullum and Co., Ltd.*)

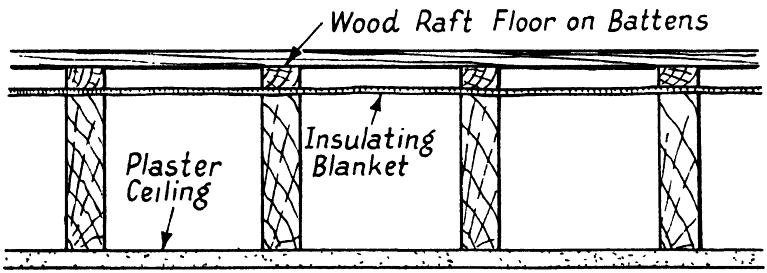


FIG. 123. WOOD FLOATING FLOOR ON UNCOVERED JOISTS

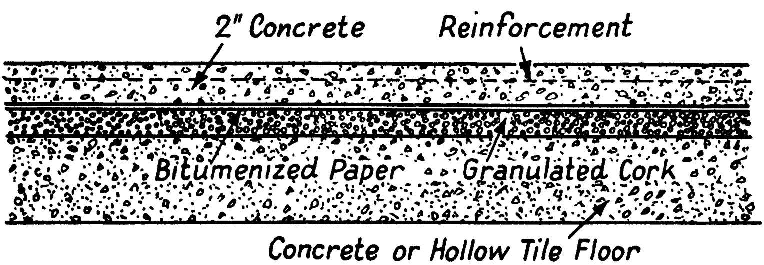


FIG. 124. CONCRETE FLOATING FLOOR

floorboards upon battens) are normally supported upon a layer of insulating material such as eel-grass blanket (Cabot quilt), felt, or fibreglass quilt (Figs. 119 and 120). Insulation gains of 15–20 phons are obtainable by this means, an improvement which, if supplemented by the effect of a carpet on underfelt, should give satisfactory living conditions beneath the floor. Another method of insulating the wood floor from the structural floor is to hold it with insulated floor clips, several types of which are on the market. These clips are constructed on the lines of ordinary floor clips, except that the top and bottom halves are separated by insulating material such as asbestos fabric or rubber. One such is illustrated in Fig. 121. One proprietary wood floating floor uses rubber insulating blocks (Fig. 122) and is loaded with tiles held beneath the floorboards.

As mentioned above, wood raft floors are equally suitable for use with wood-joist structural floors and solid floors. When they are used on wood-joist floors, the joists can either be covered with floorboards (which may be useful if the floating floor is to stand upon insulating pads) or can be left uncovered (see Fig. 123). A wood floating floor has a practical advantage which appears to be more difficult to secure in the case of concrete floating floors, namely that service pipes can be run beneath it. Needless to say, wood floating floors should not be fixed by nails or screws passing through the insulating material. They are normally held in place by the skirting, from which they should be insulated.

Concrete Floating Floors. A concrete floating floor has several practical advantages, and is preferable in some cases to a wooden floating floor. It can be insulated either with an insulating blanket or with blocks of rubber or similar material. In the former case the insulating blanket is laid on the structural floor, and the concrete which is to form the floating floor can then be poured directly on to it. Care must, of course, be taken that no gaps are left between adjoining strips of blanket, otherwise the concrete may penetrate to the structural floor below. Covering the blanket with a layer of waterproof building paper is an additional precaution which can be taken in this connexion. Typical insulating blankets which can be used are fibreglass quilt, eel-grass blanket (Cabot quilt), and slag-wool blanket. Materials such as cork granules, steel wool, kapok, or coco-fibre can also be used. These materials are spread over the structural floor, covered with bituminized paper, and concrete is then poured on. (See Fig. 124.) Insulations up to 25 phons are obtainable from the above constructions. (See Table XXI.)

A concrete floating floor insulated with rubber blocks has been found very effective, insulations of up to 25 phons being readily obtainable. The Building Research Station (England) has evolved a special method of constructing such floors. (See Fig. 126.) Paper is laid over the structural floor and banded screwed pipe sockets are distributed over it. The concrete which is to form the floating floor is poured on, to the level of the top of the pipe sockets. When the concrete has hardened, wooden blocks are dropped into a limited number of sockets, and steel plugs screwed in above them so that the floating floor is gradually lifted. When it has been raised to rather more than the required height, rubber pads are dropped into the remainder of the sockets and steel plugs are screwed in. These plugs are screwed down into contact with the rubber and the plugs above the wooden blocks are then removed; finally the wooden blocks are replaced by rubber pads and their plugs are replaced. The heads of the plugs can afterwards be covered to give the floor a uniform

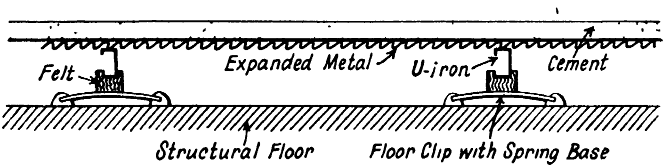


FIG. 125. CONCRETE FLOATING FLOOR ON SPECIAL FLOOR CLIPS

level. One advantage of this floor is that the rubber pads can be replaced if necessary.

As an alternative, permanent shuttering may be placed on the rubber pads and concrete poured on to this. Care is then necessary to prevent the wet concrete from penetrating joints in the shuttering and thus perhaps forming a solid bridging between floating and structural floors. Another type of floating floor, insulated upon felt-lined chairs, which was installed in the National Broadcasting Company's studios in New York is shown in Fig. 142. A similar type of floor was used in the Berlin Rundfunkhaus and has been described by v. Braunmühl.* The insulation in this floor was supplied partly by metallic springs. (See Fig. 125.)

Floating Floors—General. A floating floor necessarily raises the floor level, and measures must accordingly be taken to preserve the levels either by carrying the treatment over all the floor of the building or else by raising the level of the untreated floors. Particular attention must also be paid to the skirtings, since ordinary skirtings would short-circuit the insulation of the floating floor. A successful treatment is to provide a strip of felt between the floating floor and the bottom edge of the skirting board (Fig. 126).

Concrete floating floors, besides possessing value for insulating against footstep noises, find an application when it is necessary to insulate a number of light machines, e.g. in a school or laboratory workshop. The floating floor obviates the necessity for the individual insulation of each machine and, on account of its considerable inertia, provides a steadier base than would be obtained by individually

* H. J. VON BRAUNMÜHL: *Zeits. für Techn. Physik*, Vol. 16, p. 571, 1935.

insulated machine bases. Incidentally, it should be mentioned that floating floors are, of necessity, somewhat springy. This is a feature which is not necessarily unpopular in residential quarters, but should be guarded against where steadiness is necessary, e.g. in a laboratory.

Independent or Suspended Ceilings. Another method of increasing

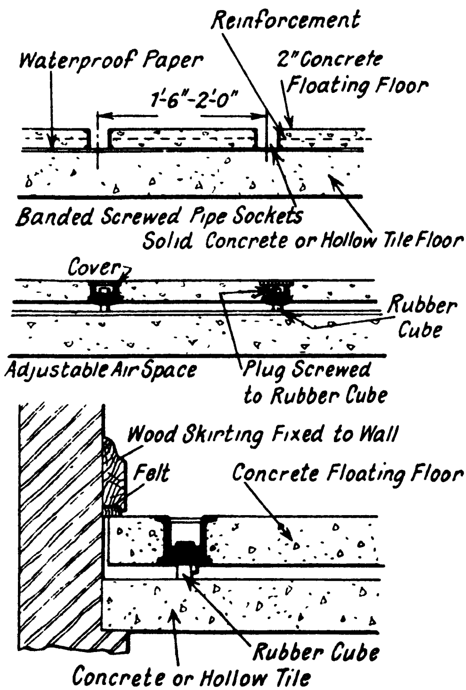


FIG. 126. DETAILS OF THE BUILDING RESEARCH STATION'S CONCRETE FLOATING FLOOR

the insulation provided by a floor is to fix below it an independent or an insulated ceiling. The former probably finds its greatest use in conjunction with wood-joist floors, since in this case the ceiling joists can be spaced between the floor joists (Fig. 127) to minimize the loss of headroom. In special circumstances, however, an independent ceiling can be used in conjunction with solid floors (Fig. 128); improvements in insulation of 15 phons or so can be obtained.

If the head-room is limited, a suspended ceiling can be used though it is unlikely to be as effective as an independent ceiling, unless it is extremely well insulated from the floor. An example of an effective construction is shown in Fig. 129 (*a*), in which the suspended ceiling (consisting of lath and plaster on battens) is held by floor clips set in the under side of the floor, felt being interposed between the clips and the battens. The insulation is not perfect, as nails must be driven through the clip into the batten; but it appears to have value. An alternative is to use acoustic floor clips

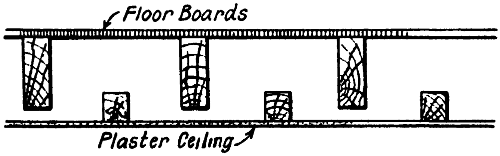


FIG. 127. INDEPENDENT CEILING BELOW WOOD JOIST FLOOR

which are constructed so that there is no metallic connexion between the top and bottom halves. (See Fig. 129 (*b*).) Other devices will no doubt suggest themselves to the reader.

An insulated suspended ceiling which was designed to provide especially good insulation for the National Broadcasting Company's

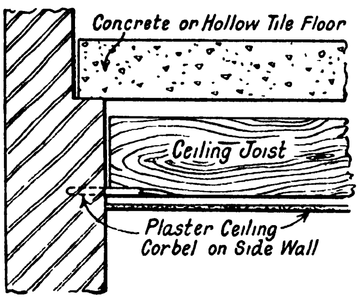


FIG. 128. INDEPENDENT CEILING BELOW CONCRETE OR HOLLOW TILE FLOOR

studios in New York is illustrated in Fig. 143. A similar type of suspended ceiling was described by v. Braunmühl.

Insulated or suspended ceilings have two disadvantages which should be pointed out: one is the loss of head-room, referred to above. The other is that, unlike floating-floor treatments, they only affect the sound coming through the ceiling and do not affect any noise coming from the side walls of the room. (See Fig. 130.)

The treatment has an undoubted utility, however, in that it can be used in conjunction with a floating floor to obtain specially good insulation. It finds another important application in existing buildings where alterations of floor level are impracticable.

USE OF FLOOR COVERINGS

Soft floor coverings such as carpets owe their impact-insulating value presumably to their elasticity, owing to which the sharpness of impact of a footfall is lessened. Soft coverings tend to remove the high-frequency components in the impact sound,* changing the sound from a sharp "tap" to a low "boom."

No measurements appear to have been made upon very thick pile

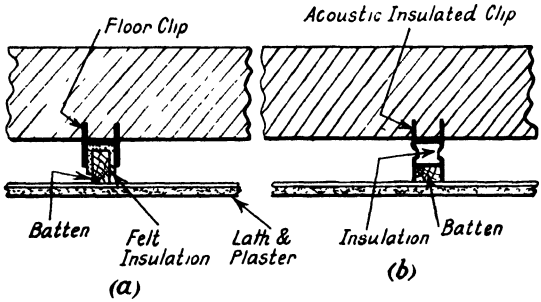


FIG. 129. INSULATED SUSPENDED CEILINGS
(a) Using ordinary floor clips.
(b) Using special acoustic floor clips.

carpets, and it is possible that these may have considerable value; ordinary Axminster carpet (about ⅓ in. thick) on underfelt (½ in. thick), however, effects an improvement of only between 5 and 10

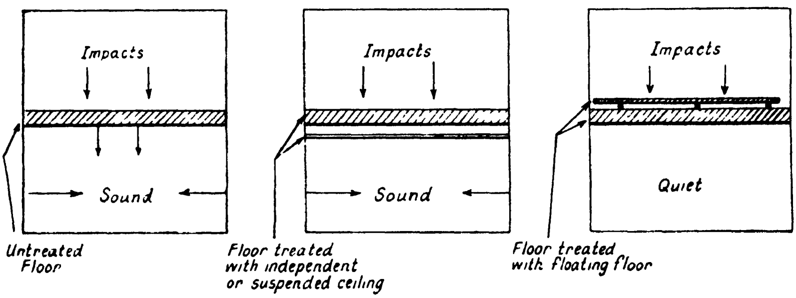


FIG. 130. ILLUSTRATING THAT AN INDEPENDENT OR SUSPENDED CEILING AFFECTS SOUND COMING THROUGH THE FLOOR ONLY, WHILE A FLOATING FLOOR REDUCES THE SOUND COMING THROUGH THE FLOOR AND VIA THE SIDE WALLS

phons, which though useful when added to the effect of some other treatment is not sufficient by itself to render an average untreated floor acceptable. Floor coverings incorporating sponge rubber provide greater insulation than this. These should be specially useful in corridors or other places where they are not required to support heavy furniture. Ordinary linoleum appears to have very little value. Soft floor coverings have, of course, the additional value of reducing the noise of footfalls, etc., in the room containing the source of noise.

* A. GASTELL: *Akustische Zeits.*, Vol. 1, p. 24, 1936.

USE OF FILLINGS IN WOOD-JOIST FLOORS

The use of fillings in wood-joist floors is quite old, though it was not, of course, used as a sound-insulating measure. Ashes, rubble, and clay, to mention only a few materials, have been used for this purpose: cases have been reported in which the floors of ancient buildings have been found to be filled with sea-shells.

The effect of fillings upon impact-insulation has been studied by Kreuger and Sager and by the National Physical Laboratory. It appears that filling the space between the joists of a wood joist floor (pugging, see Fig. 131) has some advantage, increasing appar-

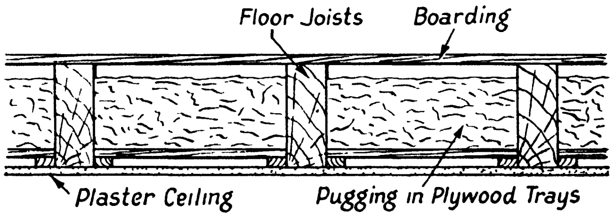


FIG. 131. FILLING BETWEEN THE JOISTS OF A WOOD JOIST FLOOR

ently with the weight of the filling. Light fillings, e.g. of peat or cork dust, have very little value, while heavy fillings of shingle (up to 40 lb./sq. ft.) effect a considerable improvement. Even so, the resulting floor appears to be no better than an equally heavy solid floor. Filling the space between the battens of a wood floating floor does not appear to be of any advantage.

The improvements obtainable from fillings are, as in the case of floor coverings, unlikely by themselves to make an average floor acceptable. However, the improvements obtainable from floor coverings, fillings, floating floors, and insulated ceilings appear to be approximately additive, so that securing satisfactory insulation is a matter of selecting the most convenient combination of treatments for the purpose.

TABLE XXI

Insulation of Floors against Impact Sounds

(a) Insulation against impact sounds afforded by various treatments applied to a 7 in. hollow tile and concrete floor.

Description of Treatment	Dead load on underlays (lb./sq. in.)	Insulation Gain (phons)
Concrete Floating Floors		
2 in. concrete resting on 1 in. rubber cubes on the structural floor (no skirtings). Rubber cubes on 18 in. centres, loaded to about 50 lb. per cube.		
1. Spacing between floating and structural floors : 2 in.		25
: 1 in.		20
: $\frac{1}{2}$ in.		15
Floor having skirtings as follows— : $\frac{1}{4}$ in.		10
2. No skirting (no contact between floating floor and walls) .		20
3. Steel skirtings		15
4. Skirtings of 4 in. by 2 in. wood insulated from floor by $\frac{1}{2}$ in. felt		15
5. Skirtings of 4 in. by 2 in. wood, against floor . . .		15
6. Mortar bridging gap between floating floor and walls . .		15
3 in. concrete resting on 1 in. rubber cubes on the structural floor. Rubber cubes on 18 in. centres, loaded to about 75 lb./sq. in. (no skirting).		
7. Spacing between floating and structural floors : $\frac{3}{4}$ in. . .		25
2 in. concrete resting on underlays as follows—		
8. Glass-silk quilt, single layer (nominal $\frac{3}{4}$ in.) . . .		20
9. Glass-silk quilt, double layer		25
10. Eel-grass quilt, single layer ($\frac{1}{2}$ in.)		15
11. Eel-grass quilt, double layer		20
12. Slag-wool blanket, double layer ($\frac{1}{2}$ in.)		15
13. Steel-wool pads, 1 in. thick (12 in. by 6 in. on 24 in. centres)		15
14. Granulated cork, 1 in. thick		10
15. Asbestos fabric ($\frac{1}{4}$ in.)		10
16. Clinker (2 in. coarse), on underfelt		10
17. Clinker and granulated cork (mixed)		10
18. Clinker (2 in. coarse)		5
19. Underfelt ($\frac{3}{16}$ in.)		5
Wood-raft Floating Floors	**Dead load on underlays (lb./sq. in.)**	
1 in. by 6in. boards on 2 in. by 2 in. battens on 18 in. centres, on underlays as follows—		
20. No underlay, battens in clips	—	0–5
21. Glass-silk blanket, $\frac{1}{2}$ in. thick, single layer .	$\frac{1}{3}$	10
22. ,, ,, ,, double layer .	$\frac{2}{3}$	15
23. ,, ,, ,, double strips, 6 ft. by 6 in.	$\frac{1}{3}$	15
24. Slag-wool blanket, $\frac{1}{2}$ in. thick, single layer .	$\frac{1}{3}$	10
25. ,, ,, ,, double layer .	$\frac{1}{3}$	10
26. Eel-grass quilt, $\frac{1}{2}$ in. thick, single layer . .	$\frac{1}{3}$	10
27. ,, ,, ,, double layer . .	$\frac{1}{3}$	10
28. Wallboard ($\frac{1}{2}$ in.) of wood shavings bound with cement, strips 6 ft. by 6 in.	$\frac{1}{3}$	0–5
29. Rubber pads, 1 in. cube	20	15
30. Fibreboard pads, $1\frac{1}{2}$ in. by $1\frac{1}{2}$ in. by $\frac{1}{2}$ in. thick.	15–30	5
31. Felt pads, 2 in. by $1\frac{1}{2}$ in. by 1 in. thick . .	10	10
32. Asbestos fabric pads, 2 in. by $1\frac{1}{4}$ in. by $\frac{1}{2}$ in. thick	10	5
33. Clinker (3 in.)	—	0–5

TABLE XXI—(*contd.*)

Description of Treatment	Insulation Gain (phons)
Isolated Ceilings	
7 in. by 2 in. joists resting on 4 in. by 3 in. wall plates, supported on corbels on side walls.	
34. ¼ in. plaster on ⅜ in. plaster board, plates direct on corbels, gap at edges bridged with plaster	15
35. ¼ in. plaster on ½ in. fibreboard, plates direct on corbels, gap at edges bridged with plaster. (Placing rubber pads on the corbels and stopping the ceiling short of the walls does not in these cases improve the insulation gain.) .	15
Suspended Ceilings	
36. ¼ in. plaster on ½ in. fibreboard on 2 in. by 2 in. battens held in felt-lined clips.	10
37. Ditto, edges bridged with plaster	5
38. ¼ in. plaster on ½ in. fibreboard on battens held in uninsulated clips	5
39. ⅜ in. plaster on ⅜ in. plaster board on battens held in felt-lined clips	10
(Increasing the weight of No. 38 from 7 lb./sq. ft. to 15 lb./sq. ft. by adding alternate layers of plaster and plaster board increased the insulation by nearly 5 phons.)	
Soft Floor Coverings	
40. Sheet rubber (1/16 in.) on ¼ in. sponge rubber . . .	20
41. Rubber cork (⅛ in. hard) on 3/16 in. soft rubber cork . .	10
42. Rubber-felt blocks (1¼ in.)	10
43. Axminster carpet (⅛ in.) on underfelt (⅛ in.) . . .	10
44. Hard rubber cork (¼ in.)	10
45. Sheet rubber (¼ in.)	5
46. Axminster carpet (⅛ in.)	5
47. Lino (1/8 in.) on 1/10 in. cork	5
48. Douglas fir blocks (1⅛ in.)	5
49. Lino (⅛ in.)	5
50. Lino (⅛ in.) backed with roofing felt	5
51. Additional concrete (3 in.)	0

(*b*) *Insulation against impact sounds afforded by various treatments of a wood-joist floor of* 9 *in. by* 2 *in. joists on* 17 *in. centres, lath and plaster ceiling, and* 5 *in. by* ⅞ *in. floorboards. All floors covered with linoleum.*

52. Wood-joist floor with space between joists filled with slag wool up to within 1 in. of floorboards	3
53. Ashes filling space between floorboards and plywood trays attached to the joists 5½ in. below floorboards . .	5
54. As (53), but with thickness of ashes reduced to 2½ in.. .	5
55. Wood-joist floor, but floorboards replaced by raft floor (of 5 in. by ⅞ in. floorboards on 2 in. by 2 in. battens on 17 in. centres) resting on eel-grass blankets laid across the joists	5
56. As (55), but with glass-silk blanket instead of eel grass . .	10
57. As (54), but with floorboards replaced by raft floor resting on sheet of ½ in. fibreboard laid across the joists . .	5
58. As (54), but with the floorboards replaced by raft floor resting on 2 in. by 1½ in. by ½ in. fibreboard pads nailed to the joists at 3 ft. centres	5
59. As (54), but with addition of raft floor resting on eel-grass blanket laid on the floorboards	10
60. As (59), but with glass-silk blanket instead of eel grass .	15

CHAPTER XIV

CONDUCTION OF SOUND THROUGH THE BUILDING FABRIC

TRANSMISSION of sound through the building fabric has only recently been the subject of experimental investigation. It is, of course, well known that noise generated in one part of a building (particularly by hammering) can often be heard over an extended area. The origin of such sources of noise is often difficult to locate, as for example when hammering which appears to be in an adjacent room is actually found to be some distance away.

Some measurements upon the transmission of sound through building materials have been made by Meyer,* who experimented with isolated specimens of the materials concerned in the form of bars. His results show that in the four building materials steel, brick, concrete, and wood, the sound attenuation increases in that order, being least in steel and greatest in wood.

Probably the first measurements upon sound-transmission through the building fabric were made by Berg and Holtsmark in Norway,† who, leaving a loudspeaker operating in one room in a building, measured the sound in all the other rooms. The results they obtained showed that while the difference between the sound levels in the loudspeaker room and the room adjacent to it was about 35 db. (the sound-reduction to be expected from the particular partition used), the difference of intensities between others of the same row of rooms was very much less (only 3–4 db.). This showed that sound does not reach a distant room only by a process of being transmitted through the successive intervening partitions (otherwise it would have dropped 35 db. in intensity as each room was passed). Berg and Holtsmark accepted this as evidence that the sound reached distant rooms by another path, viz. by the structure of the building. Sound is, of course, in these circumstances audible in the structure when an ear is pressed against it. From these measurements they deduced that this structure-borne sound decayed in intensity by about ½ db./ft. in the particular building they studied (18 in. brick walls; 4 in. reinforced concrete floors). A similar attenuation has been observed in a reinforced concrete building.‡

A. Gastell in Germany has measured the attenuation in the structure of buildings of noise due to impacts.§ He concluded that reinforced concrete and steel-framed buildings transmit

* *Vereines Deutsche. Ing.*, Vol. 78, p. 957, 1934.

† R. BERG AND J. HOLTSMARK: *Royal Norwegian Sci. Soc., Proc.* No. 22, Vol. 6, 1933.

‡ J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 50, p. 368, 1938.

§ A. GASTELL: *Akustische Zeits.*, Vol. 1, p. 24, 1936.

such sounds more readily than do buildings of brick. He also tested a steel-framed building in which, by wrapping the steel girders with 5 mm. cork, contact with the brick panels had been prevented. (See Fig. 132.) He found the attenuation of impact sounds was considerably improved by this treatment and was, in fact, about as great as in a brick building. The attenuation of noise due to impacts on the structure of a brick building has also been measured by Knowler* who found that the loudness in different rooms decayed at the rate of 0·3 phon per foot distance of the room from the source of impact. This figure was obtained for a sharp impact: for a dull blow, causing a lower-pitched noise, the corresponding figure was about 0·5 phon per foot. Factors such as the extent of window area in the various walls cause variations in the above figures. The general indications are that many factors besides the material used combine to determine the degree to which sound is attenuated during its passage through the building structure and that the general statements regarding the effect of any one type of construction must await a more extensive series of measurements.

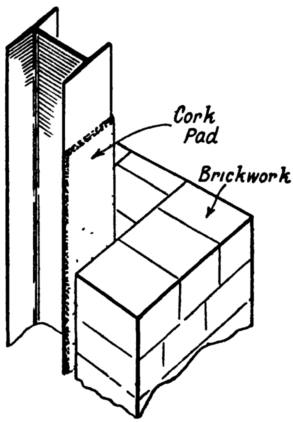


FIG. 132. GIRDERS OF STEEL-FRAMED BUILDING WRAPPED WITH CORK TO PREVENT SOUND-TRANSMISSION BETWEEN GIRDERS AND BRICK PANELS

Hofbauer and Bruckmayer† in Austria have experimented with the special patent wall construction shown in Fig. 133. This method of building walls (termed "Novadom") dispenses with mortar but appears to rely upon frictional forces for its stability. The bricks in any one course are laid touching each other, but without any cement; between each course and its neighbour is a layer of a wood-wool and cement material (of the "Thermacoust" or "Heraklith" type.) There is said to be so much friction between bricks and the wood-wool slabs that a building constructed in this way is perfectly stable, and it is understood that a number of buildings in Austria have been built using "Novadom." It is to be expected that walls of this type would have acoustical advantages, since the layers of binding material would probably not transmit vibration so easily as does solid material, and the air spaces between the bricks should provide some insulation against sound travelling in a horizontal direction. The measurements published by the inventors of this construction gave

* A. E. KNOWLER, *Phil, Mag.*, Ser. 7, Vol. 31, March, 1941.

† G. HOFBAUER AND F. BRUCKMAYER: *Akustische Zeits.*, Vol. 2, p. 249, 1937.

an attenuation of about 10 db./ft., which is very much greater than the corresponding figure for ordinary brickwork.

At present it appears that if transmission through the structure is to be reduced, this end is more likely to be achieved by interposing definite discontinuities in the structure than by using special materials. Examples of the application of the "principle of discontinuity" are given in Chapter XV.

Insulation of Buildings against External Vibration. There does not seem to be much information available regarding the insulation of a building as a whole against vibration originating outside

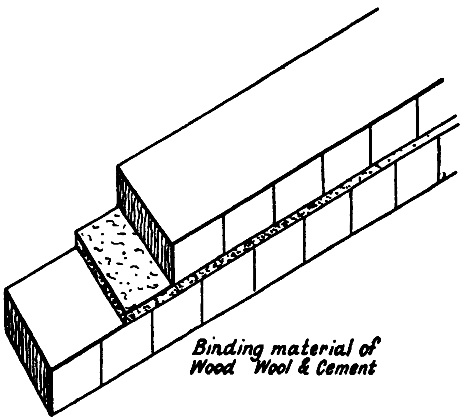


FIG. 133. "NOVADOM," A METHOD OF DRY-WALLING IN WHICH THE HORIZONTAL COURSES OF WOODWOOL-CEMENT BLOCKS REDUCE THE TRANSMISSION OF STRUCTURE-BORNE SOUND

the building. Theoretically, the principle of providing a low-frequency support, which is applied in the case of machinery, should also be applicable to insulating buildings. A good many buildings have been built upon elastic material which has been used under the foundations, or more often under the stanchions only. Cork has been used occasionally; so also have bituminous materials and asbestos. No test results appear to have been published, however.

As explained in Chapter VI, it is difficult to provide insulation at very low frequencies. This is particularly unfortunate where one is aiming at preventing traffic vibration from reaching a building, since traffic generates considerable low-frequency vibration. A method which has been tried in such cases is to abandon any attempt at insulating the building, but instead to erect the building on a concrete raft with the object of increasing its inertia. Shell House in Berlin was reported to have used this method, apparently with success, the concrete raft having a minimum thickness of 3 ft., an air space being left between the retaining walls and the main structure.

Several reports have appeared to the effect that cutting a trench in the ground between the source of disturbance and the building has proved effective in reducing the transmission of vibration. Other experiments, however, appear to have shown that, while the trenching cuts off the earth waves which are propagated through the earth layer intersected by the trench, other waves pass round the trench, and the net effect of the trench is generally small. It seems probable that where trenching has proved successful, the trench must have cut through a layer of earth having specially good conducting properties.

While it is possible that some degree of protection can be obtained by the methods described above, the better plan seems to be to avoid the trouble, if possible, by placing the building a sufficient distance from the source of vibration. In this connexion it is said that rock and chalk transmit vibration readily, particularly high frequencies; clay and sand transmit chiefly low frequencies, particularly if wet. It is commonly held that firm, dry gravel is the best building soil for minimizing the effects of vibration.

CHAPTER XV

GENERAL CONSIDERATIONS IN THE DESIGN OF A SOUND-INSULATED ROOM

In the previous chapters we have considered the factors which influence the sound-transmitting properties of the various features, taken singly, which make up the modern building. As, in practice, sound enters a room simultaneously through a number of paths—walls, doors, windows, ventilators, etc.—it is the purpose of the present chapter to describe methods of assessing the contribution which sound transmitted by individual paths makes to the total sound energy in a room. The paths will, so to speak, be viewed collectively, and principles will be described which should be taken into consideration when a sound-insulated room is being designed.

One general and obvious principle is that in an economical design the amount of sound conducted into a room by the various paths should be about the same. There is, in fact, no point in making certain parts of the room structure highly insulating if other parts insulate but moderately.

A sound-insulated room may be required in any of a wide variety of positions. The term is rather vague, and may mean anything from a "soundproof" test chamber to rooms in an hotel or block of flats in which attention has been paid to obtaining reasonably quiet conditions.

CALCULATION OF INSULATION PROVIDED BY A COMPLETE ROOM

The method of calculating the sound-insulation of a complete room varies in its details, but the general treatment is—

1. Calculation of effective insulation against transmission by direct paths, e.g. directly through a partition or floor.

2. Calculation of the allowance to be made for the absorbent conditions of the rooms concerned.

3. Estimation of the allowance to be made for transmission by indirect paths, e.g. through the building fabric.

These three aspects are dealt with in this order below.

1. Insulation against Transmission by Direct Paths. For the purpose of calculating the effective insulation against transmission by direct paths a very convenient formula obtained by Jaeger* in 1911 is required. This formula is also of very great use in many other connexions. It states that if the density of acoustical energy, i.e. the energy in unit volume, in a room is E, then the rate e at

* S. Jaeger: *Sitzungsber. Akad. Wiss. Wien*, **IIa**, Vol. 120, p. 613, 1911.

which energy falls upon any area S in the room is given by the expression—

$$e = SEV/4 \text{ energy units per second} \qquad (1)$$

where V is the velocity of sound. As only relative figures are required for our purposes (absolute values being unimportant), this formula can be used in a simplified form, namely—

$$\text{Energy falling upon area } S \text{ per second} = KSE \qquad (2)$$

where K is a constant, the precise value of which is immaterial. E, being the energy density, may be taken as a measure of the intensity of the sound in the room.

As an example of the use of this formula, the extent to which the insulation provided by a door is spoilt by an imperfect closure will be calculated. Consider a door having an area of 20 sq. ft. and a sound-reduction factor of 20 db. If there is gap $\frac{1}{10}$ in. wide between the door and its frame and the perimeter of the door is 24 ft., the gap will have an area of $\frac{1}{5}$ sq. ft. The sound-reduction factor of this gap will be taken as 0 db., though, as described in Chapter XI, it may differ somewhat from this value. The acoustical energy falling upon the door and gap is, by Jaeger's formula, proportional to their respective areas. Thus 100 times as much sound falls upon the door as upon the gap. However, since the arithmetical sound-reduction factor of the door is 100 (20 db.) while that of the gap is 1 (0 db.), it follows that the door and the gap transmit equal amounts of sound. Put in another way, twice as much sound is transmitted through the combination of door and gap as if the closure had been perfect. The effective sound-reduction factor of the door is therefore only 50 (17 db.).

Transmittance. It will be noticed that in the above calculation the factor which determines the transmitting powers of the door or of any other structure is the ratio—

$$\frac{\text{Area}}{\text{Arithmetical sound-reduction factor}}$$

i.e. Area × Fraction of incident sound-energy transmitted.

This ratio is termed the *transmittance*, and is an extremely useful conception which can be applied to all sorts of partitions, windows, ventilating ducts, etc. It should be noted that the arithmetical sound-reduction factor, not the sound-reduction in decibels, is used in this formula. In the above calculation the transmittance of the door and the gap both equal $\frac{1}{5}$ sq. ft. Transmittance is measured in square feet if the area of the transmitting element is given in square feet. The figure given for the transmittance may be regarded as the area of an aperture which would have the same sound-transmitting power. It will be noticed that it bears a very close analogy to the "square feet of open window" used to express the sound-absorbing power of materials when calculating reverberation periods.

The conception of transmittance is of great value when calculating the insulation of a composite partition (e.g. a wall containing doors and windows). Jaeger's formula shows that, as in the example of door and gap cited above, the transmittance of such a partition is equal to the sum of the transmittances of the elements of which it is composed. As an example, consider a wall of area 200 sq. ft. and sound-reduction factor 100,000 (50 db.) containing two windows each of area 20 sq. ft. and sound-reduction factor 1,000 (30 db.) and one door of area 20 sq. ft. and sound-reduction factor 400 (26 db.). We will assume that the door and window closures are perfect. Then the transmittances of the elements are—

Wall (area 140 sq. ft.): $\frac{140}{100{,}000} = 0{\cdot}0014$ sq. ft.

Two windows (area 40 sq. ft.): $\frac{40}{1{,}000} = 0{\cdot}040$ sq. ft.

One door (area 20 sq. ft.): $\frac{20}{400} = 0{\cdot}050$ sq. ft.

The total transmittance is therefore 0·0914 sq. ft.

We may now calculate the "effective sound-reduction factor" of the composite partition—

$$\frac{\text{Transmittance}}{\text{Area}} = \frac{200}{0{\cdot}0914}$$
$$= \text{about } 2{,}000\ (= 33\text{ db.})$$

Thus the sound-reduction factor of the wall is reduced by 17 db. by building the windows and door into it.

A calculation of this type is very simple to carry out* and can be extended to include other building elements such as ventilation gratings or ducts. For example, in a calculation of the transmittance between a pair of neighbouring rooms there should be included a term for the transmittance of any duct which connects them. Thus if the arithmetical attenuation along the duct is R (see Chapter VIII) and the area of opening into the room is S, the transmittance may be taken at S/R, and should be added to the transmittance of the other items.

2. Effect of Absorption on Transmission of Sound between Two Rooms. The effect which the sound-absorbent conditions of the room surfaces have upon the effective insulation provided by the structure has been recognized for a long while, and a formula from which the

* A table which simplifies the process still further was given by C. J. Morreau in *Engineering*, 13th August, 1937.

magnitude of the effect can be calculated has been deduced. This formula has received some direct experimental verification* and is generally accepted. Its development is very simple, and as the calculation should help the reader to understand the principles involved, it will be set down here.

Consider two rooms, 1 and 2 (Fig. 134) and let there be a source of sound (loudspeaker, noisy machinery, etc.) in room 1. Then Jaeger's formula states that the energy falling per second upon

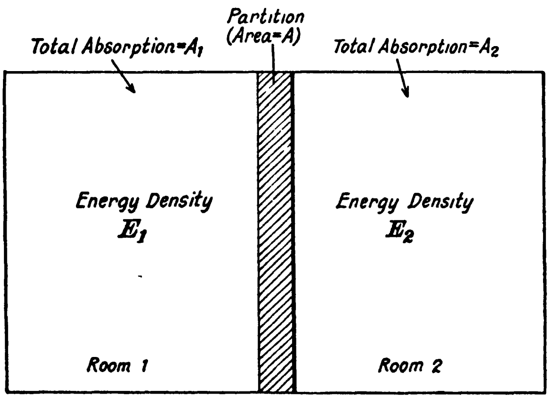


FIG. 134. THE EFFECT OF THE SOUND-ABSORPTION OF THE SURFACES OF TWO ADJACENT ROOMS UPON THE SOUND-TRANSMISSION BETWEEN THEM

unit areas in rooms 1 and 2 is KE_1 and KE_2 respectively, where E_1 and E_2 are the respective sound-energy densities in rooms 1 and 2.

Room 1. In room 1 the total sound energy falling per second upon the partition is, by Jaeger's formula, KE_1A (A being the area of the partition). The amount of energy transmitted through into room 2 per second is therefore KE_1A/R, where R is the sound-reduction factor.

Room 2. Fixing our attention upon room 2, we see that when conditions have settled down (reached equilibrium, as a scientist would say) the amount of sound energy entering the room must be equal to the sum of the energy leaving it and the energy absorbed in it. By putting this statement into the precise language of mathematics a useful formula can be obtained, as follows—

The energy leaving room 2 through the partition is KE_2A/R (compare the similar expression obtained for room 1). The energy absorbed will be $KE_2 \times$ (sum of products obtained by multiplying

* P. E. SABINE: *Journ. Acoust. Soc. Amer.*, Vol. 10, p. 102, 1938.

each individual area in a room by its absorption coefficient) = KE_2A_2, where A_2 = total absorption (see Chapter V). We can express this in the form of an equation—

$$\text{Energy entering room 2} = \frac{KE_1A}{R}$$

$$= \frac{KE_2A}{R} + KE_2A_2 \quad \text{(energy leaving and absorbed in room 2)} \qquad (3)$$

$$\therefore E_1 = E_2(1 + A_2R/A)$$

which gives the relation between the sound intensities in the two rooms. The calculated amount by which the actual ratio of intensities in a pair of neighbouring rooms exceeds the sound-reduction factor of the partition between is shown in Table XXII for various partition areas and total absorption. It will be seen that for average furnished rooms (partition 200 sq. ft. and total absorption 200 units) the actual ratio of intensities is about the same as the sound-reduction factor. Formula (3) shows one fact which is at first surprising, namely that if the total absorption $A_2 = 0$, then $E_1 = E_2$; i.e. the loudness of the sound is the same in both rooms, however effective the partition between them. A little thought will show that this is to be expected, since in a room which contains absolutely no absorbent, the sound builds up by repeated reflection until it is so intense that as much is transmitted back through the partition as is entering.

TABLE XXII

CALCULATED AMOUNT BY WHICH THE RATIO OF INTENSITIES OF THE SOUND IN TWO ADJOINING ROOMS EXCEEDS THE SOUND-REDUCTION FACTOR OF THE PARTITION DIVIDING THEM

Total Absorption in Receiving Room (sq. ft.)	Area of Partition (sq. ft.)			
	100	200	300	400
	(db.)	(db.)	(db.)	(db.)
50	− 3	− 6	− 8	− 9
100	0	− 3	− 5	− 6
200	+ 3	0	− 2	− 3
400	+ 6	+ 3	+ 1	0
1,000	+ 10	+ 7	+ 5	+ 4

The equation does not tell the whole story. It will be noted that it makes no mention of the absorption in room 1. That is because it deals only with the ratio of E_1 to E_2, and not their absolute values. If we go one stage farther and calculate the absolute values, it appears, as indeed is obvious, that the intensity in the second room depends equally upon the absorption in both rooms.

The lack of sufficient absorption in either room will lead to unnecessarily noisy conditions in the supposedly quiet room. The conditions are particularly bad if both rooms lack absorbent. Consequently it is advisable to ensure that there is plenty of absorbent in both the noisy and the quiet rooms, either in the form of furnishings, curtains, etc., or any special treatment; if the amount of absorbent is limited, the *total* available absorption should be divided equally between the two rooms. Practical considerations affecting the use of sound absorbents are given in Chapter V.

3. Transmission by Indirect Paths. The contribution which sound transmitted by indirect paths makes to the general sound intensity

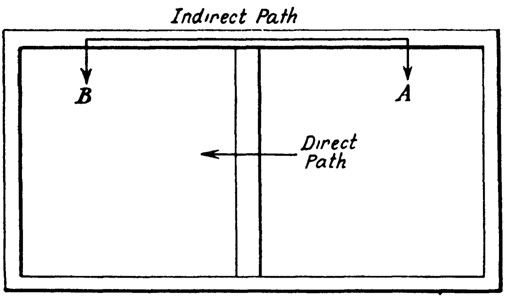


FIG. 135. THE EFFECT OF TRANSMISSION BY INDIRECT PATHS UPON THE INSULATION BETWEEN A PAIR OF ROOMS

in a room is a point which has been studied only recently (see Chapter XIV); probably, as more results are obtained, more exact methods of allowing for this form of transmission will become available.

(*a*) *Transmission between Adjoining Rooms.* Usually indirect transmission between two adjoining rooms takes place via the flanking walls and floors; Fig. 135 should make the point clear. Direct transmission from the noisy room to the quiet room takes place because the intervening partition is set into vibration by the sound; indirect transmission occurs because the flanking walls and floors also are set into vibration, and this vibration can travel along them for quite considerable distances.

The sound intensity in the room containing the source of noise is usually approximately uniform over the room, and consequently the acoustical pressures will be the same on all the walls and floors. The amplitudes of vibration of all the walls and floors of the noisy room (including the partition) will therefore, at least if they are solid, depend for all practical purposes solely upon their sound-reduction factors. This follows because, as explained in Chapter IX, the sound-reduction factor of a partition is determined by the amplitude of vibration it develops when subjected to sound having a given intensity. Thus if, to take a simple example, they are all solid, their amplitudes will depend, practically speaking, only upon their weight, in accordance with the mass relation. This has been observed experimentally.* As a practical example, if the walls and partition were all of 9 in. brick, they would all have the same amplitude of vibration. If, however, the partition were of 3 in. breeze blocks, its intensity of vibration would be some 10 db. more than that of the flanking walls.

The extent to which the vibration generated in the flanking walls and floors is conducted along to neighbouring rooms depends upon circumstances. Probably all the facts are not yet known, but the following statements have experimental backing—

1. Vibration is conducted less easily along walls on the ground floor than along walls on other floors.

2. Very little vibration is conducted along concrete floors laid directly on the ground.

3. Although in the noisy room the vibration of the walls and floors is determined largely by their weight, the vibration transmitted through the structure to other rooms is influenced by other factors as well. It is found that the vibration in the flanking walls and floors in these rooms tends towards a common level at any given distance from the noisy room. The vibration of light flanking walls falls, and maybe the vibration of heavy ones rises somewhat. Transmission along a light-weight flanking wall is not, therefore, so serious as might be expected; in fact, the evidence is that such a wall behaves much as if it had about the same weight as the heavier walls and floors to which it is attached. The word "heavier" used in the preceding sentence is important, and its significance will appear from the examples which are given later.

The relative contributions made to the total sound intensity by vibration of the various walls and floor and ceiling of a room may be taken as proportional to the products of the areas of the walls and their respective average intensities of vibration. (The term "intensities of vibration" is used loosely here as meaning "mean square amplitude of vibration."). It will be appreciated, therefore, that in a room in which, as is usually the case, the combined area of the flanking walls and floors is markedly greater than that of the partition, it is easily possible for the sound transmitted directly through the partition to be much less than that transmitted by indirect paths.

To illustrate the remarks made above, the effect of transmission by indirect paths in four commonly occurring cases will now be discussed.

Case 1. In Fig. 136 (*a*) is shown a pair of neighbouring rooms, the partitions and flanking walls and floors all having about the same weight, e.g. 9 in. brick walls and 6 in. concrete floors. In these

* J. E. R. Constable: *Proc. Phys. Soc.*, Vol. 51, p. 53, 1939.

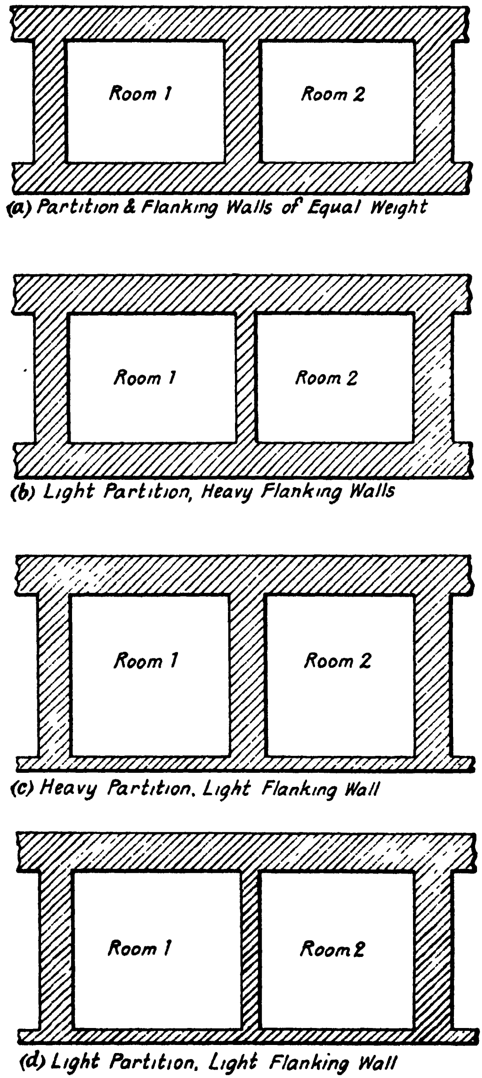


FIG. 136. TRANSMISSION BETWEEN ADJACENT ROOMS

circumstances the vibration of the walls and floors of room 1 (containing the source of noise) will all be about the same; there being little attenuation along the flanking walls and floors, the vibration of the wall and floor surfaces in room 2 will also all be about the same. As, usually, the area of the partition will be small compared to that of the other surfaces, it can happen that the transmission by indirect paths is greater than that through the partition. Examples have in fact been observed experimentally in which the indirect transmission was six or seven times as great as the direct transmission.* In such cases there would be no advantage in increasing the insulation provided by the partition unless the other surfaces were treated at the same time; for example all the surfaces could be faced with plastered plaster board fixed to insulated battens.

It should be added that there is evidence that by increasing considerably the weight of the partition the transmission along the flanking walls and floors would be decreased as well as that directly through the partition, but this is probably a remedy which will not often be practicable.

Case 2. A second case is illustrated in Fig. 136 (*b*), in which a light partition has been substituted for the heavy partition in Fig. 136 (*a*). In this case the indirect transmission will be much the same as before, but the direct transmission through the partition can be considerably greater. In this case increasing the insulation provided by the partition can effect a useful improvement, but (see Case 1 above) there would as a rule be no advantage in giving the partition a sound-reduction factor greater than that of individual flanking walls and floors.

Case 3. In Fig. 136 (*c*) is shown a construction which differs from Fig. 136 (*a*) in that one of the heavy flanking walls has been replaced by a light wall which might, for example, be a corridor wall built of light partition blocks. In this case the flanking transmission will be very little different from what it was in Case 1, for the vibration of the light wall is restricted by its connexion with the heavy partitions and floors. The total transmission of sound between rooms 1 and 2 will accordingly be about the same as in Case 1.

Case 4. In Fig. 136 (*d*) is shown another case which often arises, namely a combination of a light flanking wall with a light partition. The experimental evidence shows that even in this case the indirect transmission is little different from what it would be in rooms constructed as in Case 1. The direct transmission will, of course, be much larger, and it would be beneficial to increase the sound-reduction factor of the partition up to about the same as that of the individual heavy flanking wall and floors.

It seems from the above that as a rough general rule it may be taken that in average buildings there is no point in installing partitions having a sound-reduction factor greater than about 55 db.,

* J. E. R. Constable: *Proc. Phys. Soc.*, Vol. 51, p. 53, 1939.

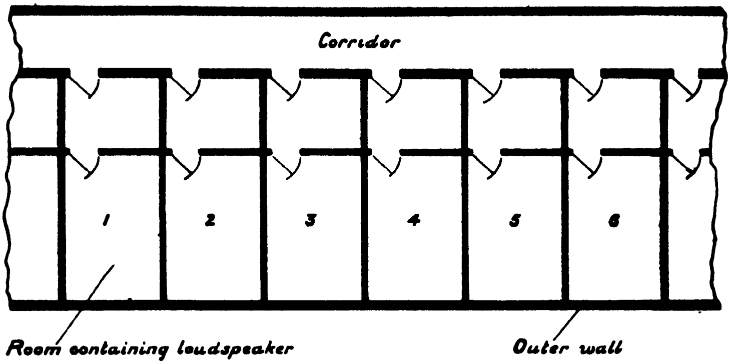


FIG. 137. TRANSMISSION BETWEEN DISTANT ROOMS

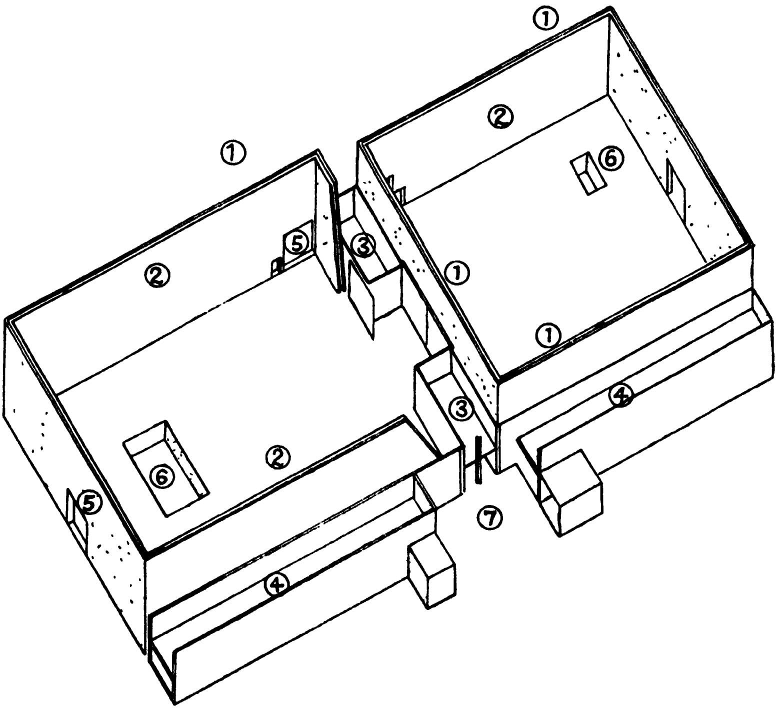


FIG. 138. FILM STUDIOS AT SHEPPERTON, ILLUSTRATING STRUCTURAL SEPARATION

1. Studios—structurally separate.
2. Soundproof lining disconnected with structure.
3. Solid brickwork structurally disconnected, for fan chamber, etc.
4. Dressing-rooms and offices structurally separate.
5. Sliding doors soundproofed.
6. Water tanks.
7. Hall and property stores ceiling removed to show disconnexion.

(*Connell Ward & Lucas*)

since the main wall and floors will not generally be better than this. If, subsequently, methods such as are mentioned in Chapter XIV for reducing indirect transmission are used in buildings, then higher insulations will be practicable for partitions.

As a result of indirect transmission it is to be expected that the insulation provided by a partition is likely to appear to be less in practice than it is when measured in the laboratory (where indirect transmission is prevented), the loss being greatest for partitions having the greatest insulation. As an example, it may be mentioned that, in one pair of rooms examined, the average insulation of a 9 in. brick wall was 46 db. as compared with laboratory figures of 52 db.,* the loss being largely attributable to indirect transmission.

(*b*) *Transmission between Distant Rooms.* Although indirect paths are important when adjoining rooms are considered, they play a major part in transmission to distant rooms. Were it not for transmission through the structure, the sound intensity in a series of rooms would decrease in steps of about the magnitude of the reduction factor of the partitions separating them. Actually this does not occur in practice, as the reader is probably aware. Measurements made upon a series of rooms,† as shown in Fig. 137. led to the results given in Table XXIII—

TABLE XXIII

TRANSMISSION TO DISTANT ROOMS THROUGH THE BUILDING STRUCTURE

Room	Approximate Distance from Centre of Room 1 (ft.)	Airborne Sound Intensity in Room (decibels above an arbitrary zero)
1	—	71
2	11	32
3	22	24
4	33	18
5	44	20
6	55	18

It will be noticed that after room 2 there is only a small drop in sound intensity as the distance from room 1 increases. This is clearly due to sound-transmission by indirect paths, since transmission along the corridors was proved to be negligible in this case, probably because of the "sound lock" provided by an anteroom. Other measurements (see Chapter XIV) have led to similar results. It will be seen from the above results that the sound intensity in the sixth room was not so very much less (14 db.) than that in the room next to the noisy room.

* J. E. R. CONSTABLE: *Proc. Phys Soc.*, Vol. 51, p. 53, 1939.
† J. E. R. CONSTABLE: *Proc. Phys. Soc.*, Vol. 50, p. 368, 1938.

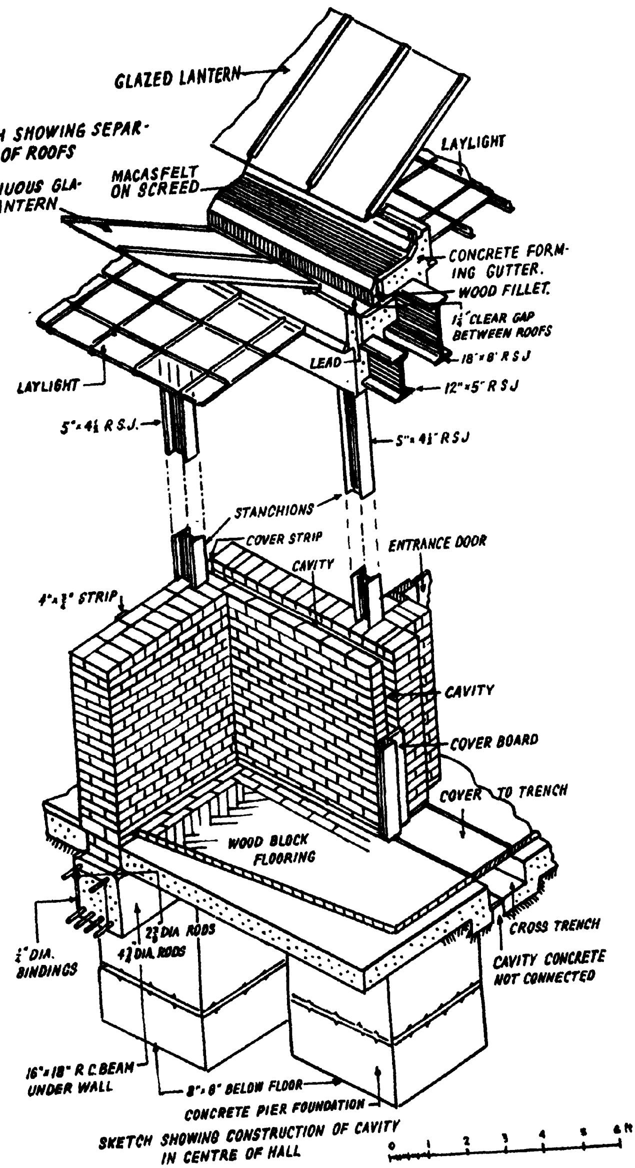


FIG. 139. THE ROYAL SOCIETY MOND LABORATORY, CAMBRIDGE

Construction of roof, walls, and foundations.

Note. The roofs of the two sections of the building overlap, and only lead aprons, a mortar joint filling, lightly nailed battens, and two insulating pads join the sections.

Principle of Discontinuity. The importance of using discontinuities in construction to reduce transmission by indirect paths is becoming increasingly realized. For example, in the film studios built at Shepperton (Great Britain) each studio was arranged to be structurally separated from its neighbour. The isometric sketch in Fig. 138 illustrates this point. A similar device was used in Broadcasting House, the headquarters of the British Broadcasting Corporation, in which the studios are contained in a tower which is structurally separate from the remainder of the building. Another example is the Royal Society Mond Laboratory in Cambridge (Great Britain) which was, as shown in Fig. 139, provided with structural discontinuities in floors, walls, and roof to isolate one part of the building from the other.

The above are examples of rather specialized constructions. An example of a more conventional building in which separation was provided is the Gilbey Building in London. The foundations of this building were insulated with cork, and to prevent the transmission of internal noises to offices, vertical cork joints carried to the full height of the building were provided which divided it into three separate units, two of which contain the services and the third the offices.*

When it is desired to insulate a single room, e.g. a test room, from the building structure, a satisfactory design is to construct the room as a separate box and to support it upon elastic material proportioned so that the frequency of vibration of the room on its supports is as low as possible. It is advisable to make the room of as massive construction as possible, and, of course, care must be taken that the insulation is not spoiled by rigid connexions such as would be provided by electricity conduits or gas pipes.

There is an example of this type of construction in the Acoustics Laboratory at the National Physical Laboratory, where the experimental rooms stand upon slabs of cork or, in some cases, numerous small pads of rubber. The loading used is round about 50 lb./sq. in., and the natural frequency of each room upon its supports is believed to be between 20 and 30 c.p.s. In these rooms special provision has been made for lifting the rooms for the purpose of renewing the insulation, should this be necessary.†

In one test room,‡ springs have been used instead of elastic materials to insulate the room from the building structure. Fig. 140 shows the general arrangement, in which the room is suspended from a steel roof structure. The suspension is of the pendulum type, with rods at each corner attached to spring mountings on the roof structure (see Fig. 141), and to special connexions at the base of the room. Lateral vibrations of the room are limited by rubber buffers. The

* *Building*, July 1937.

† *N.P.L. Annual Report*, p. 59, 1932.

‡ K. D. McMahan: *General Electric Review*, Vol. 41, p. 523, 1938.

room, which is designed primarily for testing the noise of fans and other ventilating equipment, contains several interesting features of design. An average insulation of 80 db. is claimed against noises originating in adjoining rooms.

A type of construction which is similar in principle to this has been used in the National Broadcasting Company's studios in New

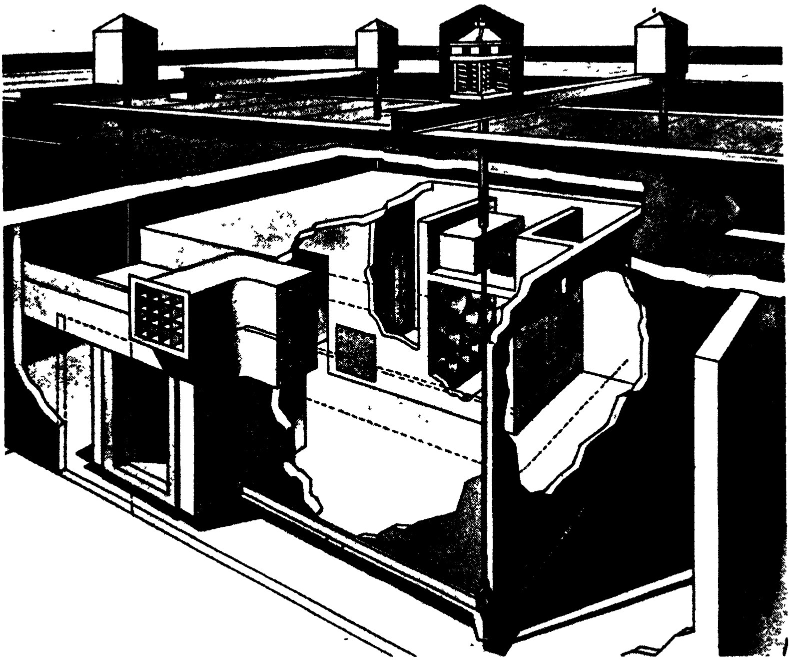


FIG. 140. A METHOD OF INSULATING A SINGLE ROOM
(Aphonic room of the General Electric Co., New York.)
(*International General Electric Co. of New York Ltd.*)

York. All the internal surfaces of the rooms concerned are covered with a heavy layer insulated from the structure; the floor is covered with a floating floor, the ceiling with a suspended ceiling, and the walls with plasterwork supported on insulating material. The construction is shown in Figs. 142–144 (inset).

A less elaborate type of construction has been described* suitable for test-rooms or studios which has the merits of ease of erection and removal. The rooms are composed of panels consisting of two sheets of steel cemented to two sheets of composition board with

* *Journ. Acoustical Soc. of Amer.*, Vol. 15, No. 1, p. 80, 1943.

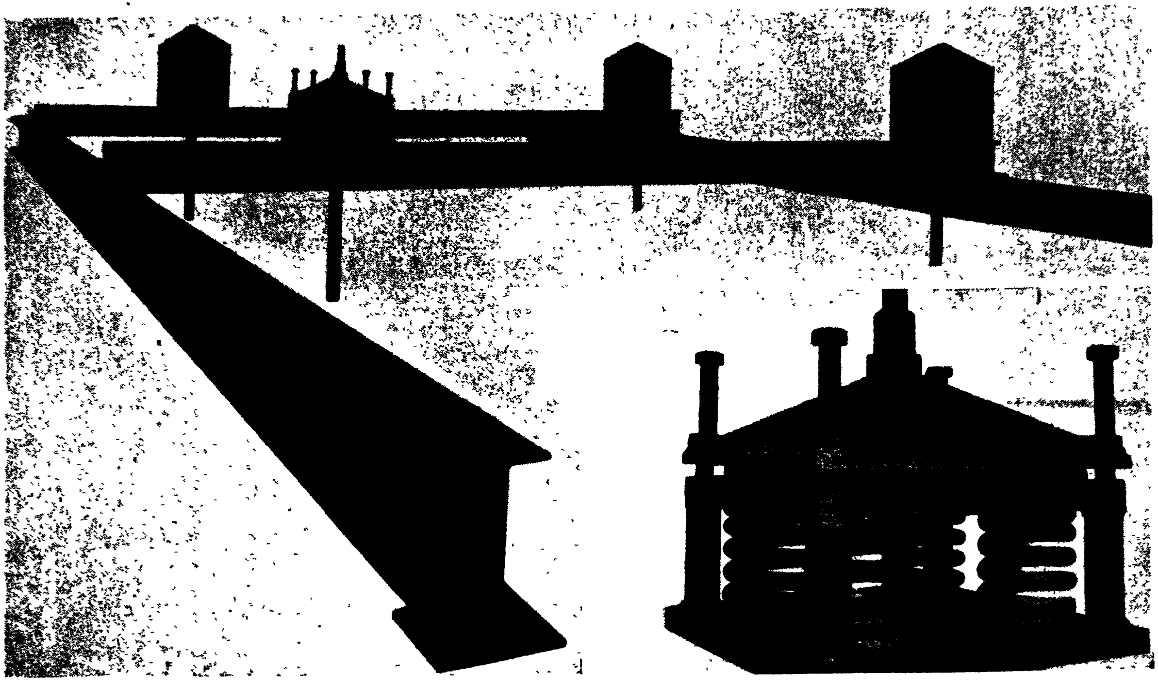


FIG. 141. DETAIL OF SPRING MOUNTINGS SUPPORTING ROOM IN FIG. 140
(International General Electric Co. of New York Ltd.)

a rockwool blanket between, and are supported on industrial type rubber mountings. An insulation of 43 db. is claimed for this construction, while 57 db. is obtained if a second room completely encloses the first room (except that the floor of the second room consists of the floor of the building).

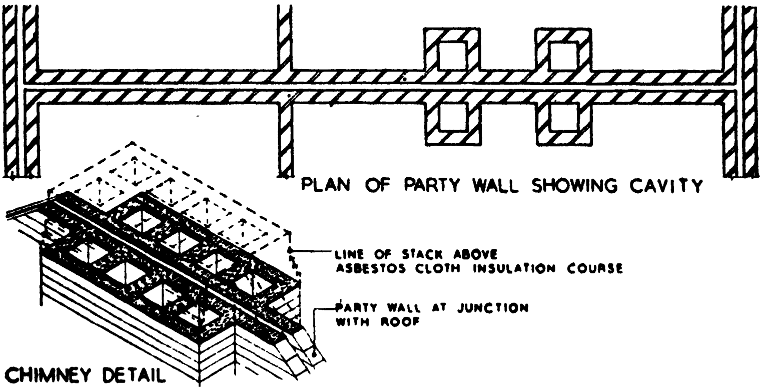


FIG. 145A. DISCONTINUOUS CONSTRUCTION FOR CAVITY-WALLED DWELLING HOUSES
(*H.M. Stationery Office*)

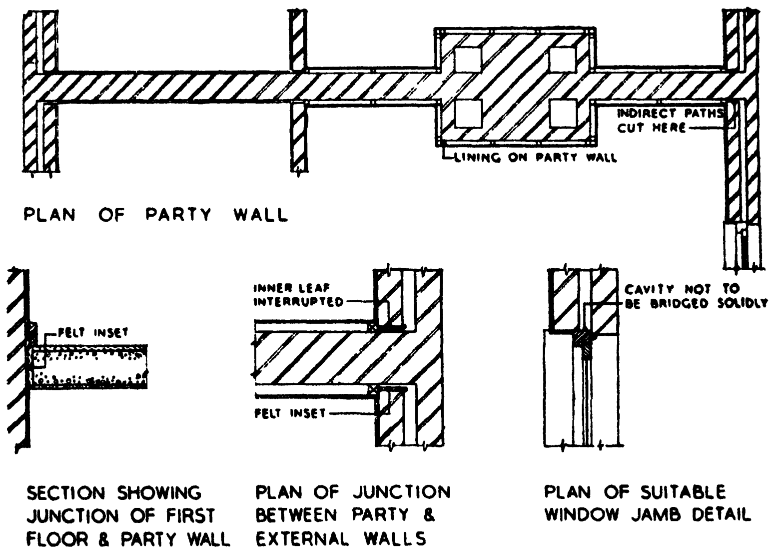


FIG. 145B. TREATMENT OF PARTY WALL AND DISCONTINUITY IN FLANKING WALLS IN DWELLING HOUSES
(*H.M. Stationery Office*)

In the case of house and flat construction, the value of the principle of discontinuity has been emphasized in the Report of the Acoustics Committee of the Building Research Board of the Department of Scientific and Industrial Research published as No. 14 in the series "Post-War Building Studies."*

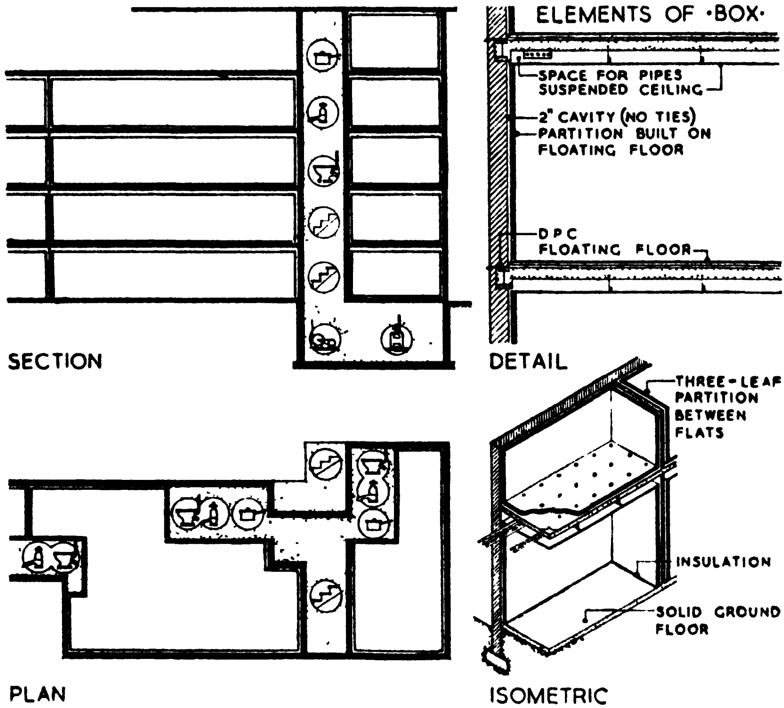


FIG. 145C. INSULATED BOX DESIGN FOR FLATS
Each room needing quiet forms a box which is insulated from the structure.
(*H.M. Stationery Office.*)

One construction, which has been experimentally tested, was found to yield an insulation of about 60 db. This was a simple and inexpensive design for houses in which each house constitutes a separate shell, the houses being cavity walled, both in the external and party walls (see Fig. 145A). The cavity in the external walls is continuous with that in the party wall. The chimneys are divided in common with the other portions of the party wall till just below roof level; they may be joined before they penetrate the roof, but then a sound-insulating layer such as asbestos cloth should be inserted in place of one of the mortar joints; alternatively the chimneys may penetrate the roof separately. The design may be

* H.M. Stationery Office, 1944.

adopted with solid external walls, the cavity in the party wall being then continuous to the outer face of the building where it is closed by a suitable type of expansion joint. In either case the party wall should be built if possible without ties, or only with twisted wire ties spaced as far apart as possible.

Other constructions, for which figures do not appear to be available, consist of an inner shell in the form of a lining round the rooms which are separated by the party wall. The lining material is usually plasterboard, fibreboard, or better, plastered lath, in each case mounted on battens. The battens should be fixed by felt lined clips. Alternatively the party walls only may be lined, and transmission along the flanking walls may be reduced by inserting discontinuities as shown in Fig. 145B. Fig. 145B shows the lining applied only to the living room walls, as the main sources of noise (e.g. radio) are usually in this room.

Similar principles applied to flats were given successful trials. All rooms needing quiet form a shell which is insulated from the supporting structure. The shell consists of a floating floor carrying lining walls and a suspended ceiling. Fig. 145C gives a diagram plan illustrating the principle. Fuller description and detailed drawings may be found in "Sound Transmission in Buildings" by Fitzmaurice and Allen.*

* H.M. Stationery Office, 1945

CHAPTER XVI

THE CHOICE OF A SOUND-INSULATING CONSTRUCTION

Loudness Reduction Factor of Partitions. So far, in this book, discussion of sound-insulation has referred only to differences in *intensity* of sounds of similar character. The ear, however, reacts differently to sound waves containing the same energy but differing in pitch (see Chapter I), so that when selecting an insulating construction, the choice should be governed by considerations of the reduction in equivalent loudness rather than the reduction in intensity which the construction will afford. The problem presented to the architect is not, at first sight, an easy one, for he requires to select a construction, the insulation of which can only be expressed by a series of figures (one for each frequency), these figures being in decibels to suit a noise of which all that is likely to be known is the equivalent loudness, expressed as a single figure in phons. The properties of the ear which are to a large extent responsible for this situation do, as a matter of fact, at the same time provide a simplification.

A Useful Rule. As was explained in Chapter IX (see Fig. 85) the sound-insulation of a partition normally increases as the frequency rises. In fact, for an average single partition the insulation increases by about 5 db. per octave (or frequency-doubling). The variation is greater in the case of a complex partition. Now, it happens that the ear is more sensitive to differences in low-frequency sounds. (See Fig. 9, Chapter I.) That is to say that, whereas for frequencies in the neighbourhood of 1,000 c.p.s. a 1 db. change of intensity is appreciated as a 1 phon change of loudness, in the neighbourhood of 100 c.p.s. a 1 db. change of intensity is appreciated as about 1½ phons change in loudness.* This compensates to some extent for the decreased insulation of partitions at low frequencies, and it so happens that this compensation is almost complete for single partitions having an insulation between 35 and 55 db. at 1,000 c.p.s. As the insulation of most partitions used in buildings in practice lies within this range, and the insulation at 1,000 c.p.s. is usually about the same as the insulation averaged for all frequencies (last column, Table XIV, Chapter IX), it follows that we can make the general rule that for most solid building partitions the average sound-insulation in decibels is numerically approximately equal to the reduction in loudness, expressed in phons, which is produced in the frequency

* The question of giving the sound-reduction factors in phons has also been studied by W. BAUSCH: *Gesundheitsingenieur,* Vol. 59, p. 757, 1936; E. MEYER: *ibid.,* Vol. 60, p. 750, 1937; A. GIGLI AND G. SACERDOTE: *Alta Frequenza,* 4–5, p. 229, 1936.

range 100–2,000 c.p.s. For sounds of higher frequency the reduction in loudness will be greater than the average sound-insulation. The above-mentioned relation affords a useful way of assessing the effect of a solid partition, but we must make clear that it is at best only an approximation to the truth. It is not possible to make a similar statement regarding complex partitions, since their behaviour is so variable. In so far, however, as many complex partitions transmit low frequencies more readily than a single partition having the same average insulation, it is wise not to attach too much significance to the mean sound-reduction factors of such partitions.

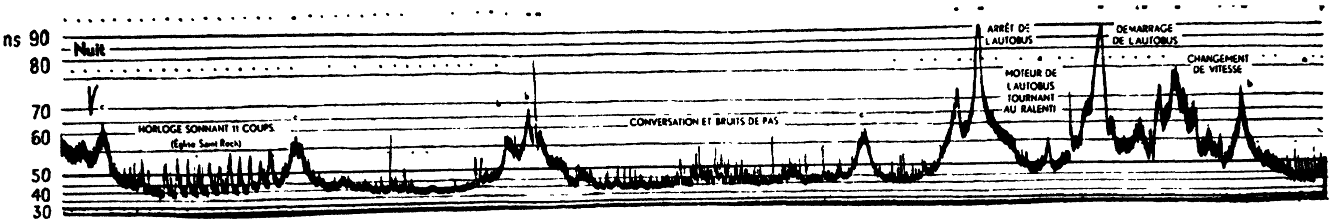
For simplicity the above discussion has dealt with the loudness reduction afforded by partitions where direct transmission alone is considered. The problem is rather more complicated, since transmission by indirect paths and sound-absorption effects have also to be taken into account. However, the same argument will apply to these, and accordingly we may say that provided the walls of the rooms concerned are solid (or, if complex, do not transmit low frequencies markedly more than would a solid partition having about the same insulation), the average sound-reduction, allowing for the effects of absorption and indirect transmission, will be nearly enough equal to the loudness reduction. Thus a pair of rooms separated by a 9 in. wall would be expected to show a loudness reduction of about 52 phons if the effects of indirect transmission and of reverberation were negligible. In practice, however, there would probably be up to 5 phons loss on account of indirect transmission and a possible further 5 phons on account of lack of absorption.

Consequently the actual loudness-reduction factor will be between 42 and 52 phons, depending upon the absorption. That is to say that if in the noisy room the loudness is 80 phons, the loudness in the "quiet" room will be between 28 and 38 phons.

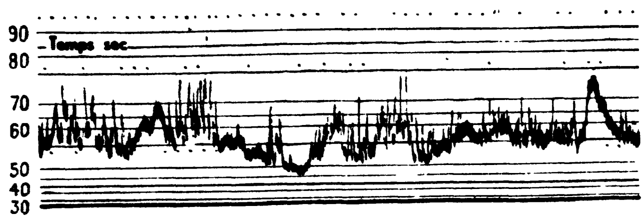
Methods of Estimating the Insulation Required. It will be seen from the above example that if the loudness of the noise against which insulation was required could be specified, and if the maximum tolerable loudness in the "quiet" room could be specified, there would be a means of choosing a suitable construction.

Figures for tolerable noise levels in rooms which give some assistance in this connexion have been given by various authors,* in other countries. In Great Britain, the most authoritative guidance so far available comes from the Acoustics Committee of the Building Research Board of the Department of Scientific and Industrial Research in a Report published in 1944 under the title "Sound Insulation and Acoustics"—Post-War Building Studies No. 14. The levels to which intruding noise should be reduced in rooms used for different purposes are listed, allowance being made for the fact that there is always a certain level of background noise in a room, which

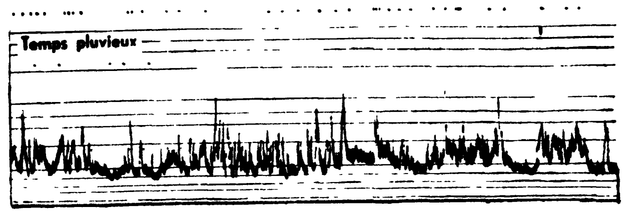
* V. O. Knudsen: *Architectural Acoustics* (John Wiley & Co.); H. Kreuger and J. H. Sager: *Proc. Roy. Swedish Inst. Eng. Res.*, No. 132, 1934.



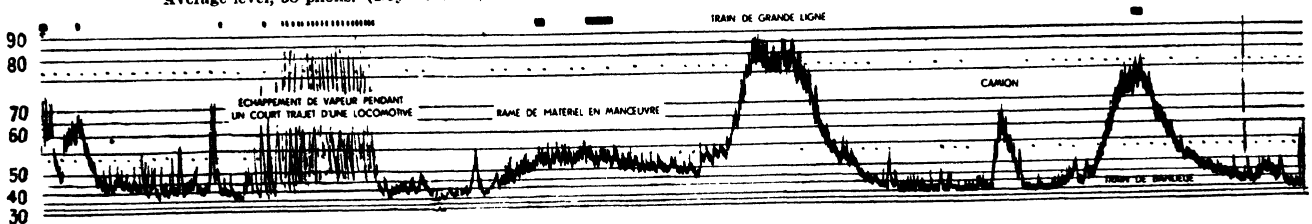
(*a*) Noise level in the Rue Saint-Honoré, Paris (10.57 to 11.10 p.m.). Average level, 50 phons.



(*b*) Noise level in the Rue Saint-Honoré, Paris (5.30 to 5.37 p.m., 9th August). Average level, 58 phons. (Dry weather.)



(*c*) Noise level in the Rue Saint-Honoré, Paris (5.35 to 5.42 p.m., 10th October). Average level, 52 phons. (Wet weather.)



(*d*) Noise level in the Rue Vercingétorix, Paris (5.37 to 5.41 p.m.). Average level, 52 phons. (Near heavy rail traffic.)

FIG. 146. FLUCTUATION IN INTENSITY OF TRAFFIC NOISE

helps to mask the intruding sounds. Table XXIV summarizes the conclusions reached in this Report.

TABLE XXIV

LEVELS TO WHICH INTRUDING NOISE SHOULD BE REDUCED IN VARIOUS ROOMS

Occupancy of Room	Noise Level (phons)
Study or sleeping	15
Reading or writing	20
Boardroom	30
Sedentary office work: quiet conversation	35
Average office, telephone work, and restaurant	40
Noisy office	60
School classroom	30
Hospital wards in urban areas	20

For the loudness of commonly occurring noises reference may be made to Table IV, Chapter I. Using these two tables a rough idea may be obtained of the insulation required.

Another method of estimating the insulation required relies upon the effect known as *masking*. If two sounds are heard simultaneously, then one will mask the other (which will not then be heard), provided the difference of loudness is sufficient (about 20 phons). Accordingly, if the expected noise level in a residential room is 35 phons and the noise level in the room next door will be of the order of say 70 phons, an insulation of 55 phons can be expected to make the sound entering the "quiet" room 20 phons less loud than the noise already there, and it should accordingly not be noticeable.

Effect of Fluctuations in Loudness of Noise. It has been implicitly assumed in the above calculations that the loudness of the noises concerned are constant. This is, of course, quite untrue generally. Most noises—street noises (see Fig. 146) and radio form good examples—vary over a wide range from minute to minute. Hence, if one is calculating the insulation required to reduce the incoming noise to a certain given level, it would first of all be necessary to decide whether one meant by this that—

1. At its *loudest* the incoming noise should not exceed a certain figure, or

2. That it should not do so on the *average*.

The problem is complicated, and is mentioned here not because a solution will be proposed but so that the reader can appreciate the difficulty.

One further difficulty should also be mentioned. If the insulation is calculated by allowing for the masking effect of the noise already in the room, one is faced with the difficulty that the masking noise (commonly conversation) will be continually varying in intensity, so that there will be occasions (when the level of the masking noise is low) when there will be no masking effect and the incoming noise will become audible. An everyday example will illustrate this point. While talking is in progress in a room, noise entering from a neighbour's room (e.g. radio) is commonly inaudible. During the inevitable lulls in the conversation, however, the sound entering from the other room becomes noticeable, and may be even objectionable. It would require a very elaborate construction to make the entering sound always inaudible.

Specifying the insulation required in these circumstances becomes then a matter of deciding how *frequently* interfering noise is to be heard as well as how loud it should be.

It must be concluded that satisfactory specification of insulation from noise-level measurements alone is, with the information at present at our disposal, a difficult matter. The fact appears to be that the noise conditions which will prove acceptable (and hence the insulation required) is largely a matter for personal judgment rather than for scientific measurement. For this reason the architect who knows what degree of quietness his client requires (it is a question of *degree* of quietness, for *absolute silence* is not achievable except in very special circumstances) is in a better position for specifying the insulation required than anybody else. He will know, from his experience, that with similar conditions of noise a certain construction was or was not satisfactory for the purpose he has in mind. He will be able (at least in most cases) to find, from the information given in this book, the numerical value of the insulation provided by previous constructions and can improve upon or repeat them as he wishes.

Suggested Minimum Values for the Sound-insulation of Constructions. Using the methods indicated above, and obtaining opinion from experienced sources, the Acoustics Committee of the Building Research Board have made, in the Report referred to above, the following proposals for standards of insulation (Table XXV).

TABLE XXV

STANDARDS OF INSULATION

(*a*) Between the living room in one dwelling and the living or bedrooms in an adjoining dwelling—usually by party wall	55 db.
(*b*) Between the living room and other rooms (except service rooms) in the same dwelling	45 db.
(*c*) Between bedrooms and other rooms in the same dwelling	35 db.
(*d*) Between school classrooms and corridors and between one classroom and another	45 db.
(*e*) Between bedrooms in hotels, if radio or musical instruments not used	45 db.

In comparing the values in Table XXV with the laboratory measurements of the insulation of partitions given in Tables XV and XVI, it should be remembered that the measured values for the heavier partitions may exceed those obtaining in practice by up to 6 db. on account of conditions of test, as explained in Chapter IX.

An insulation less than that provided by a 9 in. wall (52 phons) is not usually acceptable for a wall dividing houses or flats. As mentioned earlier, the higher insulation will often necessitate the rooms being built as discontinuous structures.

Standards of quiet for impact sounds are equally important, at least in the case of residential buildings, for the majority of complaints in blocks of flats are concerned with impact sounds rather than with airborne sound. Table XXVI gives the standard of insulation against impact sound suggested by the above Report in terms of the improvement over the insulation afforded by a bare concrete floor.

TABLE XXVI

STANDARDS OF INSULATION AGAINST IMPACT SOUND

Occupancy	Improvement over insulation of bare concrete floor
Typing, noisy office	5 phons
Telephoning, average office . .	10 ,,
Minimum recommended, for flats .	15 ,,
Reading or writing	30 ,,
Study or sleeping	35
School classrooms	15

In the case of timber floors, the figures in the above table should be increased by 5 phons.

CHAPTER XVII

PREVENTING NOISE FROM LEAVING A BUILDING

THE greater part of this book is concerned with constructing buildings to prevent entry of noise. The reverse, namely constructing a building or part of a building from which the issue of noise is prevented, is, however, frequently required. Examples are factories and power stations; which, if in residential areas, may have to be specially constructed to prevent the emergence of noise. The practice of placing transformers out of doors has at times proved troublesome from the noise standpoint. Occasionally the only remedy is to enclose the transformers in a suitable building.

In the design of such buildings, as in the case of buildings intended to exclude noise, attention must be paid to reducing the transmission of both structure-borne and airborne sound.

Reducing Structure-borne Sound. Structure-borne sound will reach surrounding property by conduction, either through the intervening earth or through a common building structure. Some reduction of transmission via the earth can possibly be obtained by inserting insulating pads between the building and its foundations or by erecting the building on an exceptionally massive concrete raft, or by trenching. There does not appear, however, to be any clear evidence that these methods are particularly effective for this purpose. They are mentioned because they have often been recommended. Conduction through the building fabric can also be reduced by the methods described in Chapters XIV and XV. There can, however, be no doubt that the better plan is to insulate the cause of vibration from the building, thus dealing with the nuisance at its source. Heavy machinery such as generating sets and large reciprocating compressors have been successfully dealt with in this way (see Chapter VI).

Reducing Airborne Sound. A great deal can be achieved by suitable planning. Windows, unless they are sound-insulating, should, if possible, only be inserted in sides of the building which do not face towards other property. Where there are several buildings it is a sensible and obvious step to arrange for the noisiest to be screened from surrounding property by the others. In this connexion it will be remembered (Chapter I) that owing to acoustical diffraction effects it is not sufficient that the noisy building is optically screened, i.e. invisible from the surrounding property: the buildings used as screens should be as high as possible, particularly where low-frequency sound is concerned. Incidentally, it should be remembered, as is obvious from Fig. 147, that a screen which might be valuable for screening buildings on the same level may prove totally ineffective as regards buildings on a higher level. When selecting the site, therefore, it is as well from the acoustical point of view to avoid a position at the foot of a hill which is likely to be built upon. It is wise also to avoid reflecting surfaces such as might be provided by adjacent high buildings (Fig. 148). The acoustical desiderata are, in fact, a level piece of land

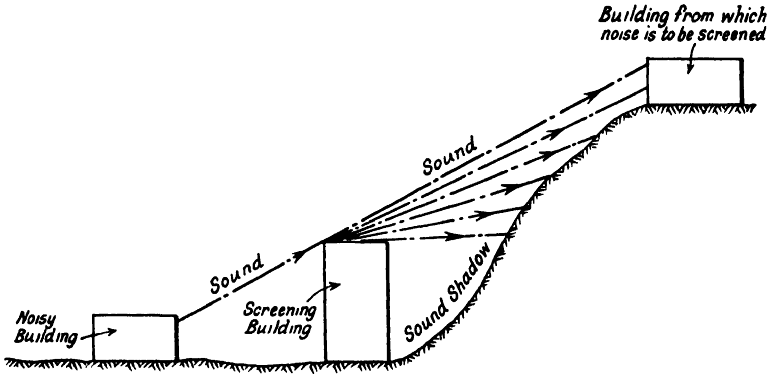


FIG. 147. ILLUSTRATING HOW A SCREEN WHICH MIGHT BE VALUABLE IN SCREENING NOISE FROM BUILDINGS ON THE SAME LEVEL IS INADEQUATE TO SCREEN BUILDINGS ON A HIGHER LEVEL

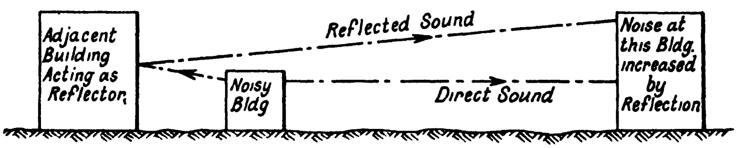


FIG. 148. ILLUSTRATING HOW AN ADJACENT HIGH BUILDING CAN, BY ACTING AS A REFLECTOR, INCREASE THE NOISE HEARD AT NEIGHBOURING BUILDINGS

surrounded as far as possible by a thick belt of high trees and having no high buildings near to cause reflection effects.

It is often not possible to deal with the noise problem by planning alone. It is then necessary to take steps to restrict the emergence of sound from the building concerned. The construction of sound-insulating walls, doors, and windows and the use of sound-absorbent treatment in the interior will not be dealt with here, as it has been discussed already (Chapters V and IX–XII). This section will instead be confined to certain special features peculiar to the problem of preventing the emergence of noise from buildings.

It often happens that the roof of a factory is of quite light construction. If noise is not to emerge from such a building, the roof should be treated as well as the doors and windows. The roof insulation can often be improved merely by making it airtight, e.g. by laying roofing felt over or below it. A further improvement is to be expected if the roof is converted into a double construction by fixing an inner skin of building-board or similar relatively non-porous material below the rafters.

If greater insulation is required (and also where the roof is of glass to give natural light), a possible construction is to erect a horizontal ceiling, incorporating glazing if necessary, cutting off the roof from the remainder of the building. The space between the new ceiling and the roof should be rendered sound-absorbent as described

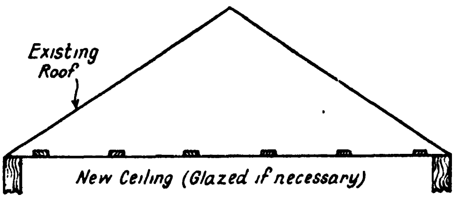


FIG. 149. A METHOD OF REDUCING THE SOUND TRANSMITTED FROM A BUILDING THROUGH THE ROOF

in Chapter V. (See Fig. 149.) Incidentally, double constructions of this kind have the additional advantage of reducing heat loss from the building.

Ventilation. The building, once soundproofed, will probably require a system of ventilation. Methods of preventing the transmission of sound through the ventilating system have already been dealt with (Chapter VIII). Only one problem calls for special notice. Aero-engine test beds, by reason of the intense noise generated, require careful sound-insulating treatment. The problem is in this case complicated by the fact that the engines while under test have to be in a powerful air stream, which is drawn from the outside. To reduce the sound conducted along the inlet and exit ducts calls for extensive treatment. In the case of one factory the engine test house (see Fig. 150) consists of two buildings, one inside the other and completely separated by an air space. Both buildings rest upon cork insulation. The inner one is lined with absorbent, as are also the inlet and outlet ducts. The outlet duct, incidentally, is about 100 ft. long and is directed towards waste land. Treatment which has been applied to existing test houses in America is described by R. Walsh and E. D. Eaton.*

Construction of Belfries. Many people like listening to bells in the distance, but not everybody is prepared to enjoy the same bells when heard near by. It has accordingly become an important

* *Journ. Aeronaut. Sci.*, Vol. 4, p. 107, 1937.

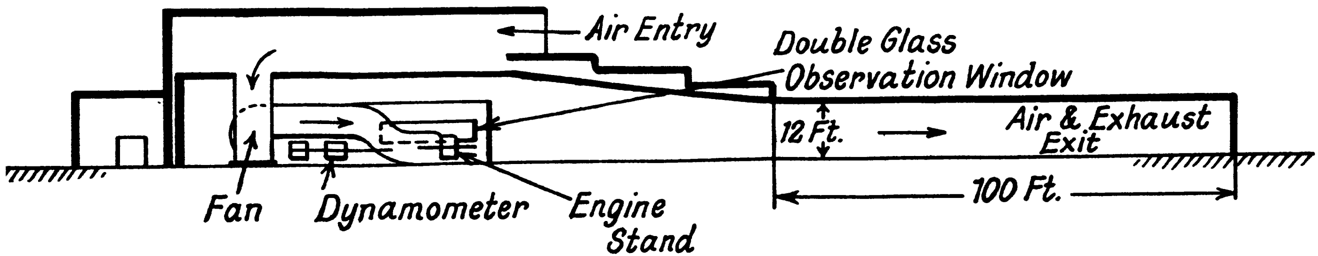


Fig. 150. Scheme of Silenced Aero-Engine Test Bed

acoustical problem to design belfries so that while the bells can still be heard at a distance the sound in the immediate neighbourhood of the belfry is kept at a reasonable level.

The problem does not appear to have been the subject of exact measurement, but the following are the recommendations usually given. The sound-windows at the sides of the belfry should be blocked up almost entirely, preferably with brickwork but alternatively with heavy boarding caulked or lined with roofing felt. New windows should then be cut in the roof of the belfry. Belfries designed on this principle are said to have been used in the Church of the Annunciation, Chislehurst (which has an octagonal louvred roof behind a parapet), and All Saints Church, Basingstoke, which has a wooden spire with four louvred dormer-shaped windows just above the parapet. If daylight is required in the belfry, sound-insulating windows can be provided in the sides. It is also recommended that the bells should be placed as low down the tower as possible so as to prevent their being heard directly through the sound-windows. This should not be overdone, however. W. Bond* has quoted the examples of a church in which the bells were 15 ft. below the windows and could only be heard inside the church. When the belfry at Lincoln Cathedral was reconstructed, the bells were lowered and the sound-windows were provided with reversible louvres, so that while normally they slope downwards, they can be made to slope upwards when the bells are being rung, with the object of directing the emergent sound away from the ground. It appears that these alterations were very successful, both in reducing the sound near by and in increasing the intensity at distances away from the cathedral.†

* *Journ. R.I.B.A.*, 10th August, 1935.

† See *Journ. R.I.B.A.*, 42, Third Series, No. 16, 29th June, 1935.

CHAPTER XVIII

NOISE AND THE LAW

THE control of noises which affect the occupants of buildings is a matter of monetary importance. The architect cannot prevent occupants of a building being disturbed by noise which arises outside except by incurring the expense of making the building more or less soundproof. There are, however, various bodies within whose province it lies to prohibit certain classes of noise; much has already been done, but more could be achieved if the public were sufficiently insistent.

Noises which affect buildings are conveniently divided into local noises which are peculiar to the district concerned, and general noises which are likely to be found almost anywhere. Local noises such as the noise of factories, aerodromes, garages, electricity stations, and even church bells are frequent causes of complaint, and can often be dealt with by concerted and, if necessary, continued action.

Of general noises, that of traffic probably concerns the architect and his client most. In city streets, trams, particularly at curves and crossings, are probably the worst offenders, being well seconded by steam lorries and other heavy commercial vehicles. Sports cars, motor-cycles, and antiquated delivery vans can make themselves objectionable, and even ordinary private cars can be very disturbing, particularly at night, when cornering or ascending steep hills. Other noises which cause general complaint are loud-speakers and gramophones, street hawkers and street musicians, barking dogs and other noisy animals, and, not least, low-flying aeroplanes.

It is not always necessary or advisable to resort to legal proceedings to abate a noise. Factory owners, electricity undertakings, and others have in many cases voluntarily taken steps to reduce the noise emerging from their premises. If requests do not produce a satisfactory response, legal action may be taken, the nature of which will depend on the individual case.

IN GREAT BRITAIN

In this country noise comes within the reach of the law in two ways. It may be dealt with by proceedings at common law if in any particular case it can be identified as a nuisance; or it may offend against a statute (including by-laws made by local authorities in the exercise of their statutory powers), in which case the appropriate authority will deal with it. These two aspects are dealt with below. It should be pointed out, however, that while every care has been taken to ensure that the information given is correct at the time of writing, the authors cannot guarantee that every detail of the legal position has been completely and accurately described.

An actionable noise nuisance has been defined in the courts as one which interferes with the reasonable comfort and enjoyment of one's premises, and it is no defence in common law to say that the best known means have been taken to reduce the noise complained of, or that the cause of the nuisance is the exercise of a business or trade in a reasonable manner (except in the case of a body acting, without negligence, under statutory powers). Injunctions have been granted in various cases restraining the noise, or, in the case of noisy building operations, restricting them to certain hours. The penalty for breach of an injunction is imprisonment or, in the case of corporations, sequestration of property; damages may be awarded as well as, or instead of, an injunction. In suitable cases an action may be brought in the County Court, but it is then essential to claim damages as well as an injunction, since the County Court, unlike the High Court, may only grant an injunction as additional relief in an action in which damages are also claimed. An injunction is thus a powerful weapon; but actions at common law take time, and are therefore not a suitable remedy for noises which are likely to be only temporary. In addition, not only the cost of proceedings, but the difficulty in some cases of identifying offenders, and the reluctance to commence proceedings or give evidence, render this remedy less convenient. It may, of course, happen that a noise affects the King's subjects at large and so constitutes a public nuisance; the perpetrator is then guilty of a misdemeanour for which an indictment will lie at common law. Noise nuisances which affect only one person or a determinate number of persons come under the heading of private nuisances, when the remedy in common law is a civil action.

Statutes and by-laws provide a remedy against many noises which cannot conveniently be dealt with at common law. The most important statutory regulations (apart from those dealing with road traffic, which will be dealt with under that section) are the Public Health and Local Government Acts and the by-laws of local authorities made thereunder. Any by-law made by a local authority must be confirmed by the Home Secretary, and in some cases by the Minister of Health. A by-law cannot be made for the suppression of a nuisance where an existing enactment in force already deals with that nuisance. By-laws can be made by county councils and borough councils under the Local Government Act (1933), section 249, dealing, *inter alia*, with noisy animals and birds, noisy instruments, and noise from loudspeakers. To assist local authorities the Home Office has prepared model by-laws, which have been widely adopted, dealing with these noises and other nuisances. These by-laws prohibit noisy hawking, the use of steam organs so as to cause annoyance, and require street musicians to remove to a distance of 100 yards from a house, office, church, or hospital on request. The model by-law on loudspeakers, gramophones, etc., is as follows—

No person shall: (*a*) in any street or public place or in connexion with any shop, business premises, or other place which adjoins any street or public place and to which the public are admitted, or

(*b*) upon any other premises by operating any wireless loud-speaker, gramophone, amplifier, or similar instrument make any noise which shall be so loud and so continuous or repeated as to cause a nuisance to occupants or inmates of any premises in the neighbourhood.

Provided that no proceedings shall be taken against any person for any offence against this by-law in respect of premises in paragraph (*b*) unless the nuisance be continued after the expiration of a fortnight from the date of the service on such person of a notice alleging a nuisance, signed by not fewer than three householders residing within the hearing of the instrument as aforesaid.

Anyone aggrieved by a noise which might possibly contravene local by-laws may complain to the police: offenders against by-laws are prosecuted in the courts of summary jurisdiction, which can impose a penalty not exceeding £5.

An important remedy against noise has been put into the hands of local authorities by local Acts passed during recent years. A number of local authorities, including the London County Council, have obtained by local Act provisions applying to noise nuisances the procedure of the Public Health Act (1936), for the abatement of sanitary nuisances. The provision usually allowed is as follows—

1. A noise nuisance shall be liable to be dealt with as a statutory nuisance under the Public Health Act (1936). Provided that no complaint shall be made to a Justice under section 99 of the said Act unless it is signed by not fewer than three householders or occupiers of premises within hearing of the noise nuisance complained of.

2. A noise nuisance shall be deemed to exist where any person makes or continues or causes to be made or continued any excessive or unreasonable or unnecessary noise and where such noise (*a*) is injurious or dangerous to health and (*b*) is capable of being prevented or mitigated, having due regard to all the circumstances of the case. Provided that if the noise is occasioned in the course of any trade, business, or occupation it shall be a good defence that the best practicable means within the meaning of the said Act of preventing or mitigating it have been adopted.

3. Nothing contained in this section shall apply to a railway company or their servants exercising statutory powers.

4. Nothing in this section shall affect the power of the Corporation to make by-laws under section 249 of the Local Government Act (1933).

A statutory nuisance may, under the Public Health Act (1936), be dealt with by a court of summary jurisdiction, failing compliance with an abatement notice issued by the local authority. If the nuisance is proved to exist, the court shall make a "nuisance order" requiring the defendant to abate the nuisance, and a fine not exceeding £5 may also be imposed. Any person failing to comply with a nuisance order is liable to a fine of £5 on conviction and to a further fine of £2 for each day on which the offence continues after conviction. The local authority may then abate the nuisance and recover the expenses incurred. Proceedings may be taken in the High Court by a local authority against a person committing a nuisance if it is deemed that summary proceedings would afford an inadequate remedy.

Construction of Buildings. The Public Health Act (1936), section 61, authorizes the making of by-laws for regulating the materials to be used in the construction of buildings, and it is possible for such by-laws to deal with materials from the point of view of the transmission of noise. The local authority may, indeed, if required by the Minister of Health, be obliged to make such by-laws. These could be a very important weapon in the hands of local authorities and the Ministry of Health.

Traffic Noises. A number of regulations have been made regarding traffic noise. Noise made by the vehicle or its load and noise emitted by warning devices are dealt with in the Motor Vehicles (Construction and Use) Regulations, 1937.

Some of the legislation incorporated in these regulations must be regarded as undergoing a trial stage. In common with other legislation, it is not always strictly enforced, one reason for this being the difficulty of proving that a given noise is excessive. It is obviously desirable to be able to substitute noise measurements for necessarily vague allegations. An important step in this direction was the institution, in 1934, of a Departmental Committee of the Ministry of Transport on "Noise in the Operation of Mechanically Propelled Vehicles." The Committee have published a number of reports containing recommendations regarding permissible noise levels which have, in so far as they concern new vehicles, been accepted by manufacturers. The Committee recommended a noise limit measured under certain standard conditions of 90 phons for new vehicles and 95 phons for others.

As regards motor horns, etc., it was felt that a single loudness limit which would be applicable to all warning devices was required. Obviously a horn sufficiently loud to attract the attention of the driver of a heavy goods vehicle might be too loud to be agreeable to the residents in a quiet street. As a compromise between conflicting interests a noise level of 100 phons measured at a distance of 20 ft. was recommended, and by agreement between the Ministry of Transport and vehicle manufacturers, no horns with a loudness exceeding this figure are fitted to new motor vehicles.

The annoyance caused by aircraft is as a rule too intermittent to constitute an actionable nuisance, although nuisance actions have sometimes succeeded in obtaining injunctions restricting pleasure flights over certain property. Provided aircraft fly high enough for safety they do not appear to contravene any regulation, and furthermore the Air Navigation Act (1920) provides that no action shall lie in respect of trespass or nuisance by reason of the flight of aircraft over any property at a height above the ground which, having regard to weather and all other circumstances, is reasonable. The legal position then depends on what a court will consider reasonable.

COUNTRIES OTHER THAN GREAT BRITAIN

A brief account is given of some of the more interesting regulations and recommendations which have been made in different countries with a view to reducing noise. In some cases these have obviously been dictated by local conditions or customs; but others are of general interest, particularly those which are of the nature of building regulations.

Regulations concerning the Suppression of Noise. Police or municipal regulations against noise of various kinds are, of course, to be found in almost every country.

Most cities have regulations dealing with traffic noise; for instance the use of motor horns is often forbidden at night, and in some cities, notably in Italy, during the day as well, offenders being liable to a small fine on the spot. In Germany there is in force a series of technical regulations for motor vehicles, including clauses about silencers and approved types of horn; in addition it is understood that traffic noise is regulated by measurement, engine noise being restricted to 85 phons. In Paris a graduated series of speed limits is imposed, depending on the weight of the vehicle; at night heavy vehicles are prohibited in certain streets. Noisy loading and unloading of goods is often subject to restrictions. In Warsaw the use of horse vehicles with untyred wheels is frowned upon, those with tyred wheels being granted a tax reduction.

Other street noises such as hawking, newspaper-selling, and advertising by the use of noisy instruments are frequently entirely prohibited: in Paris these and noisy amusements at fêtes and fairs are subject to a special police permit.

The noise of church bells is apparently a more serious problem in Continental cities than in Great Britain. Cases are reported in which agreement has been reached with the church authorities that no bells would be rung before 6 or 7 a.m. Chiming public clocks present a similar problem, which is often dealt with by adjusting the mechanism so that the chime is put out of action at night.

The noise of loudspeakers and gramophones used on private premises is dealt with in various ways. In Paris, for instance, if a loudspeaker is audible in the street, or if a complaint is made to the police, the police can intervene directly, while in Belgium windows must be closed in a room in which a loudspeaker is in operation. Elsewhere it is merely laid down that such apparatus must not be used to the annoyance of the neighbours.

Noisy industrial operations due to factories, building, demolitions, etc., are in many countries restricted to the hours of day, or are only allowed at night by special permit. The problem is tackled in another way in Warsaw, where the municipal regulations contain a clause relating to zoning, in which noisy factories are allowed only in certain districts. In France certain kinds of works likely to disturb the amenities of the neighbourhood may not be set up without a special permit; before this is granted, any objections by local residents are heard, and the issue of the permit may be made subject to the guarantee that steps will be taken to prevent disturbance. (For instance, permission to run an aero-engine testing establishment was made subject to the provision of an effective silencing arrangement.)

Building Regulations. Building codes which contain clauses dealing with sound-insulation exist in some countries, including Germany, Austria, Hungary, and Czechoslovakia. It is gathered that in some countries (though not all) these codes are more of the nature of model specifications than generally enforceable rules, but they have considerable value in that they are standards which have presumably been considered as acceptable and practicable.

Party Walls. Individual recommendations vary somewhat from country to country, e.g. the minimum insulation, averaged for low-, medium-, and high-pitched sounds, to be afforded by party walls ranges from 48 db. (in Germany) to 60 db. (Czechoslovakia). Some countries have gone farther and have framed their regulations so as to exclude those light complex partitions which, judged from their average insulation, appear to be satisfactory but actually (see Chapter IX) are ineffective for low-pitched sounds. In Germany* this has been achieved by specifying that the insulation in the range 100–550 c.p.s. should be at least 42 db. (the insulation in the range 550–3,000 c.p.s. being at least 54 db.), while in Hungary the regulations simply state that the insulation should be at least that afforded by a solid wall weighing 70 lb./sq. ft. at all frequencies.

Floors. The minimum insulation against airborne sound afforded by floors over inhabited rooms is in most cases required to be the same as or rather greater than that of party walls. For hospitals, the Austrian code† recommends that floors should afford an insulation of 65 db.

The insulation to be provided by floors against footstep noises is specified in a number of different ways. According to some codes,‡ ordinary footsteps in the room above should not create a noise level of more than 40 phons in the room below, or 35 phons where special quiet is required. This figure is, of course, influenced by factors other than the insulation of the floor. In the German code it is

* "Technische Bestimmungen für Zulassen neuer Bauweisen," *Zentralblatt der Bauverwaltung*, Vol. 32, p. 875, August 1938.

† "Hochbau. Schutz gegen Schall- und Erschütterungen." (*Oesterreichischer Normenauschuss*, Vienna, 111, 1936.

‡ Municipal Board of Prague: "Rules for Judging Buildings from the Standpoint of Heat- and Sound-insulation," 1934.

laid down that the noise in the rooms below the floor should not exceed 85 phons when the floor is struck with a certain impact machine, this figure referring to a lower room containing one unit of absorption (see Chapter XIII); it is stated that the noise of footsteps in most ordinary rooms will then be between 25 and 45 phons. Other countries have confined themselves to making certain regulations about the construction of floors in order to deaden footstep sounds: these may prescribe that the flooring should be laid on some kind of pugging or other insulating layer or that, as in parts of Holland, an independent ceiling should be used. (See Chapter XIII.)

External Walls. Recommendations regarding the insulation afforded by external walls usually specify a figure about the same as that adopted for party walls. This figure is subject to correction for the transmission through the windows, if any.

Partitions. The insulation required of partitions between rooms in the same dwelling depends upon circumstances: it has been recommended that they should have a minimum insulation of 40 db. One code suggests an insulation of 45–60 db. for partitions used in hospitals.

Doors. Doors have received so far only rather superficial attention. Recommendations* have called for a minimum insulation of 30 db., but a lot must depend upon the position in which the door is used. One code specifies a minimum of 55 db. for the insulation of doors in hospitals.

Windows. Windows appear to have received as little attention as doors. One recommendation is that double windows in an external wall should have an insulation of 35 db., but the requirements must depend a good deal on circumstances.

Plumbing. Noise from plumbing is referred to in various codes. The attachment of piping to walls less than 4½ in. thick is not recommended.† Another prescribes that pipes run in floors or walls should be covered with felt in their entire length.

Machinery. Noise from machinery is dealt with in various codes. One code recommends that no machine or mechanical power transmission should be fixed on or in contact with party walls. Other recommendations have been made, regarding the necessity for the provision of silencers, insulating foundations, and so on.

Ventilation. In America a standard has been proposed‡ to the effect that no noise resulting from the operation of an air-conditioning system shall exceed the loudness level of the noise in the room when normal activities are in progress and no part of the air-conditioning system is operating. In Germany it has been

* *Das Lärmfreie Wohnhaus*, V.D.I. Verlag, Berlin, 1938.

† *Merkblatt für den Schallschutz im Wohnhaus*, V.D.I., Verlag, Berlin, 1938.

‡ Chicago Standards, 1936. (See *Heating, Piping, and Air Conditioning*. Vol. 8, p. 653, December, 1936.)

recommended* that the noise made by ventilating systems in different buildings should not exceed certain specified levels.

In Great Britain and, it is believed, in America, the building regulations of the local authorities do not as yet contain any direct reference to such matters as the sound-insulation which should be provided by structures. In Great Britain local authorities have power to make such regulations (or may be obliged by the Minister of Health to do so) under the Public Health Act, 1936. Some of the difficulties in the way of drawing up regulations of this kind have been discussed, and it is clear that any standard could only be a compromise between what would be considered good conditions and what would be considered practicable.

* *V.D.I. Lüftungsregeln*, V.D.I., Verlag, Berlin, 1937.

APPENDIX

TABLE XXVII

CONVERSION TABLE—DECIBELS TO NUMERICAL REDUCTION FACTORS

Reduction Factor	Decibels	Reduction Factor	Decibels
1·25	1	79·4	19
1·58	2	100	20
1·99	3	316	25
2·51	4	1,000	30
3·16	5	3,160	35
3·98	6	10,000	40
5·01	7	31,600	45
6·31	8	100,000	50
7·94	9	316,000	55
10	10	1,000,000	60
12·5	11	3,160,000	65
15·8	12	10,000,000	70
19·9	13	31,600,000	75
25·1	14	100,000,000	80
31·6	15	316,000,000	85
39·8	16	1,000,000,000	90
50·1	17	3,160,000,000	95
63·1	18	10,000,000,000	100

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