PORCELAIN AND OTHER CERAMIC INSULATING MATERIALS

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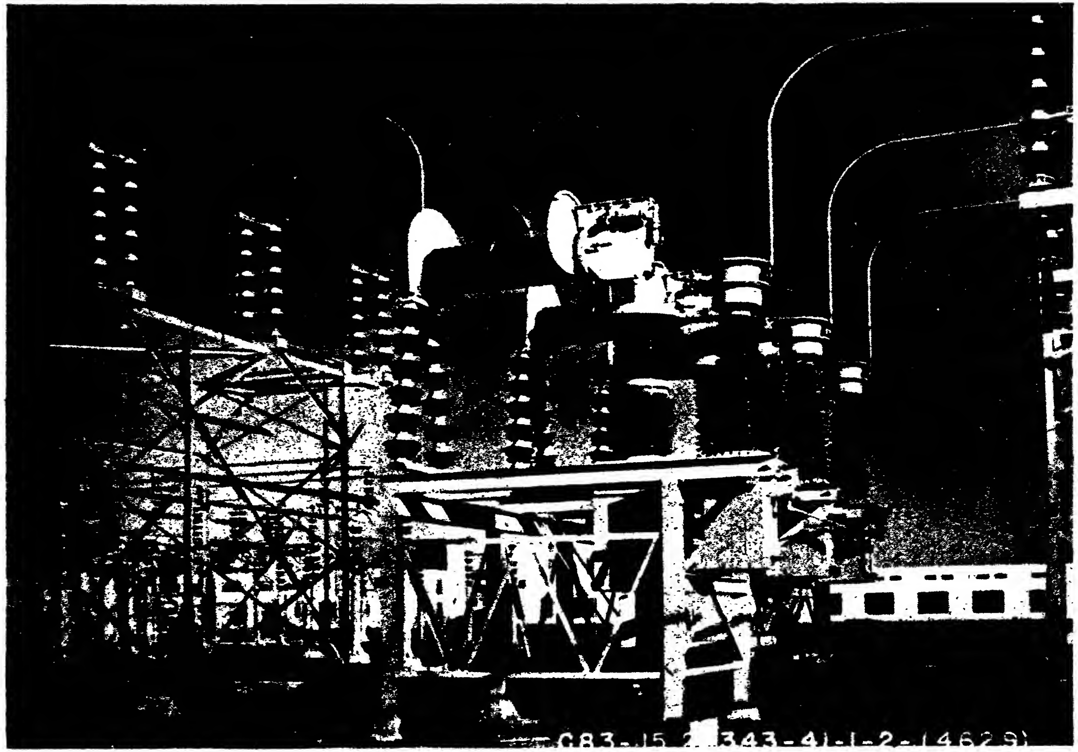
VOLUME ONE



THREE-CYCLE IMPULSE TYPE 196 230 k.v. OIL CIRCUIT BREAKER.
(General Electric.)

This picture also shows other electrical high tension apparatus in the manufacture of which a great variety of porcelain insulators is used. (By kind permission of *Electrical World*.)

PORCELAIN & OTHER CERAMIC INSULATING MATERIALS

By

DR. ING. ERNST ROSENTHAL

With a Foreword by

A. E. L. JERVIS

VOLUME ONE

RAW MATERIALS, MANUFACTURING PROCESSES,
TESTING AND CHARACTERISTICS

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FOREWORD

The author of this book bears a name which is as well-known on the Continent in connection with porcelain as, for instance, is the name of Wedgwood in this country. Rosenthal china is treasured in many Continental homes just as are pieces of Wedgwood over here. The name, therefore, carries with it a great tradition for domestic and art porcelain. The author of this book has during his lifetime seen this tradition carried into electrical porcelain manufacture and then into the highly specialised field of low loss ceramics, condensers, resistors, etc. He is also keenly interested in earthenware and laboratory ware.

After leaving High School, Dr. Rosenthal spent many years in the family factories, as part of his training for the subsequent post of Technical Director. The Rosenthal organisation was one of the first to lay great stress on the value of research, and the inauguration of their 2 million volt laboratory aroused considerable interest.

It was in the Rosenthal laboratory that the writer of this foreword, on one of his yearly visits, met the author. This has been considered sufficient excuse for his reading the proofs of this book and also for his persuading Dr. Rosenthal to write the book in a simpler form than was originally intended, so that, in addition to appealing to ceramic experts and those electrical engineers who specialise in insulation problems, it might also appeal to every other type of electrical engineer and also to electrical students.

Within recent years plastics and improved glass have come very much to the fore, and the publicity adopted by the respective industries has been so good that the man in the street knows a lot more about them than he does about ceramics. He knows that cups and saucers break when carelessly handled, but of the mechanical strength of correctly designed 220,000 Volt insulators he knows nothing.

The ceramic industry is old, reliable, progressive and modest.

This book gives some idea of the highly technical nature of its achievements. It was about time someone blew its trumpet.

A. E. L. JERVIS,
6, Charterhouse Square,
London, E.C.1.

January 1st, 1944.

AUTHOR'S PREFACE

THIS book is written primarily for engineers and manufacturers who use, or contemplate using, porcelain and similar ceramic materials in their products or in their electrical or chemical plants. The writer of this book was for many years the Technical Director of one of the largest porcelain organisations on the Continent, and at the time of writing is engaged as a consultant to one of the leading British technical porcelain manufacturers, to a well-known earthenware manufacturer and to leading electro-technical engineering firms in this country. Throughout his life he has been in constant touch with engineers who are specially interested in all the problems connected with the uses and characteristics of ceramics.

They all express the view that, in spite of their interest, they are much less familiar with these materials, their characteristics and manufacturing processes than with other materials. Many of them feel that ceramic materials would be even more widely used in industry to-day were they not so unfamiliar to them.

The reasons for this unfamiliarity are many. As students little information regarding ceramics was given to them, whether they studied at the Universities in Great Britain or in the United States, or at the Technical High Schools on the Continent, in the course of their normal electrical engineering or chemical studies. Furthermore, there are few books, if any, in the English language at least, dealing with porcelain or other dense ceramic materials written for the electrical engineer or the chemist. Whereas the progress made during the last decade, by for instance the glass and the plastic industries, has become generally known, not only to the engineers interested in these materials, but also to the general public, progress in ceramics is far less appreciated, although the progress made by the ceramic industry is at least equally impressive. In the United States and on the Continent, the leading technical porcelain companies inform their business friends periodically regarding certain new developments, and the interested reader of ceramic journals is kept informed of details regarding scientific progress. Such periodical publications, however, cannot of course give so comprehensive a survey of the entire field of porcelain, its uses and possible applications, as is given in text books on other materials of similar technical importance.

This is not only regrettable from the point of view of the porcelain industry, but also from the point of view of industry generally, since ceramics could further advance industrial progress if both their excellent technical characteristics and also their limitations were more generally known.

Should, therefore, the writer succeed in giving manufacturers and engineers a clearer picture of the characteristics, uses and manufacture of ceramics, he will feel that he has been of service to industry generally.

Although this book is not written primarily for the manufacturers of ceramic materials, the writer hopes that it may be of interest to them as well. This applies not only to those ceramists who are interested in technical porcelain, but also to those who are connected with other branches of the ceramic industry, such as the earthenware, domestic china sections, etc.

Raw materials, manufacturing methods and plant used in the various branches of the ceramic industry are generally very similar. One branch of the ceramic industry can learn very much by studying another branch of this industry. In particular, the studying of the achievements of the technical and electro-technical porcelain industry is of great interest to all ceramists, since the porcelain insulator industry has perhaps in many directions been the most progressive branch of the ceramic industry. The very nature of electrical porcelain manufacture involves close collaboration between highly qualified engineers and experienced ceramists. Many suggestions for improvement in porcelain manufacture are made by those customers who have regularly to visit insulator works for the purpose of witnessing tests on their designs. For instance, the engineer of a firm mass-producing electrical components may on the occasion of a visit to the porcelain factory ask, " Why don't you use mechanical conveyors as we do ? Why not have a look at our works to see whether you cannot make use of a similar idea ? " The engineer who uses the spraying method for covering certain metal work with a very uniform and thin layer of varnish may ask, " Why don't you use the spraying gun for glazing of porcelain instead of dipping ? Give me some insulators and some glaze and I will try out the idea for you." Another engineer may point out that in his factory metal articles similar to those being hand-pressed by the porcelain manufacturer are in fact automatically pressed in his own works with consequent saving of time and labour.

PREFACE

Although the adaptation of processes used for metal work to those used for ceramic manufacture may involve lengthy experiments, a close collaboration between the electrical and mechanical engineer and the ceramist has, in many cases, led to considerable success.

On the other hand, of course, the electrical porcelain manufacturer can gain much by drawing on the experience of the earthenware section and other branches of the ceramic industry.

During the last 30 years, the writer has had the opportunity of collaborating with ceramic manufacturers in England, U.S.A., Russia, France and Germany and of ascertaining how production methods differ in the various countries. In this book he describes some of the differences, in the hope that they may be of interest to readers.

In the framing of this book to suit a wide range of readers, certain sections of it have been dealt with in a much simpler form than the author originally intended, and much has been omitted. This omission will partially be made good in a second volume which will deal in more detail with the application of ceramic materials to the electrical industry.*

The writer would like to express his thanks to Mr. Hubert Dagnall, Mr. Gilbert Harris and Mr. John Harris (Directors of Bullers, Limited) for the interest they have taken in this book, and for the assistance they have given ; and to the firms who have assisted him by placing at his disposal the photographs published in the book.
He would also like to offer his thanks to Mr. G. Parr, editor of *Electronic Engineering*, who first suggested the writing of this book, who was most helpful and put at his disposal a number of blocks used in connection with articles written by the present author and published in *Electronic Engineering*. The editors of *The Electrical Review*, *Wireless World*, *Distribution of Electricity*, *Ceramic Industry and Electric World* also very courteously placed several blocks at the disposal of the author. He would like to thank them. Last but not least the author would like to express his gratitude to his friend, Mr. A. E. Leslie Jervis, who so kindly read the manuscript.

E. R.

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* A book on " Stoneware and Porcelain as Materials of Construction for the Chemical Industries " by Dr. Felix Singer will be published by Chapman & Hall.

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INTRODUCTION

Ceramics have served industries developed by mankind for many centuries.* The electrical industry—one of the youngest branches of industry—has used it for about six decades, since first the need for an impervious insulating material arose. With the progress of science and the evolution of the various electrical industries, the development of the different ceramic materials has had to keep step, and for the different branches of the various industries materials have been evolved possessing different technical characteristics according to their application.

The first ceramic material to be used as an insulating material in the electrical industry was porcelain, which still is the most important one in use. Apart from porcelain, a considerable number of other ceramic materials have been developed and used for other purposes according to the special application in hand.

By the term " ceramic material " one implies a material made of clay or similar inorganic substance formed in a plastic state, dried and fired at temperatures high enough to impart to the material the necessary mechanical strength.

Many branches of the ceramic industry have only been developed within recent years whilst other branches were founded more than 12,000 years ago, the ceramic art being one of the oldest practised by the human race.

The first ceramic articles were bricks. Remnants of brickwork found in Egypt and in other parts of the world are estimated to be 12,000 years old. The technique of glazing bricks and pottery articles is not so ancient, but even this is 5,000 years old.

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* The word " ceramics " is of Greek origin. In Ancient Hellas, the potter was called " Kerameus " and " Keramos " meant both the product of the potter and the plastic raw material used in pottery. Nowadays, we understand by " ceramics " not only the manufacture of pottery articles, but also the manufacture of all articles in which clay or similar plastic raw material is used, and which, after having been shaped, are subjected to a firing process to give them the necessary strength. Furthermore, we understand by " ceramics " that branch of technology which deals with the manufacture of ceramic articles, their technical characteristics and the raw materials used in their manufacture.

Under the general term " ceramic ware " are included, for instance, bricks, tiles, pipes, terracotta, earthenware, stoneware, china, and porcelain, which all contain clay substance. In exceptional cases, however, articles made of ceramic raw materials but having a plasticizer other than clay or similar substance, are classified as ceramics, provided that after shaping they are subjected to a firing process. Two typical examples of such articles are (*a*) refractory materials where cement is used as a plasticizer instead of clay; (*b*) alumina bodies which are made plastic by treating with certain acids.

INTRODUCTION

Porcelain was first manufactured in China in the mediæval ages and then in Europe in the seventeenth century for artistic purposes. Later on came tea and dinner-sets and other household articles. The porcelain first manufactured for the electrical industry was modelled on the same lines as domestic and artistic porcelain. Very soon, however, it became apparent that the special characteristics necessary for technical purposes required a material quite different in composition, manufacture, and appearance from the domestic and artistic ware.

Porcelain was first used by the electrical industry for high and low tension line insulators and for insulation in high and low tension apparatus. Different mechanical and electrical characteristics were required for the various applications.

For high tension line insulators in addition to imperviousness to humidity and high surface resistance, high mechanical strength and high puncture strength were required. For extra large insulators suitable for voltages up to 234 kV., the adaptability of the body for forming into complicated shapes of large dimensions was of special importance.

For low tension apparatus, on the other hand, it was necessary to develop bodies which lent themselves to rapid manufacture on automatic presses to very exact dimensions.

The manufacturers of electrical heating apparatus and electric furnaces required the development of insulating material which would withstand high temperatures and rapid changes without deterioration of the ohmic resistances and mechanical strength; whereas the requirement of imperviousness against moisture was less important.

Porcelain used in the chemical industry has to be very resistant to temperature changes and to the influence of the various chemicals according to the purposes in hand. In other cases, very great hardness and resistance to abrasion are more important; whereas in other instances great thermal conductivity is desirable.

The development of high frequency technique which has taken place within recent years has required insulating materials possessing special properties; first of all, low dielectric losses especially at high frequencies, and secondly, high mechanical strength so that the necessary properties can be provided in the smallest possible size.

For other purposes the high frequency technique required insulating materials possessing a very high permittivity combined with a small power factor. This was used for the manufacture of condensers which were required to take up as little room as possible.

For other purposes, the radio technique required insulating materials possessing permittivity independent of the temperature or changing with the temperature in a negative sense.

To meet these diverse requirements from the technical point of view new ceramic materials have had to be developed in which the clay or china clay predominant in the porcelain bodies has to be replaced by other inorganic substances according to the specific requirements.

CHAPTER I

PORCELAIN

ALTHOUGH in the old days porcelain was not used for technical purposes, some brief information about the origin and development of porcelain manufacture may be of interest to the electrical engineer especially since the history of the development of porcelain manufacture to some extent explains the different porcelain technique employed in the various countries.

If we understand by the term " porcelain " a translucent white material manufactured of kaolin (china clay) and fluxes such as feldspar or stone, then it is correct to say that the first porcelain was manufactured under the Ting (or T'ang)* Dynasty (A.D. 618-907). Vitrified stoneware of a grey or brownish colour was produced in China as early as 200 B.C. From that time onwards continuous progress was made under the succeeding dynasties and in the fourteenth to fifteenth centuries under the double Ming dynasty Chinese pottery acquired the qualities which have rendered it famous.

In Japan, although Japanese annals refer to porcelain manufactured in the first century, it was only in the seventeenth century that porcelain was actually made.

The first pieces of Chinese porcelain were brought to Europe by the Arabs in the twelfth century, but not before the Venetian, Marco Polo, returned from his voyages to the Far East in 1295 bringing porcelain from China did it become known where this material was actually made.

In the seventeenth century many experiments for reproducing china were carried out in Europe, especially in the castles of the European Princes, but only in the year 1709 did Johann Friedrich Boettger succeed in manufacturing what was regarded as porcelain in the castle of Frederick Augustus II, at Meissen, in Saxony. His intention was to make gold, but by firing various clays he succeeded in producing something very similar to porcelain. The first specimens were rather brown in colour, but by using a local kaolin he produced some cups which, to the astonishment of everybody, were exact replicas of the then mysterious china porcelain. Although the

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* A recent source for this information is given in the Book " Key to Pottery and Glass," by Bernard Rackham, formerly of the Victoria and Albert Museum. The information is from discoveries in China and Research work carried out there.

processes were kept very secret similar ware was produced in the succeeding decades in other Courts in various European countries.

In France the first porcelain was manufactured in 1740 at Vincennes. The factory was later transferred to Sevres. The French porcelain was somewhat different from the Chinese porcelain and the porcelain manufactured in the Central European countries in the following respect. Instead of the natural fluxes such as feldspar or stone, artificially melted glasses (fritts) were used to obtain the desired vitrification ; but in the nineteenth century this method was largely replaced by using French feldspars. The manufacture of porcelain was started in England much later than in Central Europe and France and a kind of soft porcelain was made about 1745 in Chelsea.

In Staffordshire the manufacture of bone china was introduced in 1772. Bone china derives its name from the fact that bone ash is used as a flux instead of feldspar (as in the case of the European hard porcelain) or instead of artificial fritts (as in the case of the French soft porcelain).

The so-called hard porcelain (consisting of kaolin (china clay), feldspar and sand fired at a temperature of about 1,400°C.) was never manufactured in England for household or domestic ware (and the same applies to the United States) at least until the end of the Great War 1914–1918. When industry generally, and the electrical industry especially, required a ceramic material impervious to moisture, unattackable by atmospheric conditions, and having a smooth and self-cleaning surface, it was natural that in those countries where hard porcelain was manufactured for household purposes the same factories started to make the first insulators and other technical articles ; whereas in the United States and England where hard porcelain was not then manufactured special factories were started to deal exclusively with the manufacture of technical porcelain. This difference in origin explains the difference in the manufacturing methods of porcelain insulators in this country and the United States on the one hand, and in Central European countries on the other.

In the Central European countries porcelain insulators are fired at a temperature of about 1,400°C. and upwards in a reducing atmosphere, since the manufacturers of hard porcelain wanted to produce an absolutely white ware possessing a very hard glaze unattackable by acids and by scratching with steel knives and forks. These special properties were of course not of primordial importance for the manufacturers who made electrical insulators exclusively.

The result is that whereas the American and English insulator manufacturers fire at temperatures of about 1,300°C. in neutral or oxidising atmosphere and use more ball clay, the Central European insulator manufacturers fire at 1,400°C. and upwards in a reducing atmosphere and use more white burning kaolin (china clay).

The materials produced by the different manufacturing methods differ in colour—the English and American having an ivory colour and the Continental a white colour. The mechanical and electrical characteristics of the materials manufactured by the different methods are, however, very similar.

FORMATION AND STRUCTURE OF PORCELAIN

Before discussing the raw materials used in the manufacture of porcelain, we must get a picture of the part which the individual raw materials play when the porcelain is formed in the fire of the kiln. To make this picture simpler only the part played by kaolin, clay, quartz, and feldspar will be discussed here.

In the unfired body the clay substance acts as the plastic constituent and imparts to the body its workability. The methods of shaping ceramic materials are based on the plastic quality of the china clay and ball clay. The term " plasticity " is applied to anything which can be deformed under mechanical stress without losing its cohesion and which is able to keep the new form given to it.

Later on something more will be said about the plasticity of ceramic raw materials.

Quartz and feldspar (the other two ingredients) have the effect in an unfired body of decreasing the plasticity of the ball clay and kaolin, and of decreasing the rate of shrinkage during the drying process. (They are " opening " materials.) Their chemical effect takes place at high temperatures in the furnace. When the shaped articles are subjected in the furnace to increasing temperature, the first noticeable changes take place at 500–600°C. when the clay substance loses its chemically combined water. The clay substance starts to dissociate at this temperature, forming Alumina (Al_2O_3) and Silica (SiO_2). Between 900–1,200°C. part of the alumina combines again with part of the silica forming an alumina silicate of the composition $3Al_2O_3.2SiO_2$—the so-called " Mullite " which mineral will be described in detail in the chapter " Raw Materials."

At a temperature of about 1,200°C. the feldspar melts to a very viscous glass. From this temperature onwards the formation of porcelain takes place. With increasing temperature the viscosity of the feldspar's glass decreases and its ability to dissolve or fuse silica, alumina and mullite increases. Owing to the surface tension of the molten feldspar, the unmolten ingredients are forced together and the interstices are filled with glassy matrix. By this means the material becomes finally free of pores and the undissolved ingredients become more and more attacked and dissolved by the feldspar glass. Owing to the fact that the glasses rich in alumina and silica have a higher melting point than feldspar, the glassy matrix becomes more viscous by the dissolving of parts of alumina and silica and the body does not lose its shape when temperatures above the melting point of feldspar are reached.

In the last firing phase the glassy matrix is able to dissolve a considerable percentage of the undissolved quartz particles if the quartz has been ground very finely and if there is sufficient time and temperature for the glass matrix to attack and dissolve more and more of the undissolved particles. The higher the temperature the quicker the chemical and physical processes take place.

The electrical and physical characteristics of the porcelain body depend very much on the degree to which these dissolving processes are carried. For the best mechanical strength this process must not be carried so far as to cause the finer quartz particles to dissolve, whereas for high electrical puncture strength and for high resistance against thermal shocks these quartz particles have to be dissolved to a higher degree. The limit of admissible dissolution of quartz is reached at the point where the whole body becomes soft. If the temperature is further increased all the undissolved particles (clay, mullite, and quartz) are more and more dissolved. Under these conditions the articles would be overfired and become deformed. The most suitable firing temperature depends of course on the composition of the body, on the composition of the raw materials and on the characteristics required of the design. For a given ratio of clay, quartz, and feldspar a somewhat lower firing temperature gives higher mechanical strength, and a somewhat higher firing temperature gives a higher puncture strength and resistance to temperature shocks. This is only true if the fineness of the grinding and the methods of preparing the body are the same.

Apart from the interaction which takes place between the feldspar and the quartz, interaction also takes place between the molten feldspatic glass and the clay substance, as mentioned above. The clay, after having lost its chemically combined water, dissociates into alumina and silica, and at about 1,200°C., mullite crystals are formed having a composition of $3Al_2O_3.2SiO_2$. These form a fine network throughout the whole body. The formation of mullite starts at a temperature where the feldspar becomes viscous and reactions take place between the viscous feldspar glass and the silica set free by the decomposition of the clay substance.

100 parts feldspar dissolve at about 1,400°C. 20–30 parts of clay substance, dependent upon whether it is sodium or potassium feldspar. This question will be dealt with later on in more detail.

100 parts feldspar dissolve at the same temperature about 10–32 parts of quartz. A feldspatic glass having dissolved 20–30 parts of the clay substance may dissolve at 1,400°C. 20 parts of quartz (in the case of potassium feldspar) and up to 50 parts quartz (in the case of sodium feldspar). This means that 100 parts potassium feldspar can eventually dissolve 20 parts quartz ; whereas 100 parts sodium feldspar can dissolve 30 parts clay substance plus 50 parts quartz.

The final porcelain product obtained after the firing process has been completed consists therefore of mullite crystals, undissolved quartz particles and a glassy matrix. It is very difficult to give exact figures about the proportion in which these three constituents prevail. The Continental insulator porcelain body consists of about 40–50 parts of clay (one-third being ball clay and two-thirds china clay) ; about 35–40 parts quartz and about 15–20 parts feldspar. This porcelain obtains the right structure and the best technical properties when fired at 1,410°C. (S.C. 14) approximately.

The American and English insulator porcelain which is fired at 1,300°C. (S.C. 10) has (apart from the fact that the ratio between ball clay and china clay is about 50–50) more feldspar (between 20–25 per cent.) and less quartz (between 25–30 per cent.) than the Continental insulator porcelain mentioned above, and results in a structure akin to that of the Continental porcelain at the lower temperature of about S.C.10, owing to its higher feldspar content, its higher content of ball clay and its lower content of quartz.

If we assume a case where the feldspar content is about 25 per cent., about 8–12 per cent. of quartz and clay may be dissolved by the feldspar and the glassy matrix may therefore be in the neighbourhood of 35 per cent. The rest may be one-half undissolved quartz and one half mullite crystals.

In the case of the Continental porcelain the glassy matrix is richer in silica than in the case of the English and American insulator porcelain. This results in a somewhat lower heat expansion of the finished porcelain product, the Continental being between 3 to 4×10^{-6} and the English and American between 4·5 and $5{\cdot}5 \times 10^{-6}$ dependent on the feldspar content and the fineness of the grinding.

Silica in dissolved form, *i.e.* in the form of a glassy matrix rich in silica, tends to decrease the heat expansion coefficient, whereas quartz in crystalline form tends to increase the heat expansion coefficient of the fired product. This can easily be understood if one remembers that the coefficient of thermal expansion of quartz is 13×10^{-6} parallel to the main axis and $7{\cdot}9 \times 10^{-6}$ at right angles thereto, whereas the coefficience of thermal expansion of fired silica is $0{\cdot}6 \times 10^{-6}$.

If cups or plates for dinner ware were manufactured of the same composition as that used for electrical insulators, and were fired at the same temperatures at which insulators are fired in order to give the best mechanical characteristics, such plates would be only very slightly translucent and only then if they were made rather thin. Since translucency and white colour are important for china or porcelain dinner and tea-sets, the composition of the body for this kind of ware has to be different and considerably more feldspar has to be used for the same firing temperatures. In addition *more* china clay and *less* ball clay have to be used to give a brilliantly white fired product. Whilst ball clay increases the mechanical and electrical strength, it gives a greyish colour in a reducing atmosphere and an ivory colour in an oxidising atmosphere.

Much thought has been devoted to the question as to whether the mullite crystals in the porcelain increase the mechanical and electrical strength, whether a more glassy and homogeneous structure is more favourable and what part the undissolved quartz particles play with regard to the technical characteristics of the finished product. With regard to electrical porcelain there is one thing certain, and that is that the firing temperature and the body composition have to be such that the final product has no porosity and has as few enclosed pores as possible. The slightest porosity would make an insulator unusable under humid atmospheric conditions even if a slight porosity were completely covered by the glaze. Enclosed pores tend to create ionised air interstices in the insulating material and these would considerably decrease the dielectric properties. This will be explained in the chapter dealing with dielectric properties.

With regard to undissolved particles, it is obvious that such particles would decrease the resistance to sudden temperature variations owing to the greater heat expansion coefficient of the quartz as compared with that of the glass matrix and the mullite crystals formed by decomposition of the clay substance. The volume variations of the various silica modifications which are of importance in connection with resistance to temperature variations will be discussed later on.

Porcelain bodies which are designed to withstand considerable temperature changes contain, therefore, as a rule, no big undissolved quartz particles.

With regard to the mechanical and electrical strength it is not easy to say whether the mullite crystals have a definite influence. Experiments carried out to increase these crystals by separately introducing mullite crystals into the composition of the body have shown no improvement over a porcelain body having no separately introduced mullite crystals fired at the same temperature.

To obtain any advantage of mullite, sillimanite, and other crystals having a very similar composition and crystalline structure, it is necessary to use them in much greater proportion and to employ much higher firing temperatures. If one compares thin sections of Continental porcelain and American or English porcelain under the microscope one finds that as a rule the Continental porcelain contains more mullite crystals, but the mechanical and dielectric strengths are the same. (Certain characteristics of the Continental type are, however, superior; for instance, the resistance to abrasion and to sudden temperature variations, but it is difficult to say whether this is due to the higher mullite contents or to the higher silica contents of the glassy matrix of the "Continental type" of porcelain, or to both.)

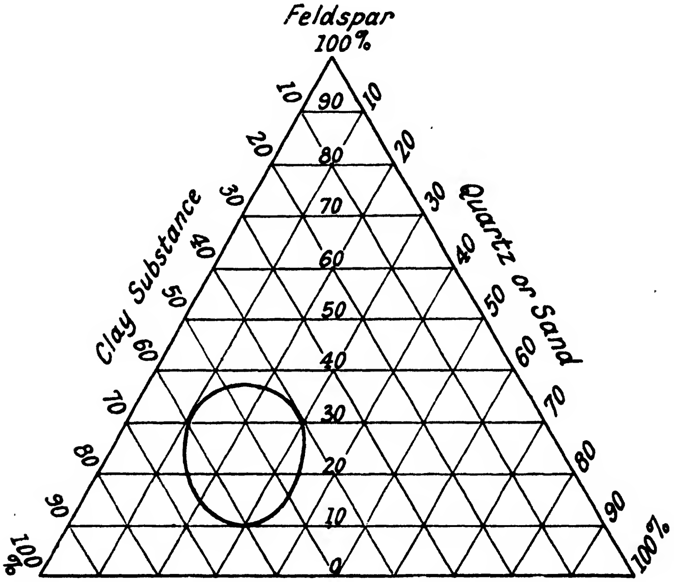

Fig. 1.—Composition of porcelain: Clay substance 40–65; Quartz 10–35; Feldspar 10–35.

With regard to puncture strength it has been found that this is better the more homogeneous the structure of the porcelain. This is not astonishing because the different power factors and the different permittivities of the various constituents would cause uneven field concentrations if they were not pretty equally distributed over the body.

On the other hand, undissolved quartz particles evenly distributed and of moderate size have a favourable influence on the mechanical properties, especially on the tensile strength and mechanical impact strength. They give to the body a certain elasticity compared with a body containing a higher percentage of glassy matrix, which makes the body non-elastic. A porcelain used for rod-shaped tension insulators, for instance, possesses a greater tensile strength when somewhat underfired (which means that only a small percentage of the quartz particles are completely dissolved).

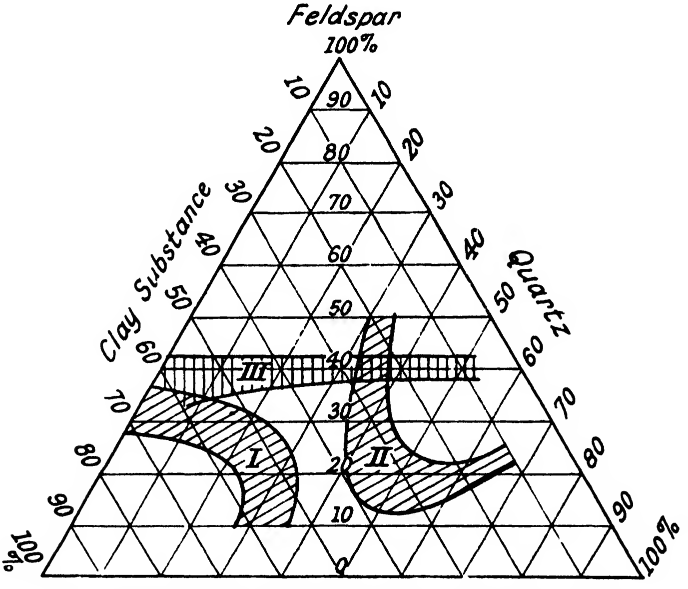

FIG. 2.—Area I: Good thermal shock resistance. Area II: High mechanical strengths. Area III: Good breakdown strength.

Fig. 1 shows in the form of a triangle the composition of porcelain. The area covered by the oval ring represents the more usual composition of porcelain bodies, and Fig. 2 indicates very roughly the relation of the technical characteristics to the composition of the porcelain. It shows, generally, that an increase in feldspar increases the puncture strength; an increase in clay substance increases the heat resistance and resistance to temperature shock, and an increase in silica increases the mechanical strengths (particularly the shock resistance).

This is, of course, only a very general picture since the firing temperature and the grinding methods and grinding time of the raw materials play an almost equally important part as the percentage of the composition. Not all china clays having the same chemical composition impart to the porcelain body the same technical characteristics. Generally speaking, the more plastic china clays are more favourable if great mechanical strength is aimed at; whereas the less plastic ones are more favourable as regards resistance to temperature shocks. The same considerations apply to the ball clays. In this case, even more than in the case of china clays, the physical properties of the clay particles play a very important part, but owing to the very complex conditions existing during the formation of the porcelain body it is not possible to give an exact indication as to how the various ball clays influence the mechanical characteristics of the fired article. It is most probable that apart from the grain size the molecular structure of the clay substance plays an important part.

Many ball clays contain a considerable amount of silica and since the size of the grain of the silica particles plays an important part for many purposes, it may be helpful to grind the ball clay in grinding cylinders in order to decrease the particle size of its silica ingredients. This point is very often overlooked. Regular elutriation tests of the ball clays should be carried out.

The more plastic china clays and ball clays cause a greater shrinkage during the drying and firing processes and large insulators containing a great proportion of very plastic ball clay and china clay are difficult to dry even with modern drying equipment; and even if the drying process is carried out very carefully and successfully and drying cracks avoided, small surface cracks may very often be formed during the firing if the body is very rich in plastic clay and the feldspar and sand are very finely ground. Careful drying before and after the glazing is essential in such cases.

The choice of the right kind of china clay and ball clay and the duration of the grinding process have to be carefully balanced both with regard to the technical characteristics of the finished article and with regard to the workability of the plastic body.

The silica can be introduced in various forms. It can be introduced first by a pebble or true flint, prepared by calcining and grinding flint pebbles which are found, for instance, on the coasts of France and Belgium, and in the Thames Estuary. Secondly, quartz sandstone can be ground and the ground sand flint introduced into the body. Thirdly, rock flint made by grinding rock quartz from pegmatite dyke can be used, and fourthly, sand already ground by nature can be employed.

The introduction of different forms of silica makes no noticeable difference to the technical characteristics of the porcelain if their chemical compositions are the same, *i.e.* if pure silica is used, except in the case of resistance to temperature shock. (In the case of earthenware the conditions are different, owing to the lower firing temperature and the lower feldspar contents of the earthenware body. The nature of the silica used has, in the case of earthenware, a great influence on its thermal expansion.)

Pebble flint body is more liable to crack under the influence of sudden temperature changes. As regards the dielectric and mechanical properties, no difference can be observed.

In this chapter only ceramic bodies which owe their plasticity to the use of clays are discussed, since these are the bodies generally used for the manufacture of high and low tension porcelain insulators for commercial frequencies.

The raw materials from which insulator porcelain is made are fundamentally the same as the raw materials from which the Chinese made their first porcelain, although the manufacture of the body, its composition and the selection and preparation of its raw materials have made considerable progress under scientific research. The main reason why the raw materials, feldspar, stone, and silica are used and will continue to be used for the manufacture of insulator porcelain is the low price of these materials. Ball clay and china clay on the one hand cannot be substituted by better materials; only the purification process can and will be further improved. Feldspar as a flux and sand as an " opening " material, on the other hand, could be substituted by materials which would improve the technical characteristics. Feldspar can be substituted by some other flux, such as another silicate or by a fritt which may improve certain of the technical characteristics. For instance, magnesium silicate can be used instead of the alkali aluminium silicate feldspar. This forms a glassy matrix having a smaller heat expansion coefficient which increases the resistance to temperature shocks. The magnesium silicate glass matrix which is formed by the use of the mineral talcum as a flux at the same time increases the mechanical strengths. On the Continent, such bodies are used for the manufacture of high tension insulators, in cases where either a higher mechanical strength or a higher resistance to sudden temperature changes than that of feldspatic porcelains is required.

Bone china, which is made in England and in the body of which bone ash (calcium phosphates) forms the flux, instead of feldspar, has a very high resistance to temperature changes. ("Note on the durability of Bone China in hotel ware compared with feldspatic porcelain," A. S. W. Odelberg.)* These alternative fluxes are more expensive than feldspar—particularly so, since for the manufacture of insulator porcelain pure feldspar is not necessary. Materials like pegmatite or stone which contain feldspar and sand and which are very cheap are used for the manufacture of porcelain insulator bodies.

A technical advantage of feldspar compared with other fluxes is the fact that it imparts to the body a larger firing range. With the advent of the tunnel ovens which permit of keeping the temperature range within very small limits, the importance of a large firing range becomes less imperative if technical advantages can be achieved by fluxes causing a small firing range. This is the reason why, for laboratory porcelain and for spark plugs, feldspar is largely substituted by fluxes forming a glass matrix with a lower heat expansion coefficient and a higher electrical resistance at elevated temperatures.

From what will be discussed in the chapter dealing with the puncture strength it will be seen that dielectric puncture strength is partly disruptive and partly thermal. From the fact that the thermal factor plays an important part, it can be clearly understood that even in the case of high tension insulators working at normal temperature high ohmic resistance at elevated temperatures is important and improves the dielectric puncture strength.

For the manufacture of spark plugs which, for internal combustion engines have to possess a great mechanical strength combined with high puncture strength at elevated temperatures, specially prepared fritts or materials like Dumortierite ($8Al_2O_3.6SiO_2.B_2O_3.H_2O$) are used as fluxes.

Flint or sand used in the insulator bodies as " opening " materials can be substituted by other materials which have a lower heat expansion coefficient and a more uniform thermal expansion and contraction than has silica. For this purpose, materials like sillimanite, andalusite, and kyanite or mullite are used, having the composition $Al_2O_3.SiO_2$ or $3Al_2O_3.2SiO_2$ respectively. These aluminium silicates have a smaller and more uniform thermal expansion than silica but they are not so easily dissolved by the glass matrix as is the case with silica, and consequently, higher firing temperature or more

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* Transactions Ceramic Soc., 1931, p. 125.

efficient fluxes have to be used. This fact, in addition to the higher price of these minerals, is the reason why they are only used for the manufacture of insulators where special characteristics at higher temperatures are required.

Alumina (Al_2O_3) is also used to replace silica in porcelain bodies where a uniform and small thermal expansion is required—*i.e.* for the manufacture of insulators where high resistance to temperature shocks is required. This material is also not easily dissolved by the alkali alumina silica glassy matrix and a higher proportion of fluxes or more efficient fluxes have to be employed when alumina is introduced into the porcelain body, or higher firing temperatures have to be used.

To meet the special requirements of high frequency technique and the special requirements of electrical heating components, bodies have been developed whose compositions differ fundamentally from the composition of the normal insulator porcelain. These special bodies will be dealt with in the appropriate chapters.

CHAPTER II

INSULATORS FOR SPARK PLUGS

INSULATORS for spark plugs have to meet extraordinary requirements in many respects. They have to resist very great mechanical stress since they are rigidly assembled (the complete component must be airtight) in metal parts which are under constant vibration and which, owing to the heat developed in the engine, expand and exert heavy pressure on the insulator. The temperatures to which both insulators and the metal parts are subjected are especially high in the case of aircraft engines and great progress has had to be made to meet the requirements of the aircraft industry.

In former times insulators for spark plugs were made of porcelain but very soon spark plugs made of talcum and other Clinoenstatite bodies proved to be superior owing to their greater mechanical strength and to their higher ohmic resistance at high temperatures. A further increase in mechanical and dielectric strength at high temperatures and great resistance to temperature shock became more and more important, and steatite bodies were considerably improved by modifying the composition in a way which is described later on in the chapter dealing with high frequency ceramics.

In America spark plugs were made of improved porcelain consisting of clay, sillimanite ($Al_2O_3.SiO_2$) or mullite ($3Al_2O_3.2SiO_2$) and specially prepared magnesia fritt (by the Champion Spark Plug Co.). These bodies were improved by the replacing of the fritts by minerals like Dumortierite.

The demands of the Motor Industry have brought forth a wide variety of bodies made of alumina, and many patents covering the materials used and the manufacturing methods have been granted. A recent article tells of a method used by the Lodge Company in making high alumina plugs. Chromic oxide in the body imparts a pink colour and some plasticizer seems to be used since the body is vacuum plugged.

The Siemens-Schuckert Werke have developed a body called " Sinter Korund " which consists of pure alumina. The sintered alumina is made plastic by the treatment with a small quantity of diluted hydro-chloric acid (800 cm.^{3} water, 80 cm.^{3} hydro-chloric acid 38 per cent. conc.; O. Ruff Ber. Deutsche Keramische Gesell. 1924, p. 157) and in this state can be shaped by pressing, extruding, and other manufacturing methods common to the ceramic industry.

The firing temperature is as high as 1,800°C. at which temperature the alumina particles are baked together and a very fine network of corundum crystals is formed. No glass formation is present. The melting point of pure alumina is 2,015°C.=3,659°F. It is 215°C. higher than the temperature at which spark plugs are fired. Spark plugs made of pure alumina have excellent properties, in particular high dielectric strength and very high ohmic resistivity at high temperatures.

CHAPTER III

INFLUENCE OF GLAZES ON THE TECHNICAL CHARACTERISTICS OF PORCELAIN*

UNGLAZED ceramic materials appear to the naked eye to have smooth surfaces, but under a strong microscope minute projecting peaks can be observed. The quality of the surface has a great bearing on the surface resistivity of an electrical insulating material. Surface resistivity is largely dependent on the humidity skin which, in a moist atmosphere, forms on any surface to a thickness that increases with the roughness of the material and with the humidity content of the atmosphere. The surface resistivity of a material decreases with the increasing humidity content of the atmosphere. For instance, in an atmosphere of 30 per cent. humidity, the surface resistance of unglazed porcelain ranges between 20×10^{12} and 40×10^{12} ohms per cm.^{2}; but in an atmosphere of 98 per cent. humidity it is only about $0{\cdot}001 \times 10^{12}$. This decrease in surface resistivity is smaller the smoother the surface.

Glazed porcelain has, in a dry atmosphere, approximately the same surface resistance as unglazed porcelain, but in a humid atmosphere of, for example, 98 per cent. humidity the figure becomes $0{\cdot}1 \times 10^{12}$ ohms. per cm^2. This dependence of surface resistivity on the quality of the surface and on the humidity content of the atmosphere is a characteristic not only of porcelain but also of all insulating materials. A porous material shows a much more rapid decrease in the surface resistance with increasing atmospheric or surface humidity. Porcelain is an absolutely dense and vitrified insulating material and this is the reason why the surface resistance in a highly humid atmosphere is only 200 times smaller than in a dry atmosphere (for glazed porcelain) whereas in the case of porous materials the surface resistivity in an atmosphere of 98 per cent. humidity is more than a million times smaller than in a dry atmosphere. The considerable improvement of surface resistance under humid conditions by the application of a glaze is one of the reasons for the latter. Another reason is that a matt unglazed surface would more quickly collect dust, smoke and all kinds of impurities. Glazed surfaces can much more easily be cleaned automatically by rain or, for instance, with damp rags. (Figs. 3 and 4 illustrate at 75 diameter magnification the smooth surface of the glaze and the

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* Figs. 3–6 appeared previously in an article by the present author on "Insulator Glazes." (*Electrical Review*, No. 27, 1942.)

rough surface of the bisque.) All insulators used in the open air and most of those used in enclosed rooms are, therefore, provided with a ceramic glaze. (Most specifications for porcelain high-voltage insulators state that the glaze shall cover all the exposed porcelain parts of the insulator but that it shall not be depended upon for insulation.) The latter provision means, in effect, that the porcelain body must be free from pores and possess after immersion in water, in an unglazed state, the required dielectric strength.

FIG. 3.—Rough, unglazed porcelain surface section perpendicular to the unglazed surface and photographed under ordinary transmitted light. The magnification of 75 diameters shows how the surface is formed of small undissolved particles.

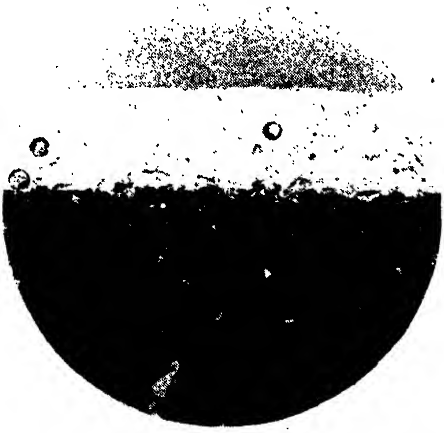

FIG. 4.—Junction of glaze and biscuit magnification 75 diameters, showing how the glaze combines with the porcelain surface and dissolves parts of its surface layer. The smooth surface of the glaze will be apparent.

As a rule only those parts are left unglazed where, for one reason or another, a certain roughness is required, *e.g.* where metal parts have later to be affixed by cement or, as in the case of ceramic articles, used on indoor apparatus, where high surface resistance is not essential.

The glaze on a porcelain insulator is composed of raw materials similar to those used for the body, but fluxes are added which cause the mixture to melt at the firing temperature of the insulator (1,300°–1,400°C.).

Insulators are clay-dipped, as the potters say. This means that the glaze is applied by dipping when the insulator is in a dry state but before it is fired. Instead of immersing the insulator in a watery glaze suspension, the glaze may also be applied by spraying.

In domestic and art porcelain manufacture, the glaze is applied on a prefired article, but it was discovered very early that this was not necessary for thick-walled articles for electrical purposes. Later it was found that it was not even necessary for thin-walled ones if precautions were taken to prevent deformation during dipping. Glaze spraying is one of the means of preventing this deformation.

Only seldom is a low-temperature glaze applied to a prefired insulator ; for instance, if certain coloured glazes have to be applied which would not withstand the temperature to which the insulator is subjected during firing. (The remarks which follow with regard to improvement of the mechanical characteristics of the body by virtue of the glaze do not apply to this type of glaze.) High-temperature insulator glazes (fired at a temperature of 1,300°C. and higher) have not only a very great influence on the surface resistivity of the insulator but also on its mechanical and physical characteristics.

One of the most important factors which influence the mechanical characteristics of the glazed body is the ratio of the heat expansion of the glaze to that of the body. There is no general agreement as to which ratio is the most favourable. In early days the opinion held was that both glaze and body should preferably have the same coefficient of thermal expansion.

Subsequent investigations proved, however, that such a simple law did not apply. These investigations disclosed that the most suitable glaze has to be found by numerous experiments (by trial and error) for each and every body.

The tensile strength, the modulus of rupture and the other mechanical characteristics may be improved very considerably by the application of a glaze the thermal coefficient of which bears the proper ratio to the thermal coefficient of the body.

The resistance to sudden temperature changes, however, may be more favourably influenced by another glaze.

If the thermal expansion of the glaze does not fit to that of the body, a considerable decrease in mechanical strength may result.

These phenomena have nothing to do with the mechanical strength of the glaze itself. Taking a cylindrical test specimen covered with a thin glaze, the cross-sectional area of the glaze is exceedingly small compared with the cross-sectional area of the porcelain. The glaze may, however, decrease or increase the mechanical strength of the test specimen by 50 per cent. The fact that the use of certain glazes so considerably improves the mechanical characteristics of the insulator can be explained by the stress conditions prevailing in the glaze and in the surface layer of the porcelain body. If stress conditions in the glaze are not correctly related to those in the insulator body, the elastic limit of the glaze may be reached and thus different kinds of failure of the glaze may occur.

CRAZING AND PEELING

If we take the case of a porcelain rod which is covered by a glaze having a greater heat expansion than that of the rod, then when both are cooling down in the kiln the glaze has a tendency to assume a smaller length than the rod. The rod, however, takes a firm grip on the soft and viscous glaze and will not allow the glaze to shrink more and to follow its natural tendency to become smaller than the rod. In other words, the glaze (while sticking firmly to the rod when rod and glaze are cooling down) is subjected to tensile stress, being prevented by the rod from assuming its natural smaller cold-state length. This tension may cause rupture of the glaze either during cooling or later on in service as the result of some external cause. This breaking usually takes the form of numerous cracks and is generally known as " crazing."

The contrary applies if the glaze has a smaller heat expansion than the body. In this case when both are cooling after firing the glaze contracts less than the body. It has a tendency to assume a greater length than the rod. The rod, however, will not allow the glaze to acquire a greater length than itself—in other words, the glaze is compressed to a smaller size than that which it would possess if it were not compressed by the porcelain rod. This stress may also cause rupture of the glaze, but in this case it shows itself in another form than that described in the case of a glaze having a greater coefficient of thermal expansion. The glaze is pressed away from the porcelain, this phenomenon being called "chipping" or "peeling."

INCREASED TENSILE STRENGTH

Many experiments have been carried out in different countries and the results have been published by various authorities. In the United States Rowland ("Electrical Engineering," No. 55, p. 618, 1936) reports that in special cases the tensile strength is increased as much as 80 per cent. by a suitable glaze and an increase of 40 per cent. is quite normal. Similar results have been obtained by Continental research workers, the tensile strength of unglazed porcelain being given as 240–320 kg. per $cm.^2$ and of glazed porcelain as 300–500 kg. per $cm.^2$ (Hescho Mitteilungen, 1926). Tests carried out in English factory laboratories give similar results.

The application of a suitable glaze not only increases the tensile strength but also the other mechanical characteristics. For instance, the compressive strengths of unglazed cylindrical test specimens possessing cross sections of 160 $cm.^2$, 80 $cm.^2$, and 20 $cm.^2$ are 900, 1,000, and 1,700 kg. per $cm.^2$ Corresponding figures for glazed cylinders are 2,000, 2,300, and 4,300 kg. per $cm.^2$ The above figures are minima, not maxima (*i.e.* when the porcelain begins to crumble) (Hescho Mitteilungen).

These considerations apply only to porcelain glazes which fuse at the maturing (vitrification) temperature of the porcelain as generally used in high-voltage insulator manufacture.

APPLICATION TO FINISHED ARTICLES

Low temperature glazes which are applied to the finished ceramic article and which are fused in a second firing at a lower temperature, behave differently and are as a rule not able to increase the mechanical strengths of the ceramic article. (For instance, in earthenware manufacture, and as mentioned above, in certain insulator manufacture.) In contradistinction to high temperature insulator glazes, this type of glaze generally contains strong fluxes like lead oxide, etc., which are not contained in the porcelain body.

These glazes form, with the surface layer of the porcelain, combinations which may behave very differently from the body. The composition of the glaze does not in this case play so predominant a part as in the case of high temperature insulator glazes. Other considerations are of equal importance.

Insulator glazes are composed, as mentioned above, of similar materials to those of the body, *i.e.* clay, silica, and feldspar, but their proportion is such as to decrease the fusing point. This means that the feldspar content is considerably increased, but the clay content accordingly decreased as compared with that of the body. Smaller amounts of other fluxes, such as dolomite, magnesite or lime, may be added in order to impart to the glaze the most suitable fusing temperature and the most suitable coefficient of thermal expansion. Such fluxes, insofar as they are not contained in the composition of the body, have, however, to be used only in such small quantities as not to make the glaze too dissimilar to the glassy matrix formed in the porcelain body during the firing process.

In insulator design, much use is made of the strengthening effect of the glaze on insulator bodies. Previously, the attachment of the porcelain to the metal work was facilitated by the provision of unglazed or partially glazed surfaces in contact with cement. In present-day designs in place of the conventional form of insulator head a smooth and unbroken glazed surface—especially in the design of cap and pin insulators—has been introduced (Fig. 5).* Other types which make use of the strengthening effect of the glazes on insulator bodies are solid-core line and station post insulators, and the so-called motor and long-rod (Langstab) insulators which are used on the Continent to a very great extent as suspension and strain insulators (Figs. 5*a* and 6).

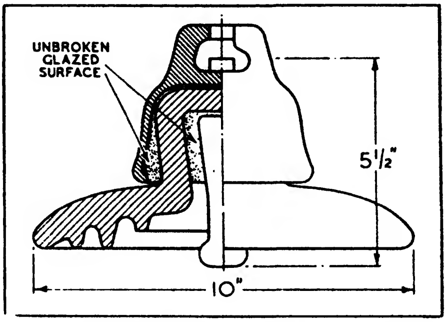

FIG. 5.—Cap-and-pin suspension insulator: Porcelain having unbroken glazed surface subjected to compressive stresses. Electro-mechanical strength B.S.S. 6,804 kg. Average breaking load 9,000 kg.

In the case of glasses (which have many similarities to ceramic glazes) it has been found possible to calculate the thermal expansion if the composition of the glass is known. The exact thermal expansion of glazes cannot, however, be calculated from their composition, the reason being that first, glazes are not true glasses, but are still partially opaque and, secondly, a vivid interaction takes place between the glaze and the body. The composition of the fired glaze is, consequently, quite different from the composition of the

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* Preface, " Cap and Pin Insulator Catalogue," Bullers, Ltd.

raw materials of which the glaze is composed. During the firing, an interface is formed between glaze and body. In the case of high temperature porcelain insulator glazes, the properties of the interfacial layers are intermediate between those of the body and the glaze. In the case of other types of glazer this interfacial layer has however not necessarily a thermal expansion which lies between the thermal expansion of the body and that of the glaze. Crystals may be formed in this interfacial layer and impart to it a quite different thermal expansion.

The Author noticed this recently when developing suitable glazes for talcum-clay bodies.

Parmelee and Rodreguex, Journal of American Ceramic Society, January, 1942, described a similar expansion conduct of interfacial layers when studying earthenware bodies and glazes.

There is agreement amongst most research workers who investigated inter-action between body and glaze that those glazes which are very similar in their composition to the composition of the body, do not dissolve so much of the body as do glazes the composition of which is dissimilar to that of the body, and are not, therefore, apt to develop interfacial layers which may have a very different behaviour. In other words, the higher the alumina and silica content of the glaze, the less the composition of the glaze is changed by combining with the surface of the body (so far as bodies in which clay substance is the main component are concerned).

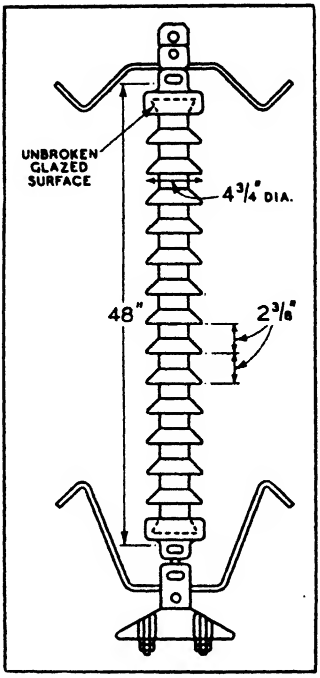

FIG. 5 (*a*).—Suspension insulator: Long-rod (Motor) type, originally designed by Motor Columbus Co., Baden, Switzerland. Porcelain having unbroken glazed surface subjected to tensile stresses. Working voltage 100 kV. Maximum working load 3,600 kg. Miniumm breaking load 6,200 kg. Flashover, dry 950 kV. wet 315 kV., at 50 cycles.

Another important difference between high temperature porcelain glazes and glasses is that the former are fired in the oven at a temperature which matures or vitrifies the porcelain (1,300°–1,400°C.) which is higher than the softening temperature of glass. This makes possible the use of a very high silica and alumina content for insulator glazes. The high silica and alumina contents explain the great hardness, mechanical strength and resistance to chemical attack of glazes.

The fit between body and glaze can be measured by various methods.

Steger measured it by glazing one side of a bar 260×20×3 mm. in size, and heating it to 800°C. As the furnace is heated, the stress resulting from the difference in expansion of glaze and bar causes the bar to deflect until 800°C. is reached.

The glaze then becomes plastic and the stresses are zero. If the bending of the bar is below zero, the glaze is in compression and may "peel," if it is above zero, the glaze is in tension and may "craze."

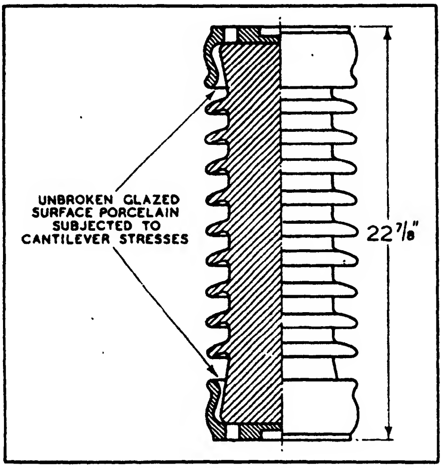

Fig. 6.—Line-post solid-core insulator. Porcelain having unbroken glazed surface—subjected to cantilever stress. U.B.S. cantilever 1,300 kg. Flashover voltage, dry 200 kV., wet 147 kV., at 50 cycles.

Another method of measuring the ratio of thermal expansion of glaze and body is described by Schurecht, "Fitting Glazes to Ceramic Bodies," Journal, American Ceramic Society, March, 1942.

The test specimen is a ring having a height of ½ in., wall thickness ¼ in., diameter 2 in. The ring is slit with a carborundum wheel, or another suitable cutting device. Only the outside wall of the cylinder is glazed. If the ring expands after firing, it indicates that the glaze is in tension; if the ring contracts, it indicates that it is in compression. Any expansion or contraction of the ring can be observed by reference marks consisting of 2 thin metal rods, or glass rods, which are cemented into the upper face of the ring near to the slit.

Direct determination of the thermal expansion of glazes is carried out by measuring the thermal expansion of a glaze rod prepared from the melted glaze batch. The same apparatus and procedure can be used for the measurement, as described later in this book, in connection with the plotting of shrinkage and expansion curves of bodies and clays. The glaze specimens have to be properly annealed before the measurement of the thermal expansion is carried out. For this purpose they are first heated to the upper annealing temperature of the glaze, maintained at that temperature for an hour and then cooled to room temperature at the uniform rate of 2°C. per minute. (This is the method used by Professor Turner, University of Sheffield, for measuring the thermal expansion of glass rods.)

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There are many publications about the calculation of thermal expansion of glasses based on their percentage composition. Readers interested in this question may find interesting summaries in the following publications:

WINKELMANN AND SCHOTT: " Ueber thermische Widerstandkoeffizienten verschiedener Glaeser in ihrer Abhangigkeit von der chemischen Zusammensetzung," Ann. d. Phys. u. Chem., 51, 1884.

TURNER: Journal American Ceramic Society, Vol. 10, p. 551, 1927; Vol. 12, p. 760, 1929.

CHAPTER IV

CHARACTERISTICS OF PORCELAIN AND OTHER CERAMIC MATERIALS

THE testing of porcelain can either be carried out on test bodies specially prepared for the test in hand or on actual manufactured insulators. The testing of special test specimens gives us the knowledge of the characteristics of the various porcelain bodies, whereas the testing of the complete insulator gives results combining the influence of the insulator shape, with the influence of the characteristics of the particular body used for the manufacture of the insulator under test.

To obtain comparable figures (which exclude as far as possible the influence which complicated shapes may have on test results) special test specimens most suitable for finding the exact data in respect to the different properties are manufactured. Thorough investigations have been made as to which shapes of test specimens are the most suitable in order to obtain reliable and comparable values for the various characteristics.

The influence of the dimensions and shape of the test specimen on the values obtained is quite considerable and test results are not comparable unless the same methods and the same test specimens are employed.

Therefore in various countries industrial and technical associations have developed methods for testing electric insulating materials. With regard to ceramic insulating materials the most valuable and detailed specifications have been developed by the American Society for Testing Materials and, in certain cases, by the German Keramische Gesellschaft. In subsequent chapters the various technical and physical properties of porcelain and other ceramic materials will be discussed and also the methods used for investigating them.

A. DIELECTRIC OR PUNCTURE STRENGTH OF PORCELAIN AND OTHER CERAMIC MATERIALS*

The dielectric or breakdown strength of an insulating material is that property which determines its suitability for use as a high tension insulator. The dielectric strength may be defined as the voltage gradient at which the electrical breakdown occurs. The dielectric

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* "Dielectric or Puncture Strength of Porcelain and other Ceramic Materials," E. Rosenthal. *Electronic Engineering*, March, 1943.

strength of porcelain and other ceramic insulating materials—as well as that of all other solid insulating materials—is, to a very high degree, dependent upon the test conditions. It is calculated by dividing the breakdown voltage by the thickness of the test specimen between the electrodes and is commonly expressed in volts per mil or kilovolts per millimetre (1 volt per mil corresponds approximately to 40 volts per millimetre).

The test values for dielectric strength of an insulating material vary to an extent not generally appreciated with :

(1) The thickness of the material.

(2) The duration and rate of increase of the voltage applied.

(3) The characteristics of the voltage applied (frequency and wave shape).

(4) Electrostatic field distribution (edge effects, surrounding media).

(5) Temperature of the material.

In order to obtain comparable values for the breakdown characteristics of the dielectric, the conditions enumerated above must be exactly the same for all the materials tested.

Tests on specimens of different thicknesses, tests made with different electrodes, tests made with different rates of voltage increase, or in different surrounding media, are not comparable.

The test methods for ascertaining the dielectric strength of electrical insulating materials at power frequencies are, therefore, standardised in various countries. In the United States, for instance, there are Specifications designated D. 149/40 T. and D. 116 (Standard Methods of Testing Electrical Porcelain) and in Germany V.D.E. 0303/1929. But since wall thickness, rate of increase of voltage and the nature of electrodes are not the same in the various specifications, the values obtained in accordance with the A.S.T.M. methods and the V.D.E. methods are not comparable— the V.D.E. method giving often much higher Test Values.

The main difference between the American and V.D.E. methods is as follows : The American Tentative methods specify (for porcelain) electrodes having the shape of a metal disk 0·75 in. in diameter, with edges rounded to a radius of $\frac{1}{8}$ in. Plain, unrecessed, test pieces of uniform thickness are used. The V.D.E. recommends electrodes formed by metal coatings deposited on both surfaces of a recessed test disk. The test disk has, therefore, not a uniform thickness since one or two hemispherical cavities are inserted in the centre of one or both of the faces of the disk, the smallest wall thickness of the porcelain between the two metal coatings being 2 mm. (Fig. 7).

On the other hand, the American Test Standards for electrical porcelain provide for the thickness of a test specimen being 0·250 in. (6·35 mm.), 0·4 in. (10·16 mm.), 0·75 in. (19·05 mm.), or 1 in. (25·4 mm.).

The breakdown in the case of the German Test specimen generally occurs across the shortest distance between the two hemispherical metal coatings inserted into the disk. Field concentrations which may occur in air or under oil around the peripheral edges of the two metal coatings have no influence on the breakdown strength because the porcelain thickness between these two edges is so much greater than the shortest distance between the two hemispherical electrodes that breakdown between these electrodes occurs before any edge effects can influence the dielectric properties of the test specimen. (If, of course, the porcelain is faulty and contains, for example, air pockets or cracks, breakdown may occur between the peripheral edges of the metal coatings.)

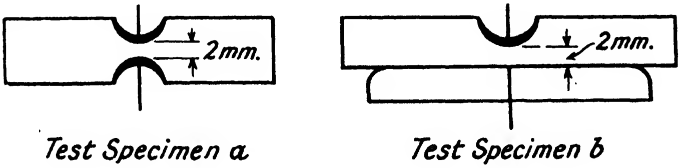

Fig. 7.—Test specimen (*a*): The electrodes being formed by metal coatings provided on the surface of two spherical cavities. Test specimen (*b*): The electrodes being formed by a metal coating provided on the surface of one spherical coating and by a metal disk with rounded edges.

In the case of test arrangements, as specified by the A.S.T.M. methods, edge effects under oil develop between the rounded edges of the electrode and the test specimen, resulting in premature breakdown of the specimen.

Relation of Breakdown Strength to Thickness of Material.—Fig. 8 illustrates the breakdown voltage of unrecessed porcelain disks of varying thicknesses under oil. This Curve was plotted by the Author as early as 1915. (Verlag G. Stalling, Oldenburg), the shape of the test specimen and electrodes being very similar to those standardised later on by the A.S.T.M. methods.

It will be seen that the breakdown strength per millimetre decreases considerably with increasing thickness of the material.

Fig. 9 illustrates the breakdown voltage of porcelain disks of varying thicknesses in different surrounding media, and illustrates the considerable influence which the surrounding media have on the breakdown voltage owing to edge effects caused by surrounding media having higher breakdown strength and lower dielectric constant than porcelain.

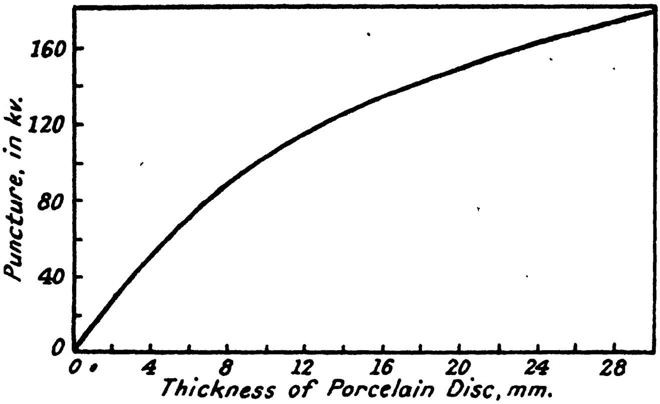

FIG. 8.—Breakdown voltage of porcelain disks of various thicknesses under oil electrodes; unrecessed disks with rounded edges. Power frequency. (E. Rosenthal, 1915.)

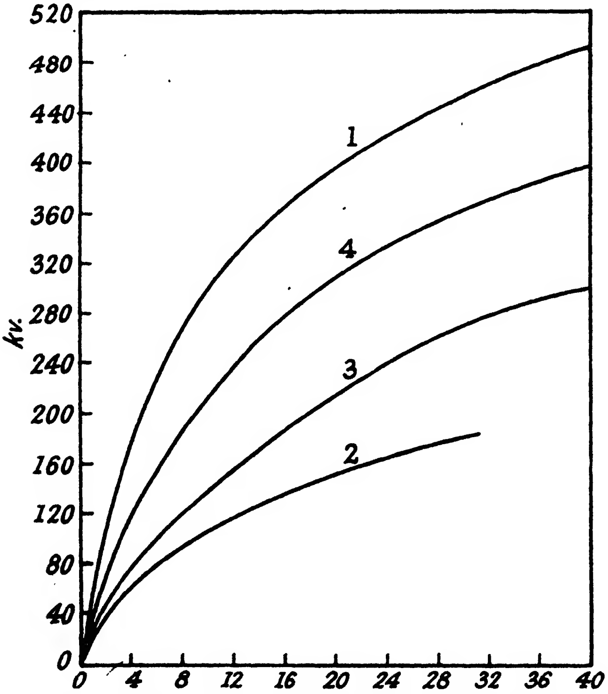

FIG. 9.—1. Actual breakdown; No edge effects (Wagner and Weicker). 2. Plates; transformer oil (pure). 3. Plates; transformer oil (used). 4. Plates; low resistance oil.

The same Figure (Curve 1) shows the breakdown voltage of porcelain disks of varying thicknesses when edge effects are eliminated, that is to say, the actual breakdown strength of porcelain.

Curve 2 shows the breakdown strength of porcelain disks of various thicknesses in transformer oil of best insulating quality. Curve 3 shows the same plates in used transformer oil, and Curve 4 the same plates in low resistance oil.

In explanation of the considerable decrease in dielectric strength per mil, with increasing thickness of solid materials, many theories have been advanced. In the early days this phenomenon was explained by the assumption that it is much more difficult to produce thick-walled porcelain disks than thin-walled ones, and that the decreasing puncture strength is therefore caused by the lower quality of thicker specimens. This explanation is, however, unsatisfactory because the decrease in puncture strength can be ascertained with almost any kind of solid insulating material and even with those where thick-walled articles are easier to manufacture than thin ones. Furthermore, thin slices cut out of an insulator disk have often a higher puncture strength per mil than that of the original complete disk.

Within the last few years physicists have made pronounced progress in the study of the dielectric failure, but in spite of this progress our knowledge of the phenomena involved is still very incomplete so far as solid insulating materials are concerned.

In order to form an idea as to why the dielectric strength of solid insulating materials decreases with increasing thickness, it may be as well to discuss at this stage the theory of breakdown of solid materials.

Theory of Breakdown. Dielectric failure of solid insulating materials may occur in one of the following ways, or in a combination of both :

(*a*) In disruptive breakdown ;
(*b*) In thermal breakdown.

Disruptive failure is one which results directly from an electrical overstress of the dielectric material without perceptible internal temperature rise. It is caused by ionisation and collision within the molecular structure of the material.

Disruptive failure occurs in the case of solid insulating materials only under special conditions, and accurate test values of pure disruptive dielectric strength for such materials are not easily obtained. If tests are made on very thin specimens so that heat may easily be dissipated by the electrodes and a sufficiently high voltage is applied to cause instantaneous breakdown, that there is no time for heat to develop in the thin section, the failure is purely disruptive. Impulse tests on thin ceramic sections cause a breakdown which is predominately, or almost purely, disruptive. With increasing thickness internal temperature effects modify the characteristics of disruptive failure. The breakdown strength per unit wall thickness at first decreases slowly with increasing wall thickness and then more rapidly when a certain wall thickness is reached, the breakdown showing more and more the characteristics of thermal breakdown with increasing wall thickness. Heat developed under the influence of the alternating electric field between the electrodes can less easily be dissipated when the wall thickness increases. When a certain thickness of the specimen is reached, a further increase in wall thickness will then no longer result in an increase of breakdown voltage. The Curves (Fig. 9) show that this critical wall thickness, an increase of which would not cause a further increase in breakdown voltage, depends not only on the dielectric properties of the test specimen but also on the nature of the surrounding medium. Theoretically, the disruptive breakdown voltage is proportional to the thickness of the test specimen (E. B. Shand, " Dielectric Strength of Glasses," El. Eng. Trans., August, 1941). The curves show that for commercial frequencies and for thicknesses such as are used in actual insulator design, disruptive breakdown is the smaller and thermal breakdown the larger of the two components causing the actual breakdown. Disruptive breakdown strength is the higher the more homogeneous the structure of the insulating materials. Thermal breakdown strength is determined by :

(1) Electrical conductivity (reciprocal of volume resistivity).
(2) Thermal conductivity.
(3) Power Factor.
(4) Dielectric constant of the insulating material (specific inductive capacity, or permittivity).

The higher the dielectric constant and the higher the power factor of the test specimen, the higher will be the electrical losses and more heat will be developed. The heat developed reduces the volume resistance of the material and more current will develop further heat until breakdown occurs.

It is well known that every insulator coming within the influence of an electric alternating field consumes a certain amount of electric energy and transforms it into heat. The electrical energy lost in this way is given nearly enough by the following equation :

$$N = V^2 2\pi f C \tan\delta$$

where V is the voltage.
f the frequency.
C the capacity of the test specimen.
$\tan\delta$ the tangent of the loss angle, or the power factor of the insulating material.

Since increased energy loss means increased heat generated, it can be concluded from this formula that insulating materials having a higher power factor possess a lower dielectric breakdown strength, particularly at high frequencies and if the voltage is applied for a long period, or increased at a small rate, *i.e.* if the thermal component of the actual breakdown is predominant. The disruptive breakdown, however, seems to be less dependent on the power factor.

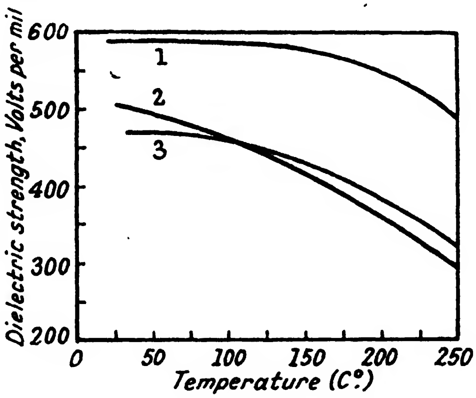

FIG. 10.—Dependence of breakdown strengths of 3 Steatite (Clinoenstatite) materials on temperature.

1. Alsimag 196 (power factor 0·14 per cent. at 60 cycles).
2. " 35 " 0·30 " " "
3. " 197 " 0·20 " " "

The curves (Fig. 10) illustrating the influence of temperature on the breakdown strength of 3 Steatite materials also show the influence of power factor on the thermal breakdown strength, particularly at elevated temperatures.

Although the phenomena causing breakdown cannot be attributed exclusively to the two factors " disruptive " and " thermal " breakdown, there is no doubt that these are the two most important factors and that breakdowns which occur in practice are in most cases the result of these two factors.

Short-time (or impulse) tests are predominately disruptive in their nature and long-time tests, high frequency tests and tests at elevated temperatures are predominately thermal. In most cases, disruptive and thermal effects combine to produce failure. If the breakdown is purely disruptive the breakdown current increases from a substantial steady value to breakdown in a fraction of a microsecond.

Electrostatic Field Distribution and Edge Effects. Both in the actual application of insulation and in the testing of it for breakdown strength, it is not easy to avoid conditions which lead to local field concentrations and similar effects which reduce the breakdown voltage.* These are generally referred to as " edge effects " because they are observed at the edges of electrodes, although field concentrations are, of course, not limited to the edges of the electrodes. Unequal field distribution, concentration of the field, edge effects, etc., etc., have a great influence on breakdown voltage. Even in elaborate tests it is not easy to eliminate electric field concentrations completely. Many discrepancies in published data on the breakdown strengths of solid materials result from small differences in the test arrangements causing edge effects of various strengths. In addition to the concentrations at the edges of the electrodes, these effects are produced by imperfect contact between the electrodes and the insulation, by scratches in the electrode surface, when the electrode is in the form of a thin metal foil or metal coating, by included air-pockets or pores in the test specimen, and by scratches and other imperfections of the surface of the dielectric itself. A special type of edge effect is that connected with the influence of the ambient medium on the field distribution, such as insulating oil.

Dielectric tests are frequently made under oil in order to eliminate flashover of the test specimen. Most insulating oils have a dielectric constant much lower than that of porcelain and glass so that the electrical stress in the oil will be correspondingly higher than in the material having the higher dielectric constant. Under these conditions, Corona discharges will form in the oil long before the breakdown voltage of the test specimen is approached. Streamers develop on the surface of the test specimen, commencing on the edges of the electrode. The higher the resistance of the insulating oil, the more concentrated are these discharges. These streamers

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* E. B. Shand, " Dielectric Strength of Glass," *Electrical Engineering*, Transaction Section, August, 1941.

produce intense voltage gradients along the surface of the insulation rapidly causing disintegration. If this action keeps on long enough, a hole may be bored into the surface of the test specimen causing dielectric failure before the actual breakdown strength of the test specimen has been approached. This type of failure is largely dependent on the dielectric strengths of the oil, and to a lesser degree only on the dielectric properties of the test specimen. Fig. 9 shows the influence of various oils on the puncture strength of porcelain. It can be seen that the higher the dielectric strength of the surrounding medium, the lower the breakdown strength of the test specimen. These curves show very clearly the great influence which the dielectric properties of the surrounding medium have on the dielectric properties of the test specimen and that tests made in different surrounding media are not comparable.

Edge effects, also, play a very important part in actual breakdown under normal service conditions. Imperfections between the electrode and the insulator surface produce field concentration which very often is largely responsible for breakdown at voltages far below the actual breakdown voltage of the insulating material in question.

In the design of electrical insulators and components, like bushings, etc., where metal parts have to be affixed to the porcelain insulator, these conditions have to be carefully considered and field concentrations avoided as far as possible. This can be achieved by suitable design of both the electrodes and the insulator and by suitable assembly methods. The application of conductive and semi-conductive coatings on the surfaces of the insulator (particularly on curvatures with generous radii) and the connecting of metal coatings with the metal work have been used to an increasing extent during recent years in order to improve field distribution.

In this connection reference may be made to the importance of the hard and non-attackable surface of porcelain and porcelain glazes. Surface irregularities and scratches produced on the surfaces of an insulator by metal parts during assembly may cause edge effects which may be responsible for early breakdown. Fortunately, both porcelain and porcelain glazes are so hard that scratches caused by metal parts are practically excluded. Any imperfections of the surface (whether they be due to scratches caused by a tool or by the live metal-work under service conditions, or whether they be cavities invisible to the naked eye caused by atmospheric conditions and resulting in a matt surface) are bound to cause edge effects with the inherent detrimental influence on breakdown strength. Very few insulating materials possess the same hardness and unattackability by chemical and atmospheric influences as does porcelain.

Duration and Rate of Increase of Applied Voltage. Fig. 11 shows the dependence of breakdown voltage of porcelain on wall thickness and the rate of increase of voltage. It can be seen that for thin sections the influence of different rates of voltage increase is very small. The influence of rate of voltage increase becomes more pronounced with increasing wall thickness. The breakdown strength of test specimens of great wall thickness is lower when the voltage is slowly increased, compared with breakdown strength measured at more rapid rates of voltage increase. In the case of impulse voltage, the breakdown strength is higher than in the case of tests carried out at commercial frequencies—the more so the thicker the test specimen. It can be seen, therefore, that the rate of voltage increase, or in other words, the time during which the voltage is applied, is an important factor in determining breakdown voltage.

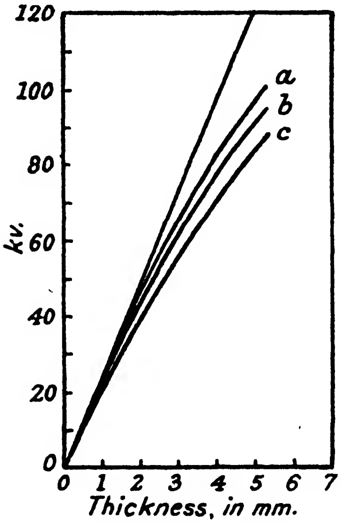


FIG. 11.—Dependence of breakdown voltage of porcelain on wall thickness and rate of increase in voltage. (Rosenthal-Mitteilungen, Draeger, 1926).

(*a*) Impulse voltage.
(*b*) Voltage increase 250 V. per second (50 c/s).
(*c*) Voltage increase 25 V. per second (50 c/s).

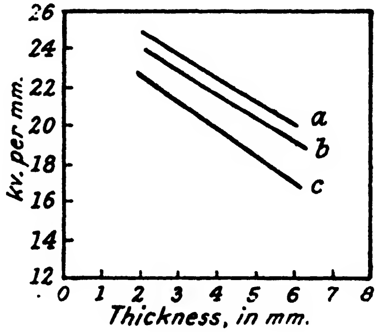


FIG. 11 (*a*).—Porcelain breakdown strengths in kv. per mm. with varying wall thicknesses and rate of increase in voltage.

(*a*) Impulse voltage.
(*b*) Increase 250 volts per second (50 c/s).
(*c*) Increase 25 volts per second (50 c/s).

Curve (*c*) in this figure shows the breakdown voltage of porcelain discs if the voltage is increased by 25 volts per second; curve (*b*) if the voltage is increased by 250 volts per second, and curve (*a*) under a steep wave impulse. The tests at commercial frequency were made in oil, whereas the impulse tests were made in air. The results of impulse tests in oil and in air do not, however, differ very much if the tests are made under conditions which exclude edge effects. The effect of rate of increase of voltage on dielectric strength is more pronounced in the case of bakelised laminated insulating material (Fig. 11 (*c*)).

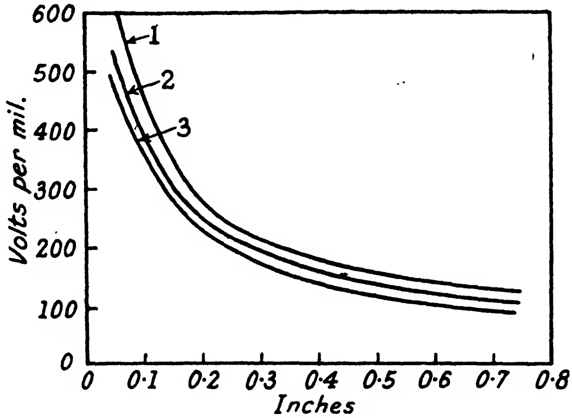


FIG. 11 (*b*).—Dependence of breakdown strength on thickness of test specimen (3 Steatite bodies). 1. Alsimag 196. 2. Alsimag 35. 3. Alsimag 197.

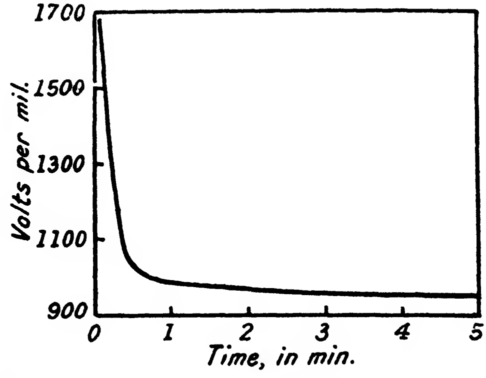


FIG. 11 (*c*).—Effect of rate of increase of voltage on dielectric strength of black varnished cambric. (A.S.T.M. Standards, p. 64.)

The A.S.T.M. Standards provide for short-time tests and for step-by-step tests. With regard to the short-time tests, it is provided that the voltage shall be increased from zero to breakdown at a uniform rate. The rate of rise is 0·5 or 1·0 kV. per second, depending on the total test time required and the voltage time characteristic of the material. The step-by-step test provides that an initial voltage will be applied equal to 50 per cent. of the breakdown voltage in the short-time test.

The voltage will then be increased in equal increments as laid down in the various material specifications. For testing electrical porcelain the A.S.T.M. Standards, however, make no provision for the step-by-step test.

With regard to porcelain and other dense ceramic material, it can be stated that it does not age under the influence of electrical stress. Tests carried out show that depreciation does not take place—at least during a period of many years—at power frequency. For instance, if the breakdown strength of a test specimen has been ascertained, a voltage of 10 per cent. below the breakdown voltage can be applied to it for many years without causing breakdown (of course if no irregularities are present in the test specimen).

Effect of Voltage Characteristics on Breakdown Strength of Ceramic Materials. With direct current the breakdown voltage of porcelain is 20–30 per cent. higher than with alternating current at commercial frequencies.

The breakdown strength of solid materials is lower at high frequencies than at low frequencies. It has been mentioned that as the frequency is increased, the dielectric losses increase and the temperature in the test specimen increases. As a consequence of the high temperature developed in the test specimen, the breakdown voltage drops. The power factor of the dielectric plays a very important part in the dielectric strength of the materials at high frequencies. For instance, the breakdown strength of improved Clinoenstatite bodies is 35–45 kV. per mm. at 50 cycles, and 25–27 kV. per mm. at 1 M.C. The breakdown voltage of this special type of ceramic body drops, therefore, only by about 40 per cent. (breakdown voltage at 1 M.C., compared with that at commercial frequency). In the case of porcelain the breakdown voltage drops by 50–60 per cent. and in the case of most glasses by 70 per cent. under corresponding conditions.

The influence of wall thickness on breakdown strength is more important at high than at low frequencies. If, by employing thin sections and massive electrodes, the heat developed by the high frequency field is quickly dissipated, the breakdown strength per unit thickness is higher than otherwise. There are puzzling exceptions to the general rule that the breakdown strength is higher at low frequencies than at high frequencies. Rutile bodies, for instance, have higher breakdown strength at high frequencies than at low frequencies. This refers to certain rutile bodies, the power factor of which is 100 times higher at 800 cycles than at 1 M.C., and 300 times higher at commercial frequencies than at 1 M.C. In such very special cases the breakdown at low frequencies is thermal and at high frequencies disruptive in character.

Influence of the Temperature of the Material on Dielectric Strength. Fig. 12 illustrates the dependence of breakdown strength of porcelain on temperature variations between 20°–160°C. It can be seen that within this temperature range the breakdown strength of porcelain at power frequency decreases only very slightly, and the less so the slower the voltage increase. In the case of impulse voltage the decrease with increasing temperature is more noticeable. From these curves it can be inferred that at a temperature of 160°C. the breakdown is purely thermal under all voltage conditions.

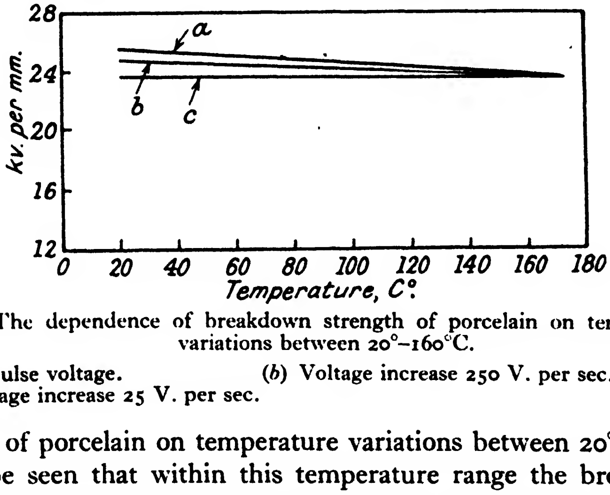


FIG. 12.—The dependence of breakdown strength of porcelain on temperature variations between 20°–160°C.

(*a*) Impulse voltage. (*b*) Voltage increase 250 V. per sec. 50 c/s.
(*c*) Voltage increase 25 V. per sec.

Fig. 10 (referred to above) shows the dependence of breakdown strength of Steatite articles at temperatures varying between 25°–250°C. The decrease in dielectric strength between room temperature and about 100°C. is not considerable in the case of two of the materials, both possessing a very low power factor.

The decrease in dielectric strength between room temperature and 250°C. is only about 15 per cent. in the case of the material

AlSiMag 196, owing to the extremely low power factor and high volume resistance at elevated temperatures of this special material. The same breakdown values at high temperatures are attained with other Clinoenstatite type materials having the same power factor and volume resistance. Breakdown strength at temperatures higher than 80°C. is, generally speaking, better the higher the volume resistivity at elevated temperatures and the worse, the power factor of the material under test.

SPREAD OF PUNCTURE VALUES OBSERVED

In order to obtain a reliable average value of the puncture strengths of a material, it is necessary to make a considerable number of tests. The American S.T.M. Standards only specify for porcelain a number of five, but a greater number gives a more reliable average.

The spread varies (*a*) with the frequency, (*b*) with the temperature, (*c*) with the duration and rate of increase of the voltage applied, (*d*) with the wave shape, and (*e*) with the electrostatic field distribution.

The spread is smaller at high frequencies and larger at low frequencies, and it is smaller at elevated temperatures compared with room temperatures.

In carrying out impulse tests, one observes a greater spread of punctures than at commercial frequencies.

The punctures lie closer together when the test arrangement excludes edge effects as far as possible. Edge effects tend to increase the spread of the observations.

It would, therefore, appear that there is a smaller spread in values in the case of thermal breakdown than is the case when the breakdown is preponderantly disruptive.

At normal power frequency (50 cycles per second) the spread can be as much as 25 per cent. up or down, although if the rate of the voltage increase prescribed by B.S.S. 137, namely 1 kV. per second, is adhered to the variation will only be of the order of ±12½ per cent. In other words, the more slowly the voltage is increased, the greater the spread of observations.

The graph (Fig. 12 (*a*)) was prepared by repeating twenty times tests at various rates of voltage increase. The horizontal ordinate indicates the number of seconds used for increasing the voltage by 1 kV. The twenty readings so obtained were added together and divided by twenty in order to obtain the average value. The highest figure above this average was then recorded above the horizontal ordinate, and the lowest figure below the average was recorded below the horizontal ordinate.

Curve (1) is for porcelain at room temperature (15°C.) and curve (2) is for porcelain at a temperature of 150°C. Although at first glance the spread of puncture values in the case of porcelain seems to be rather considerable it is smaller than in the case of most insulating materials.

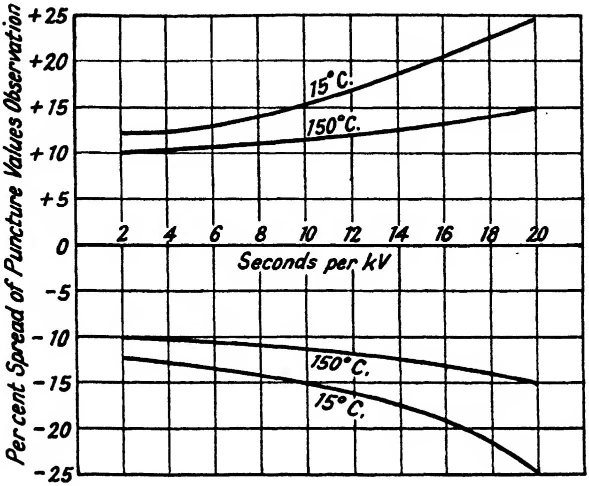


FIG. 12 (*a*).—Spread of breakdown values—observations in percentage with increasing number of seconds for 1 kV. voltage increase, 50 cycles per second. (Rosenthal, bulletins, 1926.)

B. POWER FACTOR AND DIELECTRIC CONSTANT

As mentioned above, every insulator coming within the influence of an electric alternating field consumes a certain amount of electrical energy and transforms it into heat and losses occur. It was mentioned in the previous chapter, that, when the lost energy (N) is only a small proportion of the total energy, it is given nearly enough by the equation :

$$N = V^2 2\pi f C \tan \delta$$

where V is the voltage, f the frequency, C the capacity, $\tan \delta$ the tangent of the loss angle or the power factor of the insulating material.

The power factor of a dielectric is therefore a measure of the energy loss in an alternating field. In many applications of insulating materials it is important that the loss be as small as possible. In others the dielectric loss is not of importance as such, but its uniformity is a measure of the uniformity in manufacture.

Porcelain insulators which have a higher power factor than the normal one have an unsound structure.

When the alternating voltage is applied to a capacitor the resulting current will have a small component in phase with the voltage. The phase angle θ between current and voltage will differ from 90 per cent. by the small amount δ known as the loss angle. The power factor of the dielectric is expressed as $\cos \delta = \sin \delta$. For all vitrified ceramic materials, and in fact for all sound insulating materials, the angle is so small that $\sin \delta = \tan \delta = \delta$ (when δ is expressed in radians).

The power factor is the fraction of the energy lost during a cyclic charging and discharging of a condenser formed by the dielectric. The amount of energy stored in the dielectric at a given field is proportional to the dielectric constant (permittivity). The product of the power factor and the dielectric constant is therefore a measure of the actual loss in the dielectric and it is known as the " loss factor." All dielectrics show energy losses in alternating electric fields.

In gases such as air under ordinary conditions, however, the losses are so small as to be practically negligible. Condensers with gases as dielectrics (*e.g.* air condensers=) are used as loss free standards in power factor measurements. In solids the power factor ranges from 0·1 to 0·00001 in order of magnitude.

The following table shows some typical values of power factor at room temperatures :

	Power factor at 60 cycles	Power factor at 10,000,000 cycles
Wood flour filled resin	0·04–0·3	0·035–0·1
Fabric filled resin	0·08–0·3	0·04–0·1
Asbestos filled resin	0·1–0·3	0·005–0·1
Laminated phenol resin	—	0·02–0·08
Cast phenolic resin	0·042	0·038–0·042
Styrene	0·0003	0·0003
Porcelain	0·017	0·006
Steatite normal	0·003	0·002
Steatite high frequency	0·001	0·0001
Glass	0·03–0·005	0·002–0·006
Mica	0·02–0·003	0·006–0·002
Frequalex	0·001–0·002	0·0001–0·0002

Since many noughts, especially in the figures for the low loss materials, are inconvenient to work with, the power factor is very often expressed in percentage or as power factor $\tan \delta$. FOR EXAMPLE THE POWER FACTOR 0·0001 CAN BE WRITTEN AS 0·01 PER CENT. OR AS TAN $\delta = 1 \times 10^{-4}$.

Since power factor is of interest for low and high frequency applications, the test method will be briefly described in this chapter. It must be stressed that only tests made under the same conditions give comparable results.

The conditions under which the power factor is measured, the shape of the test specimen and the shape of the electrodes and their application to the dielectric are of great importance and so is the nature of the surrounding media, the temperature and the frequency. The most important source of discrepancies in the measurement of power factor are stray fields and poor contact of the electrodes and different humidity conditions of the surrounding air. Systems of shielding have been worked out for the different measuring circuits (see the A.S.T.M. tentative methods D. 150) which eliminate the trouble of stray electric fields very effectively. It is, of course, also necessary to shield the measuring leads to the test specimen.

With regard to the electrodes it is necessary to provide close contact with the specimen: even small air pockets or interstices between the test specimen and the electrodes cause large errors in the measurement of the power factor.

Mercury electrodes are very satisfactory for general use at all frequencies. Tin foil electrodes are also used. A very thin coating of vaseline is recommended as an adhesive. The tin foil has to be applied under a smoothing pressure in order to eliminate all wrinkles and air pockets. The electrodes have, of course, to be accurately centred in respect to each other.

For testing ceramic materials the most convenient method of applying the electrodes is to provide metal coatings on the surface of the test specimen by painting or brushing on precious metal—oxide solutions which, after firing at about 750°C., form the electrode.

In the case of ceramic materials, the test specimen has the form of a disc 6 in. (15·24 cm.) in diameter. The thickness should be not less than 0·1 in. (0·25 cm.) and no more than 0·3 in. (0·762 cm.). The capacitance of a specimen shall be not less than 10 $\mu\mu f$.

For frequencies above 1 M.C. per second, the test specimens have to be smaller and the diameter of the test disc for these frequencies is standardised by the A.S.T.M. as 2 in. (5·08 cm.).

It is very important that the thicknesses of the test specimens should be uniform within ± 5 per cent. of the normal thickness, and the surface has to be as smooth and free as possible of all irregularities.

Materials with slight porosity will show very different characteristics when measured in dry or in humid atmosphere; but also in the case of dense and non-porous ceramic materials the influence of the surrounding air is of great importance owing to humidity films which may be formed on the surface.

Humidity control and exact records are, therefore, very essential. Fig. 12 (*b*) shows the variations of power factor of a Steatite group material fired at varying temperatures : Curve *A* in a dry atmosphere of calcium chloride, and curve *B* in an atmosphere of 75 per cent. relative humidity (Robinson, Journal I.E.E., November, 1940).

This material is dense when fired at 1,300°C. but more or less porous when fired at lower temperatures. If the material is dense the values for the power factor obtained in both dry and 75 per cent. humid atmosphere, lie close together.

These types of Steatite bodies fired at lower temperatures are not dense but porous, and the lower the firing temperature the greater the porosity and the higher the power factor if the measurement is taken in humid atmosphere. In a dry atmosphere both porous and dense materials have the same power factor.

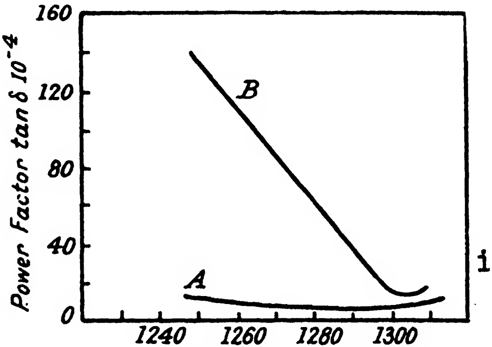


FIG. 12 (*b*).—Variation of power factor of a Steatite body with varying firing temperatures.

Since as a rule insulating materials are not used in an atmosphere which is kept absolutely dry by calcium chloride or other moisture-absorbing chemicals, measurements taken in absolutely dry atmosphere give no indication of the usefulness of porous materials for practical service conditions.

A most satisfactory method of maintaining constant humidity is given in Sect. 11 of the A.S.T.M. methods, in the chapter dealing with the methods of test for insulating resistances of electrical insulating materials (p. 342). The tests have to be made only on specimens which have been kept for at least 96 hours in air at a definite humidity and atmosphere, and the specimens have to be kept under the same humidity conditions during the test. The humidity may be maintained at any desired point by a reasonable airtight chamber in which a sulphuric acid/water containing mixture (of definite sulphuric acid/water ratio) is exposed to the air surrounding the specimen. A desiccator can be used for a constant humidity chamber provided it can be kept where the temperature is constant. The dielectric properties, especially of porous materials, are affected considerably by temperature and humidity, and it is therefore of great importance that attention be paid not only to the test conditions at the time of measurement but also to the treatment undergone previous to the measurement.

All values giving the power factor of insulating materials should indicate the frequencies in cycles per second, temperature of the atmosphere in degrees, the percentage relative humidity of the atmosphere, and, in case of porous materials, the conditioning of the specimen.

Measurements of Dielectric Loss. The Schering Bridge method is now perhaps the most widely used of all methods of measuring dielectric loss and power factor. All bridge methods consist essentially of a Wheatstone Bridge Network, the battery supply being replaced by an A.C. supply at either power frequency or some higher frequency. The detector used depends upon the frequency, a vibration galvanometer being used for power frequency work and telephones for work at higher frequencies.

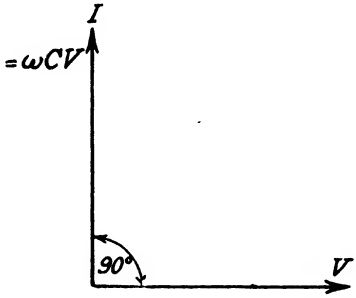


FIG. 13.—Perfect condenser; vector diagram.

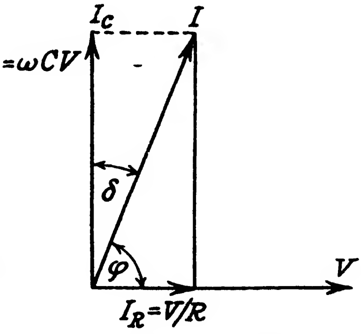
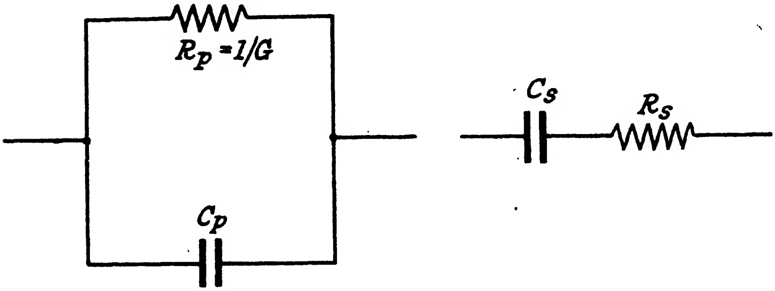


FIG. 14.—Vector diagram for equivalent parallel circuit.

Theory. If a sinusoidal voltage is applied to a perfect condenser, the current which flows into the condenser leads the voltage in phase by 90°, as shown in the vector diagram in Fig. 13.

Owing to the dielectric loss in condensers, the current in condensers used in practice leads the voltage by some angle which is slightly less than 90°, as in Fig. 14. (*Note*: The current in a pure non-inductive resistance is in phase with the applied volts.)

A condenser having dielectric losses can be represented by a perfect condenser in parallel with a resistance as in Fig. 15 (*a*) or in series with a resistance as in Fig. 15 (*b*). The current in the condenser is split into two parts—the first in the resistance branch in phase with the voltage, and the second in the condenser branch leading the voltage by 90°.



(*a*) Equivalent parallel circuit. (*b*) Equivalent series circuit.

FIG. 15.

In the case of equivalent parallel circuit for sinusoidal voltage and current the power factor is given as follows:

$$\tan\delta=\frac{1}{R_pC_p\omega} \text{ where } \delta \text{ is the loss angle.}$$

$$\text{Power factor}=\cos(90-\delta)=\sin\delta=\tan\delta \text{ if } \delta \text{ small}$$

$$=\frac{1}{R_pC_p\omega}=\frac{G}{C_p\omega}$$

where C_p =capacitance in farads.
R_p =resistance in ohms.
G =conductance in mhos., and
ω $=2\pi$ times the frequency in cycles per second.

In the case of equivalent series circuit:

$$\tan\delta=R_sC_s\omega.$$

$$\text{Power factor}=\cos(90-\delta)=\sin\delta=\tan\delta, \text{ if } \delta \text{ small}$$

$$=R_sC_s\omega=\frac{C_s\omega}{G}.$$

Schering Bridge. Fig. 16 gives the connections of a simple Schering Bridge which can be used with high or low voltages, Although this bridge is not suitable for very high frequencies it indicates the principle employed and simplifies the undertaking of more complicated arrangements.

C_x is the condenser whose power factor is to be measured; R_x being the equivalent parallel resistance representing its dielectric component, C_1 is the standard air condenser, R_3 and R_4 are non-inductive resistances, the latter being variable. C_3 is a variable condenser.

Earthed screens are provided in order to avoid errors due to inter-capacity between the high and low voltage arms of the bridge.

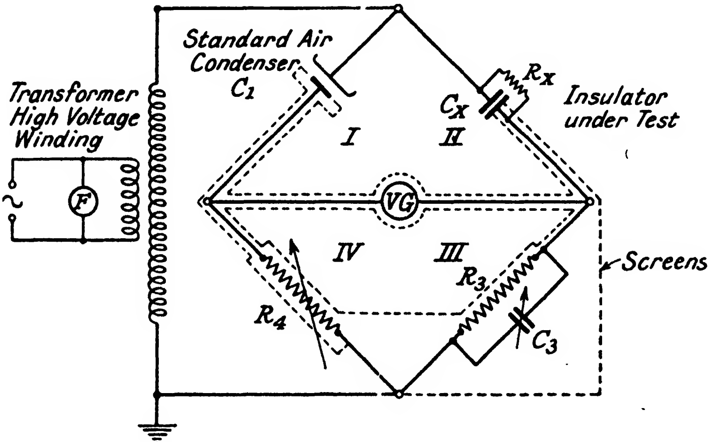


FIG. 16.—Principle of Schering Bridge.

Instead of earthing one point on the network as shown in the figure, the earth capacity effect of the galvanometer and leads may be eliminated by means of a "Wagner Ground."

V.G. (in Fig. 16) is a vibration galvanometer of a special design suited to the purpose. This must have a high current sensitivity, since the impedances of arms 1 and 2 of the bridge are usually very high. For the same reason, this method of measurement involves only a small power loss. Since the impedance of branches 3 and 4 are usually small compared with those of branches 1 and 2, the galvanometer and the resistances are at a potential of only a few volts above earth even when a high voltage supply (of the order of 100 kV.) is used, except in the case of breakdown of one of the condenser arms 1 and 2.

In use, the bridge is balanced by successive variation of R_4 and C_3

until the vibration galvanometer indicates Zero deflection. Then, at balance

$$C_x=C_1\frac{R_3}{R_4}=\cos^2\delta=$$

$$=C_1\frac{R_3}{R_4}\text{ if }\delta\text{ is small, and}$$

$$\tan\delta=R_3\omega C_3$$

where ω $=2\pi\times$frequency.
δ =the loss angle of the condenser.
$\sin\delta$ giving the condenser power factor.
C_x =the effective parallel capacity of the test condenser.
C_1 =the capacity of the standard air condenser.

For R_3, R_4, and C_3, see Fig. 16.

There are a number of Schering Bridge arrangements.

It depends on the frequencies and on the voltage conditions under which the tests have to be carried out as to which of the bridge arrangements is the most suitable for the special purpose in hand.

The Conjugate Schering Bridge (Fig. 17) is suitable for frequencies from 25 cycles per second up to 1 M.C. per second, and covers a very wide range of frequencies. It is therefore most suitable for testing ceramic materials.

In the A.S.T.M. Standards (D. 150—41 T.) five Bridge arrangements are described and the reader interested in the details should refer to these standards.

Since the Conjugate Schering Bridge is especially suitable for the testing of various ceramic materials, at low and high frequencies, the short description given there may be cited :

" This bridge is applicable for all frequencies from 25 cycles per second up to 1·0 megacycles per second. R_3 and R_4 shall be identical resistor units of a type practically free from capacitance, with resistance of the order of 10,000 ohms for use at frequencies of the order of 10 kilocycles per second and less ; 1,000 ohm units may be used for frequencies of the order of 1 megacycle per second if the capacity of the source warrants. The air capacitor C_3 is used to produce a positive reading for C_4, when C_2 alone is in circuit ; it should be no larger than is necessary for this purpose."

With the test condenser C_x in place as indicated in Fig. 17 its switch shall be closed and the bridge balanced by successive adjustments of C_2 and C_4 alternating with adjustments of the Wagner ground. When G. shows complete balance with the key at B. in either position the readings of C_4 and C_2 shall be recorded. Then the switch of C_x shall be turned to the shield and new balance values for C_4 and C_2 obtained. From the four values thus secured the equivalent parallel capacitance and the loss angle of the specimen

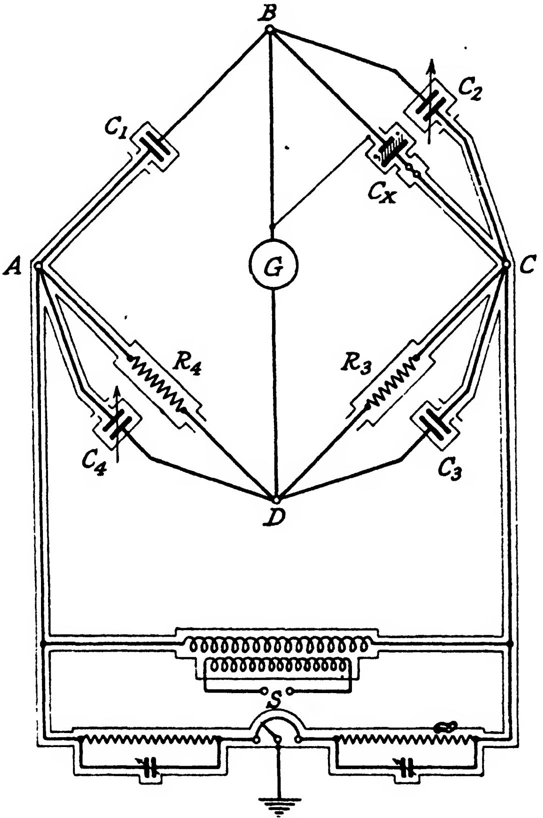


FIG. 17.—Conjugate Schering Bridge.

capacitor C_x may be calculated from the following approximate formulæ.

$$C_p = C_2 - C'_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\tan \delta = \frac{C_2}{C_2 - C'_2} \times \frac{2\pi f R_4 (C'_4 - C_4)}{10^{12}} \quad . \quad . \quad . \quad . \quad (2)$$

where C_p =equivalent parallel capacitance of the test capacitor formed from the test specimen, in micro-microfarads.

C'_2 =capacitance of the variable air capacitor in parallel with C_x, when the latter is in circuit, in micro-microfarads.

C_2 =capacitance of the variable air capacitor when balance has been restored after the test capacitor C_x has been disconnected from the circuit in micro-microfarads.

C'_4 =capacitance of the capacitor C_4 at balance when C_x is in circuit, in micro-microfarads.

C_4 =capacitance of the capacitor C_4 at balance when C_x is out of circuit, in micro-microfarads, and

f =frequency, in cycles per second.

If the change-of-standard method is not used, dependence may be placed on a single set of observations in a direct comparison of C_x with C_1, the corrections to be applied to the observations having been determined by other means. In this case C_2 shall be removed and C_1 shall be a variable standard air capacitor. At balance, approximately, the following relations hold and the calculations may be made from these formulæ.

$$C_p = C_1 \frac{R_4}{R_3} \quad \ldots\ldots\ldots \quad (3)$$

$$\tan \delta = \frac{2\pi f}{10^{12}} \times (R_4C_4 - R_3C_3) \quad \ldots\ldots \quad (4)$$

where R_3 and R_4=the resistances of the ratio arms, in ohms,

C_3 and C_4=the corresponding capacitances at balance of the capacitors across R_3 and R_4 respectively in micro-microfarads, and

C_1 =the capacitance of the variable standard capacitor at balance, in micro-microfarads.

Resonant Current Method. In addition to the Schering Bridge arrangements, resonant circuit methods may also be used to measure the power factor at high frequencies :

(1) The " resistance variation " method is applicable for frequencies from about 100 K-cycles per second up to 1 M.C. per second.

(2) The " susceptance variation " method is satisfactory from frequencies of 10 K-cycles up to 100 M.C. per second (and is specially useful for use at frequencies above 1 M.C. per second).

C. RESISTIVITY (VOLUME RESISTIVITY AND SURFACE RESISTIVITY)

An electrical insulating material is a material which has a very high resistance to the passage of electrical current (the expression " very high " is of course relative).

The " resistivity " is that property of an insulating material which determines its suitability for use as an insulator. The measurement of the resistivity of a material indicates, therefore, whether it is an insulator or not. If the volume resistivity of a material is less than 1 megohm/cm.^{3}, it may, in accordance with the A.S.T.M. Standards on Electrical Insulating Materials, normally not be considered as an insulating material. Resistivities of ceramic insulating materials are, however, very much higher than the above quoted minimum.

Approximate values of volume resistivity of some insulating materials are :

AMERICAN (A.S.T.M.) STANDARDS

	Megohm per cm.^{3}
Ivory	2×10^2
Celluloid	2×10^4
Marble	1×10^5
Plate glass	2×10^7
Amber	5×10^{10}
Fused quartz	5×10^{12}
Ceresin	$> 5 \times 10^{12}$

AMERICAN LAVA CORPORATION

	Ohms per cm.^{3}
Various Steatite products	$> 1 \times 10^{14}$

Bullers'

	Ohms per cm.^{3}
Frequalex	$> 1 \times 10^{14}$

GERMAN V.D.E.

	Ohms per cm.^{3}
Porcelain	$> 1 \times 10^{14}$
Mica	$1 \times 10^{15} - 1 \times 10^{16}$
Mycalex	$1 \times 10^{13} - 1 \times 10^{14}$
Fused quartz	$1 \times 10^{17} - 1 \times 10^{18}$
Bakelised paper	1×10^{12}
Bakelite	$1 \times 10^{9} - 1 \times 10^{12}$
Polystyrol	$> 1 \times 10^{12}$

PLASTICS IN INDUSTRY—" PLASTES "

	Ohms per cm.^{3}
Wood flour filled resin	10^{10}–10^{12}
Fibre filled resin	10^9–10^{11}
Asbeston filled resin	10^9–10^{11}
Laminated phenol resin	10^{10}–10^{13}
Urea paper filled	10^{13}
Cast phenol resin	10^9–10^{14}
Acetate	10^{12}
Vinyl	10^{14}
Acrylate	10^{15}
Styrene	10^{18}
Hard rubber	10^{12}–10^{15}
Resin impregnated wood	2–10^{10}
Resin after immersion in cold water—36 hours (surface dried)	48×10^6
Resin after immersion in hot water—3 minutes (surface dried)	$3 \cdot 8 \times 10^6$

(All the foregoing figures indicate volume resistivity at room temperature. Humidity content of atmosphere is not indicated.)

Current can pass either through an insulator or across the surface layer, or both ways. The ratio of the voltage applied to the electrode to the total current (flowing through the material plus that flowing over the surface) indicates " insulation resistance." It consists of volume resistance plus surface resistance, the volume resistance between the electrodes being the ratio of voltage to the current flowing through the volume of the insulating material, the surface resistance being the ratio of voltage to the current flowing through the surface layer. The surface layer is generally water (adsorbed from the surrounding air) which often has a conductivity millions of times that of the solid insulating material itself.

" Volume resistivity " is the resistance between two electrodes covering opposite faces of a centimetre cube, if no current flows through the surface layers. " Surface resistivity " (of a unit face) is four times the resistance between two electrodes covering opposite faces of a centimetre cube when all the current flows through the surface layer.

" Surface Resistivity " of a material is, therefore, determined by the film of water, oil or other liquid deposited on the surface of the insulating material. The surface resistivity of a material is thus dependent on the thickness of the film and on its nature. The greater the conductivity of the liquid which forms the layer, the lower the surface resistivity, and of course the thicker the humidity skin the lower the surface resistivity. The surface resistivity is, therefore, very much dependent on the quality of the surface. Smooth surfaces hold less humidity than rough ones.

A material which has high volume resistivity has not necessarily high surface resistivity. By glazing, by grinding or by polishing the surface of a ceramic article it may be made more smooth and the capacity of its surface to hold a skin of liquid thus reduced. The surface resistivity is consequently increased.

The surface resistivity of some common solid insulators may be given hereunder (taken from A.S.T.M. Standards):

Material	Surface resistivity, Megohms per cm.^{2}	
	At 25 per cent. relative humidity	At 90 per cent. relative humidity
Ivory	10 000	50
Celluloid	100 000	1 000
Marble	100 000	10
Plate glass	100 000 000	20
Amber	1000 000 000	100 000
Fused quartz	1000 000 000	100
Ceresin	100 000 000 000	100 000 000 000

At 25 per cent. relative humidity the surface film is very thin and consequently the surface resistivity very high, and therefore difficult to measure, particularly with materials having low volume resistivity.

At 90 per cent. humidity the humidity film is much thicker and the surface resistivity consequently much lower and easier to determine.

From these circumstances it may be seen that surface resistance values of insulating materials, measured in air of different humidity contents, are not comparable and that surface resistance values are meaningless unless the humidity content of the surrounding air is stated. The humidity content of the surrounding air plays a very important part not only with regard to the surface resistivity of all insulating materials, but also with regard to the volume resistivity of porous materials. If a porous material is used in humid atmosphere all the pores will be covered by a humidity skin. We have then a multitude of humidity paths through the body of the insulator.

The A.S.T.M. Standards on Electrical Insulating Material specify therefore that determination of insulation resistance of solid dielectrics shall be made only on specimens which have been kept for at least 96 hours in air at a definite humidity and temperature. The specimen shall be kept in air at this humidity during the determination. The humidity may be maintained at any desired point by using an airtight chamber in which a sulphuric acid/water mixture is exposed to the air surrounding the specimen.

The relation of relative humidity of air and density to acid/water mixture is indicated by the Curve in Fig. 18.

If the true value of volume resistivity is to be measured, the specimens have to be of such size and shape that a guard ring can be employed to eliminate surface currents and to obtain the true value of the volume resistivity. That means that the test has to be so arranged that the measured current is in the body of the material and does not pass through the surface layers.

From the figures covering volume resistivity it can be seen that the volume resistivity of nearly all insulating materials is so high that for practical purposes at room temperature the factors of safety are so high that it really does not matter whether the volume resistivity is, for example, 10^7 or 10^{17}. Under any of the following conditions, however, the position is completely different :

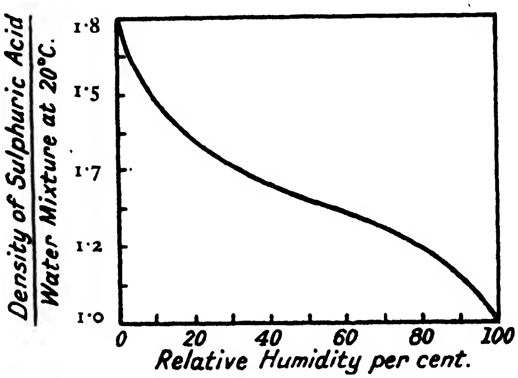


FIG. 18.—Relation of relative humidity of air and density of acid-water mixture. (A.S.T.M.)

(*a*) If a very high voltage is applied.
(*b*) If the material is porous.
(*c*) If the materials are used at elevated temperatures.

With regard to the question of volume resistivity if very high voltages are applied it can be seen from the figure given above that the volume resistivity of, say, a cubic centimetre of plate glass is theoretically high enough to insulate a voltage of 10^5 kV. (of course if it were possible to prevent flashover).

The volume resistivity is, however, only of theoretical interest when considering very high voltages, since breakdown would actually occur at much lower voltages. The reasons for this phenomenon have been dealt with in the chapter dealing with Breakdown Strength.

With regard to porous materials it has been mentioned that although their volume resistivity may be very high in dry atmosphere, it may be very low in a humid atmosphere. When the possibility of contact with humid atmosphere is not absolutely excluded, porous materials are, therefore, as a rule, not employed in electrical apparatus designed for use at room temperature since plenty of dense ceramic materials are available. But porous ceramic materials are used to a very great extent at high temperatures since they possess not only a high resistivity at these temperatures but also withstand very sudden temperature changes. Porosity has then no longer a detrimental effect on volume resistivity since the humidity skins of the surface and in the pores are evaporated at high temperatures.

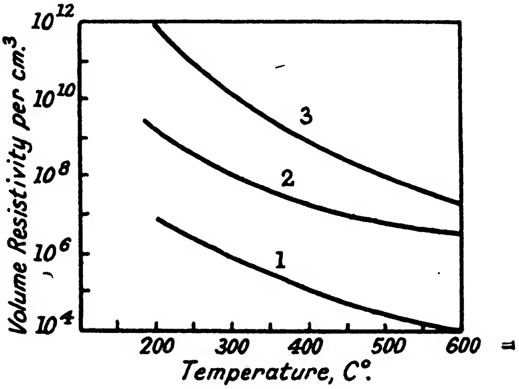


FIG. 19.—1. Porcelain. 2. Steatite. 3. Improved Steatite.
Volume resistivity between 200°C. and 600°C.

The volume resistivity of ceramic materials at elevated temperatures is higher than that of most other insulating materials. The volume resistivity of ceramic materials decreases of course with increasing temperature as it does in the case of all insulating materials, but the rate of decrease is smaller especially compared with all organic insulating materials and with most glasses. Ceramic materials fired at very high temperatures and containing only small amounts of fluxes are better in this respect than those fired at lower temperatures and containing a large amount of fluxes, particularly of feldspar. Clinoenstatite bodies have very good insulating characteristics at high temperatures.

Fig. 19 illustrates the volume resistivity of a porcelain body, a Steatite body and an improved Steatite or Clinoenstatite body.

D. MECHANICAL CHARACTERISTICS OF CERAMIC MATERIALS

(*a*) **Resistance to Impact.** Tests for impact strength are intended to determine the relative toughness of materials as indicated by the energy used in breaking a standard test specimen in one blow. The test is based upon the assumption that the resistance to shock depends upon the ability of materials rapidly to equalise concentrated stresses by elasticity (or deformation without failure). Standard pendulum impact machines are used to carry out this test and a standard test specimen has to be broken by the pendulum in one blow. This test shows, therefore, the resistance of the test material to shock loads.

The author of this book believes he was the first to use a pendulum impact machine in an investigation of the toughness of porcelain and the effect which a variation in the composition of a porcelain body has on its shock resistance (" Die Technischen Eigenschaften des Porzellans," 1915, Gerhard Stalling, Oldenburg). It was found that as far as vitrified porcelain bodies are concerned an increase in quartz and an increase in clay substance in turn increases the shock resistance ; whereas an increase in feldspar decreases the shock resistance. Slightly underfired porcelain has a higher shock resistance and overfired ware a lower shock resistance.

The methods of testing impact resistance in porcelain have been standardised by the American Society for Testing Materials and by the Deutsche Keramische Gesellschaft.

The A.S.T.M. has standardised as test specimens unnotched cylinders 6 in. in length, the diameters being 0·5 in., 0·75 in., or 1·125 in., whichever value is more nearly comparable to that of the finished product. The D.K.G. has standardised rods of 120 mm. in length and 16 mm. in diameter and has also standardised a pendulum impact machine—capacity 10 cm. per kg. A small machine of this type has been found more suitable for ceramic investigations than the larger metal testing machines.

There are two types of pendulum impact test machines in use, the one differing from the other in the method of holding and striking the specimen. The one is the Cantilever beam or the Izod type, in which the specimen is held at its lower extremity as a vertical cantilever beam and is broken by a blow delivered at a fixed distance from the edge of the clamp holding the specimen. This test requires a notched specimen and is used extensively for ascertaining the shock resistance of metals.

The second method, more suitable for measuring the shock resistance of ceramic materials, is the Charpy test in which the specimen is held as a horizontal beam supported at each end and is broken by a side blow delivered midway between the supports.

For this test specimens of other materials may be either plain or notched, but ceramic materials are tested un-notched. The machine for this method is accurate to 1 per cent. The machine has to be designed in such a way that the centre of percussion of the striker is at the point of impact, *i.e.* the centre of the specimen under test.

The test specimen is supported at each end on horizontal rigid faces and also leans against rigid vertical faces, in such a position that its centre of gravity lies on a tangent to the arc of travel of the centre of the pendulum. The edges of the blocks should be rounded to a radius of 0·125 in. and the supports should be 4 in. apart. (" A.S.T.M. Standards Impact Test 1941," p. 174). The energy expended by the machine in breaking the specimen has to be calculated. This value is equal to the difference between the energy in the pendulum blow and the energy remaining in the pendulum after breaking the specimen. The greater the impact strength of the test specimen the less the energy that will remain in the pendulum and the smaller will be the angle through which it swings after having broken the test specimen.

The impact strength is expressed by the A.S.T.M. in ft. lb. per in.^{2} and by the D.K.G. in kg. cm. per cm.^{2}

2·5 kg. cm. per cm.^{2}=approximately 1 ft. lb. per in.^{2}

This ratio permits comparison of the values published in German, American and English papers.

The D.K.G. publishes the following values, all expressed in kg. cm. per cm.^{2} :

Porcelain, extruded and cast	1·8–2·2
,, pressed	1·3–1·6
Steatite	3–4
,, high frequency bodies (low-loss)	4–5

The American Lava Corporation publishes values varying between 1·8 and 2·1 ft. lb. per in.^{2} for their dense Steatite materials.

Steatite and Porcelain Products, Limited, give in their Brochure *All-British Low Loss Ceramics* the impact strength of porcelain as 0·84–0·98 in ft. lb. per in.^{2} and 1·82–2·1 in kg. cm. per cm.^{2}, and for the various Frequentite and Steatite bodies 1·3–2·3 in ft. lb. per in.^{2} and 2·8–4·5 in kg. cm. per cm.^{2}

In order to provide a comparison of porcelain and Steatite with other insulating materials, the following figures are given :

Mycalex has a shock resistance in ft. lb. per in.^{2}	1·5–2·8
Cellulose has a shock resistance in ft. lb. per in.^{2}	0·3–1·0
Phenolic resin wood filled resistance in ft. lb. per in.^{2}	0·3–0·5
Phenolic resin fabric filled resistance in ft. lb. per in.^{2}	0·5–2·5
Laminated phenolic paper filled resistance in ft. lb. per in.^{2}	0·3–3·8
Laminated phenolic fabric filled resistance in ft. lb. per in.^{2}	0·8–7·5

(As mentioned above 2·5 kg. cm. per cm.^{2} = approx. 1 ft. lb. per in.^{2})

The carrying out of regular impact resistance tests is of great importance and interest to the insulator manufacturer both for the control of manufacture and for research purposes. The brittleness of ceramic materials is one of their less favourable properties and needs constant control. Even slight alterations in composition or treatment of the body have a marked influence on the results of the impact test.

(*b*) **Tensile Strength.** The tensile strength of a material may be defined as the number of pounds or kilos pull per square inch or square centimetre required to break the specimen. It is obtained by dividing the total load (in pounds or in kilos) required to break the specimen by the area of cross-section of the specimen (in square inches or square centimetres) at the point where the specimen breaks.

In measuring the tensile strength of ceramic materials it is of the greatest importance (*a*) to use suitable specimens and (*b*) to mount these specimens in such a way that they are submitted exclusively to tensile stress, so that no bending or shearing stresses occur which may cause considerably lower values (Figs. 20 (*a*) and 20 (*b*)). In one typical test piece the diameter at the centre is reduced to 1⅛ in. for a distance of 1 in., both ends having a conical shape which allows of an arrangement of suitable grips for holding the specimen. These grips should be self-aligning and should grip the specimen in a manner which does not cause pinching near the minimum section of the cone and which does not cause local compression at the ends of the metal grips.

The grips are arranged in the form of a universal joint such as is used for maintaining a compass in position. A small ring is situated inside the first ring and pivoted by means of pins in a plane perpendicular to the universal axis. This inner ring is of conical section and holds the porcelain specimen in place with the aid of split bushes. The test specimen has to be fitted with a compressible gasket around each conical end. This is the arrangement standardised by the A.S.T.M. (" Test for Electrical Porcelain," p. 264).

The D.K.G. has standardised a test specimen having the form of a rotating " 8 " the mid-section having a diameter of 20 mm. The mounting is performed in a similar way to that described by the A.S.T.M., but copper or lead foil is recommended as a gasket around each enlarged end.

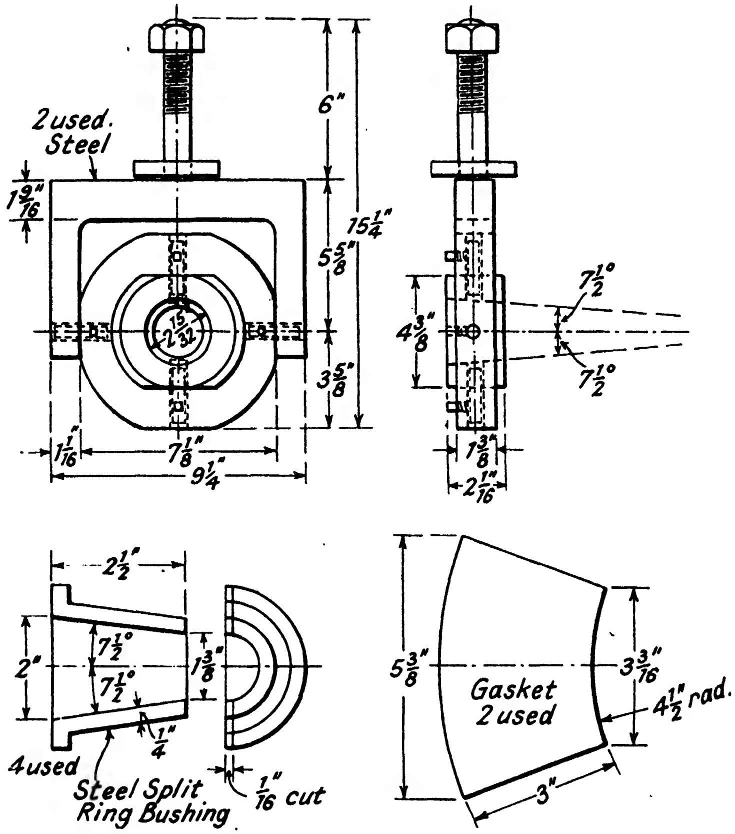


FIG. 20 (*a*).—Grips for tension testing of porcelain.

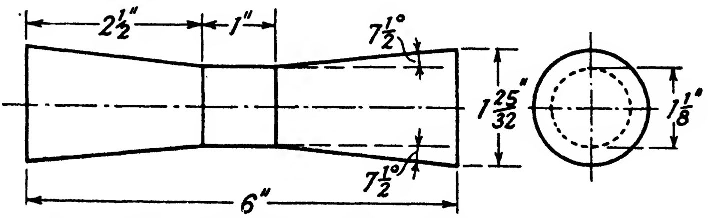


FIG. 20 (*b*).—Specimen for tensile strength tests. (A.S.T.M.)

A method which is not described in either of the test specifications is to use as test specimens rods with conical ends coupled with end caps. Between the cap and the porcelain end there is a gap into which molten lead is poured. This method of mounting the specimen obviates " pinching " near the minimum section and also obviates local points of compression. Of course, the specimen and the metal caps have to be held concentrically whilst the fluid lead is poured in. If the test specimen and the end caps are very slightly out of centre this does not matter, because the lead is soft enough to allow the porcelain to move slightly when the specimen is submitted to tensile stress in the testing machine. In other words, a certain degree of self-alignment is obtained. With this method of mounting, provided there are no pinholes or other flaws in the specimen, most of the test results obtained lie very close together.

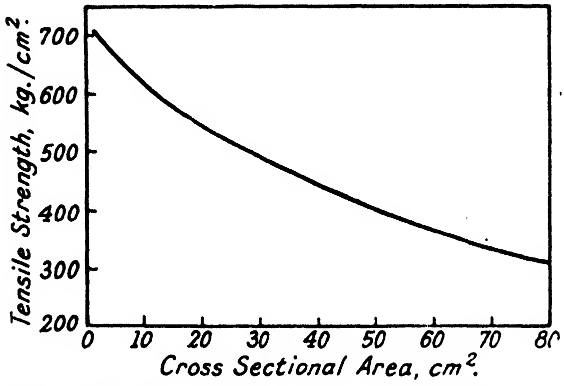


FIG. 21.—Tensile strength of cylindrical test specimens made of Steatite with varying cross-sectional areas.

When a specimen has been tensile-tested to destruction, the fracture should show the entire cross-sectional area to consist of a very coarse granular surface. This indicates that the entire area was correctly subjected to tension and that the entire cross-section resisted it.

If the specimen is not completely subjected to a pure tensile test, and compression and bending are partially introduced, the surface is then divided into distinct areas—the area of tension and the area of shear (the latter being much more smooth).

The tensile strength of ceramic materials is very dependent upon the size of the cross-section. For instance, a Steatite test specimen with a cross-section of 10 sq. cm. has a tensile strength of 600 kg. per cm.^{2} with a cross-section of 50 cm.^{2} only 400 kg. per cm.^{2} and with a cross-section of 80 cm.^{2} only 300 kg. per cm. (Fig. 21).

This is the reason why the cross-section of test specimens has to be standardised. Values obtained on specimens having different cross-sections are not comparable.

The tensile strength of a ceramic test specimen is affected by the type of glaze employed. The glaze may decrease or increase the mechanical characteristics. This question is dealt with in the Chapter on " Glazes." In this section, however, it may be sufficient to say that the use of a glaze having an appropriate coefficient of thermal expansion increases the tensile strength very considerably. An increase of 85 per cent. in the tensile strength of a vitrified porcelain body has been achieved by the use of a suitable glaze and an increase of 40 per cent. is quite normal.

TABLE SHOWING TENSILE STRENGTH FOR THE MOST IMPORTANT CERAMIC AND CERTAIN OTHER INSULATING MATERIALS

Steatite and Porcelain Products	kg. per cm.^{2}	lb. per in.^{2} $\times 10^3$
Porcelain	300–400	4·2–5·4
Frequentite " S "	400–500	5·7–7·1
Frequentite	550–850	7·8–12

American Lava Corporation	lb. per in.^{2}
Various Clinoenstatite materials	8,500–10,000

Bullers'	lb. per in.^{2}
Frequalex	8,500–11,000

Deutsche Keramische Gesellschaft and Association of German Insulator Manufacturers	kg. per cm.^{2}
Glazed porcelain	300–500
Unglazed porcelain	240–320
Steatite	550–850
Steatite high frequency	550–950

(100 kg. per cm.^{2} = 1·422 lb. per in.^{2}, or 100 lb. per in.^{2} = 70·3 gram. per cm. or 7·03 kg. per cm.^{2}).

To facilitate a comparison with other insulating materials, the following data may be of interest:

	lb. per in.^{2}	
Mycalex	6,600– 7,300	from *Plastics in Industry*, by " Plastes."
Phenolic resin wood filled	4,000–11,000	
Phenolic resin fibre filled	6,500– 8,000	
Phenolic resin asbestos filled	4,000–10,000	
Laminated phenolic paper base	7,000–18,000	
Laminated phenolic asbestos base	7,000–18,000	
Laminated phenolic cloth base	8,000–15,000	
Jabroc bakelised laminated wood	32,000–47,000	

	tons per sq. in.
Celluloid	2½
Cellulose acetate	3–5
Polystyrene	2½–3
Polyvinyl chloride	4½

(*c*) **Compressive or Crushing Strength.** The compressive strength of ceramic insulating materials is very high. It is not easy to obtain very uniform results on test since initial failures occur before the ultimate compressive breakdown strength has been reached, owing to the fact that it is very difficult to get the flat surfaces of the test specimen absolutely smooth and parallel. In the case of impact, tensile, and modulus of rupture tests on ceramic specimens, a slight variation in composition may cause large variations in test results. This is not the case usually with compressive tests. Variations in test results due to variation in composition are not so marked.

The compressive strength of ceramic insulators is, therefore, not ascertained regularly for production control. Cylinders are used for test specimens and the following dimensions are standardised in the United States: 1·125 in. (2·86 cm.) both in length and diameter.

The D.K.G. has standardised test cylinders of 16 mm. diameter and height. Both in the case of the American and D.K.G. Specifications it is laid down that flat surfaces should be made as smooth and parallel as possible before firing and that after firing the flat surfaces should be ground smooth and parallel. If it were possible to obtain surfaces with a high degree of accuracy, both smooth and parallel, no initial failures would occur. These conditions are, however, very difficult to obtain.

Irregularities of surface have, therefore, to be equalised by placing contact pads (cushions of blotting paper or soft metal sheets) between the upper and lower faces of the specimen and the self-aligning heads of the testing machines.

Since the compressive strength of ceramic materials is very high compared with their other mechanical characteristics such as their tensile strength and modulus of rupture, designers of porcelain insulators design them in such a way that they are mainly subjected to compressive stresses in all those cases where very high mechanical characteristics are required and where, at the same time, the dimensions have to be kept small.

The compressive strength of ceramic materials is, in a similar way to that mentioned in connection with tensile strength, dependent on the cross-sectional area of the test specimens. Test specimens with small cross-sectional area have a somewhat higher compressive strength per unit cross-sectional area than cylinders possessing a larger cross-sectional area (Fig. 22).

With regard to porcelain insulators, it can be stated that the compressive strength may be considerably improved by a suitable glaze.

There is no agreement as to whether a glaze possessing a higher or lower thermal expansion is more favourable in this respect. Steatite or other bodies of the Clinoenstatite type are not considerably improved in this respect by the application of glazes.

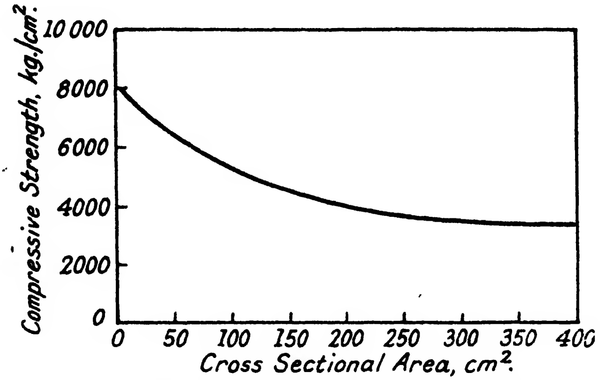


FIG. 22—Compressive strength kg./cm.^{2} of cylinder made of Steatite.

TABLE OF COMPRESSIVE STRENGTH

Porcelain (Steatite and porcelain products)		4,500–5,000 kg. per cm.^{2} 64,000–78,000 lb. per in.^{2}
Frequentite " S "		6,000 kg. per cm.^{2} 85,000 lb. per in.^{2}
Frequentite and Frequalex		9,000–9,500 kg. per cm.^{2} 128,000–135,000 lb. per in.^{2}
Steatite		8,500–9,200 kg. per cm.^{2} 120,000–130,000 lb. per in.^{2}
American Lava Corporation Ltd.		
Various Steatite and High Frequency materials		75,000–85,000 lb. per in.^{2}
D.K.G. and German Association of Insulator Manufacturers		
Porcelain (glazed)	extruded	4,000–5,500 kg. per cm.^{2}
,, (unglazed)		4,000–4,500 ,, ,,
,, (glazed)	pressed	3,000–4,000 ,, ,,
,, (unglazed)		3,000–3,500 ,, ,,
Steatite		8,500–9,500 kg. per cm.^{2}
,, high frequency		9,000–10,000 ,, ,,

To facilitate a comparison with other insulating materials the following data may be of interest :

Polystyrol (Trolitul) (German Publication)	950 kg. per cm.^{2}
Bakelite ,,	1,200–2,000 ,, ,,
Bakelised paper ,,	1,500 ,, ,,
Laminated paper sheet (" Plastes," Plastics in Industry)	9–18 tons per sq.^{2}
Polystyrene (" Plastes," Plastics in Industry)	7 ,, ,,
Aniline formaldehyde resins	9 ,, ,,

(*d*) **Flexural Strengths (Modulus of Rupture).** During the course of manufacture routine tests for flexural strengths are not regularly carried out for the purpose of ascertaining how variations in composition and firing affect the mechanical characteristics of the body, if the test for tensile strength is used for this purpose. On the other hand, determination of fluxural strength is recommended because of its greater economy, convenience and reproducibility.

The flexural strength of ceramic materials changes roughly in direct proportion to the tensile strength; but the influence of body and manufacturing modifications is, as a rule, more clearly shown by tensile strength tests. For instance, four different Steatite bodies manufactured by the American Lava Corporation (AlSiMag bodies 35, 196, 197, and 211) have a tensile strength of 8,500, 10,000, 8,500, and 7,500 lb. per in.^{2} respectively, and the modulus of rupture of the same bodies is 20,000, 22,000, 20,000, and 18,000 lb. per in.^{2}.

As an average the modulus of rupture is somewhat more than twice the tensile strength, as far as dense ceramic materials are concerned and can be three times the tensile strength in the case of porous ceramic materials.

According to the A.S.T.M. Standards, test specimens should have the form of cylinders 6 in. (15·2 cm.) in length, and 1·125 in. (2·86 cm.) in diameter. They are supported on two steel wedge-shaped blocks, the supports being 5 in. (127 mm.) apart and the specimen should be laid upon them with ½ in. (12·7 mm.) overlap at each end.

The load is applied to the top of the specimen at right-angles to the specimen and midway between the supports by means of a wedge-shaped pressure piece.

If M is the modulus of rupture, P is the load in pounds at rupture, l the distance between the supports in inches, d the diameter of the specimen in inches,

then
$$M = \frac{8Pl}{\pi d^3}.$$

The D.K.G. standardise round rods having a diameter of 16 mm. and a length of 50 mm., laid on 2 supports 400 mm. apart.

According to the D.K.G. the flexural strength of porcelain is :

Extruded		
Glazed	900–1,000	kg. per cm.^{2}
Unglazed	400–800	„ „
Pressed		
Glazed	600–700	„ „
Unglazed	300–600	„ „

The flexural strengths of the various Steatites vary between 1,200–1,600 kg. per cm.^{2}

MODULUS OF RUPTURE OF SOME INSULATING MATERIALS

Mycalex	1,000	kg. per cm.^{2}
Fused silica	700	,, ,,
Clinoenstatite (Steatite bodies)	1,200–1,600	,, ,,
Titanium bodies	900–1,500	,, ,,
Bakelised paper	1,500	,, ,,
Polystyrol	1,100	,, ,,

(The above-mentioned figures are quoted from German Literature.)

From the American literature, the following values may be quoted :

Clinoenstatite bodies	18,000–22,000	lb. per in.^{2}
Titanium bodies	20,000	,, ,,
Porous talcum bodies	8,000–9,000	,, ,,

E. RESISTANCE TO THERMAL CHANGE; TEMPERATURE CYCLE TESTS

The resistance to thermal change is very dependent upon the type of glaze applied to the ceramic bodies. There are many methods by which it is possible to test resistance to thermal change. The A.S.T.M. Standards provide for cylindrical test specimens having the same dimensions as those for the flexural strength test. They specify that these test specimens shall be immersed first in a cold water bath at Zero °C. and then transferred quickly to a hot water bath at about 100°C., where they have to remain again for about 10 minutes before being put back into the cold water. Such temperature cycles have to be continued until the specimen breaks. Good porcelain or other ceramic material will, however, withstand such a great number of these temperature cycles that they have to be repeated very often and so this method is not a practical one.

In the case of tests on finished insulators, it is laid down in American specifications that each insulator has to undergo 10 such complete temperature cycles, and that at the end of the 5th and 10th cycles the specimen should be checked for electrical soundness by being subjected to momentary flashover. It is required that the insulator should not deteriorate under this test.

In the case of test specimens, a useful test is to heat the specimens in an electric furnace for 10 minutes ; then with the aid of tongs to transfer them to a cold water bath. The first immersion takes place after 10 minutes' heating at 200°C. The temperature of the electric furnace is then raised by 25°C. after each immersion and the experiment repeated until the specimen breaks. For materials possessing very high resistance to temperature change, other test methods may be used such as immersion of the test specimen in melted metal alloys. The temperature of the metal bath has to be chosen according to the temperature to which the articles are subjected under service conditions.

The resistance to temperature change is the greater the lower the thermal expansion and the larger the thermal conductivity of the material.

Consider, for example, two ceramic rods each with the same coefficient of thermal expansion, but one with high thermal conductivity and the other with low thermal conductivity. The body with the higher thermal conductivity will be found to be more resistant to cracking when certain parts, but not all, are suddenly heated up, because heat is conducted quickly away from those parts which are suddenly heated, so that stresses due to different degrees of expansion in various parts of the body cannot form. In other words, the heat is more quickly distributed over the whole rod. If one part were very hot and the other very cold in the case of a body with low thermal conductivity, the hot part would, owing to the thermal expansion, increase its volume and the stresses set up between the hot part and the cold parts would break the rod.

Consider also another case. Two rods, each with the same thermal conductivity, one possessing a low thermal coefficient of expansion and the other a large coefficient of expansion. Then, if the two rods are heated, the difference in volume which occurs between the hot and cold parts of the rod will be smaller in the case of the rod with the lower coefficient of thermal expansion. The internal stresses set up would be smaller.

If a material existed which would not expand at all when heated up, then its resistance to temperature change would be infinite, because no stresses would be set up at all even if one part of the body were heated up very quickly to a very high temperature and the other part were to remain absolutely cool. If, on the other hand, a ceramic body were to possess the same thermal conductivity as metal then the resistance to sudden temperature changes would also be extraordinarily great since no differences of temperature in the test specimen would occur. Both these cases cannot of course be achieved with ceramic bodies, but it is possible to decrease the thermal expansion and to increase the thermal conductivity. So far no ceramic bodies have been discovered which have at the same time both an extraordinarily high thermal conductivity and a low coefficient of thermal expansion.

In order to improve resistance to temperature changes of ceramic materials, it is therefore necessary either to increase their thermal conductivity or to decrease their thermal expansion. The linear thermal expansion of most ceramic raw materials lies between $3{\cdot}0 \,.\, 10^{-6}$ and $8 \,.\, 10^{-6}$ per °C.

The thermal expansion of the finished ceramic materials is within the same limits.

There are only a few materials which have a lower thermal coefficient of expansion than that just mentioned. (For instance, certain clay and talcum mixtures form, when fired at temperatures above 1,100°C., ceramic materials having a thermal expansion of $1{\cdot}1$–$2{\cdot}5 \,.\, 10^{-6}$. This low thermal coefficient of expansion is due to the formation of the mineral cordierite which possesses the formula $2MgO\ 2.Al_2O_3\ 5SiO_2$).

Ceramic materials possessing such a low thermal coefficient of expansion possess very good resistance to thermal shock.

The thermal conductivity, and thus the resistance to temperature changes of the resulting bodies, on the other hand, can be increased by the addition of substances which possess greater thermal conductivity than average ceramic materials. Such substances, are, for instance, ferro silicon, silicon carbide, and corundum. The conductivity value of commercial ferro silicon lies between 15 and 18 K. cal. per m.^{2} per h. °C.; silicon carbide between 9–10 K. cal. per m.^{2} per h. °C., whereas the thermal conductivity of porcelain is only 1·9 to 2·2 K. cal. per m.^{2} per h. °C.

Use is made of such raw materials possessing high thermal conductivity in the production of certain ceramic insulating materials in order to impart to them greater resistance to temperature change. The more these substances are added, the higher will be the thermal conductivity of the body. If too much is added the porosity of the resultant body will become too great and its mechanical characteristics too feeble. It is not possible to manufacture *dense* ceramic materials containing ferro silicon or silicon carbide (which, owing to their high thermal conductivity, would possess very great resistance to temperature changes) because these materials are not chemically related to the clay base and do not react with it at the temperatures normally used for ceramic manufacture. In the case of corundum, however, which is crystallised alumina and therefore related to clay, reaction takes place at temperatures several hundred degrees higher than those used normally for the manufacture of ceramic materials.

Such Corundum bodies which possess very favourable characteristics are referred to in the chapter dealing with "Alumina".

F. THERMAL CONDUCTIVITY

The thermal conductivity of ceramic materials is not only of importance in improving the resistance of the body to temperature changes (for instance, in the case of electric fire heating elements). It also plays a very important part when ceramic insulators are required in the design of electrical apparatus where it is desirable to lead away heat (as in the case of ceramic casings enveloping elements which must not be thermally insulated).

The thermal conductivity of a material is the rate of heat flow per unit area and per unit temperature gradient in the direction perpendicular to the area. Thermal conductivity is expressed in various ways. In the case of ceramic materials the thermal conductivity is usually expressed in K. cal. per m.^{2} h. °C. on the Continent and in Cal. per sec. per cm.^{2} per °C. in American literature.

From the German technical literature the following values may be quoted :

Mica	0·29–0·5
Fused silica	1·2
Steatite bodies	1·9–2·2
Porcelain	2·0
Rutile bodies	3·0–3·5
Bakelised impregnated paper	0·25
Polystyrol	0·14

(All these figures are in K. cal. per m.^{2} per h. °C.)

From American technical literature, the following values may be quoted :

Steatite bodies	0·006
Cordierite bodies	0·003
Porous magnesium silicates	0·005

(All these figures are Cal. per sec. per cm.^{2} per °C.)

In the A.S.T.M. Standards on electrical insulating materials, a method of testing is described and a Table of conversion factors for various thermal conductivity units is given. The reader interested in further details may be referred to these specifications.

The apparatus used for determining the thermal conductivity consists of a heating plate, a cooling plate, 3 or 4 thermocouples, a galvanometer and an ice bath. A specimen of unknown conductivity is placed in a series with a reference standard of known conductivity between plates which are maintained at different temperatures. When a steady state of heat flow is attained the temperature difference across the reference standard and the test specimen is measured and the conductivity of the test specimen is calculated by the following equation :

$$K=K_1\frac{L}{L_1}\times\frac{\Delta t_1}{\Delta t}$$

K =the conductivity of the test specimen.
K_1 =the conductivity of the reference standard.
L =the thickness of the test specimen.
L_1 =the thickness of the reference standard.
Δt =the temperature difference across the test specimen.
Δt_1=the temperature difference across the reference standard.

The A.S.T.M. recommend reference standards having considerable ranges of conductivity made from rubber in which graphite is incorporated in varying amounts. Standards have been made from a base compound of high rubber content and different proportions of 300-mesh pure graphite. The composition of the base compound is given as follows :

	Per cent.
Plantation rubber	96
Zinc oxide	1
Stearic acid	0·75
Tetramethylthiuram disulfide	0·25
Sulphur	2
	100

The conductivities of the standards are as follows :

Graphite, per cent.	Thermal conductivity Watts Cm.$^{-1}$ (deg. Cent.)$^{-1}$
0	0·00143
15	0·00183
30	0·00248
45	0·00383
60	0·00824

A convenient size of the test specimen is a disc of approximately 20 sq. cm. and 1 cm. thickness. The reference standard shall have the same shape and size as the test specimen and shall have a conductivity not less than half and not more than twice the conductivity of the test specimen.

The heating and cooling plates shall be flat pieces of metal. Good thermal contact between metal plates and specimens is essential. The face of the ceramic test specimen in contact with the heating plates should be accurately ground. Thin, soft rubber sheets may be interposed between the plates and the specimen for the purpose of insuring good thermal contact. Pressures of the order of 200 grm.

per sq. cm. are usually sufficient to ensure such. The temperature difference across any specimen shall not be greater than 50°C. and not less than 10°C. The temperatures at the two surfaces of the reference standard and the temperatures at the two surfaces of the test specimen are measured by thermocouples.

G. POROSITY

Ceramic materials used as insulators have, as a rule, to be vitrified and non-porous. For other technical applications and in the case of insulators used at very high temperatures, the materials may be slightly porous. There are even applications where a certain porosity is required (for instance, in the case of valve spacers).

To make certain that a given ceramic material is suitable for high tension purposes, a test specimen may be submitted to the porosity test as specified for insulators. A specimen (75 per cent. of the area of which has to be free from glaze or other surface treatment and freshly broken) is put into a testing solution which consists of 1 grm. fuchsin in 1 litre of alcohol (50 per cent.). The specimen and the testing solution are then placed into the pressure chamber, in which 4,000 lb. per in.^{2} pressure has to be applied, for 15 hours, or a pressure of 10,000 lb. per in.^{2} for 6 hours. The porosity is indicated by penetration of the dye into the body of the ceramic material to an extent visible to the unaided eye. If the dye penetrates between the glaze and the body the glaze is not correctly attached to the body. B.S. 137/1941 specifies 0·5 per cent. alcoholic solution of fuchsin under a pressure of 2,000 lb. per sq. in. for 24 hours.

There are two tests for measuring the porosity of ceramic materials. The first method is for relatively coarse and porous bodies (0·1 per cent. absorption and over). The amount of water which they absorb is measured and the porosity is expressed as a percentage by weight of the water absorbed. The specimen is first weighed (after having been dried at a temperature of 120°C.) and is then cooled in a dessicator. The specimen is then boiled in water and weighed again after the surface water has been wiped off with a cloth. The difference between the weight in dry state and after immersion in boiling water gives the weight of the water absorption.

The second method is used for more dense porcelain bodies (if water absorption is less than 0·1 per cent.) and very often indicates porosity even in cases where the fuchsin test is negative.

This method is based on the amount of gas contained in a specimen of known volume and expressed in percentage per volume. Freshly broken test specimens are put into a receptacle or porosimeter. The volume of gas which is contained in the specimen is removed by evacuation of the receptacle and its quantity ascertained. (The procedure is described in detail in the A.S.T.M. Standards (" Test for Electrical Porcelain," p. 270) and by E. W. Washburn and Elmer N. Bunting, " The Determination of the Porosity of Highly Vitrified Bodies," Journal of American Cer. Soc., Vol. 5, pp. 527–535 (1922), and Louis Navias, " Metal Porosimeter for Determining Pore Volume of Highly Vitrified Ware," Journal of American Cer. Soc., Vol. 8, pp. 816–821 (1925).

CHAPTER V

RAW MATERIALS *

CERAMIC raw materials can be classified into two main groups.

First, the plastic raw materials which include the clays, kaolins, bentonites, and to a certain degree, talcums. Secondly, the non-plastic materials the most important of which, for the manufacture of porcelain, are : Silica (in the form of quartz, sand or flint), feldspar, stone, pegmatite, lime, magnesite, sillimanite, and alumina.

The plastic materials (as the name indicates) form, when mixed with water, plastic pastes which can be moulded into shape and then retain the shape so given them. After drying and heating to a predetermined high temperature, the plastic materials lose their plasticity and become hard bodies, the shape of which cannot be altered without completely breaking them.

The non-plastic materials act partly as " opening " materials in order to prevent excessive shrinkage during drying and firing, and several of them also act (in a greater or lesser degree) as fluxes, helping and speeding up the densification of the body.

A. PLASTIC MATERIALS

Kaolin or China Clay.† Kaolin which is frequently (especially in England) called " china clay " is a decomposition product of various feldspatic rocks, such as granite, porphyrite, pegmatite, etc.

The name " kaolin " is assumed to come from the Chinese words " Kao-ling " which means " high ridge." It is believed that this term referred to a certain region from which the kaolin or china clay was originally obtained.

Potassium feldspar which is the main constituent of these rocks is a combination of potash (K_2O) and Alumina (Al_2O_3) with silicic acid (SiO_2). It has the formula $K_2O.Al_2O_3\ 6.SiO_2$ and contains 16·9 per cent. potash, 18·3 per cent. alumina, and 63·8 per cent. silicic acid. Feldspar gradually decomposes under the influence of

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* The reader interested in more detail with regard to American ceramic raw materials may be referred to the Directory of ceramic materials published by " Ceramic Industry," Chicago, December, 1942. And the reader interested in more details with regard to Continental raw materials may be referred to William Funk, " Rohstoffe der Feinkeramik," Julius Springer, 1933, and E. Greber, " Traité de Céramique Paris, Soc. Franc. d'Editions Littéraires et Techniques, from which publications some information contained in this chapter has been collected.

† So called because it is an essential ingredient of " China " (porcelain).

carbonic acid gas and water—especially if the rocks are covered by marshes and bog earth, and if the access of atmospheric oxygen is prevented. The potash gets into solution and is carried away by currents of water. At the same time the greater part of the silicic acid of the feldspar is transformed into a soluble state, and, combining chemically with water (H_2O), a water-containing alumina silicate is formed. This combination of alumina with silicic acid possesses the formula $Al_2O_3\ 2SiO_2\ 2H_2O$. This mineral is called " Kaolinite " and contains 39·7 per cent. alumina, 46·4 per cent. silicic acid, and 13·9 per cent. chemically combined water.

One can assume with certainty that the decomposition of feldspar into kaolinite did not only take place in the manner described above. When the earth was in a state of much greater volcanic activity than it is to-day, hot acid-containing gases, vapours and hot water emanated from clefts in the earth, decomposing the rocks in a similar way as described above, transforming the feldspar into kaolinite. Other constituents, such as quartz, were not attacked and remained unaltered in the kaolinised mass. Irrespective of how this process of kaolinisation may have taken place, the final product is a substance of white-greyish or brownish tint, namely, " raw kaolin." Raw kaolin consists mainly of three substances, kaolinite particles (which the ceramists refer to as " clay substance "), undecomposed feldspar, and numerous quartz grains of various sizes.

Of course many of the impurities found in the original stone still remain in the raw kaolin, such as mica, titanic and iron compounds and other constituents in small quantities.

The present terminology differentiates between two types of deposits by designating as primary or residual kaolins those which are found at the place where the decomposition of the feldspatic rock by the weathering process has taken place ; and as secondary or sedimentary kaolins those which are first formed by weathering and are then carried away by water and re-deposited in another area. These secondary or sedimentary kaolins are something between a primary kaolin and a secondary clay. The meaning of a secondary clay will be explained later. Most of the kaolin deposits are primary (or residual).

Examples of secondary kaolins are the kaolins of Florida, South Caroline, and Georgia in the United States which were originally deposited in the sea in an area later elevated to form the Atlantic Coastal plain.

On the Continent primary kaolins are found first of all in Bohemia (Zettlitz, near Karlsbad and Chodau) which, owing to their purity and uniformity are favoured by many porcelain manufacturers all over the European Continent. The kaolin of Zettlitz is very white burning, very plastic and has very good casting properties, and that is why it is used very extensively for the manufacture of technical porcelain.

Other primary kaolin deposits on the Continent are found near Halle and near Meissen in Saxony and these are used by the German Insulator Manufacturers to a very great extent.

In France the more important kaolin deposits are found in the Mont du Limousin (in the Department of Haute-Vienne). These are extremely pure and of very good quality. Other very pure kaolins are found in Brittany and in the granite mountains of the Pyrenees. The French classify kaolins into three groups: first, kaolin-Argile which is very pure and contains only 4–5 per cent. sand, and which is used without previous purification in the porcelain and insulator industry. Secondly, the kaolin-caillouteux which means "sandy" kaolin containing 40–60 per cent. kaolin which has in most cases to be purified and washed before being used for porcelain manufacture; and thirdly, kaolin-décanté, which contains more than 50 per cent. sand and which has in any case to be purified and washed if used for porcelain bodies.

Further deposits are found in Algiers. All these deposits are extensively used by the French insulator manufacturers.

In England the main deposits of china clay are in Cornwall. This material has for many years been the most serious competitor of china clay or kaolin produced in all other parts of the world. Many other china clays have finer grain and greater plasticity and consequently greater strength in dry state—but the English clays are unexcelled on account of the better colour which they impart to the ceramic body. Apart from this, it is one of the most uniform kaolins found. It behaves well in casting, dries uniformly, reduces cracking of ware: it vitrifies at lower temperatures than most of the American and European kaolins, but of course not at as low a temperature as the secondary kaolins, such as, for instance, those found in Georgia and Florida. In the United States, apart from the secondary kaolins mentioned above, sedimentary kaolins are found in South Carolina, Georgia, and Alabama.

Kaolins possess varying degrees of plasticity. This plasticity is a typical characteristic of all clay substance-containing materials and is not only dependent upon the clay contents, but also upon their physical quality, especially on the size of the grain of the smallest clay particles. Not only do kaolins and other clays differ in this respect from each other (the clays having greater plasticity), but also within the groups of kaolins and within the groups of ball clays very considerable differences can be ascertained.

The crystal kaolinite which forms the clay substance of the kaolins and the secondary clays is a crystal of definite shape which can easily be recognised both by microscopic and X-ray analyses.

The particle size of the clay substance in clays is less than 0·01 mm. diameter, those in the kaolins being greater than those in the secondary clays. Many secondary clays, such as ball clays, contain such small particles that it is impossible to see them even with the most powerful microscope, and for a long time these very small particles were considered as non-crystalline and termed " colloidal." X-ray analysis, however, has made it certain that even those very small " colloidal " particles are of a crystalline nature.

The clay substance cannot be dissolved or decomposed by water or by diluted acids, but hot concentrated sulphuric acid decomposes the kaolinite particles completely, forming a water insoluble aluminium sulphate. Of this characteristic use is made to determine by chemical analysis the contents of clay substance.

Clay particles have the property of absorbing organic dyes, oils, and fats, *i.e.* retaining them on their surfaces so that it is not possible to wash them completely away by water. Of this quality use is made, *e.g.* when several different porcelain bodies have to be manufactured. They are stained by organic dyes in order to avoid confusing different bodies. The organic stains are added in watery solution to the clay-containing slip. The stain is then so completely absorbed by the plastic clay particles that the water comes out of the filter press completely clear and colourless.

In a similar way, oils and fats are absorbed when greasy bodies have to be produced for pressing in steel dies to avoid sticking of the plastic clay on the walls of the dies.

For use in the manufacture of porcelain washed kaolins or china clays are used almost exclusively. This washing process removes the quartz and other particles of coarser grain. Owing to their greater specific gravity they are not carried away by the stream of water, but remain behind, only the colloidal kaolinite particles and quartz and other particles of very small size being carried away. These settle down in the basins provided for this purpose.

The fineness and quantity of the quartz particles contained in the raw china clay vary according to the composition of the raw china clay. Washed china clay contains between 5–20 per cent. of very fine quartz particles.

The washing processes, which, as a rule, are carried out near to where the kaolin is found, are of very great importance. There are various types of purification and washing processes in use.

The details of the methods of washing vary—depending upon the nature of the china clays and the degree of purity which is required.

In Cornwall and in a few places in America where conditions are very favourable and allow of a more simple method of washing and refining than is possible in other places where the kaolin is mined deeply beneath the surface, clays can be treated hydraulically by being subjected to a powerful jet of water under pressure. This jet breaks up the clay, carrying away the finer parts and leaving behind the grit. The clay and water are run into a vat, and the water which carries away the clay is conducted into settling basins.

The drying of the purified kaolin is carried out in heated large basins into which the kaolin slip has been pumped.

In all other cases where the natural conditions do not allow of this relatively simple method, the kaolin has to be mined and then to be blunged in horizontal or vertical blungers. (The machinery here referred to is more fully described in a separate chapter.) A sieve at the outlet of the big blunger regulates the maximum size of the grains to be retained. The liquid containing the clay and the finer sand particles is then run through sand separators which consist of long channels, trenches or gutters made of wood or cement-coated stone. The sand is almost completely separated and the liquid holding the clay in suspension is finally run into tanks where all the solid parts can settle. The tanks are provided with suitably shaped outlets at different heights to allow of the clean water flowing away. The clay which has settled (after having passed powerful magnets) is then pumped into the filter presses where the excess water is removed and a kaolin suitable for transport is obtained.

Air separation is employed especially for clays which have to be used for dust pressing and for other ceramic raw materials used for dry mixing. A current of air is directed to the pulverised material which, by this means, is kept in suspension in the air in the same way as it would be in water. If the speed of the air current is diminished the coarsest particles settle first and the finest powder falls only when the air current is stopped.

The purification of kaolins can also be carried out by the employment of chemicals. All these chemical purification processes are based on the fact that certain chemicals have a deflocculent effect on the blunged kaolin slip

These chemicals transform the pasty, sticky clay suspension into a creamy liquid (they deflocculate it) and all impurities like sand, feldspar, etc., of a non-colloidal nature settle down. For instance, a liquid containing 0·21 per cent. sodium carbonate ($Na_2 CO_3$) or 0·49 per cent. sodium silicate ($Na_2 SiO_3$) has been found very favourable for separating the impurities from the kaolin slip.

It is obvious that the concentration most suitable for one kaolin may not be the best for other kaolins. The most favourable concentration has to be ascertained by experiment.

The liquids in which the deflocculated kaolin particles are suspended and from which the non-plastic particles have been removed owing to their greater specific gravity, are pumped into basins where flocculents such as calcium oxide in the form of milk of lime are added, which neutralise the effect of the deflocculents. The neutralised kaolin slip is then pumped into filter presses where excess water is removed.

Fig. 23.—General view of the new clay refining plant for the production of "hydro-cleaned" clay. The 8-stage process includes the use of synthetically distilled water, filtered air, blunging, magnetic separation, roto spraying, spray drying, air-floating and valve-begging.

Electrical purification is another method of separating the colloidal kaolin particles from the non-colloidal impurities. When an unpurified clay is suspended in water and the electric current is passed

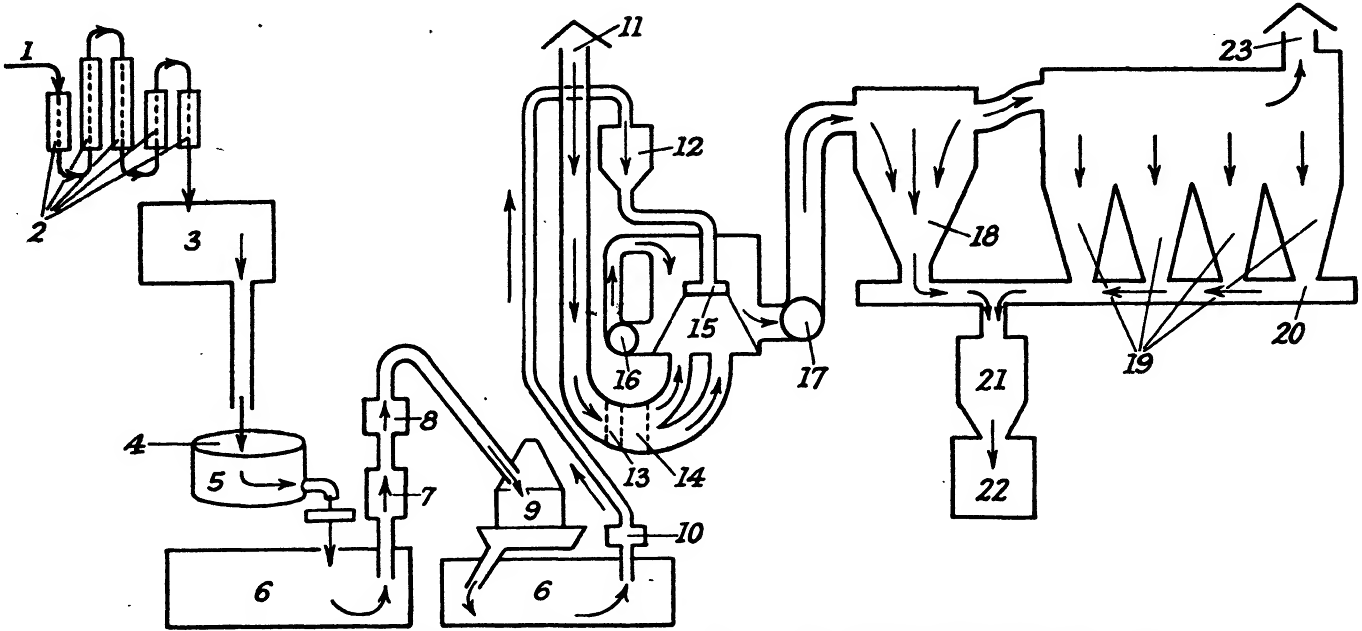

FIG. 24.—Schematic layout of clay refining plant. (Chicago Vitreous Enamel Production Company.)

1. Water supply.
2. Water treating unit.
3. Treated water storage.
4. Process begins at this point with treated water and lump clay.
5. Blunger.
6. Underground storage tanks.
7. Pump.
8. Magnetic separator.
9. Rotary sifter.
10. Pump.
11. Fresh-air intake.
12. Constant level storage tank.
13. Filter.
14. Heater.
15. High speed revolving atomizer.
16. Re-circulating fan.
17. Suction fan.
18. Primary collector.
19. Secondary collector.
20. Conveyor.
21. Hopper.
22. Bagging unit.
23. Air outlet.

through, the liquid clay tends to collect on the anode and the positively charged particles (impurities) collect on the cathode. Water can be separated from the liquid clay at the same time by this method if a suitable porous diaphragm is used. Of this behaviour of the colloidal clay substance use is made in the " electro osmosis " process.

In addition to the methods described, new centrifugal purification processes have been devised so that fractionated clays of controlled particle size make possible the use of kaolins for the manufacture of porcelain which, otherwise, could not be used for this purpose.

Figs. 23 and 24 illustrate the new 8-stage refining plant of Chicago Vitrious Enamel Product Co.* The clay is first of all blunged in a blunger (treated water is used) and then passes through sifters and magnetic separators into a chamber where by spray-drying the slip is dried instead of filter pressed. This new method produces a dried powdered material whose working properties are claimed to be enhanced by the cleaning and drying treatment. This process is particularly useful where powdered bodies are used.

Some examples of the chemical composition of various kaolins are given below :

	Georgia kaolin	North Carolina kaolin	English china clay	Florida kaolin	Alabama kaolin	Zettlitz kaolin	Boerte-witzer near Halle kaolin
	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.	per cent.
Silica . .	45·30	46·30	47·00	46·30	44·74	46·09	56·30
Alumina .	39·14	38·78	37·72	37·70	39·47	39·28	31·10
Titanium oxide .	1·54	0·04	0·15	0·50	1·29	—	—
Iron oxide .	0·27	0·38	0·96	0·80	0·55	0·76	0·60
Lime . .	0·13	0·10	0·19	0·50	0·00	0·15	—
Magnesia .	0·04	0·09	0·18	0·00	0·00	—	—
Potash .	0·15	0·34	1·57	0·20	0·00	0·15	0·25
Soda . .	0·10	0·24	0·23	0·00	0·00	—	—
Ignition loss	13·71	13·73	12·37	13·70	13·89	13·58	11·71

Ball Clays. Ball clays are rich in hydrous aluminium silicates and are of variable chemical composition and physical and chemical behaviour. They have great plasticity, and owing to their physical properties are very widely used for the manufacture of technical porcelain. Their name is derived from the original method of clay-working in England where the clay was won by open workings and taken from the pit in the form of balls weighing about 33 lb. each.

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* " Ceramic Industry," December, 1941.

In England they are found in Devon ; in America in Kentucky and Tennessee, and on the Continent (although they are not termed " ball clays ") in Bohemia and other places. But the place where the clay is most similar to the English ball clay is Wildstein in Bohemia.

Generally speaking, all clays are secondary or sedimentary clays. This means that they are not found in the place where they were originally formed but in the place to which they have been washed, by rain or streams of water. Owing to this natural washing and elutriation process the coarser particles like quartz are, as a rule, not carried away with the clay and are left behind. Other lighter particles, however, may have been carried by the same stream of water and may have found an opportunity of settling together with the clay. This is the reason why sedimentary clays have very often considerable contents of organic and inorganic admixtures (which also is the case, to a smaller extent, with secondary kaolins).

Good ball clays such as are used for the manufacture of technical porcelain are very pure and contain no detrimental admixtures.

What is known as ball clay to the practical potter is more or less a creamy burning, highly plastic clay which vitrifies usually at a temperature equal to S.C. 8 or S.C. 10. The ball clays occur in massive beds of remarkable purity and uniformity, sometimes overlain by lignite and with considerable lignite scattered through the clay itself.

" Blue ball clays " are very fine in texture and extremely plastic. The chief characteristics of this type are extreme freedom from colour when burned, extreme fineness of particles, great plasticity absence of impurities, great refractoriness and strength, after firing.

The term " black ball clay " is applied to certain white-burning plastic clays very similar to the blue ball clay, but so deeply stained with carbonaceous matter as to be black in the raw condition. This colour disappears on heating so that some of these very dark clays burn as light or even lighter than other types. The carbonaceous matter reduces the ferric oxide to ferrous oxide which has not the same staining properties as iron in the ferric state.*

A very valuable characteristic of the clays in regard to which they are superior to kaolins is their plasticity, which greater plasticity is explained by the physical quality of the clay molecules and by the presence of organic admixtures ; and the extreme fineness of the particles. As a rule one can say the greater the plasticity the greater

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* The chemical composition of ball clays is : Silica 57–46 per cent. ; Alumina 25–37 per cent. ; Ferric Oxide 1–2 per cent. ; Lime up to 0·5 per cent. ; Magnesia up to 1 per cent. ; Alkalis up to 1 per cent. ; Titanium Oxide up to 1·6 per cent. ; Loss on Ignition 11–13·5 per cent.

the shrinkage and the greater the mechanical strength of the body after drying. Great mechanical strength after drying is of primary importance for the technical porcelain manufacturer since many articles are shaped by working the body in dry state. The clays, and especially the ball clays, impart also great mechanical strength to the fired articles and that is the reason why ball clays are used to a very great extent by the manufacturers of technical porcelain (in contrast to the manufacture of porcelain table ware).

A disadvantage, however, is the great shrinkage and the consequent fact that very plastic bodies are very difficult to dry. The colloidal nature of plastic bodies makes the individual particles very tightly adhere to each other, and it is difficult for the water to evaporate out of the sticky body. The water, therefore, forces its way out of the body by causing small cracks : this is especially the case if articles are not of uniform shape and possess unequal wall thickness. It is obvious that the water evaporates more quickly on the surface causing contraction near the surface. (The more so the more plastic the clay.) But the inside of the insulator remains moist, does not shrink and the resulting tension causes the article to crack. Modern humidity drying equipment (which will be discussed later) slows down too rapid surface drying, greatly improving the drying process of large articles. Very plastic ball clays have, however, to be mixed with less plastic ones and with not too plastic china china clays and a sufficient amount of " opening " materials is still essential for the manufacture of large porcelain articles. The larger the article to be manufactured the more important is the employment of efficient " opening " materials, particularly if plastic ball clays are used.

Ball clays are, as a rule, more difficult to cast than china clays (the more so the more plastic the ball clay). The casting time for the same article is much longer if a great proportion of ball clay is used for the body. A cup-like article may obtain the desired thickness in one minute if the casting body contains china clay plus fluxes and " opening " materials, and it may take 15 minutes if the body contains ball clay plus fluxes plus " opening " materials.

Forms and Proportions of Water in Clays and Kaolins. The water contained in clay, and in ceramic bodies in general, is in the state of (*a*) hygroscopic water ; (*b*) water of formation, and (*c*) water in combination.

(*a*) Hygroscopic water is that which a dry body loses in drying at a temperature not exceeding 110°C. and re-absorbs in contact with moist air. The quantity of water so absorbed depends on the temperature and the hygroscopic state of the air. In very plastic bodies it may reach 10 per cent. and it may fall to less than 2 per cent. in unplastic bodies.

(*b*) Water of formation is the water added to the body to give it the plasticity and consistency necessary to the method of shaping adopted. It evaporates completely when the body is left for sufficient length of time in a dry atmosphere. It unites with the hygroscopic water and in all studies of the plasticity and of the process of drying the effect of the sum of (*a*) and (*b*) must be noted. Some of it is present in colloidal gels. When clay is heated over 110°C. all water of formation and water of absorption will evaporate and the clay will undergo considerable shrinkage.

(*c*) Water in combination is that which remains in a body which has been dried and which only disappears when the body is heated to 450°–600°C. This water forms an integral part of the clay substance and amounts to about 14 per cent. of it.

The quantity of water which a body must contain to obtain the desired degree of consistency depends on the texture of the body. Open bodies require much less water than plastic ones. It is impossible to give exact percentage figures as to how much water is necessary to obtain a body of a certain required plasticity, because this depends very much on the nature of the clays and the kaolins and on the fineness to which the " opening " materials have been ground. It is true to say, however, that for plastic bodies more water is necessary than for open bodies if the same degree of consistency is required. For the consistencies mentioned hereunder the following quantities of hygroscopic water plus water of formation have to be used. The smaller percentage given in all cases refers to an open body containing more open china clays and the higher percentage refers to very plastic bodies containing more plastic ball clays.

	Hygroscopic water and water of formation, percentage
Dry body	7–18
Stiff or semi-dry	10–20
Semi-stiff or stiff plastic body	12–25
Plastic body (normal consistency for jollying)	15–30
Oversoft body	17–35
Liquid body	20–50

The shrinkage of clays of fine-sized grain is between 15–10 per cent. ; that of medium size grain between 14–8 per cent. and that of coarse grain between 10·3–6·8 per cent. Kaolins have a shrinkage similar to that of coarse grain clays and in the case of very open kaolins an even smaller shrinkage.

It will thus be seen that the shrinkage of very fine-grained ball clays is higher than that of kaolins. A linear drying shrinkage of 13 per cent. (measured on a cast slab) may be regarded as the permissible maximum for ball clay if a considerable proportion thereof has to be used in compounding a porcelain body.

BEHAVIOUR OF KAOLIN WHEN HEATED ABOVE ROOM TEMPERATURE

Many studies have been carried out to investigate the behaviour of clay substance after the water of formation has been evaporated. Microscope and X-ray analysis have been used to get an idea about the chemical processes which take place when kaolin is heated. In addition latterly the measurement of permittivity (Dr. W. de Kayser, Boitsfort, Ber. D.K.G. 1940–2) has been used to supplement our knowledge. The conclusions are as follows :

The formula of the clay substance is not $2SiO_2\ Al_2O_3\ 2H_2O$ but $2SiO_2\ Al_2O_3\ 1{\cdot}75\ H_2O$.

The chemically combined water is almost completely evaporated at 470°C. After the water of combination has disappeared, the following chemical processes take place with increasing temperatures :

(1) Meta kaolinite ($Al_2O_3.2SiO_2$) is formed.
(2) Between 800° and 830°C. meta kaolinite is decomposed.
(3) Between 850° and 910°C. the decomposition continues and $\gamma\ Al_2O_3$ is formed.
(4) Between 910° and 975° sillimanite is formed.
(5) At 975°C. mullite commences to be formed.

Pure kaolins and clays which have been fired at about 600°C. have a whitish or yellowish colour and a greater mechanical strength than in the unfired state, although at this temperature the fusing of the particles has not yet commenced and the bodies are still very porous and water absorbent. With increasing firing temperature there is an increase in shrinkage and mechanical strength with a corresponding decrease in porosity, until the shrinkage has reached its maximum value. The temperature at which this maximum shrinkage value is reached is dependent upon the nature of the clay or kaolin.

The purer the kaolin the higher the temperature at which the shrinkage reaches its maximum value. At this temperature of maximum shrinkage the kaolin becomes completely densified—which means that no longer open pores prevail capable of absorbing water. The more kaolins and clays shrink, the greater is their density and mechanical strength after firing at a given temperature.

Clays and kaolins have no definite melting points. They become softer and softer with increasing temperatures. By the term " melting point " is understood the temperature at which a cone (formed of the kaolin or clay under test) completely loses its shape so that its apex touches its base.

Seger Cone 35 which indicates a temperature of 1,770°C. is made of pure kaolin. Cones made of ball clays have a lower melting point, that of pure ball clay lying between Cone 30–34 (1,660° and 1,750°C.).

Mechanical Characteristics of Clays and Kaolins. The mechanical strength of clays and kaolins is of great importance to the manufacturer of technical porcelain. The stronger the pre-shaped articles the easier it is to work them in dry state and the less will be the percentage breakage of dried articles when transported from one department to another or when they are suspended in saggers or on other supports during the firing process.

The flexural strength of plastic ball clays is as high as 45 kg. per $cm.^2$; medium plastic clays have a flexural strength of about 30 kg. per $cm.^2$ and unplastic clays about 10–15 kg. per $cm.^2$ Kaolins (china clays) have a flexural strength of between 5–12 kg. per $cm.^2$

The Zettlitz kaolins, on which very extensive measurements of mechanical strengths have been made, have a flexural strength of 12 kg. per $cm.^2$. The compressive strength of this kaolin is 14 kg. per $cm.^2$ and the tensile strength is 3 kg. per $cm.^2$

The tensile strength of American ball clay is given as between 125–250 lb. per $in.^2$ (8·8–17·6 kg. per $cm.^2$) The flexural strength of American ball clay is 150–500 lb. per $in.^2$ (10·5–35 kg. per $cm.^2$). (All figures are for carefully dried clays.)

Bentonite. In certain respects Bentonite resembles very plastic ball clay. Its name is derived from " Fort Benton " in the vicinity of which it is found in considerable quantities.

Bentonite is a hydrous silicate of alumina, derived from volcanic ash, its characteristics being due to the mineral montmorrillonite (Al_2O_3 $4SiO_2$ $9H_2O$). The classification of bentonites was for many years discussed by mineralogists and ceramists, who put forward various theories as to the nature of the montmorrillonite and similar crystals. The name " Bentonite " originally applied only to the material found in the Black Hills of Wyoming in South Dakota. Later on, all clays containing a minimum of 75 per cent. montmorrillonite or beidellite, and being derived from volcanic ash, were classified as " bentonite." In the chapter dealing with X-ray analysis further details are given of the structure of the bentonite crystals.

The appearance and properties of bentonite vary somewhat. The fusion point ranges between S.C. 9–13 and the chemical analysis of a typical moisture-free material is as follows :

	Per cent.
Silica[*]	64·32
Alumina	20·74
Iron oxide	3·49
Lime	0·46
Magnesia	2·26
Alkalis	2·90
Titanium dioxide	0·11
Sulphur	0·35
Chemically held water	5·15
	99·78

There are, however, several bentonites containing more lime and less alkali than that given in this analysis.

The main characteristic of bentonite is its very great plasticity. It is used in the ceramic industry in order to make non-plastic materials plastic, for which purpose only very small amounts of bentonite are necessary. An addition of 2 per cent. bentonite improves the plasticity of china clay more than an addition of 10 per cent. of ball clay. It increases to the same extent the mechanical strength of the body both in the dry and fired states. Of course, bodies which already contain enough plastic ball clay would not be improved by the addition of bentonite and their tendency to develop cracks would increase.

The addition of only 2–5 per cent. of bentonite to certain unplastic materials makes possible the production of an absolutely plastic body. For instance, if one wants to use titanium dioxide which has a very high dielectric constant and very favourable dielectric properties for the manufacture of ceramic bodies, unplastic titanium dioxide powder has to be made plastic so that it can be shaped by ceramic manufacturing methods. This has been found possible by the addition of such a small amount of bentonite that the electrical properties

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[*] " Ceramic Industry," January, 1942.

of the titanium dioxide are hardly affected. Similarly, a small percentage of bentonite can be used to make pure alumina (which is absolutely unplastic) plastic and workable. It goes without saying that the smaller the amount of bentonite admixed the smaller its influence on the physical characteristics of the unplastic component.

Different types of bentonite have varying plasticities. The more plastic the bentonite, the smaller the amount necessary to impart plastic properties to an unplastic material.

Whereas, as mentioned above, 2–5 per cent. of bentonite makes a titanium body workable, at least 10 per cent. ball clay would be necessary to have a similar effect. The dielectric properties of the latter body are, however, very poor compared with those of pure titanium dioxide.

In a similar way, other unplastic raw materials which possess favourable dielectric properties can (without losing their electrical characteristics) be made plastic and workable by the addition of a small amount of bentonite—for instance, siliconcarbide and berillium.

Talcums are described in the chapter dealing with H.F. Ceramics.

B. NON-PLASTIC MATERIALS

Feldspar : is a very common mineral in crystalline rocks and comprises a group of silicates of which the most important are the orthoclase, microcline, albite, and anorthite.

With regard to the chemical composition, the following groups have to be distinguished :

(*a*) Potassium feldspar termed " orthoclase " and " microcline " (depending upon the crystalline form). Both have the chemical formula K_2O Al_2O_3 $6.SiO_2$ and the theoretical composition 16·9 per cent. K_2O, and 18·3 per cent. Al_2O_3, 64·8 per cent. SiO_2.

(*b*) Sodium feldspar (albite) (which has a similar composition to potassium feldspar, except that the potassium is substituted by soda) Na_2O Al_2O_3 $6SiO_2$. The theoretical composition is 11·8 per cent. soda (Na_2O), 19·5 per cent. alumina (Al_2O_3) and 68·7 per cent. silica (SiO_2).

(*c*) Calcium feldspar (anorthite) having the formula CaO Al_2O_3 $2SiO_2$, and the composition 20·1 per cent. lime (CaO), 36·6 per cent. alumina (Al_2O_3), 43·3 per cent. silica (SiO_2).

(*d*) Lithium spar (spodumene) Li_2O Al_2O_3 4 SiO_2 having the theoretical composition : 8 Li_2O 29 Al_2O_3 63 SiO_2.

None of the minerals in the feldspar group is found in a pure state. Potash feldspar always contains some albite and the soda feldspar always contains some potash feldspar and some limespar.

Feldspar deposits of special purity are found in Norway and Sweden and throughout the United States in such places as North Carolina, South Dakota, Colorado, and New Hampshire. Very pure deposits have also been located in Russia. The deposits in Central Europe have a considerable admixture of silica. The purest deposits are in the Fichtelgebirge (Fir Mountain, Bavaria). Feldspar is found in association with quartz in various rocks in great abundance, the material being called " pegmatite." Cornwall stone is a feldspatic rock having the same composition as pegmatite, containing, however, somewhat more clay substance as an admixture.

For the manufacture of porcelain potassium and sodium feldspars are used to a very great extent. They are very hard minerals having a white, yellowish, and very often pinky colour and a pronounced cleavability. Generally speaking, a very white colour suggests higher soda content and a more pinky colour suggests a higher potassium content.

High soda contents, in general, cause a low deformation temperature. The fusing point of a feldspar depends upon the alkalis present. It becomes lower with decreasing potassium oxide content and increasing soda content.

Some feldspars fuse as low as S.C. 3 (1,140°C.) and others as high as S.C. 9 (1,280°C.) but generally the average fusing point is about S.C. 7 and 8 (1,230°–1,250°C.).

The fused feldspar is very viscous : only if it is heated about 100°C. above its vitrification point is it sufficiently soft so that a cone made of feldspar is completely deformed. It has to be heated a further 100°C. in order to make it fluid.

On this extreme viscosity and the large temperature range between softening and melting point its usefulness in the manufacture of porcelain depends. If a feldspar were to be substituted by fritts (possessing a small firing range between softening point and melting point), the porcelain body would be very liable to deformation during the firing process after having reached its vitrification temperature.

Manufacturers of technical porcelain to a very great extent introduce the necessary feldspar in the form of pegmatites (in England called " stones ") by the use of which they, at the same time, introduce part of the necessary silica contents of the body. If the feldspar content of these raw materials is not high enough to provide the desired feldspatic percentage of the body, some pure feldspar has to be added. Neither the pure feldspar, nor the stones nor pegmatites, have a uniform chemical composition. Their alkali content varies very often even if the raw materials are taken from the same quarry. Strict chemical control, particularly on the part of insulator manufacturers is therefore essential.

Cornish stones have an average composition of 20–22 per cent. clay substance, 38–40 per cent. quartz, and 38–40 per cent. feldspar.

Pegmatites used on the Continent have the following composition :

3–10 per cent. clay substance.
30–60 per cent. quartz.
30–40 per cent. feldspar.

In the United States feldspar is very often replaced by nepheline syenite, a rock consisting of nepheline (K_2O $3Na_2O$ $4Al_2O_3$ 9 SiO_2), potash feldspar and soda feldspar. This rock is found in New Jersey, New Hampshire, Virginia, Montana, Canada, India, and Russia. It has a similar effect on the porcelain body as soda feldspar, but is much cheaper owing to its greater fluxing power.

The rôle of feldspar in glazes is similar to that in bodies. It is used for its fluxing action but has to be ground more finely to provide more uniform and thorough reaction with the other glaze ingredients than when it is used for bodies.

Both potash and soda felspar are used in glazes. Soda feldspar imparts to the glazes a larger thermal expansion than does potassium feldspar.

Silica or Silicon dioxide (SiO_2) is a very important ingredient in all ceramic bodies. Because of this, the ceramic industry is very often termed the " Silicate " industry.

Silica, next to oxygen (with the molecular structure of which it has very great similarity), is the most abundant element found in nature. It occurs pure in nature in the form of quartz or rock crystals such as cristobalite, tridymite, amethyst, chalcedony and flint, sand, sand-stone, pebbles, etc., etc. It occurs in both amorphous and in various crystalline forms, the nature and instability of which have been the subject of many extensive studies. Within the scope of this book it will suffice to deal with those characteristics of the various silica formations which are of importance to the manufacturer of technical porcelain, namely, thermal expansion of the various modifications and the volume changes which take place when one modification is transformed into another by heat treatment.

The following are the most important crystal modifications of silica :

α quartz	β quartz
α tridymite	β tridymite
α cristobalite	β cristobalite

If α quartz is heated it is transformed into β quartz at a temperature of 573°C., β quartz is transformed into β tridymite at 870°C., and β tridymite into α cristobalite at 1,470°C.

If the silica is present in the ceramic body in the form of α cristobalite, it is transformed into β cristobalite at temperatures of 220–275°C. Considerable expansion accompanies this conversion. Another sudden expansion (of 2·2 per cent.) occurs during the conversion of α quartz to β quartz at 573°C. The conversion of quartz to tridymite at 870°C. is accompanied by an expansion of about 15 per cent. but, fortunately, at this temperature ceramic bodies are much more soft or elastic than at lower temperatures and thus this latter conversion has no detrimental effect on ceramic bodies. Conversions which take place at 220°–275°C. and at 573°C. may, however, have detrimental effects.

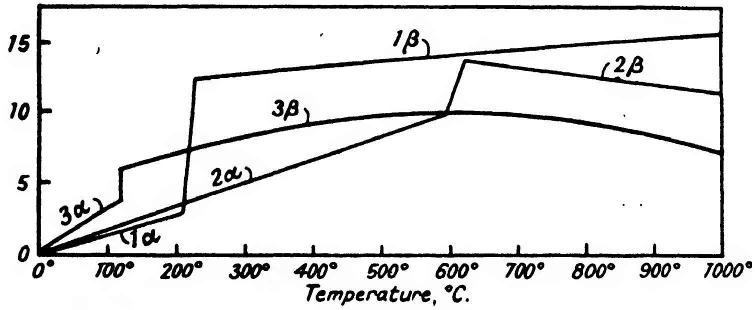

FIG. 25.—Expansion of silica minerals. (*Ceramic Industry*, January, 1943.)

1α = α Cristobalite.
1β = β ,,
2α = α Quartz.
2β = β Quartz.
3α = α Tridymite.
3β = β Quartz.

The conversions occur slowly if the temperature rise or fall takes place at low speed. If large silica grains are contained in the body and the temperature rise or fall takes place at great speed, these abrupt volume changes may cause strains in the body leading to cracks and to the destruction of the article.

The expansion of the different silica materials is illustrated in Fig. 25.

In the ceramic industry silica is also known as sand, quartz, and flint. (The term " flint " is very often given to silica in the pottery industry generally.) Strictly speaking, flint is the type of silica found in the form of pebbles on the beaches of France, Belgium, and England. These are calcined at about 600°C. whereby owing to the sudden changes in the individual crystal size the whole structure is loosened and is then more easily ground to the fineness required for the special purpose in hand.

In contrast to earthenware manufacture, however, ground pebble flint is generally not used in mass production of technical porcelain, because nature has already done the grinding of flint and sandstone in a much cheaper way than could be done by way of preparatory crushing of sand-stone, and there is plenty of naturally ground sand available for use in porcelain bodies.

Flint pebbles, however, owing to their hardness and purity are very useful grinding media in the form of balls in grinding cylinders. All the various types of silica undergo, when heated, the same range of transformations indicated above. The speed at which they transform is, however, somewhat different. This has a slight effect on the resistance of the body to temperature changes (assuming that the fineness of grinding of the various types is the same).

In the case of pebble flint conversion occurs quickest. This is the explanation why it has been found that bodies in which a considerable amount of pebble flint is used behave less favourably under sudden temperature changes.

Silica in crystal form has a high coefficient of thermal expansion. An increase of undissolved silica particles in a ceramic body increases the thermal expansion coefficient of the body. Although the various modifications of silica have a different heat expansion coefficient, the difference is not large enough to cause different technical characteristics of the respective porcelain bodies. This is not the case with earthenware bodies. Owing to the lower firing temperature used in earthenware manufacture interaction between fluxes takes place only to a much smaller extent. The size of the silica particles in porous bodies is therefore of great importance, both with regard to shrinkage and thermal expansion. Various quartz modifications also impart to porous bodies different thermal expansions. Glazes, for instance, which are suitable for pebble flint containing bodies may craze when the flint is substituted by sand in an earthenware body.

All forms of silica when heated to a sufficiently high temperature fuse and form amorphous glass. The melting point of pure silica is about 1,685°C. Fused silica has a very low thermal expansion in contrast to the silica mineral in crystal form. A high content of dissolved silica in the glassy matrix of the porcelain body reduces the thermal expansion of the body. This remark applies also to porcelain glazes.

The linear coefficient of thermal expansion of quartz glass is as low as $0{\cdot}50 \times 10^{-6}$ (per °C.) (almost one-tenth that of porcelain). The thermal shock resistance of fused silica is consequently very high and owing to this property and its high refractoriness fused silica is an excellent material for laboratory articles. Fused silica has also very favourable dielectric properties. The volume resistivity and the dielectric losses are very favourable at normal and elevated temperatures. Fused quartz is therefore an excellent insulating material where resistance to thermal shocks and good insulating properties at high temperatures are required.

Glasses very rich in silica have (although to a lesser degree) similar properties and the same refers to those porcelain glazes rich in silica.

Calcium Carbonate ($CaCO_3$) occurs in nature as whiting, limestone and calcite in large quantities.

Pure calcium carbonate has a content of 56 per cent. lime and 44 per cent. carbonic acid. When heated at a temperature of about 900°C., the calcite or limestone loses its carbonic acid completely and lime is formed. Lime combines at higher temperatures easily with alumina and silica and acts, therefore, as a flux in porcelain bodies.

For the manufacture of insulator bodies, lime is added only occasionally and in small quantities (1·5–2 per cent.) for fluxing. It imparts favourable mechanical values to the body.

Lime is a very important ingredient in glazes and has a similar fluxing action to magnesia or dolomite. It has a higher fluxing action in porcelain glazes than has feldspar. It tends to increase their thermal expansion.

In porcelain glazes lime carbonate acts as an active flux at the high temperatures which are used in the manufacture of insulators and other porcelain articles.

Magnesium Carbonate or Magnesite ($MgCO_3$) loses its carbon dioxide when heated at a temperature of 900°C. In the refined or calcined state magnesia is used in insulator bodies and glazes. Magnesite is quarried amongst other places in Austria (Styria) and in the United States (Washington and California) and in Russia.

The composition of pure magnesite is 47·6 per cent. magnesium oxide (MgO) and 52·4 per cent. carbon dioxide.

Magnesium carbonate when added to porcelain bodies acts as a flux which enables vitrification to take place at a lower temperature. Magnesium–aluminium–silicates which are formed in this way do not, however, possess a wide vitrification range. Magnesia and Magnesium silicates tend to increase mechanical strength and resistance to temperature shocks when added in small quantities. This addition has, however, the disadvantage of shortening the vitrification range. Magnesium silicate bodies (such as talcum and clinoenstatite bodies) and magnesium titanate bodies are discussed in the chapter dealing with high frequency ceramics.

In glazes, magnesium carbonate acts as a flux at high temperatures, such as are used for the manufacture of insulators. The introduction of magnesium silicates in glazes improves elasticity and decreases the thermal expansion co-efficient. This latter is a very desirable property since low thermal expansion of the glaze is very often desired as pointed out in previous chapters.

Dolomite is a rock intermediate in composition between limestone and magnesite, having the composition $CaCO_3$ $MgCO_3$.

The composition of pure Dolomite is 30·4 per cent. lime CaO, 21·7 per cent. MgO, and 47·8 per cent. CO_2. As a rule, however, the lime content is greater than the theoretical formula indicates. Deposits of Dolomite occur in many parts of the world, for instance, in England, Germany, and in the U.S. in California and Connecticut. The influence which Dolomite exerts on porcelain bodies is due to the fact that it is a mixture of magnesia and lime. The same is true of its influence on glazes in the composition of which it is a widely employed and useful ingredient. Since, however, the ratio of lime and magnesia varies very often, it is necessary to check the composition regularly or to use pure lime and pure magnesia instead. As previously mentioned, lime and magnesia have different influences on the thermal expansion of glazes.

Borax (Sodium Tetraborate), $Na_2O\ 2B_2O_3 10H_2O$ and **Boric Acid,** $B_2O_3\ 3HO_2$.

Borax and boric acid are widely used as fluxes for so-called low-temperature glazes especially on earthenware, bone china, art-ware, and other ceramic articles which are glazed at temperatures below 1,250°C. As insulators and other technical porcelain articles are fired in a one-fire process at temperatures above 1,250°C. borax or boric acid is generally not used for the manufacture of normal porcelain glazes. Since, however, for many purposes special bodies fired below 1,250°C. are now used with good results, some remarks about this very important flux may be made.

Borax and boric acid are moderately soluble in water and that is why a fritt has to be made to obtain a water insoluble boron compound which can be added to the other materials, ground, and used in a watery suspension. The percentage composition of borax is :

	Per cent.
Sodium oxide	16·3
Boric oxide	36·5
Water of crystallisation	47·2

Since the water is eliminated during the firing with other materials, 52·8 per cent. of sodium and boric oxides is left to combine in the formation of the glaze. Boric acid contains 56·3 per cent. boric oxide (B_2O_3) but is not as economical a source of boric oxide as borax on account of its higher price. It is used in cases where sodium oxide must not be present.

Boric oxide shares with silica the property of combining with bases to form glazes after fusion. It decreases, however, the fusing point much more readily than does silica, and it has therefore the important function of reducing the viscosity of glazes. Borax furthermore tends to produce a higher gloss in a glaze and decreases considerably the thermal expansion compared with other fluxes like feldspar, dolomite, or lime.

Boric acid and borax are furthermore recommended for porcelain glazes when lower firing temperatures than 1,250°C. are employed, and the necessary gloss, particularly in the case of coloured glazes, cannot be obtained by other means.

Materials of the Sillimanite Group. Sillimanite, Andalusite, Kyanite (Al_2O_3 SiO_2). These minerals have the same chemical compositions, although they possess different properties.

Ceramists very often use the term " Sillimanite " for Andalusite and Kyanite as well.

The three minerals have different crystal forms, different gravities, and different hardnesses. Sillimanite is used to a very great extent for spark plugs, insulator bodies, and saggers. It is also used for the manufacture of refractory materials, for instance, for the lining of high-temperature industrial furnaces and for all kinds of equipment for high-temperature kilns.

Sillimanite and Kyanite are found in the U.S.A., the former in

South Dakota and the latter in considerable quantities in North Carolina, Georgia, and California.

All three minerals of the Sillimanite group decompose into mullite and silica at a temperature of about 1,850°C. (Cone 38).

When added to porcelain bodies, however, all the three minerals are inverted to fibrous mullite crystals and silica at Cone 13, although dense bodies to which these minerals are added require a higher firing temperature than that.

All porcelain bodies fired at Cone 13 and higher show a certain percentage of mullite crystals. These needle-shaped crystals are formed by the decomposition of the clay substance and in former times were considered to be sillimanite crystals.

The author published in 1915* a treatise on the technical characteristics of porcelain. He investigated the relative quantities of these crystals formed in porcelain bodies and their influence on the technical characteristics and found that in insulator porcelain fired at Cone 14 about 12 per cent. of the body is converted to these crystals which, as already explained, are formed as a result of the decomposition of the clay substance. Later, by chemical and X-ray analyses it was found that these minerals are in contrast to what was generally supposed—mullite and not sillimanite crystals.

Mullite ($3\ Al_2O_3\ 2\ SiO_2$) is never introduced into ceramic bodies as such, because it is very rare in nature (it is found in small quantities in the Isle of Mull in Scotland), but mullite is formed in all fired ceramic products which contain clay and which are fired at Cone 13 or higher. It commences to form when clay is heated at 975°C., when few, small crystal needles can first be detected and ascertained as mullite by X-ray analysis or by measuring the permittivity. The quantity and size of the crystal needles increases with increasing temperatures up to 1,400°C.

Parmelee and Rodriguez (Journal of American Ceramic Society, January, 1942) have explained how the formation of mullite can be increased by the addition to the clay substance of suitable mullite-builders, such as small amounts (1 per cent.) of certain metal oxides. Lithium oxide and magnesium oxide are especially good mullite builders, both at high (1,400°) and low (1,200°) temperatures. Zinc oxide is especially good at high temperatures. Oxides of zinc, lithium, magnesium, iron, manganese, cerium, and molybdenum are good mullite formers, whereas sodium, potassium, titanium and stannic oxides are poor. Boric oxide and calcium oxide are fair.

* Gerhard Stalling, Oldenburg.

At 1,400° the yield produced by the use of ferric oxide is 94 per cent. and by lithium oxide 91 per cent.; at 1,300° ferric oxide produces 65 per cent., lithium oxide 78 per cent.:

		Per cent.
At 1,200°	ferric oxide produces	6
,, ,,	lithium ,, ,,	24
,, ,,	magnesium ,, ,,	30
,, 1,250°	,, ,,	80
,, 1,400°	,, ,,	100 mullite.

Bodies which contain the minerals of the sillimanite group, including mullite, show a uniform rate of thermal expansion. They possess a low thermal coefficient of expansion and are very resistant at high temperatures to loads of every description. Their strength is supposed to be due to the interlocking of the long needle-like crystals.

Alumina or Aluminium Oxide (Al_2O_3). Alumina is found pure in nature as the mineral corundum. The most common occurrence in nature is, however, in combination with silica. The alumina silicates such as the various clays, sillimanite, andalusite, mullite, and so on and the combination of alumina silicates with alkalis such as various feldspars, nephelites and so on, have been described previously in this book.

Alumina is produced from bauxite, the alumina hydroxide which is found in many places in Europe, America, and Asia. The fusion point of alumina is 2,015°C.=3,660°F. (corresponding to Orton Cone 42). Alumina imparts its refractoriness to ceramic bodies to which it is admixed, and the more so the higher the percentage of alumina added. Alumina has, furthermore, a smaller thermal expansion and a greater thermal conductivity than clay, silica, feldspar, and most of the other raw materials commonly used for compounding ceramic bodies. It is, therefore, used (in addition to increasing the refractoriness of bodies) for improving the resistance to sudden temperature changes. Ceramic bodies consisting of pure alumina are described in the chapter dealing with spark plugs for internal combustion engines.* Alumina is also used as an addition to clay and to clay-silica-feldspar mixtures. Clay-alumina mixtures require a higher firing temperature than that usually required for the manufacture of densified bodies. If a slight porosity is of no disadvantage, clay-alumina mixtures can be fired at about

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* In a recent British Patent (February, 1943) of the Lodge Plugs Limited, it is stated that the presence of a small amount of β Al_2O_3 in sintered alumina would give greater density and mechanical strength. β alumina is decomposed above 1,400°C. Sufficient alkali has to be present to produce 1–10 per cent. β alumina below this temperature.

1,400°C. The so-called Marquardt body, for instance, consists of about:

30–40	per cent.	alumina.
40–30	,,	calcined kaolin.
30	,,	uncalcined plastic kaolin or clay.

Such bodies are used, for instance, for the manufacture of sheaths for protecting pyrometers and for other articles where resistance to temperature changes and great refractoriness is required, and slight porosity of no disadvantage. If the articles have to be dense, 1–2 per cent. alkali is introduced in the form of feldspar or in the form of a lithia fritt.

Alumina is used for the preparation of glazes, but is, as a rule, introduced not as pure alumina, but in the form of clay, stone, or feldspar. In the manufacture of glazes, pure alumina is used in such cases where the silica contents must not be increased, as this would be the case if alumina silicates were added. Alumina influences glazes in the following way:

(1) It increases the mechanical strength and makes the glaze more resistant to mechanical shocks.
(2) It gives the glaze greater brilliance if enough fluxes are present.
(3) It gives the glaze a longer firing range.
(4) It increases the resistance to attack by chemicals.*

Most of the porcelain glazes for firing temperatures of 1,250–1,400°C. do not as a rule need the addition of pure alumina, as they are hard and resistant enough without it (since alumina is, as a rule, already introduced by feldspar and by clay), but for lead and boric acid containing glazes, which are as a rule used for firing temperatures below 1,250° and for special glazes to be fired at temperatures above 1,400°, the addition of pure alumina is occasionally to advantage.

Mica is a term applied to a number of hydrous aluminium-potassium or magnesium silicates which occur in nature as minerals of laminar structure, the thickness of each of the laminæ being very small. Fourteen varieties have been classified by X-ray analysis, the most important being biotite, muscovite, and phlogopite.

Muscovite is a hydrous potassium-aluminium silicate; biotite a hydrous magnesium-aluminium silicate; phlogopite is as well a magnesium-aluminium silicate, but contains up to 12 per cent. ferric oxide. Muscovite has the formula $K_2O.3Al_2O_3.6SiO_2.2H_2O$.

Lepidolite is a lithium-potassium-aluminium fluosilicate having

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* "Ceramic Industry," January, 1942, p. 36.

the following theoretical formula : $LiF.KF.Al_2O_3.3\ SiO_2$. Lepidolite is a very useful source of lithium to the ceramic industry, whereas muscovite and biotite are mainly used as insulating materials for the electrical industry.

Generally speaking mica is a very important insulating material and used for many purposes in the electrical industry. The dielectric power factor is as low as 0·02 per cent. at high frequency. The dielectric puncture strength is about 70 kV. per mm. at 50 cycles measured on plates of ½ mm. thickness, which is the highest figure of any known inorganic solid insulating material. The dielectric constant is almost independent of frequency and temperature and has a value of 5–9.

These favourable properties serve to explain why mica is so very widely used as an insulating material in the electrical industry. It is particularly useful in the form of plates or discs of very small wall thickness.

It is very popular as a condenser material and for use in electrical heating appliances up to 600°C.

The manufacture of insulating materials consisting exclusively of mica does not fall within the scope of a book dealing with ceramic materials, but it may be of some interest how mica is treated in the manufacture of " Micanite," an insulating material very widely used in the electrical industry. Mica is flexible only when split into very thin laminæ. Micanite is made, therefore, from split films a mere thousandth of an inch thick. The splitting cannot be economically effected by machinery, and has consequently to be done by hand. After splitting, mica laminæ are pasted together with an adhesive bonding material having insulating properties (such as shellac) oven-heated at 250°F., subjected to a pressure of 1,000 lb. per sq. in. at about 300°F. for several minutes and rapidly chilled. The resulting sheets are ground smooth to the required thickness.

Furthermore, the material " Mycalex " may be mentioned, since it is a kind of ceramic insulating material. Mycalex consists of a mixture of mica (preferably muscovite) with lead borate or other suitable glasses. This mixture is subjected to temperatures of 700°C. and higher, and at the same time pressed in metal dies under an hydraulic pressure of approximately 2½ tons per sq. in.

" Mycalex " has favourable mechanical and electrical properties (which are mentioned previously in this book) and apart from being shaped in suitable metal dies it can be worked by such operations as turning, grinding, sawing, drilling, filing, and milling. It can also be moulded with metal inserts in position.

Mica is present as an impurity in many ceramic raw materials. Owing to the small particle size of these impurities they can easily be separated from coarse particles by washing, but of course in the elutriation of china clay the particles are carried away with the light clay particles. The percentage of these particles is, however, so small that they have no influence on the properties of the body.

Mica is more resistant to weathering than feldspar. This is the reason why, in the granite and feldspatic rocks which have undergone change by atmospheric and other conditions, the mica particles remain whereas the feldspar is decomposed and borne away. The presence of mica as an impurity in ceramic raw materials was originally thought to exert a detrimental influence on the body. It has been found, however, that this supposed influence has been over-rated and that if only a small quantity is present the influence of mica is not unfavourable.

Silicon Carbide (Carborundum) (SiC) is produced by the fusion of sand and coke in an electric furnace. Owing to its refractoriness and its high thermal conductivity it is used to a great extent for the manufacture of saggers, batts, and other kiln furniture for placing the ware in ovens, particularly in tunnel kilns. Owing to its great hardness it is used to a very great extent for the manufacture of grinding wheels.

The electrical resistivity of silicon carbide is much lower than that of most ceramic materials and much higher than that of electrical conductors. Carborundum is therefore termed a " semi-conductor." Of this characteristic use is made in the manufacture of electrical heating elements which are described in the chapter dealing with electric tunnel ovens.

The resistivity of silicon carbide is 0·0936–1·95 ohms per cm.[3] With increasing temperature up to about 760°C. (1,400°F.) the resistance of silicon carbide decreases. (It has a negative temperature coefficient of resistance.)

From 760°C. (1,400°F.) to about 1,649°C. (3,000°F.) the resistance of silicon carbide increases with increasing temperature, that is to say, it has within this range a positive temperature coefficient of resistance.

In addition to the manufacture of electrical heating elements, use has been made within recent years of the relatively high electrical conductivity of this material in the application of semi-conductive coatings on the surface of insulators, replacing metallic coatings. Such metallic coatings are, for instance, applied to the surface of pin type insulators in order to eliminate radio interference. Furthermore, they are very often applied to the surface of bushings in order to improve the electric field at those places where the affixed metal flanges would otherwise cause field concentration. These metal coatings have the disadvantage of being attacked by the influence of certain atmospheric conditions in the course of time and becoming loosened, allowing air layers to be formed between the metal and the porcelain. By the replacement of conductive metal coatings by semiconductive silicon carbide coatings these disadvantages are avoided, and a very sound coating can be formed which offers practically the same electrical advantages.*

A comparison of the resistivity of electrical conductors with the resistivity of silicon carbide may be of interest. (The resistivities of insulating materials are given in the chapter dealing with " Volume Resistivity.")

RESISTIVITY OF ELECTRIC CONDUCTORS

Substance	Resistivity in in ohms per cm.^{3}	Measured at temperature °C.
Aluminium	0·00000263	0
Copper	0·000001692	20
Iron	0·00001	20
Nickel	0·0000078	20
Platinum	0·00001	20
Tungsten	0·00000551	20
" Monel Metal "	0·000042	20
" Nichrome "	0·0001	20
Carbon	0·0035	0
	0·0021	1,000
	0·0009	2,500
Graphite	0·0008	0
	0·00087	1,000
	0·001	2,000
	0·0011	2,500
Silicon	0·000058	20
" Silicon carbide " elements	0·0936 to 1·95	760

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* Conductive glazes can also be obtained by adding oxides of nickel, copper, manganese and iron to the glaze compositions (Snyder, *Ceramic Age*, 1941, [1], 7–8).

CHAPTER VI

PLASTER OF PARIS

PLASTER of Paris is, strictly speaking, not a ceramic raw material. For this reason books dealing with the Ceramic industry and with ceramic raw materials generally deal either very briefly with this material, or not at all.

Plaster of Paris is used for making the moulds by means of which ceramic articles are formed—both in the jollying and the casting processes. In the jollying process the Plaster of Paris mould forms one surface of the article, the other being shaped by a metal tool profile. In the casting process the Plaster of Paris mould forms the outer surface and very often the inner surface as well.

Due to their porosity Plaster of Paris moulds absorb a part of the water contained in the plastic body or in the liquid casting slip. They therefore not only give part of the shape to the article but they also act as a sponge. They are, therefore, used to a very great extent not only in the manufacture of insulators but in the pottery industry generally and play a more important part than many of the ceramic raw materials. Whereas in most ceramic factories the preparation of the body and glaze is carried out very scrupulously, in quite a number of works the preparation of the Plaster of Paris moulds is still somewhat casual. For this reason, in this book the question is dealt with in more detail in order to stress the fact that the preparation of the Plaster of Paris should not be considered as a side-line by Ceramists.

Plaster of Paris is prepared by heating gypsum at a temperature up to 350°F., until three-quarters of the water of crystallisation is driven off. Gypsum is a rock which occurs in many parts of the United States, England, and the Continent. Its formula is $CaSO_4$ $2H_2O$ (1 equivalent weight calcium sulphate, 2 equivalents of water of crystallisation). When, as previously stated, it is heated at a temperature up to 350°F., three-quarters of the water of crystallisation evaporates and calcined gypsum, having the formula $2Ca\ SO_4$ H_2O is formed.

The chemical analysis of a good plaster shows 6 per cent. combined water, 36·5 per cent. calcium oxide, 56·8 per cent. sulphur trioxide, and about 1·7 per cent. impurities such as limestone, iron oxide, and magnesium oxide.

When calcined plaster is mixed with water, part of this water is again chemically combined and crystals similar to those which were contained in the non-calcined rock are formed. In addition considerable quantities of water are absorbed mechanically. When calcined plaster is mixed with water one does not at first observe any apparent action but soon a slight stiffening takes place and after some more minutes the creamy mixture forms a solid mass. When this setting process continues the mass begins to develop heat and the final setting is not reached until the development of the heat has ceased.

The most important characteristics which the ceramic industry requires of Plaster of Paris moulds are that they should be absolutely smooth, free from pinholes and have great mechanical strength, upon which the life of the mould depends, and absolute uniformity of porosity which, in turn, imparts a uniform wall thickness and a uniform consistency to the ceramic article.

In order to obtain the most favourable characteristics in this respect, it is most essential that the Plaster of Paris mould should be absolutely homogeneous and that the mixing of the Plaster of Paris with water should be most carefully controlled. The less water used in the mixture the denser and the stronger mechanically the resulting product. On the other hand, if more water is used the porosity (*i.e.* the capacity to absorb water) is increased.

In illustration of the extent to which the Water/Plaster ratio influences both the mechanical strength and the porosity, the following figures are of interest :

Water-plaster ratio of weight, lb. water—100 lb. plaster.	Compressive strength, lb. per sq. in.	Water absorption by weight, per cent.
60–100	2,400	26
70–100	1,800	34
80–100	1,200	42
90–100	900	48

In the pottery industry in general and in the porcelain industry in particular, the mixing of the bodies and glazes is most carefully supervised and the most accurate methods are employed in order to preserve equal and homogeneous compositions of body and glaze throughout the year. This is not always so in the case of the preparation of the Plaster of Paris. The mixing of the Plaster of Paris with water is still very often left to the discretion of the workmen in the mould shop who, naturally, in course of time obtain considerable experience as to which mixture is the best one. One cannot, however, expect them to know without exact records which of their mixings will result in plaster moulds which give the most satisfactory articles and which will result in moulds possessing the longest life.

In the monthly journal "Ceramic Industry," January, 1942, it is described how, in certain American Potteries, a check was made on the various consistencies used in three successive mixings. In one factory the minimum variation was found to be 4 pints of water per 100 lb. of plaster. The maximum variation, on the other hand, was as much as 17 pints of water per 100 lb. of plaster.

It is obvious that the mixings should be so carefully carried out and supervised that practically no variations occur—as soon as it has been ascertained which mixture is the most suitable for the special mould in hand. It is not possible to give a general rule as to which Water/Plaster of Paris ratio should be maintained since, dependent upon the various requirements, different degrees of porosity will be found to be most suitable. It can, however, be said that it should always be the aim to use as little water as possible during the mixing since this not only results in increased mechanical strength of the mould, but keeps the porosity low. Generally speaking, it is more favourable to use Plaster of Paris moulds which absorb the water slowly. If the water is sucked out of those layers of the body which are in contact with the surface of the Plaster of Paris mould more quickly than it evaporates from the adjacent layers into the open air internal stresses may be set up. These may cause non-uniform shrinkage or even very small cracks which may increase in size as the various manufacturing processes follow.

If, in mass production, buckets are not kept very clean, the setting or stiffening will only occur after a mixing of 8–10 minutes, since impurities (such as gypsum which has already set) have an unfavourable influence on the setting process.

Mixing too long a time into the "creaming" period (*i.e.* until the stiffening process is already well advanced) will result in the formation of numerous air-pockets or pinholes. The time of stirring should therefore be carefully supervised and should not exceed a certain time. This may previously have been found to be between 4–6 minutes, if the mixing is carried out by hand.

Mechanical mixing of Plaster of Paris in well-managed pottery and insulator factories has almost generally superseded hand mixing. Control of the strength of the mould is effected by previously weighing the water and plaster used in the mix. At the same time the absorptive capacity of the mould is controlled. Mixing machines or mechanical " stirrers " have to be used in connection with carefully controlled soaking periods, for which automatic switch control may be used. It has been found that a 2–4 minutes' soaking period followed by a 2–4 minutes' mixing period gives very good results. The process is carried out in such a way that the plaster is gradually added to the previously determined amount of water. These mechanical " stirrers " or mixers consist of two or three-blade propellers operated at 300–450 rotations per minute. The mixing is carried out in a vessel, near to the bottom of which the propeller is centred (Fig. 26). Mechanical mixing, as compared with hand mixing, has the great advantage that the mixture becomes very homogeneous. This is almost impossible to achieve by hand.

FIG. 26.—Propeller mixer for preparing Plaster of Paris for mould making. (L. A. Mitchell for Messrs. J. Richards Tiles).

It has already been mentioned how important homogeneous porosity is in a Plaster of Paris mould, since uneven porosity results in an uneven quality of the ceramic product.

If Plaster of Paris moulds consist of two or more pieces it is most essential that all the pieces have the same porosity. Otherwise, the resulting ceramic products would shrink non-uniformly, resulting in distortion of the cast article.

It has been mentioned that when calcined gypsum is mixed with water part of this water is chemically combined so that a similar composition is formed to that of the original rock, with the difference that a large excess of water is incorporated and this has to be driven off by drying. Not much heat is required to remove this excess water and generally speaking room temperature is sufficient. The highest drying temperature which may safely be used for drying the moulds is 145°F. (62°C.) if the moulds are not kept too long a time at this temperature, as there is a certain amount of danger of the mould being burnt when the last traces of mechanically combined water have been evaporated. Burning of moulds has to be carefully avoided. This burning is a recalcination of the Plaster of Paris by which process the same crystal as that contained in the calcined rock is formed. If, for drying purposes, the mould is subjected to too high a temperature, for instance placed in too hot a place near a steampipe, it may lose some of its combined water and when it is put into use again it may crack and have to be discarded. Moulds which are slightly burnt are very difficult to detect, but if an unusual number of moulds have to be discarded in the clayshop on account of cracking, burning may be assumed to be the reason.

If burnt moulds are dipped into water distinct heating can be felt on the burnt surface. If such heating is observed after a period of 2–5 minutes, this is conclusive proof that the mould has been burnt. Heating is due to the fact that the burnt part of the mould again assumes water of crystallisation exactly in the same way in which the original plaster united with water when the Plaster of Paris/Water mix was first made. Since only a part of the mould is burnt the heat development is not so intensive as in the case of the original mixing.

If a temperature of 50°C. (122°F.) is not exceeded, burning will not occur. If, in the case of conveyor dryers, the mould containing the shaped ceramic article is moved within a certain time (generally not exceeding 5 hours) through the drying stove, temperatures up to 62°C. (145°F.) may be used.

One would think that it would be possible to use discarded Plaster of Paris moulds again by calcining the plaster at the same temperature at which the gypsum was calcined, but this is, unfortunately, not possible since the gypsum crystals in used pottery moulds are very much smaller than the crystals in the natural gypsum rock. The difference in crystal size results in a difference of porosity of the plaster, and since the crystals in used Plaster of Paris moulds are much smaller, the porosity of the plaster made of recalcined moulds would be much too high, and the mechanical strength much too low. This is the reason why discarded Plaster of Paris moulds cannot be used again for manufacturing purposes.

When sodium silicate or sodium carbonate is used in a casting slip the mould will effloresce. This is caused by the action of the soluble sulphate which is formed by the interaction of the sodium of the deflocculents and the calcium sulphate. This soluble salt is absorbed by the mould. When the articles are removed and the moulds are returned to the drying stoves, the water evaporates and leaves the sodium sulphate deposits on the surfaces of the moulds. The sodium sulphate appears as a fine white powder and has a detrimental effect on the ware which is subsequently cast in the mould. This detrimental effect can be avoided to some extent during the drying by placing the mould in such a position that evaporation takes place on the face opposite to the surface used for casting. The soluble salts are then drawn away from the casting face of the mould. By using organic deflocculents this effect can be completely avoided. Such deflocculents are, for instance, sodium tannate or sodium gallate.

CHAPTER VII

TESTING OF RAW MATERIALS

MUCH has been said in the published literature dealing with ceramic problems about the various testing methods for ceramic raw materials and it is not intended, within the scope of this book, to deal with these questions at great length.

It should, however, be pointed out that for technical porcelain and particularly for electrical insulator manufacture certain tests are very much more important than for other branches of the ceramic industry. The more important of these tests, which have to be carried out in order to ensure constant and unvarying technical characteristics in the finished product, are therefore briefly described.

A. MEASUREMENT OF SHRINKAGE AND THERMAL EXPANSION

Shrinkage is a very important factor which has to be carefully watched by the manufacturer of technical porcelain, since many of the ceramic articles in constant demand have to be kept within very small tolerances.

The shrinkage of the body is influenced by many factors, including:

(*a*) Shrinkage of the china and ball clays used in the body.
(*b*) The chemical composition of the feldspar.
(*c*) The kind of pegmatites or stones used.
(*d*) The fineness to which the flint, sand, and fluxes mentioned above are ground.

(A further very important item is the firing temperature. This question will, however, be dealt with later on.) In this present chapter tests which are necessary to ensure that the shrinkage does not undergo variations from time to time will be described.

Shrinkage of ceramic materials takes place in two phases, the first being the drying shrinkage and the second the firing shrinkage.

Drying Shrinkage. Each clay substance containing ceramic material which is mixed with added water shrinks during the drying process. It decreases in volume no matter which way it has been formed. Bodies, however, which have been pressed from clay powder without additional water have no drying shrinkage (of course they have firing shrinkage).

The drying shrinkage depends upon the amount of water added to the clay and to the physical structure of the clay. The more water added the higher is the shrinkage and the more plastic the clay the higher is the shrinkage also. To give an example : * If 5 per cent. of water is added to plastic clay the drying shrinkage is only a fraction of 1 per cent. If about 10 per cent. water is added, the drying shrinkage is about 1 per cent. If about 15 per cent. of water is added the drying shrinkage is about 5 per cent. An addition of from 20–25 per cent. water results in a shrinkage of about 8 per cent. and the addition of 30–35 per cent. in a shrinkage of about 10 per cent. These figures refer, of course, only to one particular type of plastic clay. The shrinkage is smaller if a less plastic clay or china clay is used. The figures above indicate only the dependence of the shrinkage on the amount of water which is added to make the clay workable.

Shrinkage is caused by the evaporation of water and is accompanied by a hardening of the body. In the drying of a body the surface first loses a certain proportion of water which is replaced by other water drawn from the interior of the body. Thus, as a capillary flow of water takes place from the centre towards the surface, it is obvious that this flow is dependent on the structure of the body and the form and size of the capillaries. The smaller the capillaries the slower the speed of drying, and the more plastic the clay the finer the capillaries.

The drying process is divided into two stages, in the first of which the greater part of the shrinkage occurs and in the second of which little or no shrinkage occurs.

During the first stage the body shrinks proportionately to the amount of water eliminated.

In the second stage, by which time nearly all shrinkage is completed, there is further evaporation which causes numerous " pores " or " spaces ", the number and size being proportional to the amount of water evaporated. In other words, the drying shrinkage ceases after a certain time of drying although there is still water of formation in the body.

If we take, for instance, the example of a plastic clay (which is made workable by the addition of 25 per cent. water and which is

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* This example is taken from " Treatise on Ceramic Industry " (E. Bourry), where the reader interested in the theory of drying will find formulæ for the calculation of volume of air necessary to evaporate given amounts of water depending on the humidity contents and the temperature of the air.

allowed to dry at room temperature) then shrinkage continues during the first, say, 50 hours only. Of course in a drying stove the drying would take place much more quickly. The water content has after that period gone down to, say, 10 per cent. and the shrinkage has reached, say, 8 per cent. From then on further drying will result in complete evaporation of the remaining water, but will cause no further shrinkage. It is quite obvious that it is important for the porcelain manufacturer to know the shrinkage of each particular body from the moment it is shaped in Plaster of Paris moulds to the time when the fired product leaves the furnace, since the size of the moulds he has to make depends on this percentage of shrinkage.

It is, however, equally important to know the shrinkage from the dry state to the fired state since many articles are shaped by turning in the dry state. The size of the tools, therefore, and the dimensions to which the article has to be turned in the dry state, depends on the shrinkage from the dry to the fired state. It is on this account essential to regularly control the shrinkage of all the china and ball clays used for the manufacture of the various bodies.

Various test specimens can be used, but it is necessary first of all that they should always be made by the same method and shaped with the application of the same amount of pressure. It is also important that they are of such a shape that they do not warp or deform during drying or firing which, of course, would upset the accuracy of the shrinkage measurement.

Slabs of, say, 8 cm. in length, 4 cm. in width, and 1 cm. in thickness (which can be formed in a Plaster of Paris mould or in a metal mould by pressing the plastic body) are very suitable test specimens, but the method of manufacturing this slab must always be exactly the same. Immediately after having been formed in the mould or die two marks are made on the surface with a Vernier Calliper giving a certain defined length of, say, 7·5 cm. After the drying has been completed (when the test specimen has assumed a white colour) the distance between the two calliper marks is measured. As a check the drying period is extended and the points again measured in order to ascertain whether further shrinkage takes place.

The speed of drying is dependent upon :

(*a*) Temperature and humidity of the surrounding air.
(*b*) The amount of water of formation used in making the body plastic.
(*c*) The general structure of the body.

The higher the temperature and the lower the degree of humidity, the quicker the drying, but, at the same time, the greater the risk of drying cracks.

The drying process has therefore to be regulated in such a way that the evaporation of water from the interior right through to the surface is at a uniform speed, otherwise the surface layers would dry more quickly than the interior. A uniform rate of shrinkage can be obtained by keeping the temperature down and also by keeping the humidity content of the surrounding air at a high level. Use is made of this latter characteristic by drying large articles in stoves in which the atmosphere possesses a high degree of humidity. This permits the application of relatively high temperatures without endangering the insulator. (The plant used for this purpose will be described later.) Shrinkage tests are of course only comparable if made under the same test conditions. If all the various ball clays and china clays used in the manufacture of an insulator body are regularly tested for drying shrinkage, one can be sure of detecting variations of the incoming ball clays early enough to prevent a variation taking place during manufacture. This variation would otherwise only be discovered when the finished article is found to be too large or too small, to the great annoyance of everybody concerned.

If a particular porcelain body is made from, say, two different china clays and two different ball clays, a change in the shrinkage of one of these materials can easily be compensated for by the use of a larger proportion of one or the other of the plastic materials, provided the control described above is exercised.

Firing shrinkage. Apart from the drying shrinkage, the second phase, the firing shrinkage, is also of great importance. The firing shrinkage is of course the shrinkage which takes place during the firing process. By the evaporation of the water of formation many empty pores are left. The shrinkage caused by evaporation of the water after the drying shrinkage has been completed is very small. The evacuation of the water of combination (which is completed at about 700°C.) leaves further empty pores behind, but does not cause further shrinkage because the pores are not closed at this temperature. From the moment, however, that silicates begin to form (round about 800°C.) the body contracts and the empty pores made by the evaporation of the water of formation and the water of combination tend to close up.

The shrinkage proceeds slowly until the commencement of vitrification, when the pores tend to disappear and the body becomes impermeable.

The specimens which have been used for checking the shrinkage from the wet to the dry stage are then used for ascertaining the shrinkage from the dry stage to the fired stage. They are put in the appropriate places in the furnace and the shrinkage is measured when the firing process is completed. All the ball clays and china clays used in the composition of the body should be regularly checked by this test. A more thorough knowledge of the behaviour of the individual raw materials can be obtained if the test specimens are measured in an experimental furnace at various temperatures, the temperature being increased by regular steps of, say, 100°C., and the shrinkage measured after each step.

If a rod made of unfired china clay, ball clay, or of an unfired porcelain body is heated in a furnace, its length simultaneously undergoes an increase by thermal expansion and a decrease owing to shrinkage. As long as the shrinkage is small (which is the case, for instance, with china clays at temperatures varying between room temperature and 540°–560°C.) the heat expansion is greater than the shrinkage and the test specimen increases in length. At higher temperatures, however, when the silicates and viscous glasses begin to form (particularly the glasses), the shrinkage is much greater than the heat expansion and the actual length of the test specimen becomes, in spite of its heat expansion, smaller and smaller.

In order to obtain exact knowledge of the behaviour of a china or ball clay rod during the firing process, it is very advisable to measure its actual length at the various stages of the firing temperatures. The methods of carrying out these very interesting measurements are described by Steger (Berichte der Deutschen Keramischen Gesellschaft, 1938) and have been adopted in the laboratories of many porcelain manufacturers.

For these measurements of shrinkage and thermal expansion the same apparatus can be used as that for the measurement of the thermal expansion of fired ceramic test specimens. This test equipment is very useful, being suitable for measuring the heat expansion of glazes and bodies and also for plotting the shrinkage-heat expansion curve of unfired ceramic bodies, and so a description may be of interest.

The arrangement is illustrated in Fig. 27. A pyrometer tube with flange (1) having a length of 500 mm., 11 mm. inside, and 17 mm. outside diameter, is closed at its lower end by a stopper (2) made of the same material as the tube. This stopper serves as the support for the test specimen (3), the upper surface of which supports a refractory rod (4) having a length of 400 mm. and a diameter of 8 mm.

This rod is made of the so-called Marquardt body (which is composed of 30 per cent. fired clay, 30 per cent. plastic clay and 40 per cent. alumina). This rod transfers any variation of the length of the test specimen during the firing process to the cross-hairs (5) in the optical sight. The rod is suspended on one arm of the balance (6). The pyrometer tube containing the test specimen and the marquardt rod is put into an electric furnace (7) having a height of 300 mm., containing a heating tube of 30 mm. diameter, its bottom end being sealed. Just over the lower end of the test specimen (3) near the stopper, two holes are provided in the pyrometer tube in order to allow the heated air to reach the test specimen. The marquardt rod is arranged to exert a very slight pressure on to the test specimen so that it may follow closely any variation of its length. For this purpose the balance (6) is provided and by putting weights on to the scale (8) the pressure which the suspended rod (4) exerts on the test specimen can be regulated and kept at the desired pressure. This slight pressure is relieved during the heating up and exerted only during the reading. The movement of the crosshairs is read by means of a micro-telescope (9), the objective having a focus of 10 cm.

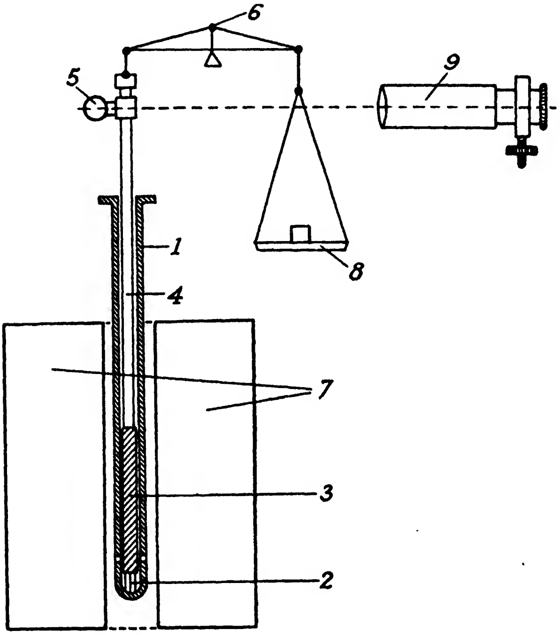

Fig. 27.—Arrangement for measuring shrinkage and thermal expansion of ceramic materials at varying temperature.

The temperature in the electric furnace is measured by a platinum rhodium-thermo element.

Fig. 28 shows the shrinkage-heat expansion of pure kaolin and the shrinkage-heat expansion of an insulator porcelain body designed for a firing temperature of 1,400°C. A study and comparison of both are interesting.

One can see that at a firing temperature of 560°C. the kaolin decomposes in both cases and the particles are drawn closer together causing slight shrinkage.

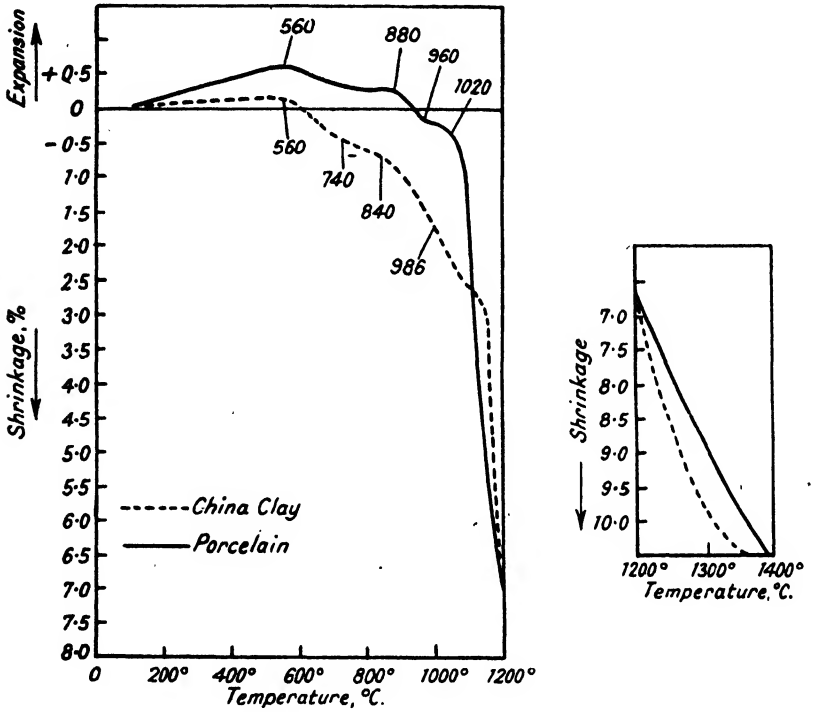

FIG. 28.—Shrinkage and thermal expansion curves of unfired china clay and of an unfired porcelain body. (Steger, Ber. D.K.G., 1938.)

At a temperature of 880°–900°C. aluminium silicates and alumina are formed. The latter disappears completely at 1,100°C. forming additional alumina silicates which cause further shrinkage, since the particles fritt (weld) together.

In the curve showing the shrinkage of the porcelain body one can see how between 560°–1,020°C. quartz and feldspar act as " opening " materials and decrease the shrinkage compared with the shrinkage of pure kaolin. At a temperature of about 1,020°C., however, quartz and feldspar start to form a viscous glass with the clay substance, causing considerable shrinkage by filling up the air pockets.

From 1,100°–1,200°C. the shrinkage of porcelain increases more rapidly than that of kaolin due to the fluxing effect of the glasses formed, and at 1,200°C. both curves cross again.

Between 1,260°–1,300°C. cristobalite is formed and during this period the shrinkage increases at a somewhat smaller rate, especially in the case of porcelain. Above 1,300°C. the shrinkage of the porcelain body continues rapidly until 1,380°C. is reached, when the shrinkage of porcelain ceases almost completely and this particular porcelain body reaches its vitrification point.

Between 1,380°–1,400°C. the shrinkage increases only very slowly, since the air pockets have now been filled. Above 1,400°C. the rate of shrinkage of porcelain is very small. This cannot be seen in the graph which only goes up to 1,400°C. Actually the shrinkage increases very little between 1,380°–1,430°C., indicating that this particular porcelain has a very large firing range (50°C. to be precise).

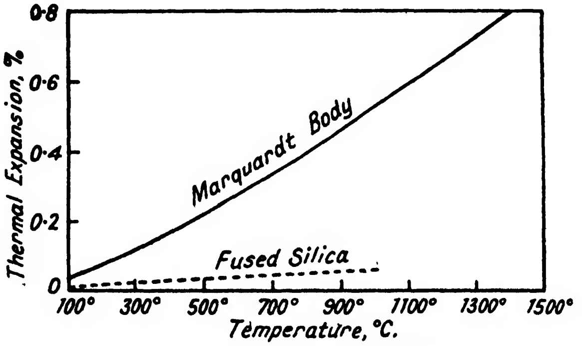

Fig. 29.—Thermal expansion of Marquardt Rod.

It is interesting to note that from 1,200°C. onwards the porcelain rod is longer than the kaolin rod. This is not due to a greater shrinkage of the kaolin, but is the result of the greater thermal expansion of the undissolved quartz particles contained in the porcelain body.

The measuring method described above records the total expansion of the test specimen, plus that of the marquardt rod.

In order to know the expansion of the test specimen it is necessary to know the thermal expansion of the marquardt rod. The thermal expansion of a marquardt rod of the composition indicated above is given in the sketch (Fig. 29) for tempefatures ranging from 100°C. to 1,400°C.

B. DETERMINING THE MOISTURE CONTENT

In all cases where the compounding of bodies is carried out by dry weighing of the raw materials, it is very important to determine and control the moisture content of the various ingredients. (By " dry " is meant a material which may already contain moisture, but to which no extra moisture is added.) Whereas the moisture content of the various unplastic material is small and does not vary very much from one consignment to another, the moisture content of the ball clay and china clay may vary considerably. Whereas the moisture content of any particular batch of purified china clay is controlled and known to the supplier (who, in most cases, is able to give reliable indications to the customer), the moisture content of

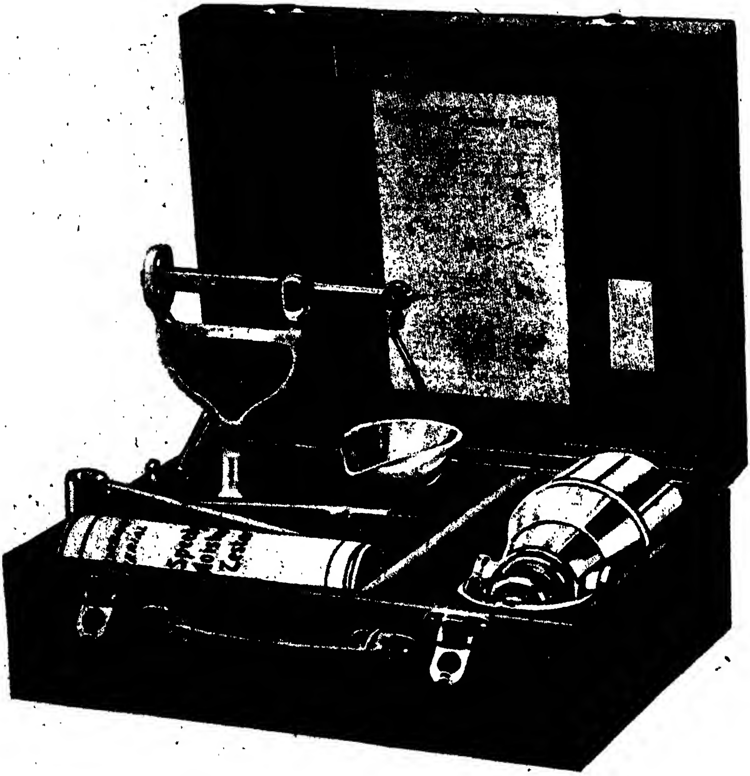

FIG. 30.—Speedy moisture tester. (Thomas Ashworth & Co., Burnley.)

the ball clay changes considerably according to the weather conditions to which it is exposed before the compounding of the body.

It is obvious that if the moisture content of ball clay is not controlled and if the moist ball clay is weighed without considering its moisture content, the amount of ball clay actually used will vary considerably.

The determination of moisture content of clay is sometimes neglected by porcelain manufacturers, although it is easily carried out. It can, for instance, be carried out by weighing first of all a small glass dish and then the glass dish plus the undried sample. The dish with its contents is then placed in a drying oven and the temperature kept for several hours at approximately 110°C. The dish is then transferred, for, say, half-an-hour, to a dessicator and when perfectly cooled it is reweighed. This process must be repeated until no more moisture evaporates.

Another method is to put the moist sample into a flask of xylene, which has to be stirred carefully and then has to be placed on an electric heating plate. The xylene boils and takes the water with it. The flask is connected by means of a tube to a condenser. The xylene and water which have been evaporated now condense in a vessel provided with a measuring burette. Owing to its higher specific gravity the water separates easily from the xylene and can be quickly read off in the measuring burette. Recently " Speedy Moisture Testers " (Thomas Ashworth & Co.) have appeared on the market in which powdered calcium carbide is mixed with the test specimen by shaking (Fig. 30). Calcium carbide combines with the water of the test specimen, developing acetylene gas. The pressure caused by the development of the gas is recorded as a percentage.

The average moisture content of the main raw materials used for porcelain bodies is as follows :

	Per cent.
Ball clay	25–28
China clay	9–12
Flint	7–11
Stone	7–11
Feldspar	7–11

C. TESTING OF CLAYS

So much has already been written on this subject, but instead of omitting this section completely and referring to standard works, the subject is briefly outlined here as far as it affects the manufacturer of technical porcelain.

A great many methods of testing clays are described in the available literature dealing with ceramic questions. In the ceramic laboratory of a factory, producing technical porcelain of various types, it is possible to confine oneself to those tests which are the most important for ensuring uniform quality of production. Most of the purified china clays are analysed by the supplier and it is therefore seldom necessary for the manufacturer to carry out chemical analyses as these are available from the supplier. The ball clays are, however, as a rule not analysed by the supplier but are shipped to the porcelain manufacturer exactly as they are won. It is very essential to know how much sand and other unplastic materials are embedded in the ball clays. There are two methods of ascertaining this : First, the mechanical method, and secondly the chemical method.

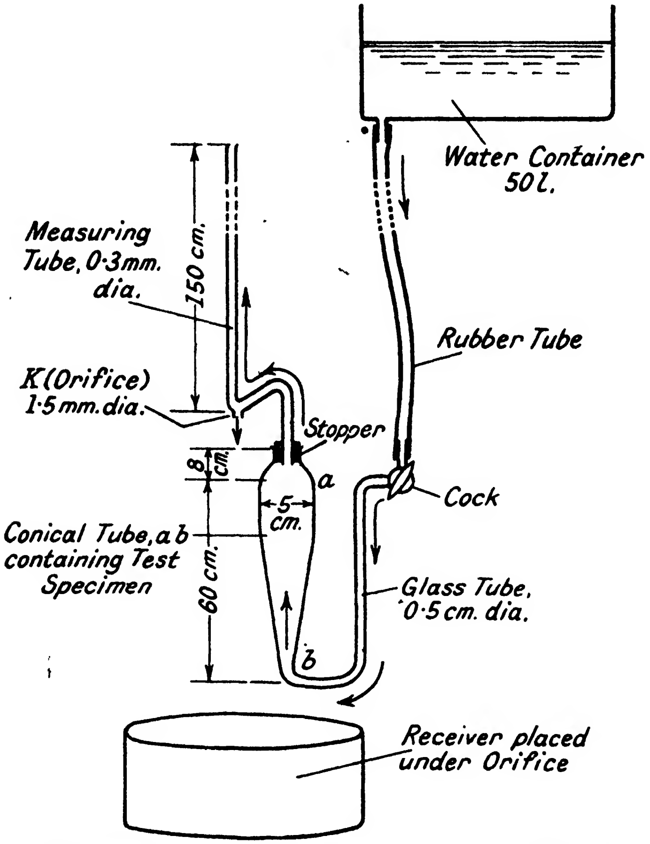

FIG. 31.—Schoenes elutriator for separation of different grain sizes of the unplastic admixtures of the clay substance.

“ **Mechanical Method.**” The separation of the coarser grains according to their size can be effected by means of sieves, but the finest grains cannot be separated by sifting. Sifting does not therefore give very complete or accurate results, but it is a very quick method of obtaining a rough idea of the physical composition. The clay is placed in suspension in water, strongly stirred and then passed through sieves. To begin with, one can take a 70-mesh sieve. Then the portion which has passed through may be sifted through a 120-mesh sieve, and after that through a 170-mesh sieve. Thoroughly purified kaolin should leave no residue on a 230-mesh sieve.

The sieves in use on the Continent are classified either by the number of wires per square centimetre, or by the number of meshes per square centimetre. In England and in the United States, sieves are graded according to the number of wires per square inch.

To assist readers of Continental, English, and American publications in comparing the various sieves, the following table may be of interest :

German Din. 1171		No. of wires per in.^{2}	
Number of wires, per cm.^{2}	Number of meshes, per cm.^{2}	American A.S.T.M.	British B.E.S.A.
130E	16,900	325	—
110E	12,100	270	300
100	10,000	230	—
90E	8,100	—	240
80	6,400	200	200
70	4,900	170	170
60	3,600	140	150
50	2,500	120	120
40	1,600	100	100
35E	1,225	80	85
30	900	70	72
24	576	60	60
20	400	50	52
18E	324	45	44
16	256	—	—
14	196	40	36
12	144	35	30
11E	121	—	—
10	100	30	25
8	64	25	22

Much more accurate results than by sifting are obtained by elutriation which allows of the separation of the various grain sizes of the unplastic admixtures of the clay substance.

Fig. 31 shows the arrangement of Schoenes elutriator. The principle of its working is as follows :

The clay which is to be investigated is put into a conical tube (or container) (*a–b*). Water is then allowed to flow from a basin arranged on a higher level (containing about 50 litres of water) through the conical tube containing the clay suspension. The speed of the flow can be regulated by a cock arranged between the water basin and the entrance to the conical tube. A low speed of flow, *i.e.* with the cock only slightly open, will carry away only the lightest particles which are allowed to flow out at the orifice (*k*). If the speed of flow is increased by a wider opening of the cock the coarser particles are then carried away. By carefully regulating the speed of the flow by predetermined standards the grain size can generally be graded into five categories. The speed of flow can be read off the long measuring glass tube provided at the upper end of the instrument. Clay particles are usually of a size smaller than 0·01 mm. (10μ). All larger particles may therefore be considered as unplastic admixtures.

“ **Chemical and rational analyses.**” The best and quickest chemical method for determining the proportion of clay substance, free silica, and feldspar in a clay, is the so-called “ rational ” analysis.

For the ceramist it is important to know the amount of each ingredient contained in any ball clay which, as previously mentioned, is not usually analysed by the clay supplier, or in the purified china clay.

The normal chemical analysis which would determine only the radicals, for instance :

Al_2O_3 (Aluminium oxide).
K_2O (Potassium oxide).
Na_2O (Sodium oxide).
SiO_2 (Silicon dioxide).

is not very indicative as, in the case of a given clay, it does not indicate whether the silica found is a constituent of the clay substance, of the feldspar, of the mica, or free silica. On the other hand, rational analysis separates feldspar, quartz, and other non-plastic ingredients from the clay substance, and in combination with the elutriation method it affords the quickest way of gaining exact knowledge of the composition of the clay in hand.

The exact method of carrying out rational analysis is described in detail in the various ceramic manuals. It will suffice to say that rational analysis makes use of the fact that when clay substance is placed in boiling concentrated sulphuric acid for 20 hours it is attacked and completely decomposed and transformed into water soluble salts. After this process there remains an unattacked residue of free silica, mica, and feldspar. After eliminating the mica by washing, the residue may be dissolved in hydrofluoric acid. Then either the alumina or the alkali content is determined (which allows for calculating the feldspar content). The rest is free silica.

As regards the non-plastic materials, there is really only one test, the introduction of which is recommended as a routine test for the manufacturer of technical porcelain. This test is for determination of the alkali contents of the feldspar, stones, and pegmatites used in the bodies. It has been previously mentioned that the feldspar content of a porcelain body has to have a predetermined ratio to the whole body, and that fluctuations must be kept within very narrow limits. To exceed the ratio would unfavourably affect the mechanical characteristics of the body, and vice versa, working below the ratio might result in a not completely vitrified body at the desired temperature. This latter defect can often only be detected *after* the dye test has been carried out on the finished articles and may result in a very high percentage of rejections, particularly in the case of insulators.

The second reason why checking of the feldspatic contents is very essential to the manufacturer is due to economic considerations. Because they are cheaper than pure feldspatic minerals, pegmatites and stones (which contain feldspar) are used.

The alkali content of these rocks fluctuates considerably, and as an excess or too little alkali content would ruin the body, it is necessary to check these raw materials before they are put into the grinding cylinders or into the mixing arc.

Every batch in the composition of which such materials with fluctuating alkali contents are used has to be freshly calculated. As soon as the result of the analysis giving the exact alkali content is available, each mixing has to be freshly calculated to suit the varying composition of the pegmatites and stones.

For other ceramic articles in the manufacture of which feldspar is used, such as porcelain dinnerware, earthenware, etc., fluctuations in the alkali contents of feldspar or stones are generally not so important. Slight variations of the alkali content would only slightly affect the shrinkage and the translucency, certain tolerances for which are allowed in the case of household articles.

As there is a much higher feldspar content in porcelain bodies for dinnerware, slight fluctuations would not result in such disastrous effects as in the case of bodies for technical porcelain and particularly for insulators.

D. INVESTIGATIONS OF CERAMIC MATERIALS BY OPTICAL AND X-RAY ANALYSIS

ELECTROMICROSCOPE AND PERMITTIVITY

In addition to the traditional chemical, electrical, and mechanical methods of testing ceramic materials, optical and X-ray analyses have been increasingly used for this purpose in recent years. The purpose of these tests is to further investigate both ceramic raw materials and the structure of ceramic fired bodies in industrial laboratories and particularly in research laboratories. With the help of the microscope, the elutriating method of investigating the fineness of the ground raw materials and the grain size of the ball clays and their sandy admixtures can be supplemented, and the nature of the crystals and of the glassy and colloidal particles can be investigated. X-ray analysis, on the other hand, provides valuable information about the crystals present in raw materials and bodies, and about their crystalline structure.

Both methods are of equal importance and supplement each other. The optical method shows, first of all, whether the material consists of a mixture of crystals or colloidal or glassy substances, and secondly, the shape and size of the crystals. The X-ray method of analysis assists the optical method and makes possible the identification of the crystals which, either owing to their smallness or their similarity to other crystals, cannot be identified by the microscope.

Since the nature of X-ray analysis is not generally known, a few remarks explaining the physical principles underlying it will be of interest.

If a beam of light is passed through a glass plate, on the surface of which 100 or 200 fine lines per millimetre are scratched, the light beam is diffracted. As is well known, the white light of the sun is a mixture of all the colours of the spectrum and contains all the rays of various wavelengths radiated from the sun. This light, if passed through the glass plate (into which the fine lines mentioned above are scratched) will diffract rays of larger wavelengths more than those of short wavelengths, *i.e.* red rays are diffracted more than the violet ones. The glass plate described is called " an optical diffraction grating." Red rays have a wavelength of 7,600 angström Units ($7{,}600 \times 10^{-8}$ cm.) and violet rays 3,800 angström Units ($3{,}800 \times 10^{-8}$ cm.). The wavelengths of X-rays are 1,000 times smaller than the wavelength of light.

If X-rays are passed through the optical diffraction grating described, no diffraction occurs. The finest grating which it is possible to scratch on a glass plate consists of 1,700 lines per millimetre, but this does not diffract X-rays either. It would be necessary to prepare a glass plate having a million lines per millimetre in order to cause a diffraction effect. Such a device is, however, impossible to produce, but Nature has put at our disposal diffraction gratings of the necessary fineness. In crystals the atoms are arranged in the form of a grating. They create planes and interstices between the planes—the distance between the planes being about 8 angström Units (8×10^{-8} cm.) which is comparable to the wavelengths of X-rays. Diffraction spectra are, therefore, readily obtained. Whereas in the case of an optical diffraction grating the spaces between the lines are of the same magnitude as the wavelengths of light, the spaces between the lattice planes of a crystal are of the magnitude of the wavelengths of X-rays (0·1–1·3 angström Units).*

In the original method of observing diffraction devised by Laue (Bayerischen Akadamie der Wissenschaft, June, 1912) a narrow beam of X-rays is passed through a slice of a crystal and falls on a photographic plate. The spot formed by the direct beam is surrounded by a series of diffraction spots according to the reflection of the incident beam by the lattice unit planes of the crystal. The distances of the diffraction spots from the centre are, therefore, dependent on the angle of the various planes and on the different wavelengths of the rays passed through the crystal slice. This dependence, and how interference effects occur when X-rays pass through the crystal are explained by Sir W. L. Bragg (Proc. Camb. Phil. Soc., Vol. 17, November, 1912) who showed that if the beam strikes the crystal planes at an angle α the difference between reflection from different planes is $CB = 2 \sin \alpha d$, d being the distance between two planes (Fig. 32).

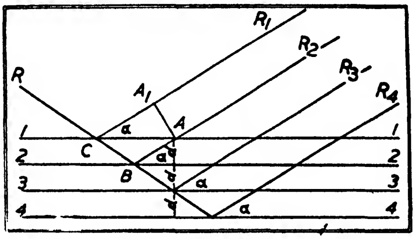

FIG. 32.—Diagram illustrating diffraction of X-ray by crystals.

If an appreciable beam is to be reflected from the successive lattice planes 1, 2, 3, 4 the waves have to be in phase, or $2d \sin \alpha = m\lambda$, λ

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* Angström is a unit of wavelength used in connection with the light spectrum. 1 angström = $\frac{1}{1000000000}$ of a centimetre.

being the wavelength. m must be an integer, otherwise the waves are not in phase and interfere with each other, extinguishing each other. If they are in phase however, a strong beam is reflected from the crystal in the direction *R* as if the rays *R*1, *R*2, *R*3, and *R*4 were reflected from point *C* on plane 1.

In ceramics, X-ray analysis is generally used not so much to investigate a well-defined crystal but a mixture of crystals of various forms and sizes. In such a case a mass of the crystal powder to be investigated may be pressed and shaped into the form of a cylinder and mounted on a hair in the centre of a cylindrical chamber around the inner periphery of which a photographic film is fixed. The cylindrical mass of powder provides a random arrangement of particles which give reflection from all the crystal planes present and produces a series of lines corresponding to each reflecting lattice plane (Debye and Scherrer, Phys. Zeit., Vol. 17, 1916).

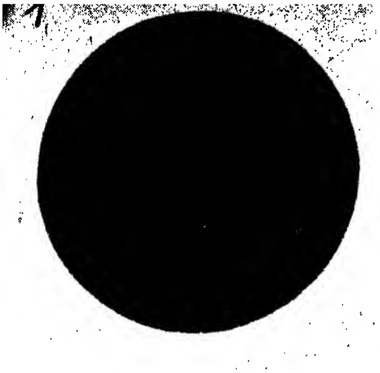
The technique of X-ray analysis is a matter of experience. The experienced investigator will have no difficulty, but the beginner has to collate his experience gradually. Fortunately, in the course of time a procedure has been built up so that it takes only a relatively short time even for a beginner to acquire the necessary experience in order to enable him to read X-ray photographs and to come to the correct conclusions. X-ray analysis is suitable for identifying and characterising the structure of crystals whereas amorphous or glassy particles which may exist in the same test specimen are difficult to ascertain by this method. For such cases the microscope is used, as explained later.

Crystal-containing materials are characterised by variation in crystal size, shape, orientation, and extent of crystallisation, all of which have a great influence on the mechanical and dielectric properties of the materials in question. X-ray analysis gives exact information about these items. For instance, an experienced investigator has no difficulty in obtaining an accurate idea of the relative quantities in which the various crystals are present, except when the crystal content is less than 5 per cent. In this case the characteristic lines in the X-ray spectrum (called " X-ray nomogram ") are too feeble.

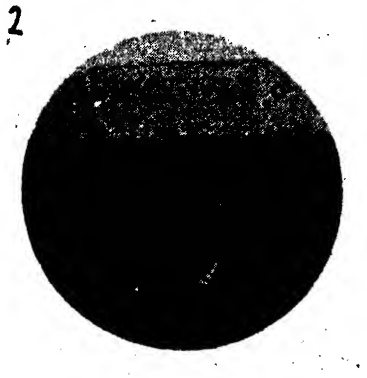
X-ray analysis of both ceramic bodies and ceramic raw materials is relatively simple because as previously mentioned they are primarily of a crystalline nature. All the crystals present are easy to identify. For example, Dolomite, Calcite, Magnesite, and Feldspar have very distinct nomograms.

As described in a previous Chapter there are various kinds of

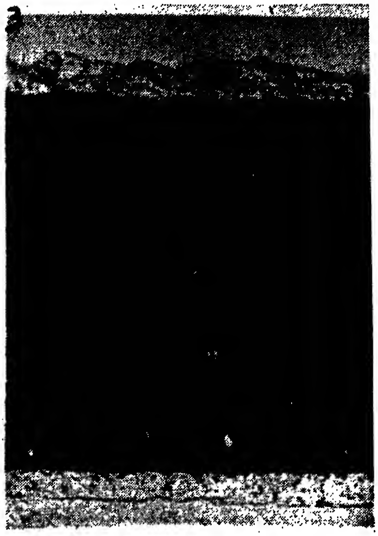
MICROPHOTOGRAPHS
(75 diameter magnification)



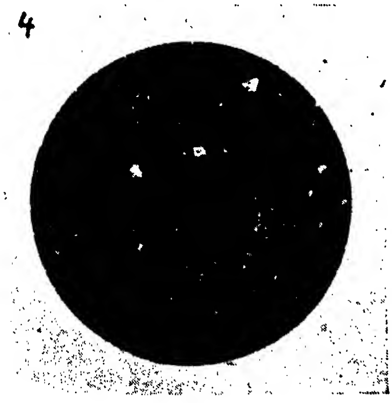
1. Section of insulator porcelain showing quartz particles, some being of considerable size.



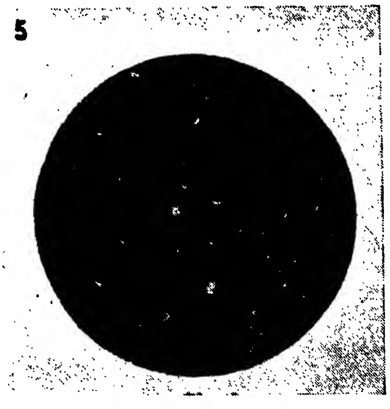
2. Section through insulator at junction of glaze coating, part of the surface of the porcelain has been dissolved by the glaze.



3. Section of porcelain crucible showing smaller quartz particle size than 33/1.



4. Fired rutile body showing crystalline formation.



5. Section of steatite with clinoenstatite crystals.

FIG. 33.

feldspar crystals. It is rather difficult to distinguish between them by X-ray analysis since their nomograms are very similar.

X-ray analysis makes it possible to identify the modifications of silica present in such raw materials as kaolins, clays, etc., and the modifications into which they are transformed in the ceramic bodies during the firing process (Fig. 34).

X-ray analysis is very enlightening in connection with all those ceramic bodies which are mainly of a crystalline nature. If, however, vitrification has taken place, in which case the crystalline structure is partially dissolved, interference makes the reading of the nomogram difficult.

X-ray analysis plays an important part in the detection and identification of the crystals which are formed in low-loss ceramic materials, like clinoenstatite, rutile, magnesium-orthotitanate, and cordierite bodies, and in ascertaining how these crystals influence the technical characteristics of the respective bodies (Fig. 35).

To give an example, ceramic bodies prepared mainly of talcum have been and are being used extensively and are designated "Steatites," which will be more fully dealt with in the chapter dealing with High Frequency Ceramics. These talcum bodies are made plastic by the addition of small amounts of plastic clay. In order to obtain a vitrified Steatite body a small amount of feldspar is admixed. When fired at about 1,300°–1,400°C. the mixture becomes dense. Steatite articles were found to possess very favourable dielectric properties at high frequencies (much more so than porcelain). These Steatite bodies were later on improved by replacing feldspar by other fluxes like barium oxide, calcium oxide, etc., their mechanical and dielectric characteristics being improved by these alterations. (These improved Steatite articles are known under such Trade names as " Frequalex," " Frequentite," etc.) The reason for this improvement can best be explained by X-ray investigations. It has been ascertained that the nature of the fluxes (although added in very small quantities) has a considerable influence on the clinoenstatite crystals formed during the firing process.

X-ray nomograms divulged that, by the alterations mentioned above, more crystals are formed and that the crystalline structure of the whole body is much more regular if suitable fluxes are employed. The power factor is thereby considerably decreased.

A comparison of various bodies proves clearly the accuracy of the supposition that the more homogeneous the body structure and the more regular the crystalline structure, the more favourable are the dielectric characteristics, especially the power factor. In-

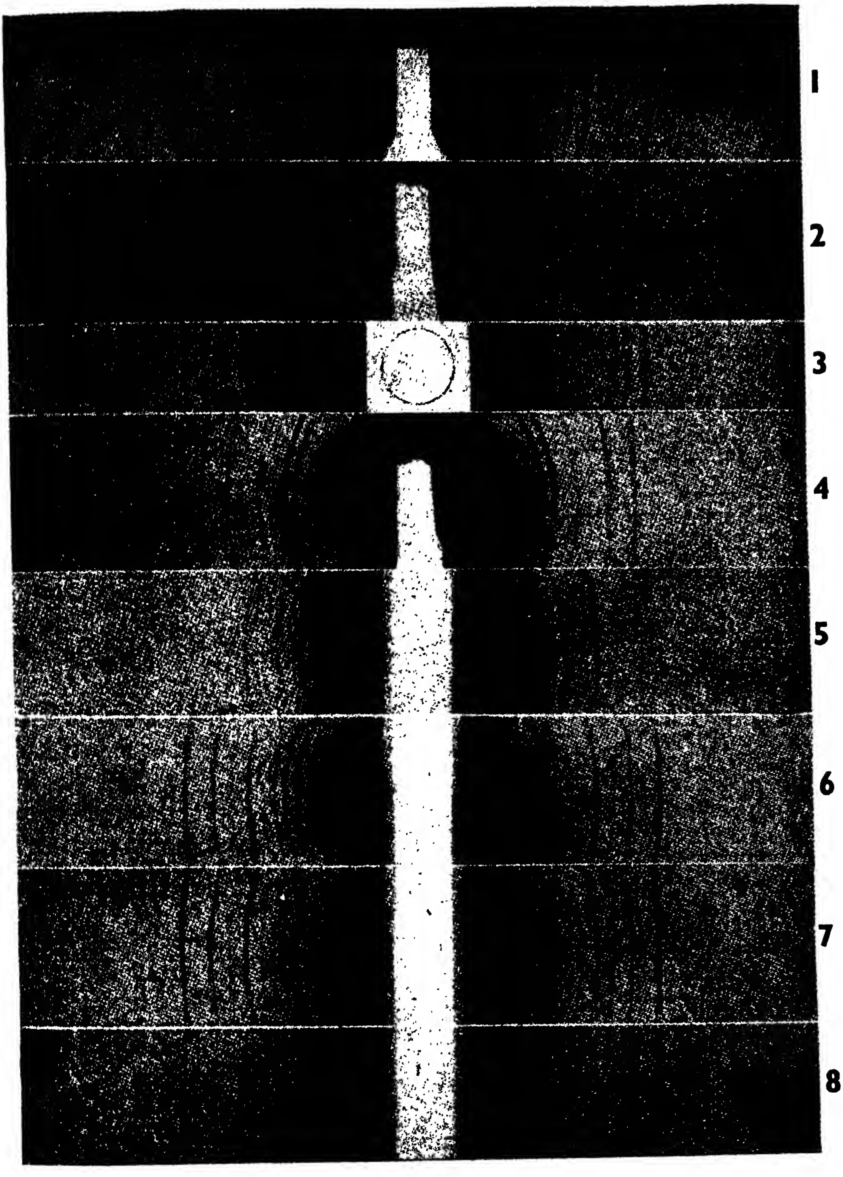


FIG. 34.—X-ray nomograms.

1. β-Quartz.
2. β-Cristoballite.
3. γ-Tridymite.
4. Nakrite.
5. Feldspar.
6. Sand—unfired.
7. Sand—fired at S.C. 7.
8. Sand—fired at S.C. 9–10.

(from Lehmann and Mields.)

vestigations carried out on other low-loss ceramic materials have led to similar conclusions. For instance, take the case of rutile bodies (which are characterised by their high dielectric constant), and the

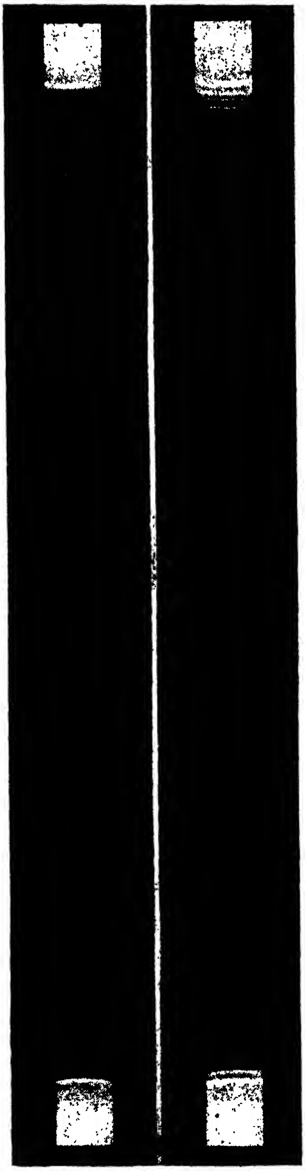


FIG. 35.—X-ray diffraction patterns of Clinoenstatite body (left) and Rutile body (right).

case of magnesium titanate bodies (whose dielectric constant is independent of temperature changes). X-ray analysis has proved that the smaller the amount of plastic ingredients and fluxes added to the materials forming those crystals which impart their electrical characteristics to the ceramic body, the more regular is the shape and size of the crystals formed and the more favourable the technical characteristics of the fired body. This question is also more fully discussed in the chapter " High Frequency Ceramics."

On the other hand, in the case of vitrified porcelain bodies, X-ray analysis is less useful because of the presence in considerable quantities of glassy and amorphous states. Nevertheless, it offers the best method of identifying the various undissolved silica particles and their crystalline structure. In other words, it discloses whether these particles are quartz, cristobalite, or tridymite.

So much for the investigation of fired ceramic articles by X-ray analysis.

Now a few words about raw materials. Much knowledge has been gained of kaolinite crystals by X-ray analysis which otherwise could not have been obtained, the reason being that the particles of clay substance are too small for optical investigation. The smallest particles which can be investigated with an optic microscope have a grain size of 1,000th of a mm. (1μ).

X-ray analysis has ascertained that many of the clay substance minerals hitherto bearing different names are in fact identical, and has also led to the finding of other new crystals belonging to this group.

Of special interest is the fact that it has been found that a considerable part of the clay substance particles which for a long time had been considered amorphous, are in fact crystals of very small size. They were considered amorphous due to the fact that they have a particle size smaller than 1μ—as small as $0{\cdot}5\mu$ and even smaller, and could not be identified as crystals by optical methods. The knowledge gained by these investigations enables one to form a picture of how kaolinite or clay substance particles, in combination with water, impart the important quality of plasticity to the clay.

X-ray analysis has, moreover, made possible the gaining of valuable knowledge of the crystals forming the extremely plastic and interesting substance "bentonite". Bentonite as previously explained is made up of montmorrillonite and similar crystals. It is a material similar to Fuller's Earth and is very important in connection with the manufacture of certain low-loss ceramic materials. Very small quantities of it transform unplastic materials, such as rutile powder, into plastic materials. Knowledge of the structure of these crystals makes the extremely plastic qualities of bentonite easily understandable. It has been found that the crystal lattice expands if water comes in contact with the dry crystal and that it contracts again when the water evaporates, like an accordion. This quality can be termed " inner crystalline swelling " and gives very interesting information about the plastic nature of clays generally.

X-ray crystallography has only been used for ceramic research work within recent years. The microscope, however, has for a long time played an important part in this field, and has imparted valuable knowledge to Ceramists with regard to the structure of ceramic materials. To digress for a moment, it is well known that with certain materials it is only necessary to examine a highly polished surface, or the fractured surface of a test specimen. In the case of fired ceramic materials microscopic examination of the surface under reflected light is, however, not very instructive.

In order to obtain a clear picture as to the structure of any fired ceramic article, a transparent thin section of the material has to be prepared. The photographs on p. 123 were taken with a magnification of 75 diameters. Such magnification can cover a sufficient area and make even very small crystals clearly visible. The study of such micrographs with a magnifying glass shows even smaller crystals which, with the naked eye, cannot be seen on the microphotograph.

Microphotograph (33/1) shows a thin section of insulator porcelain. It indicates that the material under observation is absolutely densified and free from pores. It consists of undissolved quartz particles, some being of considerable size, and of a glassy matrix in which a network of hundreds of tiny crystals is included. It may be repeated at this stage how this structure came into being. A porcelain body consists of kaolin (china clay), ball clay, flint, and feldspar. During the firing of porcelain in the kiln (in which the temperature is gradually raised to about 1,300°C.–1,400°C.), the feldspar melts and the kaolin and ball clay (Al_2O_3 $2SiO_2$ $2H_2O$), dissociate into mullite ($3Al_2O_3$ $2SiO_2$), and silica (SiO_2). The molten feldspar dissolves part of the quartz particles and the silica which is set free by the dissociation of the clay substance, forming a glassy matrix. The network of tiny crystals shown consists of mullite crystals.

As mentioned, it can be clearly observed from the microphotograph that relatively large grains of quartz are left undissolved at the temperature used. These have a favourable influence on the mechanical properties of insulator porcelain.

Insulators are generally covered by a glaze. Microphotograph 33/2 shows the junction of the glaze with the porcelain body. It can be seen that parts of the surface of the porcelain body have been dissolved by the glaze and have fused with its glassy matrix. An intermediate layer has thus been formed between porcelain and glaze consisting of a mixture of glaze and the glass matrix of the body and some partially dissolved mullite crystals and quartz particles.

Microphotograph 33/3 shows the magnification of a thin section of a porcelain crucible used in chemical laboratories. It is very similar to the section of the insulator porcelain (shown in microphotograph 33/1) except that the undissolved quartz particles are much smaller. This is the result of special treatment, which has been applied to the body in order to increase the resistance of the porcelain to sudden temperature changes.

Microphotograph 33/4 shows a transparent thin section of a fired rutile body taken with a magnification of 75 diameters. It shows that the material consists almost exclusively of tiny, regular crystals. A few larger crystals are included. These were formed by the material admixed for the purpose of making the rutile body plastic.

Microphotograph 33/5 shows a thin section of an improved Steatite article. It can be seen that it is formed almost exclusively of a mass of very fine crystals. X-ray analysis, as mentioned above, has identified these as clinoenstatite crystals. The microphotographs 33/4 and 33/5 show ceramic materials possessing a very homogeneous crystalline structure resulting in very favourable dielectric properties.

The light microscope although it has been a most useful tool at the disposal of ceramists has, as mentioned above, the limitation that the magnifications obtainable are limited and that it is, therefore, not possible with the help of the optical microscope to study the smallest particles of which, for instance, the clay substance and other plastic materials are constituted. This limitation has been removed by the development of the electron-microscope which has been improved considerably in the last few years and which will play a very important part in ceramic research in years to come.

The electron-microscope is based on the discovery that an electron, or any electrically charged particle of matter travelling through electric and magnetic fields, obeys the same mathematical laws as a beam of light travelling through various optical media.

This discovery leads directly to the possibility of constructing lenses for electrons, employing electric and magnetic fields through which the electrons are made to travel (V. K. Zworykin, " Electron-Microscope," *Electronics*, March, 1943). A beam of electrons can be concentrated or caused to diverge by an electrostatic or electromagnetic field, in a similar way as light rays are deflected by glass lenses. All the types of apparatus which use the lens system of light optics may be duplicated in electron optics. Whereas, however, the theoretical limit for the light microscope is reached by magnification of 2,000 diameter, the theoretically possible largest magnification in an electron-microscope is 200,000,000 diameter. Of course, it is not expected and not even essential that such a fantastic increase in resolving power should be achieved in the near future. From the practical microscopist point of view, resolving powers which are ten to a thousand times better than that of the light microscope are of the greatest value. Already the electron-microscope has been developed to the point where the resolving power is about a hundred times better than the light microscope, and many most interesting microphotographs magnified 70,000 times have been published recently.

The electron-microscope itself is nothing more than the electron optical counterpart of the light microscope. The well-known lenses of the light microscope have been replaced by magnetic or electrostatic lenses and an electron source has replaced the light source. A heated cathode provides the electrons. These electrons are radiated through an electronic condensing lense on the object to be examined. This electronic beam takes on the characteristics of this object when passing it. The remainder of the structure of the electron-microscope is merely designed around the fact that all the elements of the system are enclosed in a vacuum chamber. The enlarged electron image of the test specimen is then obtained on a photographic plate or fluorescent screen.

The electron microscope has so far been used in ceramic research to a limited extent only, first of all because only very few ceramic laboratories are in a position to use this rather expensive new tool, but there is no doubt that as soon as the new and improved electron-microscopes are produced on a commercial scale ceramic science will greatly benefit by its use.

Another new testing method of ceramic materials is the measurement of the dielectric constant (or permittivity) of ceramic raw materials and of fired ceramic bodies. The laboratories of firms which produce ceramic insulating materials possess in most cases all the instruments which are necessary to measure the permittivity of dielectrics. The methods of measuring permittivity have already been described in detail in a previous chapter in this book. The dielectric constant of a material is dependent on the structure of the molecules of which it is composed and, therefore, the measurement of the permittivity is able to give valuable indications on the structure and composition of the material under test and to supplement other methods of investigation.

The ratio of permittivity to the refractive index of a material is given by Maxwell's formula $K=n^2$, where K is the permittivity and n the refractive index. The permittivities of some ceramic raw materials are as follows :

Kaolin after drying at 100°C.	12·1
Alumina at room temperature	22
Alumina after heating at 950°	9·7
Sillimanite	8·7
Sillimanite after heating at 1,500°C.	6·4
Mullite	6·9
Quartz	4·0

One of the first published studies dealing with the use of permittivity measurement for investigating ceramic raw materials is " An Investigation of the Behaviour of the Clay Substance when heated from Room Temperature up to 1,000° by Means of Measuring the Permittivity," by Dr. W. de Kayser, Boitsfort, Ber. D.K.G., 1940–42, to which reference is made in the Chapter dealing with clays.

It may safely be assumed that this test method will be successfully used in future for investigating many more ceramic raw materials and bodies.

The photomicrographs shown in this chapter were prepared by the Lomax Palaeo-Botanical Laboratories, Bolton, and the X-ray nomograms of the rutile body and the Steatite body were prepared by Dr. E. Schaefer in the Cavendish Laboratories, Cambridge.

CHAPTER VIII

MANUFACTURE

THE difference between the manufacture of ceramic and other materials, such as metal parts and organic plastic materials, is that the ceramic article is not shaped from ready-made material but has first of all to be prepared from various plastic and non-plastic substances.

In this part of the book details of the manufacturing methods will be discussed. The preparation of the body and of the glazes will be dealt with, and the shaping methods described in such detail as may be of interest to the user of technical porcelain. Furthermore, the kilns in which the firing of porcelain is carried out will be described. Before going into the details, however, a short summary will be given showing the various stages of manufacture.

SUMMARY. The first stage in manufacture is the preparation of the body, which may be either liquid, plastic, or dry according to the different shaping methods. After the raw materials have been thoroughly mixed (and in the case of liquid bodies the surplus water removed) the body is homogenised. Out of the homogenised body the articles are shaped into the desired form. The shaped article is then dried and glazed and subjected, in kilns, to high temperatures. The methods of manufacturing both porcelain and low-loss ceramic articles containing talcum are very similar. The most important shaping methods are jollying, turning, pressing, extruding, and casting. With the exception only of the casting process, the plastic properties of the raw materials are utilised.

In general, a plastic body is first prepared which, for the jollying, turning, and extruding processes, is made more homogeneous by means of a kneading and de-airing device called a " de-airing pugmill." For casting purposes a very small amount of watery solution of water glass (alkali silicate) or of sodium carbonate is added to the plastic body, the free OH ions depriving the clay particles of their plasticity. (They make the body liquid, and are called deflocculants). For pressing purposes the body is dried, mixed with lubricants and passed through a disintegrator. Manufacturers who cover a wide range of technical porcelain have to use several different shaping methods. As a rule, they prepare a primary plastic body as a basis for the various special bodies necessitated by the different shaping processes. Firms which employ, for instance, only the pressing process may use with advantage a dry mixing method for preparing the body for pressing. Those firms which only employ the casting process need not make a plastic body nor use the filter press. They add to the raw materials a deflocculent (water glass and/or sodium carbonate) and that quantity of water required to obtain a casting slip of the right specific gravity and viscosity.

The jiggering, turning, free-hand throwing and jollying processes are used for manufacturing articles having a round section. The body is worked on a rotating wheel (throwing) or pressed into Plaster of Paris moulds which rotate, when by suitably formed tools the upper or inner surface is formed (jiggering or jollying), or the body is preformed in the pugmill, dried to a leather hard state and turned on lathes.

Larger or more complicated articles are made by assembling several sections in a moist condition, and using a slip which forms a homogeneous joint during firing. Insulators for electric power transmission lines, bushings, switchgear insulators and post insulators are manufactured by the various plastic methods above described.

Long pieces of symmetrical cross-section are formed by the extrusion method. Vertical and horizontal presses are used as well as normal and de-airing pugmills. The shape of the extrusion die corresponds to the cross-section of the rod or tube to be extruded. Complicated shapes can be extruded over a wide range so long as the cross-section is uniform and symmetrical.

Casting is carried out by pouring the liquid slip into Plaster of Paris moulds which absorb part of the moisture. When the desired wall thickness has been formed in the mould the remaining slip is poured back. This method is used especially in the casting of articles having unsymmetrical shapes, or in cases where small production quantities do not justify the expense of metal dies for pressing. Thick walled articles can be cast by using moulds which possess, in addition to the outer casing, a core forming the inner surface. For larger articles pressure or vacuum can be used in order to expedite casting.

Pressing in steel dies is used when large quantities are required and when the methods mentioned above cannot be employed. The pressing method is generally used for low-tension insulators which do not require great dielectric puncture strength.

The pressing methods can be classified in three groups :—

(*a*) Wet pressing.
(*b*) Semi-dry pressing.
(*c*) Dry pressing.

After the articles have been shaped by one of the methods outlined above, they are carefully dried before being sprayed or dipped in glaze so that they may subsequently absorb on their surfaces the glaze which is suspended in water.

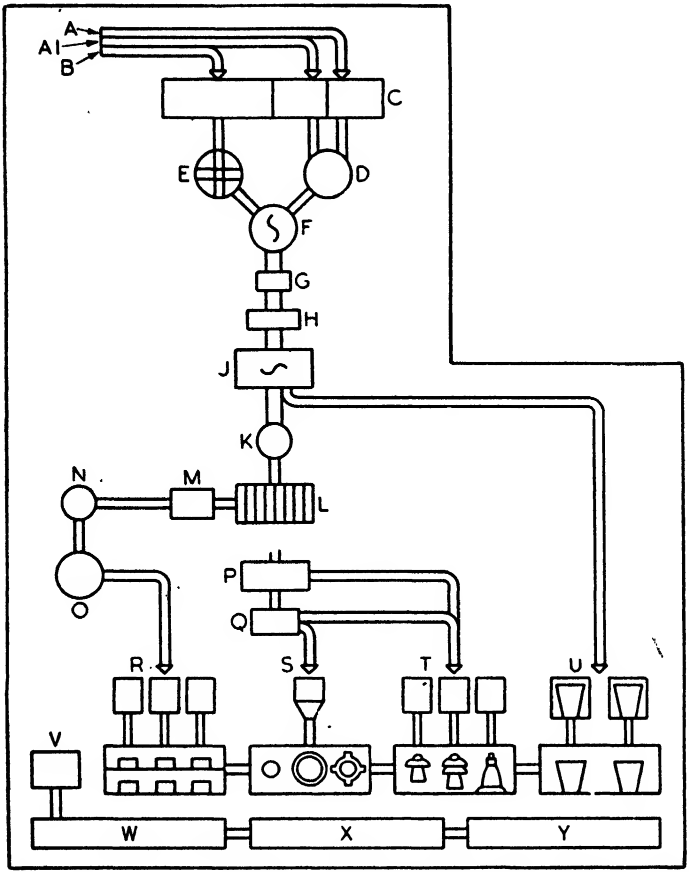


FIG. 36.—Varying stages in the manufacture of ceramic insulation materials.

A.	Supply of flint.
A1.	Supply of feldspar.
B.	Supply of clay.
C.	Silos.
D.	Grinding cylinder.
E.	Blunger.
F.	First mixing arc.
G.	Magneto.
H.	Sifting machine.
J.	Second mixing arc.
K.	Pump.
L.	Filter press.
M.	Dryer.
N.	Disintegrator.
O.	Water—oil—dry body—mixing machine.
P & Q.	Pugmills.
R.	Pressing shop.
S.	Extruding.
T.	Jollying.
U.	Casting.
V.	Dryers.
W.	Glazing.
X.	Tunnel ovens.
Y.	Test room.

In both cases the article is covered by a thin layer of those materials which form the glaze when heated to high temperatures in the

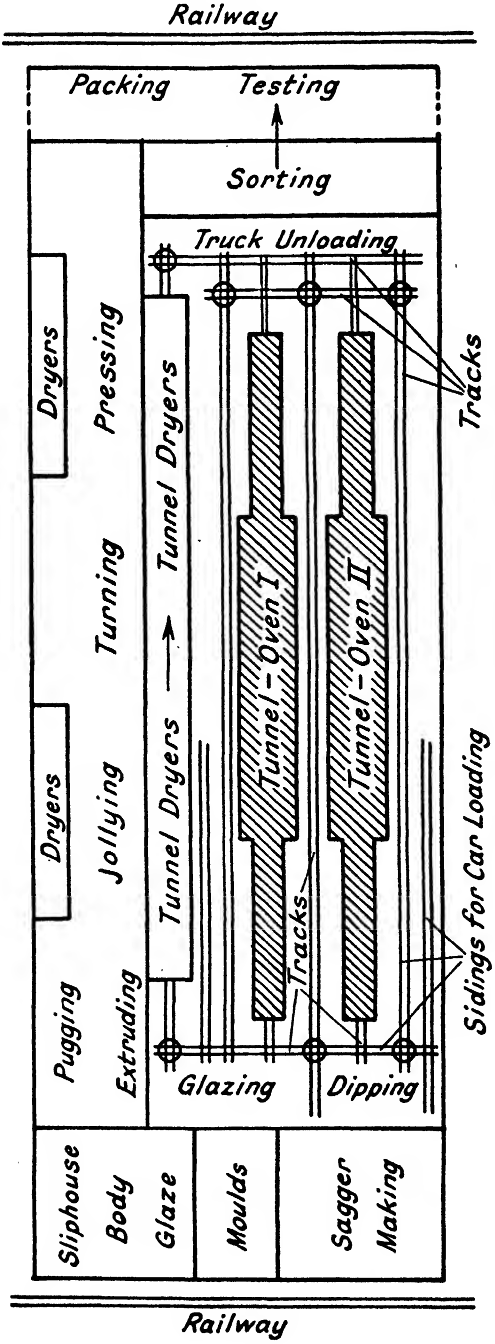


FIG. 36A.—Schematic layout for 2-tunnel porcelain factory.

furnace. After the glazing process has been carried out, the articles are put into furnaces (which may be intermittent or continuous).

In order to protect the articles against the influence of the flames in the oven and in order to prevent the glazed surfaces touching each other, the articles are put into saggers made of refractory fireclay. In the case of continuous tunnel ovens, the saggers may be replaced by other means of support.

Fig. 36 illustrates schematically the flow of production, as outlined above.

Fig. 36A shows the schematic layout of a two-tunnel oven porcelain factory. It does not require further explanation.

A. PREPARATION OF BODIES AND LAY-OUT OF BODY-MAKING PLANT

The preliminary preparation, such as the breaking of various raw materials into small pieces, their further disintegration and their purification, where necessary, is detailed in the chapters dealing with the necessary plant.

The next stage in the manufacture of the body is to mix the raw materials in the desired proportions in such a way that the desired homogeneity and consistency are achieved.

When porcelain manufacturers require all three body-consistencies, it is usual for them first of all to manufacture a plastic body. This might be described as an intermediate stage in the manufacture of a powdered body or a body slip. Raw materials are more easily mixed in a wet state (slip), which, by means of the filter press, is transformed into the plastic state. A powdered body is then obtained by applying heat to the plastic body and a slip suitable for casting is obtained by adding the requisite amount of water.

The plastic body is, therefore (as mentioned), an intermediate stage for the preparation of a casting slip or a pressing powder. (If only a casting slip or a pressing powder is required, the plastic stage is not necessary and can be skipped.)

The preparation of a plastic body will first of all be described.

In order to prepare a plastic body for porcelain manufacture, the raw materials have first of all to be weighed. There are two different methods of doing this. The first consists in weighing the raw materials in the dry state, the second in measuring the raw materials in a liquid state. The first-mentioned method is used exclusively by manufacturers on the Continent and almost exclusively in the United States. The second method is used to a great extent in Great Britain.

B. THE PRINCIPLE OF COMPOUNDING A PORCELAIN BODY BASED ON THE DRY RECIPE

In order to illustrate the principle of compounding a porcelain body based on a dry recipe, the following simple example may be given :

Assume a porcelain body is to be prepared from the following ingredients :

Weight in dry state :

250	pounds	china clay (Kaolin)
250	,,	ball clay
300	,,	quartz or flint
200	,,	feldspar
1,000		

After 250 lb. of china clay and 250 lb. of ball clay have been weighed in dry state (after their moisture contents have been ascertained), they are put into blungers (which will be described later). A quantity of water, sufficient to reduce the clay to a slip state, is added, and the blunger device set in motion. After the china clay and ball clay are dissolved and have become homogeneous slip, they are run into the mixing arcs (which will also be described later).

Feldspar and quartz are either wet ground in grinding cylinders in the factory, or they are purchased already finely ground from an outside source. In our example, 300 lb. of flint and 200 lb. of feldspar are weighed on the weighing machine and put into the grinding cylinders, where they are ground to the required fineness. If they are, however, purchased already ground to the desired fineness, the feldspar powder and flint powder are only weighed (in our example 300 lb. quartz and 200 lb. feldspar). The weighed quantities of dry material are either added to the blungers, where a premixing with the china clay and ball clay is carried out, or they are put directly into the mixing arc, into which the china clay and ball clay slips prepared in the blungers (as mentioned above) are run, and where the mixing is completed. The mixed slip is then run through a sieve into an agitated storage tank (" Agitator "), where it is stored until it is used by being pumped into the filter press.

C. THE PRINCIPLE OF COMPOUNDING A BODY BY MEASURING THE VOLUMES OF THE SLIPS

If the composition of the body is carried out, however, not by weighing the dry raw materials as described above but by measuring slips (suspensions of the materials in question in water), the individual raw materials are first blunged in separate blungers or tanks and " dissolved " into separate slips. Each slip is made to a certain gravity and kept in separate agitated tanks (in the case of the unplastic materials) or in blungers (in the case of ball clay and china clay). The most suitable gravity for each of the raw materials has been found by long experience.

It is such as to allow the ingredients to blend together easily, to pass easily through the sieves and yet not to be so thin as to cause separation by settling of the different constituents. The standardised gravities of the most important raw materials for the manufacture of porcelain (and earthenware) are as follows :

Ball clay slip (weighing 24 oz. per pint) contains 6·6 lb. ball clay per peck (or 6·6 oz. per pint).
China clay slip (weighing 26 oz. per pint) contains 10 lb. china clay per peck.
Stone slip (weighing 26 oz. per pint) contains 18·33 lb. stone per peck.
Flint slip (weighing between 30 and 32 oz. per pint according to the degree of calcination) contains 20–21·2 lb. flint per peck.
Feldspar slip (weighing 31 oz. per pint) contains 18·33 lb. feldspar per peck.

In our example we use uncalcined flint slip which contains approximately 20 lb. flint per peck.

In order to manufacture a porcelain body containing 250 lb. china clay, 250 lb. ball clay, 300 lb. flint, 200 lb. feldspar, we prepare 38 pecks of ball clay slip and 25 pecks of china clay slip in individual blungers. We use 15 pecks of flint slip and 11 pecks of feldspar slip, delivered by the mill at the above-mentioned gravity and put the slips into individual tanks. (It may be recalled that 1 peck equals 16 pints). Fractions of pecks are neglected, they could not be read exactly enough in the mixing tank.

Thus the four slips are kept in a series of individual agitated tanks and blungers and then each slip is run into the mixing arc until it reaches a definite level in the mixing arc.

The measuring is effected either by a measuring stick on which the desired levels for each slip are marked (in inches) and which is put into the mixing arc during the measuring process, or the mixing arc itself is provided with marks. In our example first the ball clay is poured into the arc until mark " A " is reached, then the china clay slip until mark " B " is reached, then the flint slip until mark " C " is reached and the feldspar slip until mark " D " is reached. In our example we measure :

38 pecks ball clay slip each containing 6·6 lb.=250 lb. ball clay.
25 pecks china clay slip each containing 10 lb.=250 lb. china clay.
15 pecks flint slip each containing 20 lb.=300 lb. flint.
11 pecks feldspar slip each containing 18·3 lb.=200 lb. approx. feldspar.

Of course, if for some reason or another during the preparation of a standard body one of the raw materials, say, the ball clay, has to be substituted by another ball clay having different composition (for instance, a higher flint content) all the marks have to be changed accordingly since the whole calculation has to be made again with due regard to the composition of the substituted material.

Various reasons can be advanced as to why measuring in a liquid state is practised in England. The most probable explanation is that as this was the method originally adopted, it was perpetuated.

Raw material grinding mills were established within the boundaries of the Five Towns, where most of the English Pottery industry is concentrated. Under these circumstances it is very convenient for the pottery and insulator manufacturers to purchase the raw materials in the form of a slip, although it might be thought that purchasing raw materials in slip state is a clumsy procedure. As, however, the slip has only to be carried over very short distances, it is considered that there is no point in removing the liquid which subsequently has to be reintroduced. Special tank lorries are available for transporting the slip.

D. LAYOUT OF SLIPHOUSE

Depending upon the state in which the unplastic raw materials are purchased, the layout of the body-making plant is accordingly designed. If the raw materials are supplied in the ground state (as is usual in the United States) they are stored in bunkers conveniently situated side by side adjacent to a truck line. This line may be at a lower level than the bunkers to facilitate discharging of the materials from the bunkers into the trucks. These trucks can be provided with an automatic weighing device and it is thus possible to convey a complete mixture to the blunger or mixing arc. The bunkers (or silos) are in many cases fed from above by a suspended monorail feeding system. After the necessary mixing, the slip runs from the blungers into storage basins (or arcs) which are of course arranged at a lower level than the blungers. The slip can therefore flow without the aid of a pumping device into the storage arcs. In these arcs the slip is continually agitated and so the storage tank is very often called an " agitator." Such a layout of the body-making plant is the most practical in cases where the non-plastic materials are bought already ground to the desired fineness.

To sum up, the general layout in such a case provides preferably for four different levels. The highest level contains the silos or bunkers ; next come the trucks, next the blungers or mixing arcs and finally the storage tanks or agitators.

On the Continent, where the unplastic materials are ground in the porcelain works, and where even small and medium-sized insulator factories have their own grinding cylinders, the most convenient layout is somewhat different.

The unplastic raw materials, with the addition of 10–15 per cent. clay and the appropriate amount of water, are first of all placed in the grinding cylinders in which they are ground to the desired grain size. After the grinding process is completed the slip is run into the blungers which already contain the dissolved kaolins and clays, and in which the mixing process takes place. The body slip is then run into an agitated storage tank. The silos for the unplastic raw materials are conveniently placed on a level above the grinding cylinders, whereas the clay and kaolin are stored in silos above the blungers.

Generally speaking, it is better to employ a greater number of blungers of comparatively small dimensions instead of a few large ones. If a slight discrepancy occurs in the mixing or weighing of the contents of one blunger, it is compensated by the fact that the contents of several blungers are run into the agitators in which they are all mixed together. Finally, the slip is pumped into the filter press.

Another reason in favour of employing a relatively large number of small blungers, grinding cylinders and storage tanks, filter presses, etc., is that it imparts the necessary flexibility to the plant and also allows of various bodies being manufactured simultaneously without having to clean the whole plant when switching over to the manufacture of other bodies.

(The use of large units is, of course, somewhat more economical as regards power consumption and so on, but this can hardly compensate for the advantages of the smaller units mentioned above.)

When the unplastic raw materials are supplied in slip form, the arrangement in the sliphouse is usually on three levels. On the highest are a series of blungers and receiving tanks ; on the middle level are the mixing arcs and on the lowest the agitated storage arcs.

For removing the iron particles, electro magnets are provided between the storage tank and the filter presses. These magnetic separators remove all the metallic iron particles. At various places (for instance, between the ball clay blungers and the mixing arcs, and between the mixing arcs and the storage tank) sieves of various mesh sizes are provided. These sieves keep back any impurities or coarse particles which may not previously have been removed.

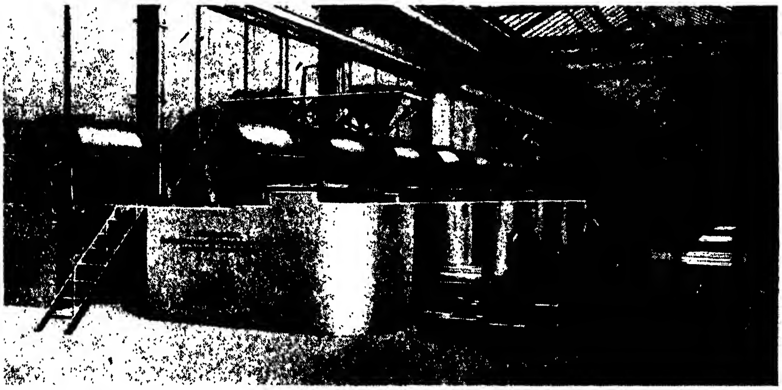


FIG. 37.—Grinding cylinders and sliphouse plant with direct electro-motor drive for each machine. (Allgem. Elektrizitats-Ges. Berlin-Hennigsdorf, later on combined with Rosenthal Insulator Co.)

Manufacturers of technical porcelain who manufacture a wide range of articles of various types and sizes, have as a rule to manufacture various bodies. It is, therefore, quite common for a factory of this type to use four, five, or even more bodies simultaneously.

The layout of the sliphouse should, therefore, take this into consideration, so that a special self-contained plant is available for each individual body. Otherwise the switch over from one body to another would be a nuisance, as all the mixing machines, filter cloths, and presses would have to be cleaned before the new body could be manufactured. Apart from the plant, which is needed for bulk manufacture of the various porcelains, a special plant for making bodies in very small quantities for experimental purposes is almost indispensable. Most insulator manufacturers install a small self-contained plant for this purpose capable of dealing with mixings of between 2 and 200 lb.

A laboratory self-contained plant, for instance, is very useful in cases where it is necessary to alter a standard body by replacing one ingredient by another. Before embarking on mass production, it is always desirable to compound a small quantity of the new body in the experimental plant, sufficiently large to permit of the manufacture of some test specimens and some different types of articles. These are tested and their characteristics measured.

In addition to manufacturing a wide range of L.T. and H.T. porcelain insulators for use at commercial frequencies, and articles for other technical applications, for instance (Chemical Industry), some insulator manufacturers make a very wide range of special bodies for high frequency application, for insulators for heating purposes and other specialities to suit the requirements of individual customers. These special bodies are dealt with in the appropriate chapters.

Those manufacturers who do not concentrate solely on a definite range of standard insulators, but also manufacture, for example, the low-loss type of ceramic insulating materials mentioned above, have, of course, to employ a wide variety of special bodies.

In former times technical directors of insulator factories considered it a very great advantage to use either one body or as few bodies as possible. This point of view has, to a great extent, been abandoned within recent years in view of the introduction of various specialised designs. A body which has been found best for one type of insulator is not necessarily the best for other types.

E. CALCULATION AND COMPOSITION OF THE BODY

(*a*) **Dry Weighing.** The procedure which the Ceramist follows in order to obtain a body of a given composition, is illustrated by the following very simple example.

It is intended to manufacture an insulator body having the following rational composition :

50 per cent clay substance.
30 per cent. quartz.
20 per cent. feldspar.

One has to consider that the raw materials are very seldom 100 per cent. pure. Neither the clay substance (as delivered by the supplier) nor the feldspar is assumed to be pure in one of the following examples.

We assume that the kaolin contains, say, roughly 85 per cent. clay substance and 15 per cent. quartz (or sand).

First, we calculate how much kaolin we have to use in order to produce a body containing 50 per cent. clay substance and what additional amount of quartz is then to be used, considering the fact that a certain amount of quartz is already introduced by the employment of a quartz-containing kaolin. We therefore have to take :

58·8 parts kaolin,
21·2 parts quartz,
20 parts feldspar,

because, according to the rational composition 58·8 parts kaolin contain 50 parts clay and 8·8 parts quartz.

21·2 parts quartz are arrived at by the fact that 8·8 parts have already been introduced by the kaolin, thus making a total of 30 parts quartz.

In the above example, we assume the use of pure feldspar. In practice, however, this is seldom the case ; it is customary (for reasons explained elsewhere in this book) to use pegmatite, which may, for example, contain 50 per cent. feldspar and 50 per cent. quartz. In this case we weigh the following raw materials :

58·8 parts kaolin.
1·2 parts quartz.
40 parts pegmatite.

The 50 parts clay in our original example derive, therefore, from the 58·8 parts kaolin, the 30 parts quartz derive from the kaolin, the pure quartz and from the pegmatite in the proportion $8{\cdot}8+1{\cdot}2+20(=30)$.

In practice, however, the clay substance is not introduced by one kind of china clay only, but by a mixture of various ball clays, china clays, etc. The rational composition of the various china clays and ball clays has first of all to be ascertained, and then the calculation of the body carried through in a manner similar to that shown above.

In a similar way, the necessary feldspar contents are introduced to the body by pegmatites or stones. The different compositions of these raw materials have of course also to be taken into consideration in order to arrive at the final composition of the batch.

If during the preparation of a body one raw material has to be substituted for another its composition has first of all to be considered so that a body having the same technical characteristics may be produced. However, as explained in the chapter dealing with raw materials, the chemical and rational compositions are not alone of importance. The degree of fineness of the non-plastic raw materials is, for example, very important, and also the degree of plasticity of the various clays used. If the body has either too great or too small a plasticity and shrinkage, one or more of the plastic clays have to be replaced by a less or more plastic ball clay, as the case may be. These clays may have different rational compositions from those which they have to replace. They may, for example, contain more quartz, in which case more ball clay is then used in order to obtain the same content of clay substance. In this case it is essential to make certain that the original ratio between clay substance, quartz, and feldspar is not fundamentally altered.

(*b*) **Wet Measuring.** The calculations described in the previous chapter are relatively simple if the compounding of the body is based on a dry recipe. If, however, the compounding is based on a wet recipe the wet recipe has first to be converted into a dry recipe. In any case, the calculation is based on the ratio of the dry materials and for that reason the dry content of the different slips has to be ascertained.

It has been mentioned earlier in this book that the various slips are supplied at so many ounces per pint, and the question therefore arises as to how one can find out how many ounces or pounds of dry material are contained in X number of pecks or pints of material possessing different standard gravities. The actual dry content in pints of slip material can be ascertained in two ways :

(1) By evaporating the water and weighing the residue.
(2) By calculation.

The first method is not employed in practice because when the specific gravity of the material is known the result can be arrived at more readily by calculation. This calculation is based on the relations existing between the specific gravity of the substance and the weight per pint in ounces.

A pint measure will hold approximately 20 oz. water. If 1 oz. of water is taken out, and a similar bulk of a substance with a specific gravity of 2·5 is added, the measure will still be full, but if weighed it will be found to have increased in weight by 1½ oz., viz. from 20 to 21½ oz. To increase the pint weight therefore by 1½ oz., 2½ oz. of material have to be added. It follows then that with slop materials weighing 24, 26, and 32 oz., to the pint respectively, the dry content (if its specific gravity is known) can be calculated.

$$\left.\begin{array}{l} \text{as } 1\tfrac{1}{2} : 4 : 2\tfrac{1}{2} : x = 6{\cdot}6 \\ 1\tfrac{1}{2} : 6 : 2\tfrac{1}{2} : x = 10 \\ 1\tfrac{1}{2} : 12 : 2\tfrac{1}{2} : x = 20 \end{array}\right\} \text{Or in the proportion of } 1 : 1\tfrac{1}{2} : 3.$$

In 1848 Brongniart published the following formulæ for converting wet to dry and vice versa, when the specific gravity of the dry material and the slop weight are known:

$$(a)\ D=(P-20)+\frac{G}{G-1}.$$

$$(b)\ P=20\times D+\frac{G-1}{G}.$$

where D=dry content, P=weight of pint in ounces, and G=specific gravity.

These formulæ are extremely serviceable, since they facilitate a rapid change from wet to dry or vice versa.*

The table hereunder gives the gravity and dry content of the four most important raw material slops in daily use for porcelain and earthenware manufacture (when the compounding of the body is carried out by measuring slops by volume).

Material	P. Weight of pints in ozs.	G. Specific gravity	D. Dry content in ozs.
Ball clay . .	24	2·5	$(24-20)\times\frac{2{\cdot}5}{2{\cdot}5-1}=\frac{10{\cdot}0}{1{\cdot}5}=6{\cdot}66$
China clay . .	26	2·5	$\frac{6\times2{\cdot}5}{1{\cdot}5}=6\times1{\cdot}66=10$
Stone (pegmatite) .	31	2·5	$\frac{11\times2{\cdot}5}{1{\cdot}5}=11\times1{\cdot}66=18{\cdot}33$
Flint . . .	32	2·5	$\frac{12\times2{\cdot}5}{1{\cdot}5}=12\times1{\cdot}66=20$

The gravity of flint varies according to the degree of calcination to which it has been subjected. The higher the calcination temperature the lower the specific gravity. Therefore, at a given slop weight the lower the calcination temperature the less the actual dry content.

(Uncalcined sand has a somewhat higher specific gravity than calcined flint and it is difficult to keep ground sand in suspension in the

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* "The Manual of Practical Pottery," C. F. Binns, pp. 8 and 9.

slop. The result is that settling of the sand takes place if not very finely ground. That is one of the reasons why firms who usually buy their raw materials in slop form employ ground flint instead of ground sand as body material.)

It can be seen that when the specific gravity of the various raw materials is the same, the dry content of the slip is proportional to the excess weight of the slip in ounces over 20 (20 being the weight of 1 pint of water).

Since the ceramic body materials referred to above all have practically the same specific gravity, it is very easy to arrive at the dry content of pint slip in ounces. It is only necessary to multiply the number of ounces in excess of 20 of any given pint of slip by the factor 1·66 (see previous Table).

Considering the fact that the weight per pint in ounces of the various slips is different (as previously mentioned) rather complicated calculations are necessary if one material has to be replaced by another having a different rational composition.

For instance, a china clay containing 90 per cent. clay substance and 10 per cent. quartz may have to be replaced by china clay containing 80 per cent. clay and 20 per cent. quartz. And, at the same time, a feldspar raw material containing, for example, 80 per cent. feldspar may have to be replaced by a feldspar raw material containing only 50 per cent. feldspar. Then the dry contents of the clay slop, the flint slop and stone slop have to be ascertained and the volumes of the various slops adjusted according to the changed compositions. The compounding of bodies by measuring the volumes of the various slips is, therefore, only practicable if the raw materials used are very consistent in their composition and do not change in the course of time, and if there is a definite certainty that the composition of the body has not to be changed.

F. MANUFACTURE OF PORCELAIN GLAZES

Broadly speaking the ceramic industry employs two principal types of glazes :

(*a*) Low temperature glazes employing fritts.
(*b*) High temperature glazes employing no fritts.

By the term " fritt " is usually inferred a glassy compound formed by heating a mixture of glaze-forming substances up to a temperature where the mixture fuses. In other words, a fritt is a kind of glass used for the manufacture of glazes. Glass-forming substances used for the manufacture of fritts are, for instance, silica, lead compounds, boric acid (or its compounds), feldspar, lime, dolomite, magnesite, zinc-oxide, etc. A preliminary fritt-making process is necessary in all cases where water soluble salts are employed in order to transform them into non-water-soluble compounds for use in the composition of the glaze, which, as mentioned previously, is applied to the body in the form of a watery suspension. If water soluble salts were contained in a glaze mixture, they would be dissolved and would therefore not remain in the glaze but would be sucked into the body of the article. They have, therefore, to be transformed into non-water-soluble compounds before they come into contact with water. This is achieved by melting them together with silica or silica compounds.

Glazes which melt at temperatures above 1,250°C. do not as a rule need the admixture of fritts because they can be made of materials which are not water soluble. The glazes which are used in manufacture of technical porcelain are generally fired at a temperature of 1,250°C. and higher, according to the vitrification (maturing) temperature of the body. (As previously mentioned, porcelain glazes are applied to the unfired body and have therefore to fuse at the temperature to which the body is subjected during firing.)

Compared with the manufacture of glazes containing fritts, glazes which do not contain fritts are relatively simple to manufacture. This is the reason why porcelain manufacturers who use frittless glazes, as a rule manufacture their own glazes. If they need glazes that contain fritts they generally buy the ready made glaze from outside. Sometimes, however, they buy only the fritts and use them in the making of their glazes, adding the mill material (*i.e.* non-water-soluble compounds).

It has been previously mentioned that in exceptional cases low melting glazes are employed in porcelain manufacture where the glaze has to be applied to pre-fired articles and/or if the glazes contain certain stains which do not withstand higher temperatures.

High Temperature Glazes. First of all, the manufacture of the normal type of high temperature porcelain glaze (not containing fritts) will be described:

The raw materials are weighed, their moisture content being duly noted, and they are then fed into grinding cylinders of a type similar to those used in the grinding of non-plastic body materials but of smaller size. The necessary amount of water is added and then grinding is carried out for about 48–60 hours. The grinding time, of course, depends on the size to which the raw materials have already been ground by the supplier. In the grinding cylinders the glaze materials are not only thoroughly ground, but they are also thoroughly mixed. If the raw materials are supplied already ground to a very fine grain size, the grinding time is reduced accordingly; but for thorough mixing, apart from grinding, at least several hours' treatment in the grinding cylinder is necessary.

The question of grain size (which, in turn, means grinding time) is more important in the case of body raw materials than in the case of glazes, because when the glaze materials fuse the individual grains disappear gradually in the glassy mass formed by the melting of the individual particles. Nevertheless the grinding time of glazes has also to be carefully watched. The smaller the individual particles, or, in other words, the greater the surface area of the glaze materials, the more vividly will interaction take place between them. By fine grinding the melting point of the glaze is automatically slightly reduced and a smaller amount of fluxes is therefore needed when the grinding time is prolonged.

Over-grinding, however, must be avoided since it would result in loss of adhesion of the glaze to the body (during drying and firing), and in subsequent " crawling " or " rolling." By these terms the potters understand a certain behaviour of glaze in which the glaze crawls away from certain spots on the surface, leaving it unglazed after firing and piling up in other parts. An explanation of this peculiarity of over-ground glazes can be found if one realises that very finely ground glaze materials have a very great surface area and absorb much water in a similar way to very plastic materials. When the water absorbed by the glaze materials evaporates during drying the glaze coating has a tendency to shrink, and since it adheres to the body surface it is subjected to tensile stresses, with the result that cracks form. When later on—during the firing process—the glaze melts and the cohesion between glaze and body surface is thereby lowered, the tensile stress prevailing in the glaze causes contraction of the glaze and draws it away from certain parts of the surface.

The grinding cylinders for glaze-materials are usually arranged in the sliphouse near to the grinding cylinders for the body raw materials, as it is generally convenient to have the silos for the glaze materials near to the other silos. When the grinding and mixing process of the glaze raw materials is concluded, the watery glaze suspension (the glaze slip) is discharged and pumped or otherwise transported to the place where the glazing of the articles is carried out.

Coloured glazes are very often used in porcelain manufacture—especially dark brown glazes for high tension insulators. Coloured glazes are produced by adding stains to white glazes.

Many recipes for the manufacture of stains have been published. The reader who wishes to pursue this subject further is, for instance, referred to " Ceramic Industry," Chicago, January, 1942, in which a number of recipes for brown stains is given. These contain, as a rule, iron-oxide, chrome-oxide, boracic-acid, zinc-oxide, and calcined alumina, all of which may be fritted together.

The melting point of glazes is generally somewhat lowered by the addition of stains which act as fluxes. Since only very small quantities of stain are necessary the composition of the glaze need not, generally, be altered as a result of the introduction of stains.

Both white and coloured glaze slips have to pass magnetic separators which remove metallic iron particles which would otherwise form dark brown spots on the glaze surface.

Low Temperature Glazes. Low melting glazes are used for certain purposes in porcelain manufacture. If the fritts used for such glazes are to be manufactured in the porcelain works, special fritt ovens for melting the fritt material are necessary, if large quantities of fritt are required. If, however, only small quantities of fritt are necessary for the manufacture of a low temperature glaze, the fusing of the fritt may be carried out in saggers fired in the kiln at the same temperature as the porcelain. In this case, the saggers have to be lined with silica or sand in order to prevent the fritt from chemically attacking the saggers and fusing on to the walls of the saggers. Even when a very thick silica layer is provided on the inner surface of the sagger, it is not always possible to remove the fritt cake from the sagger without breaking the latter into pieces because fusing cannot be obviated entirely. Saggers used for melting fritt can, in certain cases, be used only once, and it is obvious that this is not a very economical proposition.

Instead of saggers, metal containers made of special alloys capable of withstanding the requisite firing temperature may be used, but generally speaking if the quantities required are too small to justify the use of a fritt oven, it is better for the porcelain manufacturer to buy the fritts he requires from firms specialising in this line.

G. MACHINERY FOR THE PREPARATION OF THE RAW MATERIALS AND BODIES

The unplastic raw materials are (as far as porcelain factories are concerned) as a rule supplied either broken into small pieces or ground to a certain mesh. Preliminary breaking of the unplastic body materials is, therefore, as a rule not necessary in porcelain works.

If, however, in the manufacture of porcelain bodies, fired broken porcelain pieces (pitchers) are used, preparatory treatment of the hard materials is required. Preparatory breaking of raw materials is also required in the case of sagger manufacture. Mechanical crushing can be carried out by various methods, which may differ greatly from each other. The crusher is, generally speaking, a device which crushes big pieces of rock or big lumps of clays into small pieces, but it is not its purpose to produce a powder of uniform small grain size. The crusher consists essentially of a slow-speed feed cylinder and a high-speed cutting roll rotating towards each other. For primary crushing of bulky clays preparatory to feeding into the blungers both rolls are, as a rule, plain cylinders. The cutting rolls for breaking hard stones, however, are provided with iron teeth. (Fig. 38).

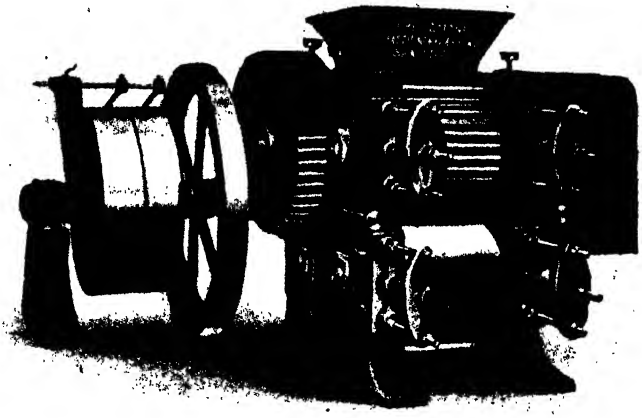


FIG. 38.—Crusher for breaking hard stones. (Reissmann.)

A device which is suitable for simultaneously crushing and grinding moderately sized unplastic materials is the edge roller, very often called a " pan and edge roller." This appliance is used in porcelain factories where materials like quartz or feldspatic rocks are supplied already broken into relatively small pieces. (Very big pieces should not be put on the roller but should previously be broken in a crusher.) (Fig. 38*a*.)

Edge rollers are supplied for capacities varying from half a ton per hour (each roller having a weight of about 350 lb., and the pan having a diameter of about 3 ft.) up to 24 tons per hour (each roller having a weight of 4,800 lb., and the pan a diameter of 10 ft.). In addition to being used for the crushing of flint, quartz, silica, feldspar and for the reduction of fritt used in glazes and enamels, they can also be used for crushing broken fired insulators (pitchers). The rollers are very often cut from granite, as metal ones may contaminate the materials. They are self-adjusting in many cases to compensate for the varying size of the materials being ground.

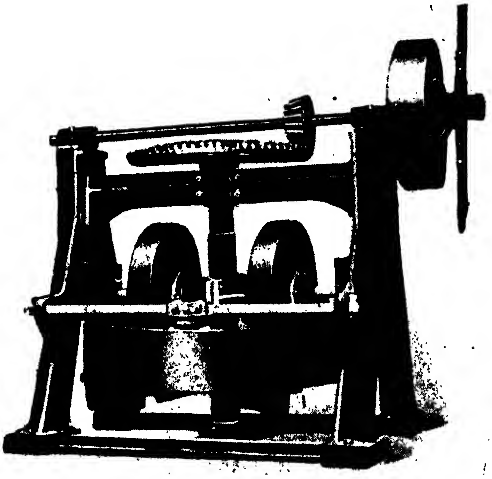


FIG. 38 (*a*).—Dry and wet pan for grinding moderately sized hard raw materials. (Patterson Machinery.)

Edge rollers do not usually grind to a uniform grain size because those particles of the materials to be ground which are under the rollers are more thoroughly disintegrated than those parts which are pushed aside by the rollers.

For producing uniform grain size "closed circuit" operation edge rollers can be used. In this design an elevator carries the crushed materials from the pan to a revolving or vibrating screen through which the particles having a small grain size fall, the bigger particles being automatically returned to the pan for regrinding.

The machines most widely used in porcelain factories for grinding unplastic raw materials are grinding cylinders, very often called " Alsing " cylinders (Fig. 39). They consist of an iron or steel drum the inside of which is lined with silica or with porcelain. The cylinders (after the silica or porcelain lining has been cemented in) are filled with pebbles or porcelain balls. These pebbles or porcelain balls act as grinders when the cylinder is set in motion. When the cylinders rotate the pebbles or porcelain balls are first lifted, together with the raw materials to be ground, and then drop, crushing and grinding the raw materials by impact. This type of grinding cylinder is also very often called a " pebble " or " ball " mill.

Grinding cylinders can be used for dry and wet grinding. The grinding media (*i.e.* the pebbles or balls, and the lining) lose a certain proportion of their weight during the grinding and small particles of the lining and of the balls get into the materials which are being ground. It is obvious that for porcelain body raw materials porcelain linings and porcelain balls are ideal, not only because the hardness of the porcelain is greater than that of natural flint (Fig. 40), but also because the particles of other grinding media would contaminate porcelain materials. In the case of flint linings, the raw materials will become richer in silica owing to the silica lost by the grinding media.

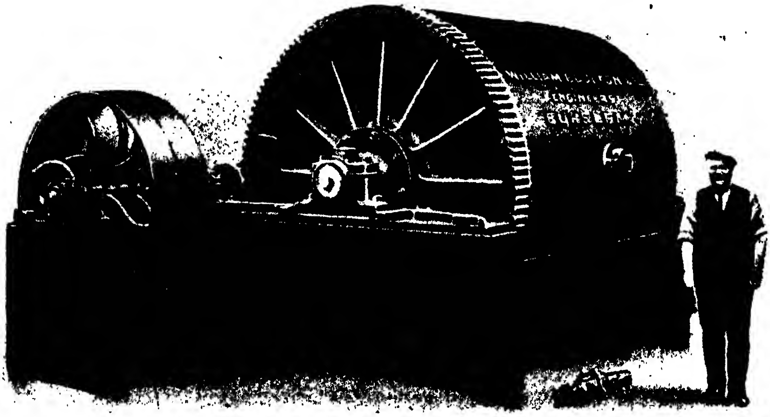


FIG. 39.—Boulton's (Burslem) grinding cylinder.

If steatite or steatite raw materials have to be ground in grinding cylinders, a lining of steatite and balls of steatite are most advisable (they possess extreme toughness).

After a suitable quantity of water and of the material to be ground is fed in, the grinding cylinder is closed and rotated until grinding and mixing are completed. As a rule one uses a weight of grinding pebbles approximately twice that of the raw materials.

The grinding cylinders should be equipped with a revolution counter since it is not the grinding time but the number of revolutions which control the fineness to which the material is ground.

Grinding cylinders are manufactured for a charge of from 1 cwt. (their external diameter and length both being about 2 ft.) up to charges of 40 cwt. (their external diameter and length being both about 7 ft.).

The grinding cylinders are supplied either belt or motor driven.

Fig. 40.—Porcelain grinding ball compared with a flint grinding ball. (Patterson Machinery.)

The most convenient drive is an individual motor for each cylinder, and in this case a stop button and a starting button make the operation very simple.

New designs provide a third button (Patterson Mill Drive) which moves the cylinder into the exact position for discharging and reloading. When the required number of revolutions has been ticked off by the revolution counter, the grinding cylinder is stopped by pressing the " stop " button. The pressing of the third button brings the cylinder into the exact discharging and reloading position.

For smaller quantities than 1 cwt., porcelain jar mills are most suitable. The design consists of a one-piece porcelain jar which may (for the purposes of protection) be enclosed in a steel shell. The corners inside the jar have to be well rounded for easy cleaning and the jar is, like the larger cylinders described above, suitable for either wet or dry grinding of the body and glaze raw materials. Such a jar mill is particularly useful in the laboratory for making small quantities of test bodies for experimental purposes.

Single jars are supplied in sizes from 9 in. diameter and 9 in. length (with a capacity of a few pounds of dry materials) up to diameters of 18 in. and 8 in. in length (having a capacity of about half a hundredweight of raw materials).

The jar is, of course, of cylindrical form, the top end being covered by a porcelain lid, the bottom end being sealed. To charge and empty the jar one has to remove it from the frame. It should, therefore, not be too heavy. For larger capacities than ½ cwt., a one-piece porcelain grinding cylinder having the feeding hole on the curved portion of the cylinder allows of filling and emptying without having to remove it from the supporting frame.

H. MIXING ARCS AND BLUNGERS

Whereas the mixing of the glaze materials (which contain as a rule very little plastic materials) is usually carried out in a grinding cylinder, the mixing of the body raw materials is carried out in mixing arcs or in blungers—if at least one of the ingredients is used in slip form.

The mixing arc (very often called an " agitator ") contains a vertical shaft on which two or more wooden or iron arms are fixed (Fig. 41 (*a*)). On these arms " gates " are suspended, the shaft and the attached arms rotating in a circular vat or tank made of iron or brickwork. The liquid is agitated by a rotary movement, the revolutions being slow, since the viscous liquid offers great resistance to the large surface of the wooden gates. If materials having similar specific gravities to each other are mixed in slip form, slow speed rotation is sufficient.

If, however, one of the raw materials has a higher specific gravity than the other, a slow motion of the stirring device would allow the heavier particles of the slip—such as non-calcined sand—to sink to the bottom. In order to prevent this, blades are used instead of gates on the rotating shaft (Fig. 41 (*b*)). The resistance offered by the liquid to the rotation of blades is considerably smaller than in the case of gates. The blades can, consequently, be rotated more quickly. Great speed in a gate stirring device could only be achieved by making the arms and gates extremely heavy and by using unnecessarily strong motors. The blades are arranged at such an angle that they lift the heavier particles from the bottom. It is advisable to fix at least two blades near to the bottom of the mixing tank so that the heavier particles are given no chance of settling. If the device is designed for blunging ball clays, blades are still used, but they are fixed higher up so that they can cut through the bulky clay lumps.

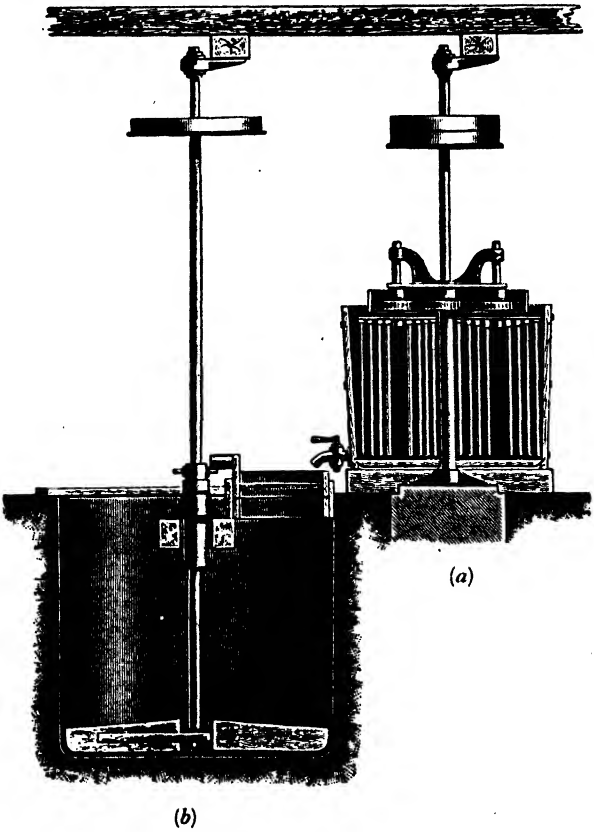


FIG. 41.—Blunger and mixing arc.

For blunging china clays both gate blungers and blade blungers can be used. The expressions " mixing arc " or " blungers " is used because the same machine can perform two functions.

For instance, after the ball and china clays have been blunged in the blunger, the flint and feldspar slips are run from the grinding cylinder into the same blunger where a thorough mixing of the slops is achieved or, alternatively, the ball and china clay blunged in the blunger at a higher level are run into the mixing arc at a lower level into which the flint and feldspar slips run, and where the mixing is carried out. The capacity of "mixing arcs" is from 36 to over 820 gallons slip and 180 lb. to over 2 tons of dry material.

The smallest units rotate with a speed of about 120 revolutions per minute—the greatest with a speed of about 40 revolutions per minute. To prevent "settling" of the heavier particles and to ensure an equal specific gravity of the slop at the bottom and at the top of the tank, a speed of about 80 revolutions or more is to be recommended.

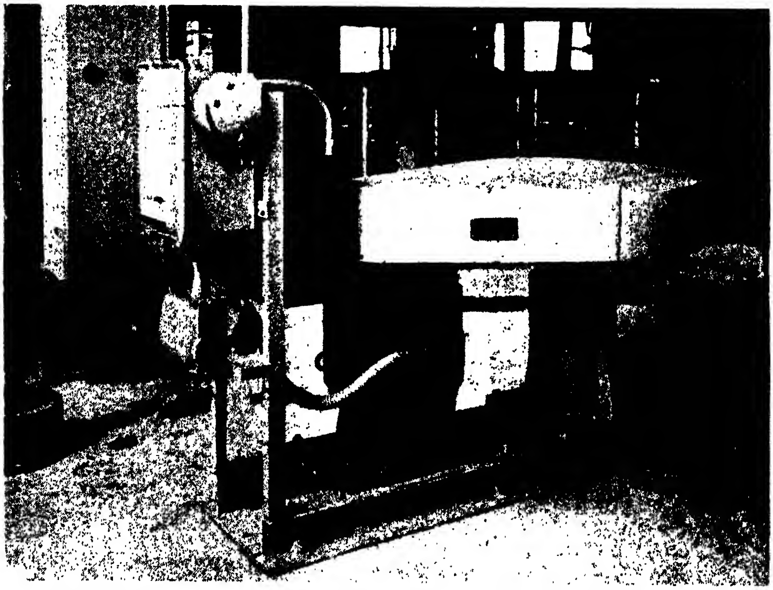


FIG. 42.—Slip mixer (propeller type). (Supplied by L. A. Mitchell for Messrs. Jos. Wedgewood.)

Consequently, medium-sized units should be used in cases where the raw materials have not the same specific gravity.

The most effective mixer is the "propeller" type stirrer which concentrates great energy in a small space (Fig. 42). The propeller rotates at a speed of 400–1,700 revolutions per minute according to the diameter of the propeller and the capacity of the tank. Smaller propellers allow higher speed. The propeller produces continuous circulation of the mixture, throwing it with considerable force against the bottom of the tank. In the case of certain ingredients having different specific gravities this type of mixer is particularly effective and produces a thorough mixing of the various materials in a very short time (i.e. it uses less power). It has the advantage that when the device has been stationary for some time and the particles have settled down and formed a sticky substance, they can be lifted very quickly when the powerful propeller is set in motion. With a blunger or mixer of the " gate " type there is always a danger that the gates may stick in the precipitation and be prevented by the viscous mass from moving. Propeller stirrers can be used both as mixers and as blungers, but for blunging lumps of plastic ball clays blungers with knife-like blades which cut the lumps and throw them upwards are preferable.

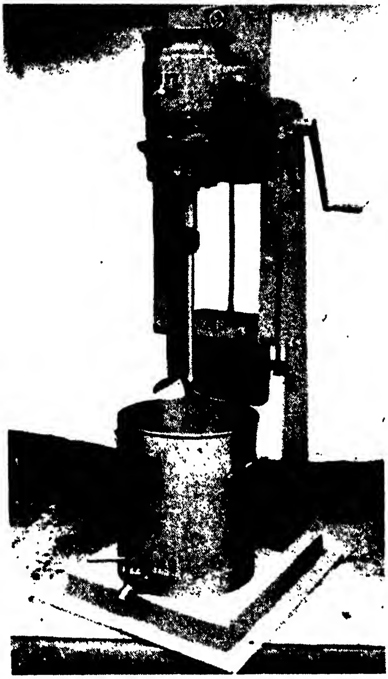


FIG. 42 (*a*).—Propeller mixer. (Apex Construction, Limited, London.)

I. DRY GRINDING AND MIXING

We have so far discussed the preparation of porcelain bodies in which at least one of the raw materials is used in slip form. In all these cases the mixing is carried out by liquid methods, although the preparatory grinding can be done, as we have seen, either by dry or by liquid method.

In both cases the weighing is, however, done by weighing dry raw-materials and the term " liquid method " should not lead to confusion with the compounding of bodies by measuring volume of liquid slips, described in the appropriate chapter. If, however, the body in question is not required in plastic state, but in dry state for pressing purposes only the preparation of the body can be carried out by dry methods without the addition and consequent removal of the water. The clays are first dried, then ground and sifted. The grinding is performed by machines similar to those described above. The same refers to the other materials.

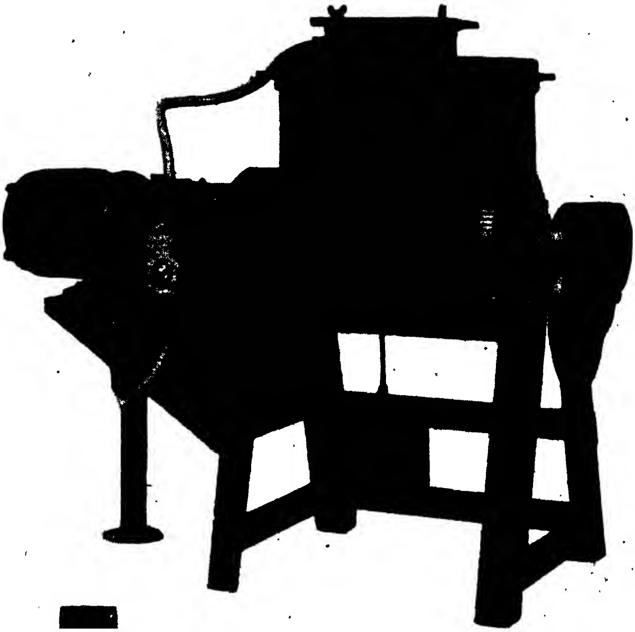


FIG. 43.—Granulating mixer built for incorporation of binders with ceramic materials. Supplied also jacketed for use with waxes as binder. (Apex Construction, Limited, London.)

Both wet grinding and dry grinding cylinders are available. Their designs are different in so far as their charging and discharging components are concerned. The discharge of the slip is performed through an outlet valve. Arrangements have, of course, to be made to retain the pebbles or balls in the mill, when the slip is being discharged. Clogging of the valve has to be prevented. During discharge an air vent must be kept open. The vent is conveniently placed diametrically opposite the outlet valve. Both vent and valve should be removable from outside in order to permit of cleaning and

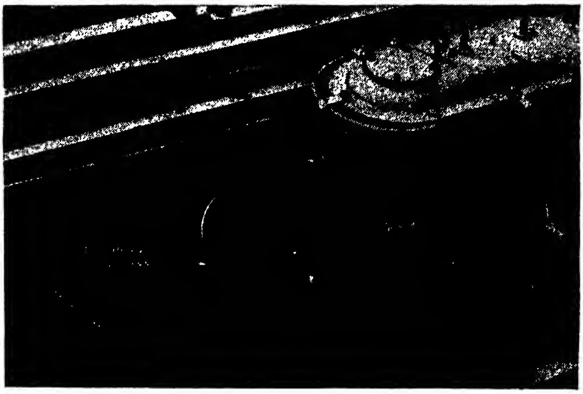


FIG. 44 (*a*).—" Cumflow " mixer for mixing dry and semi-dry materials (showing inside view). (The Liner Concrete Machinery Co., Newcastle-on-Tyne.)

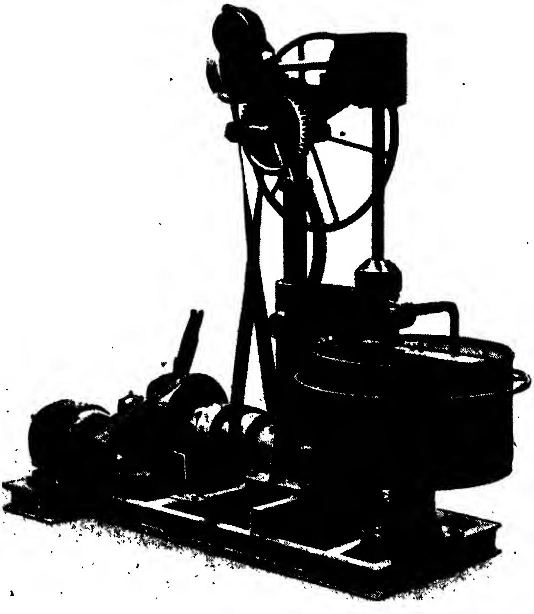


FIG. 44 (*b*).—" Cumflow " mixer (for mixing dry and semi-plastic materials, showing outside view). (The Liner Concrete Machinery Co., Newcastle-on-Tyne.)

repair. If the materials have, however, been ground in dry state, the discharge is carried out in the following way:

When the grinding is completed gates are put in the discharge hole to prevent the pebbles or balls from falling out of the cylinder. A dustless discharge housing (which should always surround mills for dry grinding) is closed, and the grinding cylinder slowly rotated for some minutes so that the ground raw materials can fall out of the discharge hole, whereas the pebbles are retained by the grating. The housing is designed in such a way that gears and bearings of the grinding cylinder are left outside the housing and thus protected against the abrasive effect of the dust. Special gaskets ensure a dust-tight seal between the mill and the housing.

As in the case of wet grinding, pebble mills are used not only to grind but also to mix the body or glaze raw materials in a very thorough way. If the clays or other plastic materials are not dry enough, they may stick to the balls when the cylinders rotate, thus preventing the balls from performing their grinding and mixing action.

For plastic raw materials which are not completely dry other designs of mills have been developed. For instance, mixing propellers are contained in cylinders, or arranged on pans and rotating in opposite directions, thereby achieving a very thorough mixing.

Housings are provided for preventing the dust from getting into the gear and the bearings, and also prevent it from contaminating the air (Figs. 43 and 44 (*a* and *b*)).

J. FILTER PRESSES

It has been mentioned that slips obtained by the liquid method of body preparation are too fluid for the immediate shaping of ceramic articles. A proportion of the water has to be removed from the slip. Water can be partially removed by the application of heat or by pouring the slip on to Plaster of Paris slabs or into Plaster of Paris vessels. The Plaster of Paris absorbs considerable quantities of water, and for experimental purposes, when only very small quantities of body materials have to be prepared, this method is still very handy. For bulk production, however, de-watering appliances have to be used.

The chief appliance for de-watering slip is the filter press (Fig. 45). This usually consists of a number of recessed plates (made of wood or iron) or unrecessed plates and frames (also made of wood or iron) forming a number of chambers. Both end faces of each chamber are covered by filter cloths, the cloths being pressed between the plates and the frames or between the edges of the recessed plates respectively.

The plates can be either round or square, each plate and each filter

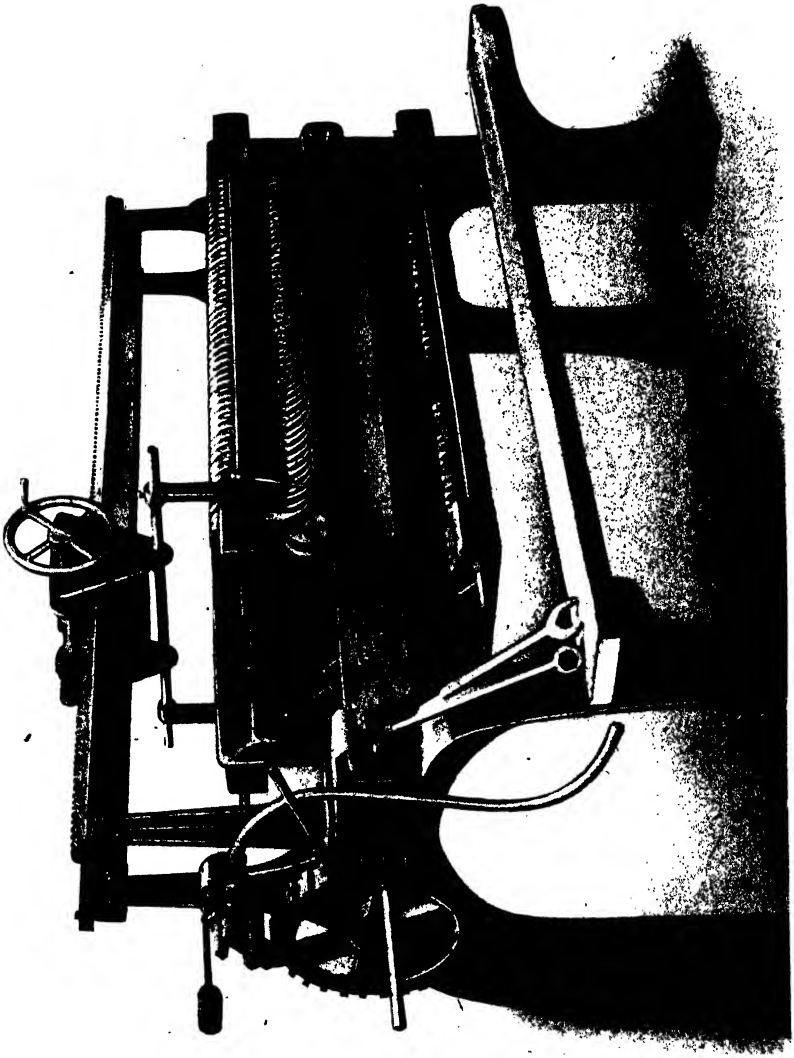


Fig. 45.—Boulton's Iron filter press. (William Boulton, Ltd., Burslem.)

cloth having a circular hole in the centre. The slip is pumped through this central aperture into the chamber. When the pressure in each chamber becomes sufficiently high the water of the slip is pressed through the cloths and runs out of the filter through recessed channels or grooves provided in the surface of each plate. Thus the solid parts of the slip remain behind and fill the individual chambers, forming plastic bodies called " filter cakes " which can be removed in readiness for the next operation. The excess water pressed out of the chamber through the filter cloths and grooves is collected in basins and can then be used again for other mixtures.

In order to allow the water to flow out of the chamber more readily additional holes may be provided on each side of each plate. Perforated zinc sheets are laid between filter cloths and plates ; these zinc sheets also often help in preventing excessive strain on the filter cloths.

The cakes have an average thickness of 1¼–1½ in. If recessed plates are employed, the thickness of the cakes is governed by the depth of the recess. Plate and frame type filter presses permit (by using frames of different thicknesses) of the changing of the thickness of the cakes. The more plastic the clay the more difficult it is to produce thick cakes. The time taken to fill the filter press varies according to the quality of the body to be pressed. Bodies containing little ball clay and much coarse unplastic material can be pressed much more quickly than those containing much plastic clay and very finely ground particles.

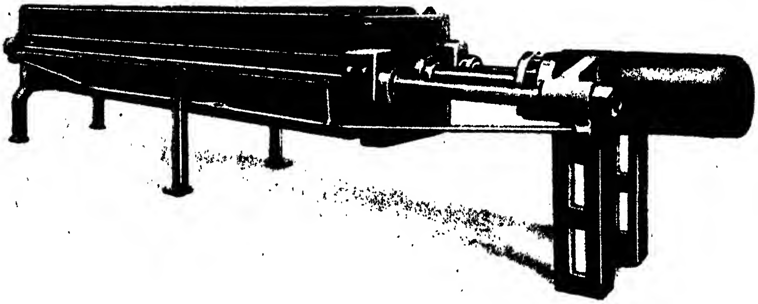


FIG. 46.—Patterson heavy duty filter press.
(The Patterson Foundry and Machine Co., East Liverpool, Ohio.)

After filtering the body still contains about 20–30 per cent. water. Plastic bodies retain more water than those bodies which contain less plastic clays and coarse opening materials. Plastic clays and very finely ground materials absorb much water which is difficult to remove by pressure.

The diameter of the filter plates ranges from 16 in. for small presses up to 36 in. for large ones, and the capacity of plastic clay produced per pressing from 350 lb. to 2½ tons—the number of chambers varying from 20 to 70.

For laboratories much smaller filter presses are available. For instance, a 10-chamber press with a plate diameter of 10 in. can produce 30 lb. per chamber or a maximum of 300 lb. of body.

In the usual design of filter presses vertical frames are free to slide along horizontal rods. The plates are pressed against each other, forming water-tight joints by means of a horizontal ram applied against the centre of one of the end plates. The simple screw which originally propelled the ram is in modern designs superseded by electrically or hydraulically propelled devices which save considerable time and labour (Fig. 46).

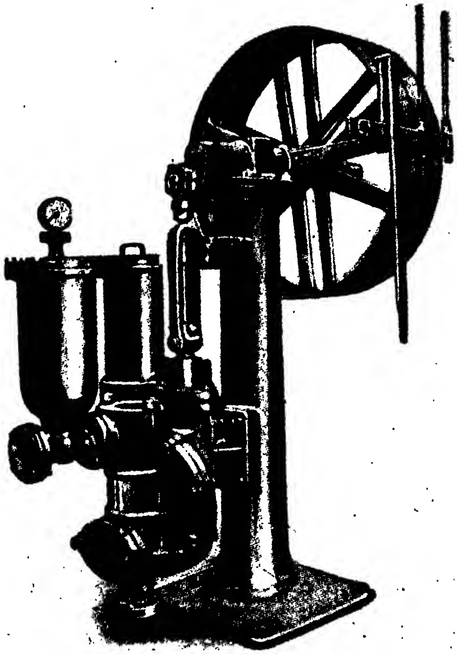


FIG. 47 (*a*).—Membrane filter press pump. German design.

The filter cloths must be washed from time to time. This can be done by allowing the water to circulate in the press or, better still, by removing the cloths and washing them in machines specially designed for this purpose.

A very good process for preventing rotting of filter cloths is treatment with copper ammonium oxide which dissolves some of the cellulose on the surface of the cotton, forming a chemical compound which (after drying) covers and protects all the cotton threads. This has another advantage in that the filter cakes are more easily removed from impregnated than from non-impregnated cloths.

In order to pump the slip into the filter presses various designs of pumps are employed. On the Continent membrane pumps are in general use. They are so named after the membrane which separates the plunger piston from the slip (Figs. 47 (*a*) and 47 (*b*)). The slip, as a rule, contains sharp-edged, hard particles which must not be allowed to enter between piston and cylinder. The membrane rises and falls at each stroke of the piston. As a result of the vacuum created by the movement of the membrane the slip is drawn through a ball valve when the membrane rises. When the membrane falls

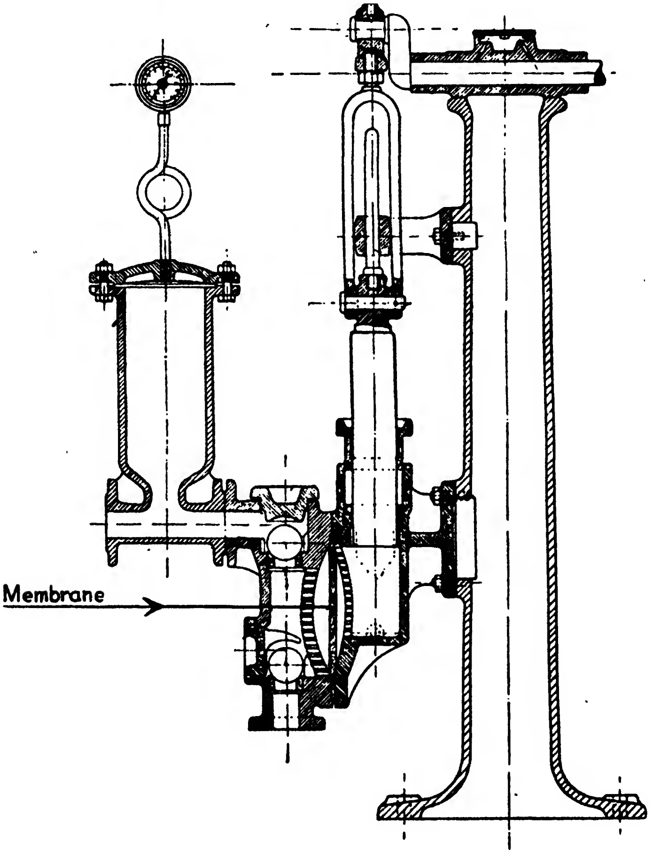


FIG. 47 (*b*).—Membrane filter press pump. Arrow points at the membrane.

the slip is pressed through another valve into the pipe connecting the pump with the filter press. The pumps have to be designed so that they pump into the presses an amount of slip corresponding to the amount of water pressed out through the filter cloths. The excess slip is discharged by a safety or escape valve. The general design is such that the safety valve is not used under normal production conditions. This means that the amount of slip pressed into the pump should be automatically regulated by devices which cause the pump to slow down and finally to stop when the maximum pressure is obtained (Fig. 48).

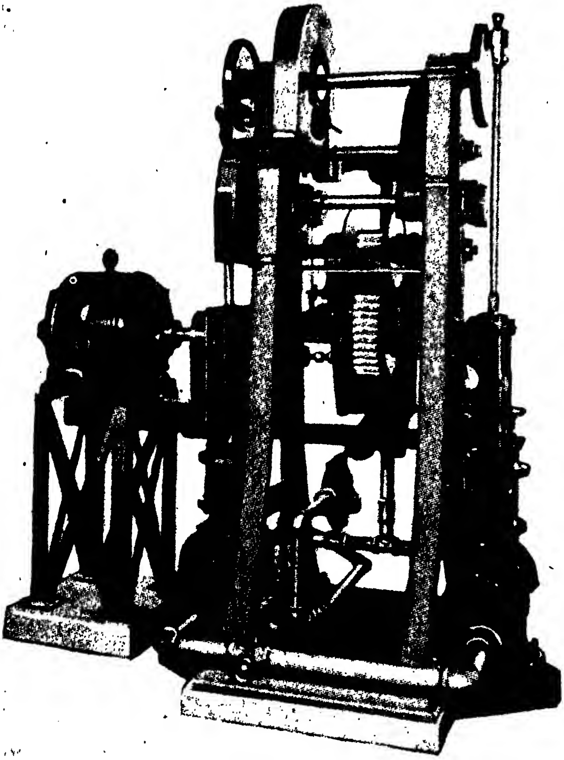


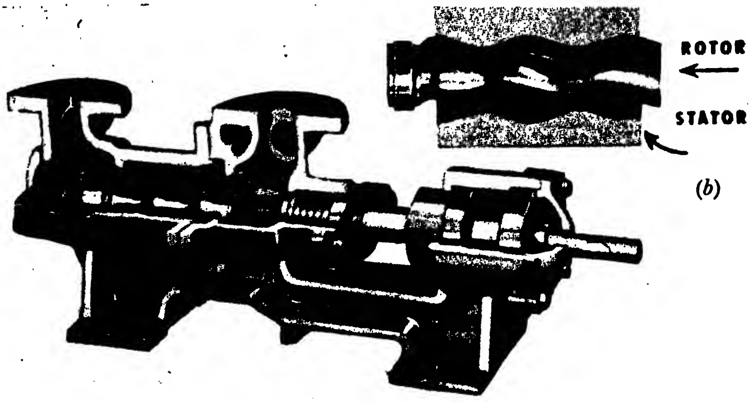
FIG. 48.—Patterson automatic variable speed filter press pump.

The Patterson Pump illustrated is provided with variable hydraulic speed control which retards automatically and gradually the number of strokes per minute in direct proportion to the pressure in the press chambers. As soon as the pressure is released due to further amounts of water passing through the filter cloths the higher pumping speed is again resumed.

Messrs. Boulton's manufacture a deadweight pump which gives similar results.

A pump radically different, *i.e.* without pulsation, is the Moyno pump (Figs. 49 (*a*) and (*b*)). A single-threaded helical rotor revolves within a double-threaded helical stator, " providing pumping action like that of a piston moving through a cylinder of infinite length."

During the last war and subsequent years, many experiments were carried out in Central Europe in an endeavour to replace the filter cloths by other filtering media. In course of time quite suitable filter plates of porous materials were developed. Porous ceramic materials were found unsuitable as the pores easily clogged and removal of the clay particles which clogged the pores was very difficult.



(*b*)

(*a*)

FIG. 49.—R. & M. Moyno pump. (Robbins and Myers Inc., Springfield, Ohio.)

The most suitable substitute for cloths was found to be a plate made of organic plastic material. Thermo-setting and thermo-plastic resins were mixed with fibres and other porous materials. This mixture leaves a predetermined amount of pores after the hardening of the thermo-plastic or thermo-setting material has taken place.

As an alternative to using a pressure filter presser the water can be removed from the slip by means of vacuum chambers or vacuum cylinders. Very efficient designs using the vacuum principle have been developed within recent years.

K. TREATMENT OF THE BODY TO MAKE IT COMPACT AND UNIFORM

The filter press cakes taken from the press are not homogeneous enough and must be pugged in a pugmill in order to obtain an absolutely homogeneous body structure.

In the pugmill the body is kneaded into a uniform mass. There are vertical and horizontal (Fig. 50) pugmills in use. They consist of iron cylinders in the centre of which rotates a shaft carrying knives. The knives are arranged in a spiral line, or in several spiral lines, so as to cut the body and to transport it towards the outlet. The end of the shaft has, in most cases, the form of a helix in order to increase the pressure near the outlet.

The plastic body, particularly in the case of horizontal pugmills, tends to stick to the knives and to rotate with them and is thus prevented from being moved towards the mouthpiece of the pugmill. In order to prevent this, counter knives are fixed on the cylinder which cut the body and remove it from the rotating knives to which, owing to its great plasticity, it may have stuck. Thus, in the pugmill the body is first cut by rotating knives and then by fixed counter knives. Due to the helical shape of the blades the body is pushed forward, cut again and pressed again, and finally pushed under pressure through the outlet mouthpiece. This has a considerably smaller diameter than the main mill barrel which itself is very often tapered in order to gradually increase the pressure exercised on the body. Thus, owing to considerable pressure, a homogeneous column of clay almost (if not entirely) free from pores and laminations is finally extruded.

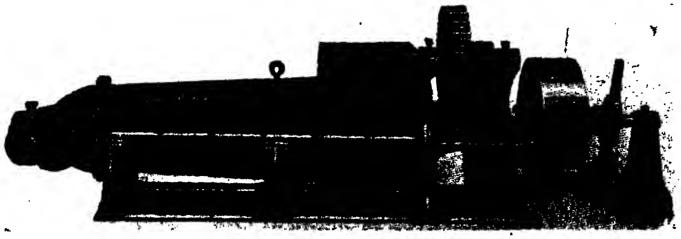


FIG. 50.—Patterson horizontal pugmill. (Patterson Machinery.)

Insulator bodies have to have an extremely homogeneous structure and must be 100 per cent. free from included airpockets, pores, laminations, etc. This is especially important in the case of high-tension insulators because even the smallest airpockets in a fired high tension insulator would form a weak point, reducing both the electrical and mechanical breakdown strength.

The treatment of the body in pugmills as described above is not sufficient because there are air bubbles and laminæ still remaining in the mixture. The body has to be homogenized more thoroughly. In former times the body, after having been treated in the pugmill, was "wedged" or "slapped." Wedging and slapping consists of cutting the body into pieces with a copper wire, throwing these pieces with great force against each other, and finally beating them with a wooden appliance similar to a long-handled hammer having a large flat face at the end. This instrument is called a "maul." This process has to be repeated until all the bubbles have been removed. It requires great skill on the part of the operator otherwise bubbles and laminations will be created instead of being removed.

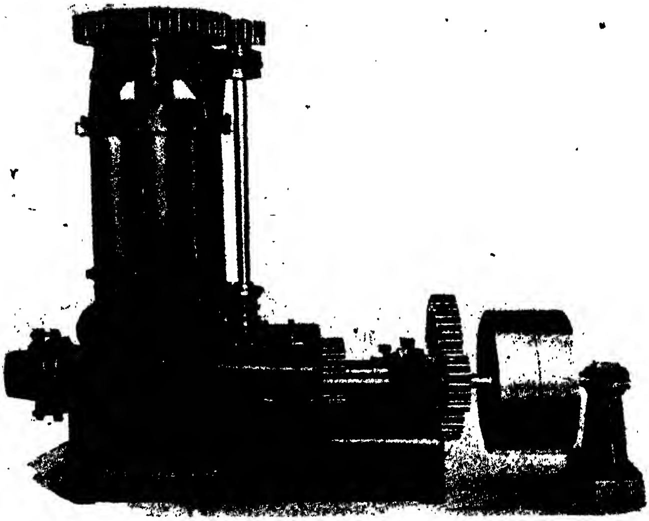


FIG. 51.—Patterson de-airing pugmill. (Patterson Machinery.)

In insulator factories on the Continent this laborious work has been replaced by tampering and kneading appliances similar to the large edge roller described previously—vertical and horizontal rollers pressing the body alternatively from both the top and sides.

In the U.S. and in England these appliances have never been used to any great extent for homogenising insulator bodies; de-airing pugmills are used instead. This latter device has, within recent years, been adopted on the Continent as well and has almost completely superseded the edge roller as far as the treatment of plastic bodies is concerned.

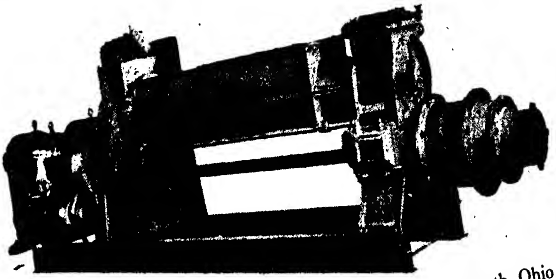


FIG. 52.—De-airing pugmill. (Fate-Root-Heath Co., Plymouth, Ohio.)

Various systems of de-airing pugmills have been developed, each having special advantages, and it is very often difficult to predict which special system is the most suitable for the case in hand.

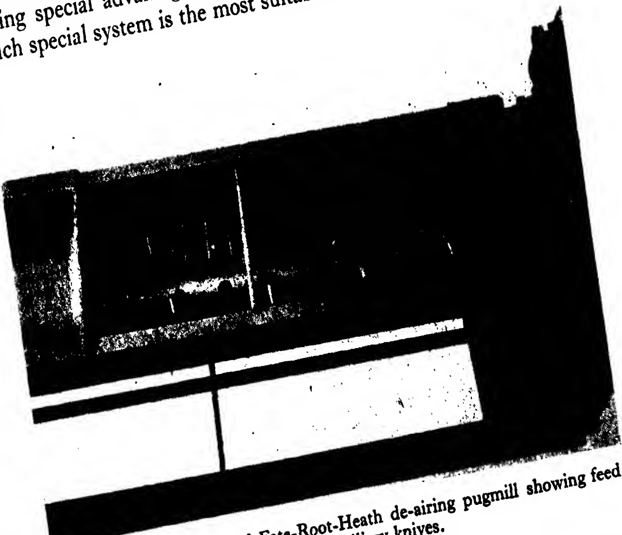


FIG. 53.—Inside view of Fate-Root-Heath de-airing pugmill showing feed knives and auxiliary knives.

Patterson de-airing pugmills are designed on the following principle (Fig. 51):

The clay, after being pugged, is not finely shredded (as is the case with most de-airing machines) but is pugged through comparatively large orifices into the vacuum chamber, where the air is partially removed, the clay passing on into a secondary pugging chamber which is a horizontal barrel, the de-airing continuing throughout the secondary pugging operation until the clay is finally extruded through the nozzle of the mill.

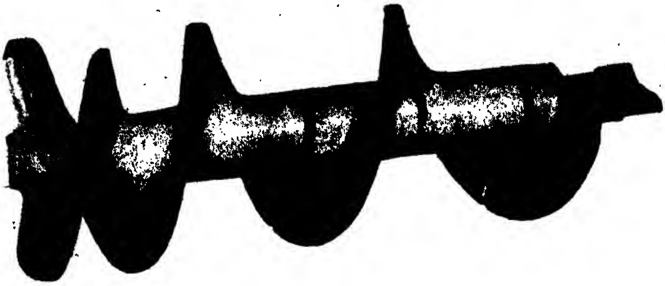


FIG. 54.—Auger mechanism of Fate-Rooth-Heath de-airing pugmill.

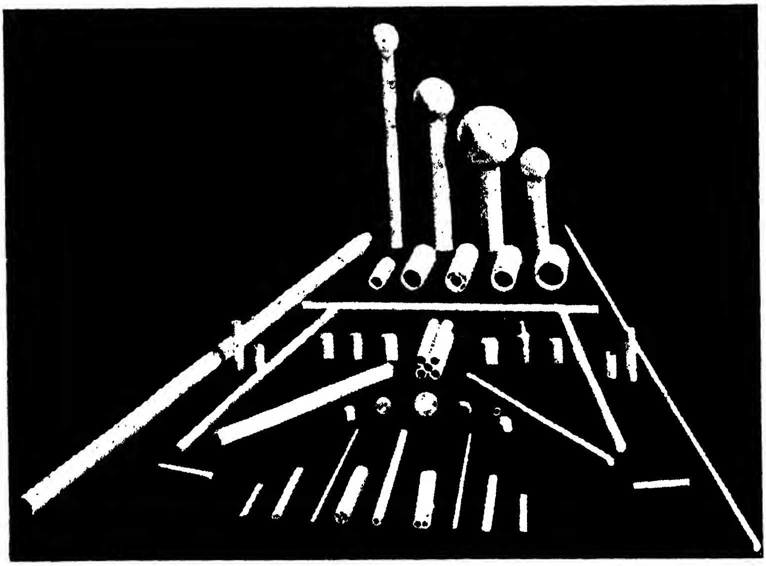


FIG. 55.—Articles extruded by Fate-Root-Heath de-airing pugmill.

The Fate-Root-Heath Co. (Fig. 52) device works on the following principle :

Two parallel shafts carrying the pug knives revolve towards each other, pugging the clay in a very thorough way. The feeder blades on the pug shafts meet and interwork with the auger shaft, making a forced feed and preventing clogging of the clay. At the front end of the machine is a closed compartment—the vacuum chamber. The two pug shafts force the clay into this vacuum chamber through two circular dies. The clay, as it enters the vacuum chamber, is broken up by means of multiple blade knives mounted on the shafts inside the chamber. The vacuum compartment is often illuminated and glass plates are so located that the interior of the vacuum chamber is clearly visible (Figs. 53, 54, 55).

L. SHAPING METHODS

By the expression " shaping methods " is of course meant all those operations applied to a ceramic body in order to give it the requisite final shape.

The body may be in plastic state in the form of a paste ; in fluid state in the form of a slip, in dry or semi-dry state in the form of a powder.

Four shaping methods may be applied to the body which is in a plastic state :

Throwing.
Jollying or jiggering.
Turning.
Extruding.

(*a*) **Throwing.** The throwing process which, in technical porcelain manufacture, is used mainly to serve the purpose of producing a very homogeneous cylindrical or conically-shaped lump of plastic body intended for further working, has been largely substituted by the extruding process which is performed by means of the de-airing pugmill. In the case of decorative china and earthenware, the throwing process has been and still is used to shape vases of complicated shape, decanters, covers and hollow articles of circular cross-section in general.

The thrower takes a lump of plastic body and places it on a throwing wheel. After having set the wheel in motion, he presses horizontally on the lump, both hands forcing it up and down—repeating this process several times. This operation, the purpose of which is to make the lump absolutely homogeneous, requires very great skill and practice. In insulator manufacture the body thus prepared used to be pressed into Plaster of Paris moulds—for instance, in the manufacture of pin-type insulators, suspension insulators, etc.—the mould giving the article its outer shape, the inner surface being formed by jollying as described later.

With the advent of the de-airing pugmill this throwing process has become almost obsolete since the de-airing pugmill produces massive cylinders of equal or even better homogeneity than those obtained by throwing. The extruded massive cylinders formed by the de-airing pugmill are very often subsequently formed into obtuse cones and similar shapes preparatory to their being pressed in Plaster of Paris moulds by a similar throwing operation, with the exception that the forcing up and down of the plastic lump is no longer necessary (Fig. 55 (*a*)).

(By Courtesy of Distribution of Electricity.)

Fig. 55 (*a*).—Throwing.

(*b*) **Jollying or Jiggering.** This process is so called because a Plaster of Paris mould which determines the outer surface of the article is placed on a jolly. The jolly is an appliance which consists of a rotating shaft on the upper end of which a disc is fixed. The disc is designed so that it will take a Plaster of Paris mould, holding it securely and yet permitting its rapid removal when the jollying process has been completed.

The inner face of the article is prepared by an iron profile carried by the jigger (see Fig. 56). The jigger is an appliance which, dependent on the purpose in hand, has to be designed in various ways. If deep cavities or holes have to be made in the body previously pressed into the mould the jigger consists of a movable frame carrying pulleys. From this frame a steel rod, on the lower part of which a negative profile is fixed, can be moved downwards into the soft body (Fig. 57). If the inner hollow of the article has to be tapered, or has to have grooves in it, the tool or profile must be movable in a horizontal direction in addition to its vertical movement. For the manufacture of discs or disc-shaped articles into which grooves have to be made the jigger consists of an inclined arm and a balance weight mounted on a pivot (a similar arrangement is used in the manufacture of cups). The end of this inclined arm is designed in such a way that the profile can be fixed on it either rigidly or allowing for a sliding movement. The profiles are made either of steel or of wood provided with a sharp metal edge. They remove the excess body and give the remainder the desired shape (Fig. 57 (*a*)).

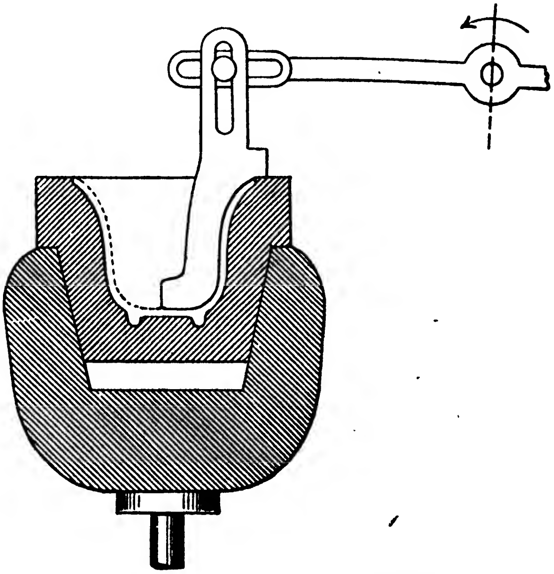


FIG. 56.—Jiggering hollow ware. (Bourry: *Treatise on Ceramic Industries.*)

It is important that the body should not be strained too much during the shaping. Excess body is, therefore, very often removed in easy stages in order to avoid shearing or torsional stresses which may detrimentally affect the homogeneity of the body. Two or three inclined jiggers may be arranged on the same framework for use one after the other.

For instance, the jollying may be assisted by removing part of the body at the place where, in later stages, the pinhole of a cap and pin type has to be jollied. Then another jigger may produce several

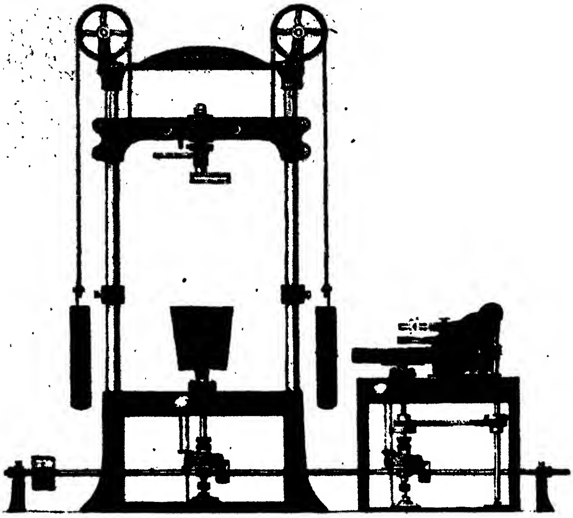


FIG. 57.—Vertical jolly for large hollow ware. (Boulton.)

(By Courtesy of Distribution of Electricity.)

FIG. 57 (*a*).—Jollying.

shallow grooves and a third jigger deepen the pre-formed shallow grooves.

Within recent years the jollying process has been substituted to a very great extent by hot pressing (described later) if the shape of the insulator lends itself to this manufacturing process and if considerable quantities are required. This applies, for instance, to many insulator types and other articles, if their height is not too great and if they do not possess axial holes passing through the insulator, as in the case of bushings.

High tension bushings for outdoor service as schematically illustrated in Fig. 58 are generally made by jollying, although sometimes for special reasons they are cast.

Bushings for very high voltages are of considerable size (details of the design and dimensions will be given in the Second Volume of this Book now in course of preparation).

Bushings for 287 kV. (now in general use in the United States) have a length of about 10 ft. and an outside diameter of 3 ft. 6 in. (Fig. 59). The manufacture of such great bushings, which after completion have to undergo very severe electrical tests, requires great skill and first-class manufacturing equipment. There are several methods of making them : One, for instance, consists in jollying the sections and joining (sticking) them together in the green state by means of slip. Whole bushings are thus built up. Other manufacturers fire the sections separately and join the sections by glazing them together in a second firing.

The most astonishing achievement, however, is the manufacture of such huge bushings in one piece. This may be done, for instance, in the following way :

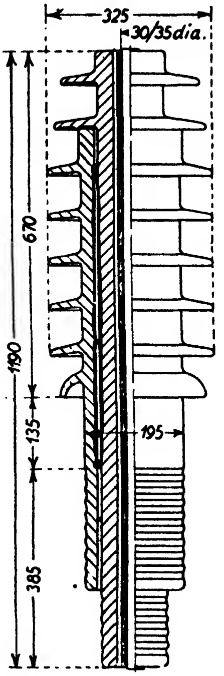


FIG. 58. — Outdoor bushing for 60 kV. all-porcelain-multitubular type. (Rosenthal Insulator Co.)

The clay, as it comes from the pugmill in the form of large cylinders, is thrown in large Plaster of Paris moulds. The diameter of these cylinders is, of course, smaller than the diameter of the mould since it is impossible to extrude with present equipment cylinders of, say, 3 ft. 6 in. diameter. These large pieces of clay are then pressed down either by a mechanically operated press or by beating with a maul. This method resembles somewhat that described previously as " wedging " or " slapping".

The process is continued until the whole of the Plaster of Paris mould is filled with a solid and homogeneous filling of plastic body. Then the mould, fixed on a rotating wheel, is set in motion and the tool, which is held on a vertical jigger, is moved and slowly pressed into the plastic body, forming a cylindrical hole. From time to time the tool has to be lifted and the excess body sticking to it has to be removed. The hole thus bored into the plastic body has a small diameter to begin with. The tool can, however, be moved not only vertically but also horizontally and the desired diameter can be produced by moving the tool gradually in a horizontal direction away from the centre of the bushing. Thus by jollying or jiggering a big cylinder with a cylindrical hole is shaped. The sheds provided on the outside of the bushing are turned later on. When the cylinder is dry enough it is lifted out of the mould by mechanical means. The sheds are produced by turning in the following manner: The bushing is placed on a rotating wheel and tools which are

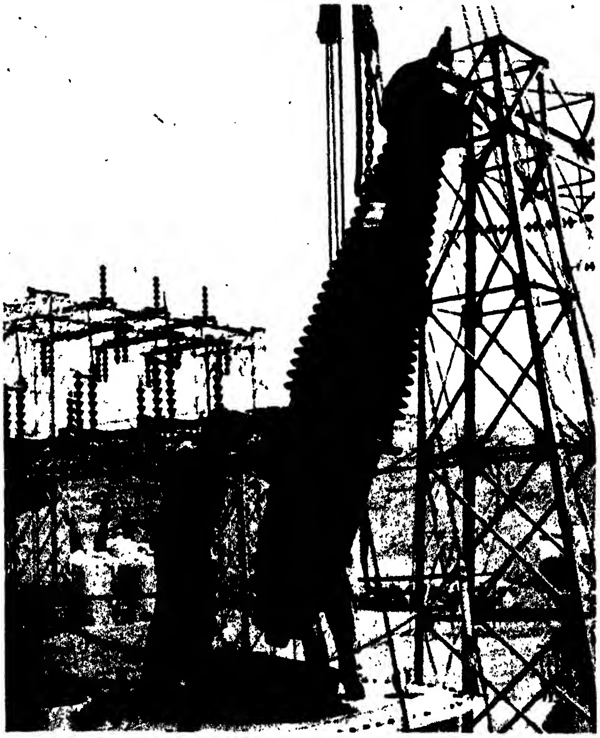
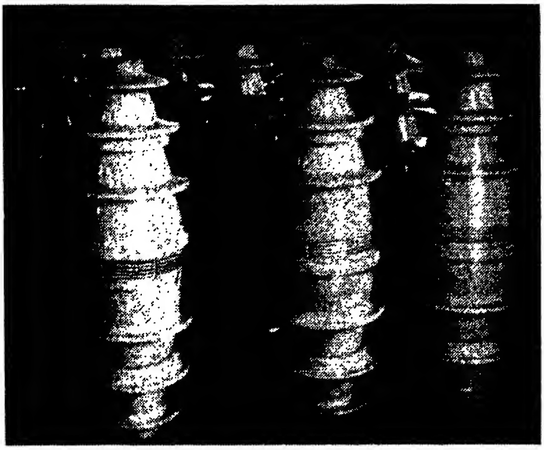
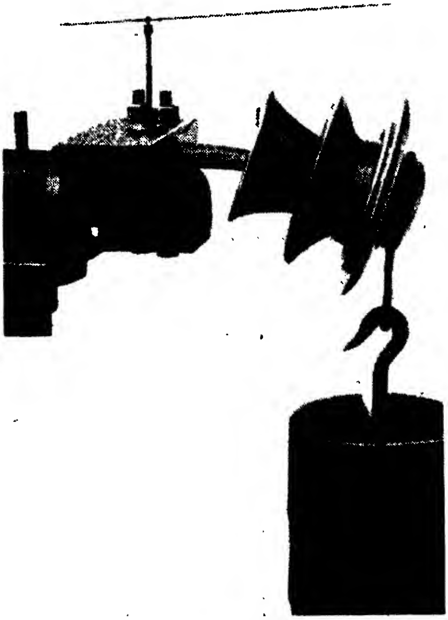


FIG. 59.—Porcelain Bushing; Type G.60 220 kV. (Manufactured by Ohio Brass Co.)



(By Courtesy of Messrs. Bullers.)

FIG. 60 (*a*).—Insulators for bushings. Such shapes are generally produced by jollying, several sections being assembled in moist condition by a suitable slip.



(By Courtesy of Messrs. Bullers.)

FIG. 60 (*b*).—Pin-type support insulator for transmission lines (manufactured by jollying) under 3,000 lb. bending load.

movable in a horizontal direction remove the excess body on the outside of the bushing, thus producing the projecting sheds.

The manufacture of large bushings in one piece, although a very difficult job, has the advantage that joining of individual sections is avoided. Joins very often form weak points electrically. It is a matter of opinion, however, which method is the best. Figs. 60 (*a*), (*b*), (*c*) (Bullers, Ltd.) illustrate insulator shaped by the jollying methods.

(*By Courtesy of Messrs. Bullers.*)

FIG. 60 (*c*).—" Hewlett " insulator string possessing high electro-mechanical characteristics. Suspension insulators are usually manufactured in the plastic state by jollying. Exceptionally, they are also produced by other processes, *e.g.* hot pressing or casting.

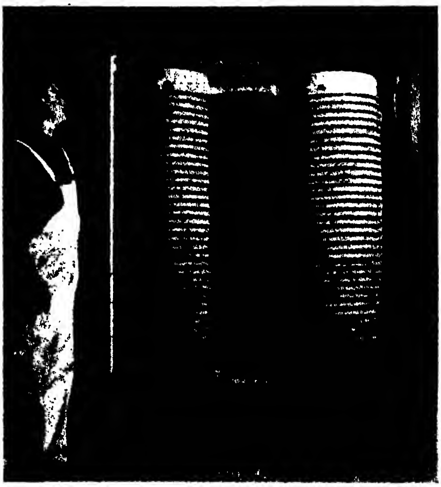


FIG. 61.—Made in one piece. This cylindrical form for a resonant choke coil, to be used on electric transmission lines, has an outside diameter of 17½ in. and a 46½-in. length—one of the largest onepiece wet-process porcelain parts made by extrusion and turning. The Derry, Pa., porcelain works of the Westinghouse Electric and Mfg. Co. is making it. Cut along the periphery of the form is a helical " screw thread " in which the wire coil is wound on the finished piece. In making it, a rough blank is re-extruded so as to remove the helical twist put in it by the first extrusion. A screw pug is not used. Differential shrinkage of clay, usually about 6 per cent. of large parts, has been reduced to 4 per cent. by this method. (*Ceramic Industry*, March, 1942).

(*c*) **Plastic Hot Pressing.** As already mentioned, a new method has been evolved within the last few years. This method consists in employing a lump of plastic body prepared in a de-airing pugmill and pressing it in a Plaster of Paris mould. This Plaster of Paris mould forms the outside of the article, the inner face of it being shaped by a rotating metal die pressed against the plastic body. This metal die or plunger is frequently heated either by means of a gas flame or electrically, and therefore this process is very often called " hot pressing." The plunger may be arranged for lowering towards the Plaster of Paris mould or the mould may be arranged for lifting towards the plunger. The body is first of all pugged and extruded by a de-airing pugmill in the form of a cylinder. A piece of body of suitable size is cut off, is put in the Plaster of Paris mould by hand and is beaten into the mould by a maul. The packing of the mould can be done alternatively by a mechanical press. Cylindrical holes can be made by a plunger as well as co-axial grooves. The ribs thus produced are of very regular size and thickness. For producing screws in the pinhole of pin-type insulators, a plunger revolves up and down in a forward and reverse direction, the mould remaining stationary. The plunger has to be provided with one or more valves for allowing the air and the excess body to escape. The pressing is very often carried out in several stages in order to avoid stressing of the plastic article and the setting up of unequal pressure on various parts of the body. For instance, a revolving plunger may be brought down on the plastic body forming part of a hole and part of the profile. A second plunger is then used for completing the hole and the final profile. It is, however, not easy to produce undercut holes or grooves by hot pressing. This is one of the reasons why this process has not so far been used extensively for the manufacture of insulators on the Continent. In the United States, where the hot pressing process was first developed, it is used extensively in the manufacture of cap-and-pin type insulators. In England this manufacturing method has also been adopted for many types of cap-and-pin type and other insulators.

In the design of cap-and-pin type insulators used in Central Europe, the pins of this type of insulator are not fixed in the pinhole by cement, but they are held in place by additional metal parts, such as iron balls, springs, etc., interposed between a steel pin and an undercut cavity provided in the pinhole of the porcelain insulator. In this case hot pressing of the article cannot be used. This is one of the reasons why hot pressing has not been used so far extensively in Central Europe. There is no doubt that hot pressing has, in many cases, great advantages. It allows much quicker production than the jollying process, saves labour and produces a very uniform porcelain body having accurate dimensions.

Automatic cup and plate making machines employing the hot

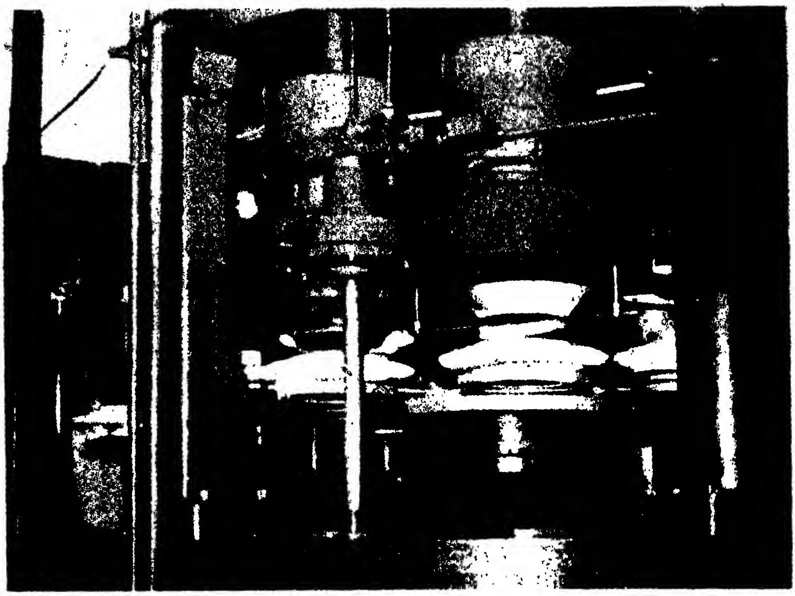


FIG. 62.—Automatic plate making machine. Hot pressing is used to shape one surface of the plate, the other is formed by a plaster mould. (*Ceramic Industry*, January, 1941.)

pressing method, replace very successfully the jollying process which has been used for making cups and plates for centuries (Fig. 62).

(*d*) **Turning.** Turning is carried out on lathes similar to those used for turning metal or wood. Before a ceramic article can be turned it must be dried to a hard state. In art pottery turning is used subsequent to jollying or casting. For instance, grooves or undercut profiles have frequently to be turned in cups, pots, vases, etc., which are produced either by jollying or casting. Similarly, in insulator manufacture the turning process was first employed for producing grooves on cylindrical tubes and bushings (Fig. 62 (*a*)). The tool for such used to consist of a small plate of steel fixed on a handle. Callipers and compasses were used for measuring the diameter and the thickness of the article being made. Very soon these tools were no longer operated by hand in insulator manufacture, but were moved mechanically along a profile. Nowadays almost all technical porcelain articles having a cylindrical bore are made by turning. Automatic turning is employed in all cases where the number of insulators to be made justifies the employment of a profile along which the tool runs.

In the case of medium and large articles the body is turned in semi-hard " green " state. Small articles are turned after careful drying in a hard (" white ") state, when all the water of formation is evaporated. Bushings having a length of more than 25 in. and an outer diameter of more than 10 in. may, for this purpose, be called large insulators. Turning in white state causes the formation of dust which has to be sucked away. White turning permits faster work than green turning and produces very accurate dimensions. The iron or steel tool can be replaced by a carborundum wheel if the body to be worked is sufficiently hard and dry. In the case of short bushings—for instance, in the manufacture of spark plug insulators—a carborundum tool may have the same length as the insulator it has to shape, and the negative profile of the insulator in hand. It operates in the opposite direction to that in which the insulator is

(By Courtesy of Distribution of Electricity.)

FIG. 62 (*a*).—Turning.

rotating. This method enables production of very great quantities at considerable speed, if the porcelain blanks (cylinders) have the necessary mechanical strength and hardness.

Cylinders are pre-formed in the de-airing pugmill by extrusion or in metal dies by vacuum pressing. The turning process plays an important part in the manufacture of ceramic parts with circular cross-section, such as solid core insulators (Fig. 63 (*a*)), " Motor " type suspension insulators (Fig. 63 (*b*)) and Langstab insulators (Fig. 5 (*a*)). These insulators will be dealt with in detail in the second volume of this work.

To give a very rough idea as to how such types of articles are produced, the following may be of interest :

In the case of " Motor " and other solid ceramic insulators the main body is produced by de-airing pugmills, the extruded cylinder so produced being pressed into Plaster of Paris moulds. The sheds are then produced by turning out the excess body between adjacent sheds. Sheds, however, which have a larger diameter than the main cylinder are formed by joining them to a projecting shoulder by the sticking method. A slip is used as a sticking medium, during the firing a seamless join is then formed by this method.

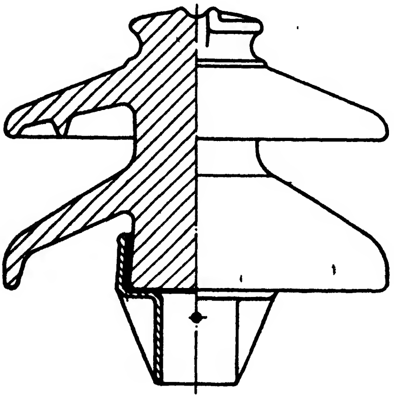


FIG. 63 (*a*).—Solid core insulator.

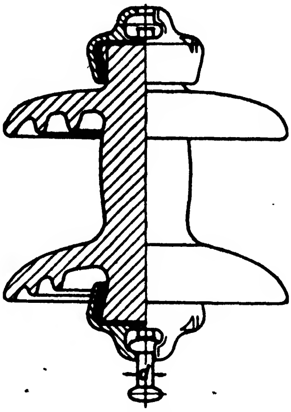


FIG. 63 (*b*).—Motor-insulator.

(*e*) **Extrusion.** The extrusion process is employed for making articles of cylindrical cross-section and considerable lengths, such as rods and tubes. Tubes and rods produced in this way may, of course, later on be cut into thin slices. Discs of intricate outer shape very often containing many holes may be formed by this method. The appliance now in general use for extrusion is the de-airing pugmill. As explained in the chapter dealing with the preparation of the body, the pugmill is at the same time used as a shaping device.

For the manufacture of tubes and rods of small diameters very small pugmills have been designed. The shape of the article to be extruded is formed by the shape of the mouthpiece or die. When the article to be pressed is hollow, a special piece, sometimes called a "bell," is provided to form the hollow. It is shaped like the hollow to be formed, and is held in position by a bridge. The bridge has to be arranged far enough behind the aperture of the die to allow the body to be rejoined again between the bridge and the mouthpiece, under the influence of the pressure exercised by the propellor and the screw of the plunger (Fig. 64).

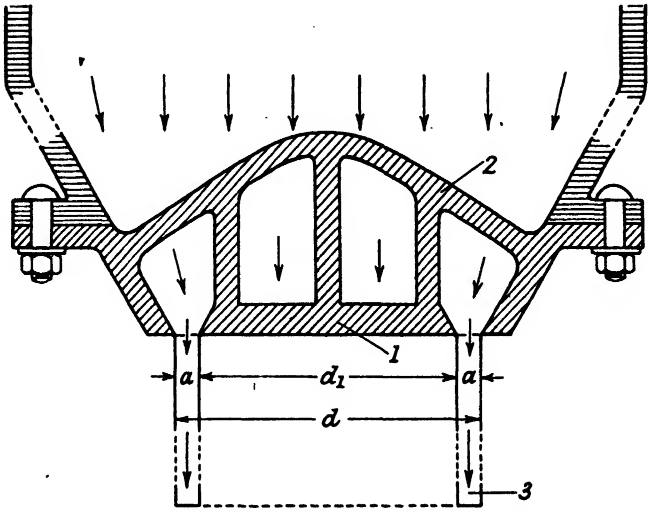


FIG. 64.—Mouthpiece of pugmill. Die for extruding tube; d=outer diameter, d_1 inner diameter. 1. Bell. 2. Bridge. 3. Tube. (Plastic Body.)

Modern pugmills are devised in such a way that the pressure is very evenly spread over the entire cross-section of the article to be extruded. In former times, when the design of the de-airing pugmill was not so advanced as it is to-day, the tubes and rods became bent under the unequal pressure distribution during extrusion. Unequal density of the body caused by unequal pressure distribution results in unequal shrinkage and consequent bending. To manufacture absolutely straight tubes vertical presses were originally designed. The press had a cylindrical box at the lower end of which a mouthpiece was affixed and from the upper end of which a piston or plunger pressed the body through the mouthpiece. The piston may be propelled either by a vertical mechanism or some hydraulic device. When the piston has reached the end of the cylindrical box it is drawn back again and body again filled into the cylinder. In contra-distinction to the de-airing pugmill, this press has to be filled after each stroke or operation, whereas, of course, the pugmill is continuously filling on one side and discharging on the other.

N.B.—It has already been mentioned that extrusion is very often a preliminary stage and that the extruded article may be finished by a cutting device, by turning or by jollying.

(*f*) **Pressing in Steel Dies.** This method is generally used when large or small quantities of either simple or complicated articles such as, for instance, low tension insulators are to be manufactured. It is not suitable for high voltage insulators which require great di-electric breakdown strength. Although the structure produced by pressing is homogeneous enough for low voltage insulators, the di-electric breakdown strength is considerably lower than the breakdown strength of articles produced by jollying, extruding or casting. This is due to the introduction of minute pores and air pockets during the pressing process. This remark does not apply to hot pressing described in the previous paragraph, which is used for the manufacture of high tension insulators to a very great extent nowadays. Apart from hot pressing, there are three other pressing methods : wet pressing, semi-drying, and dry pressing.

Wet (or plastic) pressing is carried out by placing the plastic body on the lower part of the metal die and by pressing (by a suitable device) the upper part of the die on the plastic body. The surface of the metal die is moistened with a thin layer of oil or paraffin to prevent sticking of the body to the metal. The excess body is allowed to flow out of the cavity of the die by suitably arranged valves. Whereas dry and semi-dry pressing methods allow the production of complicated shapes, pressing of plastic bodies is suitable only for relatively simple shapes. Nameplates, handles, buttons, and similar simple designs are produced by pressing the plastic body in steel dies as described above. For complicated parts, the plastic body is too sticky and would not flow into narrow holes and sharp edges in the die.

For semi-dry pressing (usually not quite correctly called " wet-pressing ") the dry body is thoroughly disintegrated into a dry powder which is then mixed with small quantities of water (10–15 per cent.) ; oil (0·5–1 per cent.) ; and paraffin (2·5–5 per cent.). (This operation may be carried out in a machine as illustrated (Fig. 43.)) The powder thus prepared is poured generously into the die and is pressed by lowering the plunger of the press, as a result of which the plastic powder flows into all the cavities of the die. After pressing, the piece is removed from the die by lifting the ejector (Fig. 65 (*a*)). The pressed piece has sufficient mechanical strength to withstand deformation when it is transferred to the driers, during the dipping operation, and when the seams (left after pressing) are cleaned off. Two articles produced by semi-wet pressing are shown in Fig. 66.

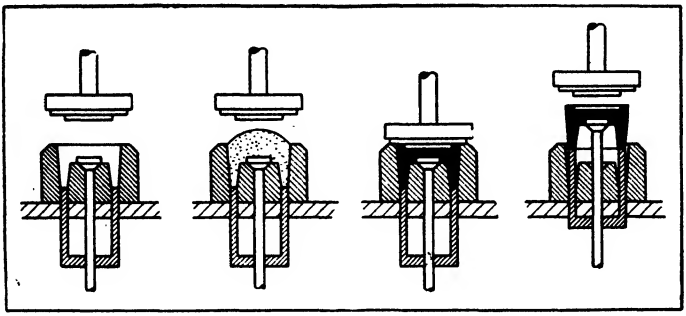


FIG. 65 (*a*).—Stages in the process of semi-wet pressing. (*Electrical Review.*)

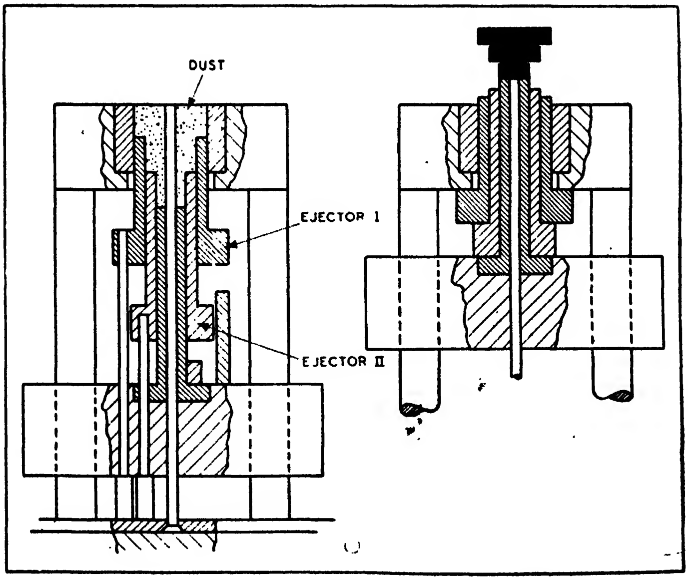


FIG. 65 (*b*).—A more complicated mould is required for dust pressing. (*Electrical Review.*)

For the manufacture of steatite and other talcum containing bodies dust pressing is used to a great extent. In this process finely divided and easily flowing granulated material is densified under high pressure and fills all the cavities of the mould. The advantages of this method are the reduction of drying shrinkage with resulting reduction of tolerances. This process is, however, only used when great quantities are required since the moulds for dust pressing are more complicated and expensive than those for wet pressing (Fig. 65 (*b*)).

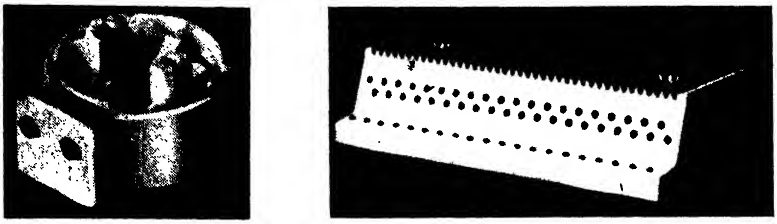


FIG. 66.—Switch base and telephone selector base produced by pressing. (*Electrical Review.*)

FIG. 67 (*a*).—Different types of presses for pressing insulators. (William Boulton, Burslem, Staffs.)

Various types of presses are in use according to the size of the article to be produced, and according to the pressure required.

Fig. 67 (*a*) shows different types of presses as produced by Messrs. Boulton. The big press in the foreground is a power driven press which is designed for pressing large porcelain articles, but it can also be used for pressing saggers of large and medium size. In the background are columns of Screw Presses for pressing articles of medium size. Fig. 67 (*b*) illustrates a Toggle Press for dry pressing when high pressures are required. This type of press is produced in the United States by Crossley Machine Company, Trenton, New Jersey. Similar types are produced in England by Apex Construction, Ltd. Fig. 67 (*c*) illustrates Automatic Press produced by F. J. Stokes Machine Co., Philadelphia. This press is designed for pressing pieces up to 5¼ in. in diameter and has a die fill of up to 2¾ in. It is arranged to compress from both top and bottom and for production of 20–60 pieces per minute with variable speed drive.

As in the case of the other shaping processes, the shrinkage is not uniform throughout the whole article. The shrinkage varies with the direction of the pressure employed during the pressing process and with the degree of pressure; the higher the pressure the greater the shrinkage.

Fig. 67 (*b*).—Toggle Press. (Crossley, Trenton—New Jersey and Apex Construction, Ltd., London.)

Very often electrical designers base their designs for ceramic insulating parts on the manufacturing methods adopted for other materials (for instance, " thermosetting plastic materials ") with which they are more familiar, but these may not be the best in the circumstances. Although it is in any case generally necessary for the designer of a porcelain component to collaborate with the insulator manufacturer, it is useful if the designer is familiar with the more obvious points which are peculiar to ceramic manufacture. In this connection a few notes may be helpful to indicate how cheaper dies can be employed and manufacturing losses can be reduced by avoiding certain pitfalls.

It is difficult to ensure that strips of considerable lengths are perfectly flat. The effect of any deviation can usually be overcome without grinding the whole surface by providing bosses about 0·2 in. high, the faces of which can easily be ground dead true (Fig. 68/1). Narrow fins and sharp junctions with the main body result in drying cracks and heavy manufacturing losses: sturdy fins and joints to the main body with generous radii and slightly sloping sides represent the right design (Fig. 68/2).

Closed square slots for registering bolt heads, etc., should not be placed close to the periphery of the article because the thin wall of porcelain is a source of weakness: rectangular slots which obviate the need for thin side walls are just as effective (Fig. 68/3). Where screws, bolts or plugs are fitted through plain holes in an insulator, an elongation of these holes will compensate for variations and shrinkage of the ceramic materials (Fig. 68/4). Unfired porcelain and low loss materials are abrasive even to specially treated threading tools. Thus a true V-thread cannot be maintained in mass production, and it is therefore better if the thread is slightly rounded (Fig. 68/5). The same considerations apply to other thread shapes. Length tolerances influence the accuracy of the thread pitch and allowance for variations in thread depths and widths must be made. It is, for instance, desirable to know the size of the wire which is to

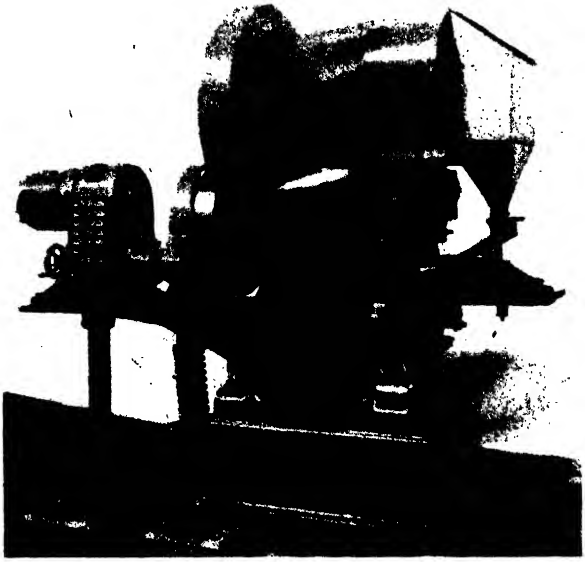


Fig. 67 (*c*).—Automatic press designed for compressing ceramics. (F. J. Stokes Machine Co., Philadelphia.)

be wound into the thread of ceramic resistance formers. External shapes should be as symmetrical as possible and round sections are preferable to multi-cornered sections.

Where markings are required on porcelain it is simpler and cheaper to provide, for example, an arrow in relief on the top surface of a disc as a direction indicator instead of using a projecting arrow.

Sharp edges and parallel perpendicular high walls are difficult to manufacture and to eject from the dies (Fig. 68/6). The glaze will

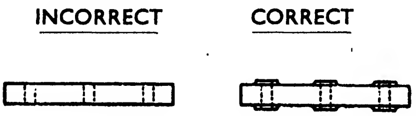


FIG. 68/1.

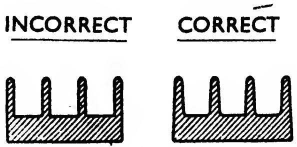


FIG. 68/2.

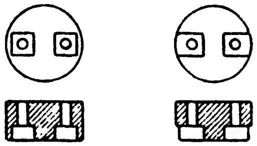


FIG. 68/3.

FIG. 68/4.

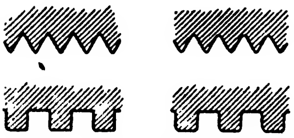


FIG. 68/5.

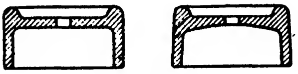


FIG. 68/6.

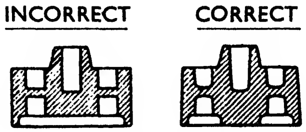


FIG. 68/7.

tend to run off sharp edges which are then left exposed : it is better to provide smooth edges and to taper the side walls. Another example : a porcelain disc of flat and uniform section throughout would sag during firing. An arched section with the minimum thickness in the centre should be employed as shown (Fig. 68/6). In the illustrations of an incorrect design of a much more complicated nature, the flat bottomed holes are of cylindrical shape and have no central support for the main body. The correct design (also shown) would employ conical holes curved at the bottom and a central support for the body. The curved section of the bottom of the holes obviates sharp corners which would lead to cracks. The conical holes allow easy ejection and the bottom centre boss is provided to prevent the sagging of the main body (Fig. 68/7).

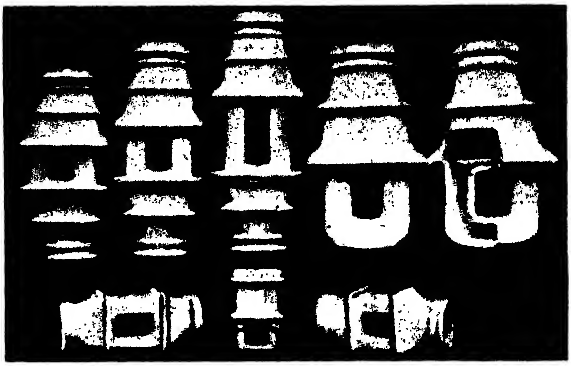


FIG. 68/8.—Castings. Continental design.

(*g*) **Casting.** As mentioned above, casting is used principally in the manufacture of articles having unsymmetrical shapes and in cases where small production quantities do not justify the expense of metal tools (Figs. 68–8/9).

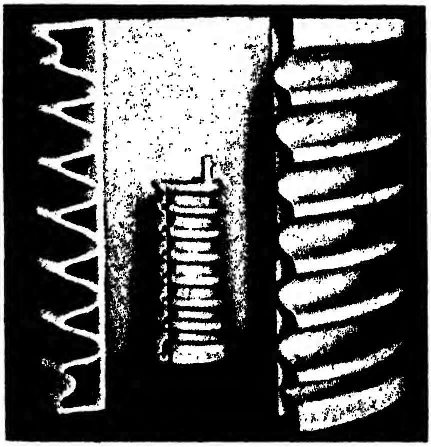


FIG. 68/9.—Porcelain section of a water resistor of Continental design (part cut away) for transmitters. A water coil is formed inside the hollow porcelain coil, providing a resistor and cooling anodes of high-power valves. Owing to its complicated shape, it is produced by casting.

Casting is carried out by pouring the liquid body or slip into a mould of Plaster of Paris. If a Plaster of Paris mould is filled with a body slip and the liquid is poured out after a certain time, the inner surface of the mould will be covered with a layer of body, a part of its water having been absorbed by the porous mould. When this layer is left in the mould, which is put in a dry place, it loses more of its water and shrinks away from the mould, so that it can be easily removed. The article removed from the mould is the negative of the Plaster of Paris mould. Its wall thickness is the thicker the longer the slip is left in the mould before the surplus slip is poured out. The thickness of the wall is not only dependent on the time during which the mould is allowed to absorb water from the slip, but also on the nature of the Plaster of Paris and the nature of the slip.

In the chapter dealing with Plaster of Paris is explained how the preparation of the plaster slip (and particularly the ratio of water and Plaster of Paris) influences the porosity of the mould and consequently its capacity to absorb water. In the chapter dealing with china clay and ball clay it is pointed out that very plastic bodies take much more time to form the same wall thickness than less plastic bodies.

The slip used for casting is, as a rule, not of the same consistency as the slip in the mixing arc which is subsequently pumped into the filter press. This slip contains too much water. It would take too long a time to cast with such a slip (called " water slip ") and the moulds would have to absorb so much water that it would be difficult to dry them and to use them repeatedly.

The body is made liquid for casting purposes by the use of a small amount of sodium carbonate and/or sodium silicate added to the plastic body as it comes from the filter press. Whereas a pint of porcelain or earthenware water slip weighs approximately 27 oz., a pint of alkaline casting slip weighs up to 36 oz., the former containing about 12–13 oz. dry substance, the latter containing about 24–26 oz. of dry substance. (In a pint of casting slip weighing 36 oz. there are, therefore, about 10 oz. of water and 26 oz. dry substance. The slip contains, therefore, about 27 per cent. water and 73 per cent. dry substance). The loss of only a small percentage of water by absorption in the mould causes the casting slip to turn hard (the water content of a casting slip is not higher than the water content of plastic body used for jollying and extruding purposes). Chemicals like sodium carbonate and sodium silicate which promote the separation of ceramic masses into the much finer particles of which they are composed are termed " deflocculents " (deflocculating agents).

Such fine particles remain for a very long time in suspension; as they are in the colloidal state.

In the chapter dealing with Plaster of Paris it was mentioned that certain organic sodium compounds, such as sodium tannate and sodium gallate, are in many respects superior to sodium silicates and carbonates. For practical purposes, however, sodium carbonate and sodium silicate are used and give, generally speaking, very satisfactory results.

Sodium silicate is produced by melting sand and soda ash in a furnace. Various proportions of the two ingredients can be used and different characteristics are obtained depending upon the ratio of sand and soda. The most alkaline silicate has a ratio of $1\ Na_2O$–$1{\cdot}6\ SiO_2$ and the most siliceous grade has a ratio of $1\ Na_2O$–$4\ SiO_2$. The most siliceous grade cannot be concentrated beyond about 30 per cent. solids without losing its liquid state and turning into a gel. The most alkaline liquid can be concentrated to about 60 per cent. total liquids without turning into a gel.

Sodium silicates high in silica have a greater deflocculating power than the more alkaline sodium compounds. In general 0·2–0·5 per cent. of sodium carbonate and silicate in watery solution are used to make a plastic body liquid. An excess of deflocculents produce a lesser liquification effect and cause even the reflocculation of the suspended clay. A unit of Na_2O introduced by sodium silicate has a larger effect in reducing the viscosity of a clay slip than the same amount of Na_2O added as a carbonate. In addition, sodium silicate eases the drying of a body and causes a hard and tough surface which may decrease loss in manufacturing in the " green " state.

The moulds used for casting are very similar to those used for jollying. They are of one or more pieces according to the shape of the article to be produced. They are designed in such a way that either only the outer surface of the article is formed by the Plaster of Paris mould (open casting) or both the inner and outer surfaces of the article are formed by separate Plaster of Paris mould parts (block casting). The excess slip may be removed either by tilting the mould filled with slip and simply pouring out the slip (open casting) or it may be removed through the same orifice through which the mould was filled (block casting), or through a lower orifice temporarily closed during the filling. This latter process is, of course, only suitable if the shape of the article to be cast allows for the arranging of an orifice near the bottom part, and is specially advisable in the case of large articles in order to obtain equal wall thickness. It is necessary, of course, to dry the moulds after each casting process. This is explained in the chapter dealing with Plaster of Paris.

The absorption of water can be speeded up by applying vacuum or pressure as the case may be. In the case of vacuum, the mould has to be surrounded by a case of airtight material and has to be hermetically sealed. The space between the case and the mould is evacuated by an air-pump. The procedure is reversed and air or slip introduced by means of pressure pump in the case of the second method. This latter method has been used to a very great extent in recent years for earthenware and china as well as for electrical porcelain. The interior of the Plaster of Paris mould is connected by pipes with a reservoir under pressure, or with a reservoir containing the casting slip and arranged at a higher level (12–20 ft. above the mould). Many moulds may, of course, be connected to such an elevated reservoir. The flow into the individual moulds may be controlled by cocks. Moulds consisting of several parts

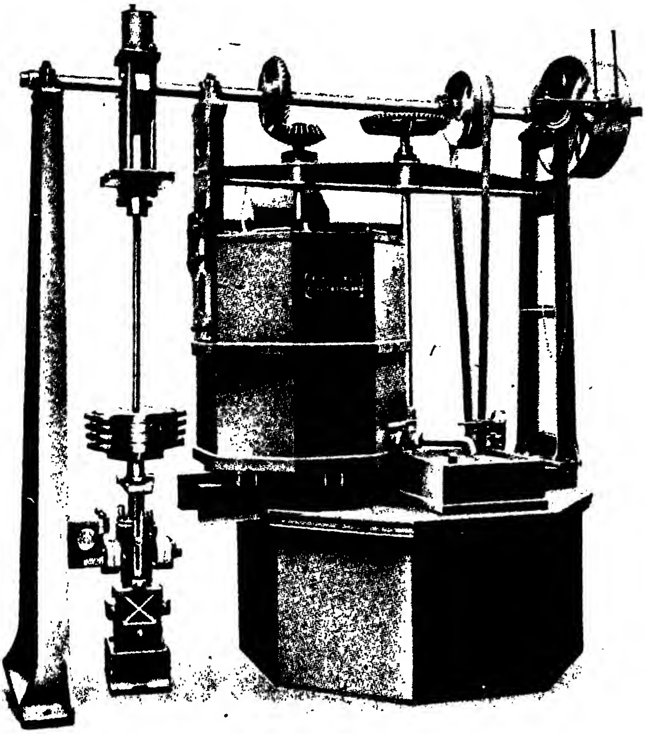


FIG. 68 (*a*).—Boulton's casting plant.

have to be held tightly together by strong metal bands. The tubes used for connecting the reservoir to the individual moulds are made of copper or other non-corrodible metal. Very suitable also for this purpose are tubes made of porcelain.

FIG. 68 (*b*).—Partial view of wet process porcelain casting shop. (Victor Insulators Inc.)

A simple plant for preparing a casting slip is illustrated in Fig. 68 (*a*) and a partial view of a casting shop is given in Fig. 68 (*b*).

M. DRYING OF SHAPED ARTICLES

It has been explained in previous chapters that ball clays and china clays are made plastic and workable by the addition of water, and that it is necessary to remove this water of formation after the articles have been shaped in order to harden them sufficiently and to carry them to the next manufacturing stages which may be, for instance, glazing and/or the placing of the articles into the saggers. It has, further, been mentioned that during drying the articles shrink, and that this shrinkage is the greater the more plastic the raw materials used. On the other hand, the more open the bodies, and the less plastic the clays used in their composition, the more rapidly the drying process takes place. During the drying process the water of formation contained in the body is evaporated by the surrounding air, and it is, therefore, obvious that the more water the surrounding air is able to take out of the body in a given time the quicker the drying process takes place. Apart from the nature of the body used for the manufacture of the articles in question, the speed of the drying is dependent on the following factors :

(1) **On the Shape of the Article.** Drying takes place the quicker the greater the ratio of the surface in contact with the drying air to the weight of the body. If various differently shaped articles, all having the same body composition and equal weight, are considered, a spherical article would require the longest drying time, whereas a suspended thin-walled tube would be one which requires the shortest drying time.

(2) **On the Temperature of the Surrounding Air.** The higher the temperature of the air used for drying the articles, the more water of formation is evaporated by the air in a given time. A cubic metre of water-saturated air at :

20°C. contains 17 gr. of water.
40°C. „ 50 gr. „
60°C. „ 130 gr. „
80°C. „ 290 gr. „

A dry air stream at 80°C. would therefore be able to dry about six times the number of articles which could be dried by a stream of air at 40°C. (This is, of course, only an example, and it would in practice not be advisable to employ dry air of 80°C.)

(3) **On the Velocity of the Air Circulation.** The speed of drying is also dependent upon the velocity with which air containing a high percentage of water evaporated out of the drying articles is replaced by fresh warm air not containing vapour. The quicker moist air is replaced by fresh dry air the quicker is the drying process.

Rapid drying is economically the desirable aim, but is technically not so easily achieved, since it may be accompanied by shrinkage fissures and cracks. Cracks will occur when certain parts of an article dry more quickly than other parts, and heavy drying losses are very likely to occur. In the drying of ceramic articles the aim of the manufacturer is to reduce the drying time to a minimum consistent with the safety of the ware. Porcelain insulators are very often of large overall size and at the same time have very great and non-uniform wall thickness. Drying of such insulators is, therefore, not an easy matter and offers more difficulties than the drying of many other ceramic types of articles. If an insulator manufacturer, however, produces only small articles, drying difficulties do not arise. Small pressed articles, for instance, can be placed on trays as they come out of the dies, and can be moved quickly on these trays into a tunnel drier. In such a tunnel drier, hot dry air (for instance, waste heat produced by tunnel ovens) is pressed into the exit end of the drier and reaches the entrance end of the drier still rather hot and containing a certain amount of water evaporated from the drying articles (counter stream).

When large and complicated insulators are to be dried, drying is carried out in such a way that as far as possible all the parts of the insulators dry and shrink uniformly at equal speed. One of the original methods was to cover the ware with damp rags (in order to decrease the speed of drying of the surface area) and to dry them at room temperature.

Generally speaking, heavy drying losses are more likely to occur :

(*a*) Where articles have an uneven section.
(*b*) Where the shrinkage of such bodies is on the high side.
(*c*) Where articles of large dimensions and large thickness are involved.

This refers, for instance, to large bushings and solid core insulators (motor insulators, long rod insulators) which may take many weeks to dry. For an output of many thousands of insulators of this kind per week, an enormous amount of factory space would be taken up and the number of insulators damaged in the workshop whilst they are lying around would be considerable unless steps are taken to speed up the drying process.

HUMIDITY DRIER

In order to speed up the drying process, humidity driers are often used. Speeding up of the drying process by the application of warm dry air is not practicable in the case of large and solid insulators, which would become " casualties " owing to drying cracks. The aim is to take the same percentage of water out of the interior of the insulator as is taken out on and near to the surface. This aim is achieved by placing the articles in air of high temperature and high humidity content (for instance, air of 95 per cent. humidity content) and then by gradually reducing the humidity content until, in the final stage, the drying is carried out by warm dry air.

Various types of humidity driers are used. Most of them aim at removing the first half of the water of formation slowly and the removal of the second half of the water of formation more quickly. (It will be remembered that shrinkage accompanies the first half of the evaporation of the water of formation only, whereas evaporation of the second half of the water produces merely an increase in the pore space and no further shrinkage.) Control of temperature and of humidity content of the hot air can be achieved by the provision of several humidity chambers, the first possessing the highest humidity content and the last the lowest humidity content. Trucks loaded with the articles are pushed through these chambers, either in an intermittent or in a continuous flow (Fig. 69). In the former case the individual chambers may be separated by insulating partitions which can be lifted temporarily in order to permit the trucks to proceed from one chamber to the next. Other humidity driers are designed in such a way that the truck remains in the same drying chamber whilst the humidity content of the chamber is slowly decreased during the drying (Figs. 70 (*a*) and 70 (*b*)).

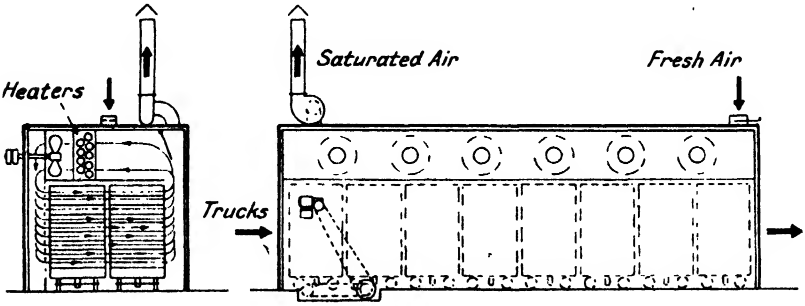


FIG. 69.—The articles enter the drier at one end and are withdrawn at the opposite end when the material is completely dry. The temperature, air saturation and air speed can be controlled to suit each stage of the drying process. (Apex Construction, Ltd., London.)

In all cases a uniform and regular circulation of the hot humid air is important in order to obtain uniformity of drying. A very strict control of temperature, humidity content and the speed of air circulation is essential if the humidity drier is to be used to the best advantage. Measuring apparatus can be observed through glass plates provided in the opposite walls of the chamber. At the same time, the decrease in weight of a cylinder made of the same body as the insulators and manufactured to a standard size should be watched at regular intervals. The cylinder is placed on a spring balance and

FIG. 70.—Drying stove for insulators. (Supplied by Messrs. L. A. Mitchell, Ltd., Manchester, for Messrs. Bullers.) Picture shows racks filled with insulators being pushed into the drying stove on trucks.

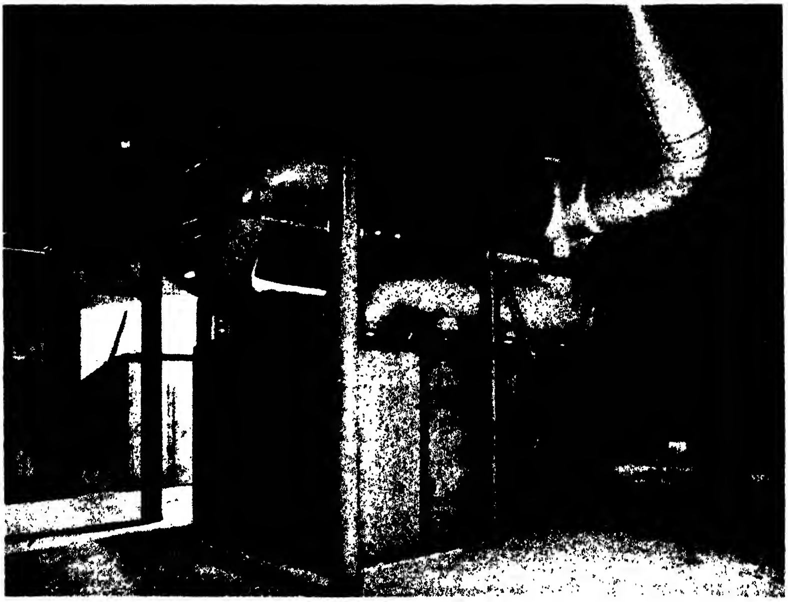


FIG. 70 (*a*).—Stove for drying electric insulators in humidity saturated hot atmosphere. (Humidity Drier.) (Messrs. L. A. Mitchell, Ltd., Manchester, for Midland Electric Manufacturers.)

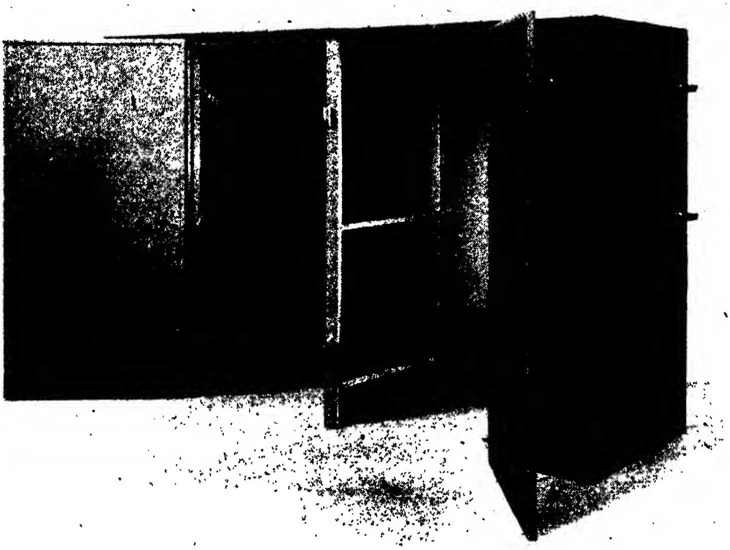


FIG. 70 (*b*).—Apex humidity tray drier.

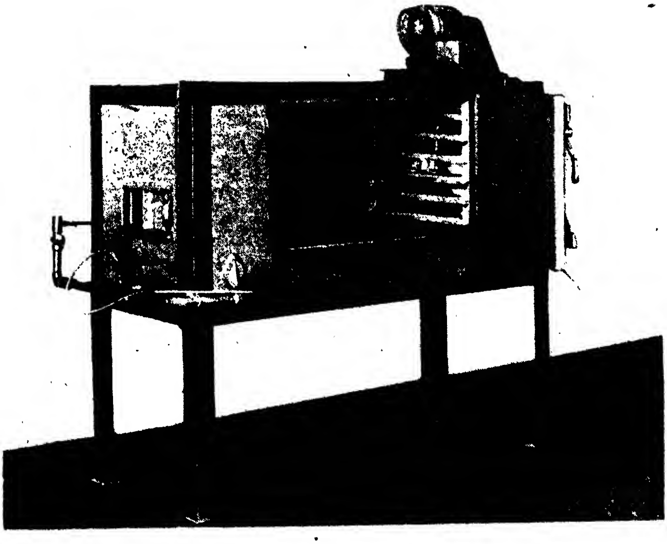


FIG. 70 (*c*).—Controlled humidity drier for laboratories to investigate best drying conditions for industrial articles. (Apex Construction, Ltd., London.)

the decrease in weight observed through a glass plate and recorded. This method really shows the combined result of heat, humidity and rate of hot air circulation. It is rightly claimed that the introduction of the humidity drier represents one of the most important improvements in insulator manufacture during recent years, since it not only reduces the losses caused by drying cracks, but also the drying time. Where weeks of drying, or even months, were previously required, the time is now reduced to a matter of days. The losses also are considerably reduced. In order to ascertain the best drying conditions for any given article, laboratory drying stoves are very useful (Fig. 70 (*c*)). The use of humidity driers is, however, complicated if a great variety of articles of different shape and size has to be dried, each requiring different drying time and different humidity content.

INFRA-RED DRYING

In the U.S., infra-red drying processes have been developed for drying porcelain articles.

In " Ceramic Industry," December, 1942, the " Near Infra-red Drying Process " is described. Heat is derived from a series of lights placed in tunnels or over conveyors near to the product to be dried. Reflectors are placed at the back of each unit to direct the infra-red rays directly on to the product. Time and labour is claimed to be saved in this process, which seems to be particularly useful for drying ware after dipping, if the ware is already fired or dried.

A pottery firm in California has recently introduced this system and is drying dipped ware by this method in approximately 5 minutes, compared with 4 hours previously needed. Another firm in Virginia uses 16 reflectors enclosed in a sheet-metal tunnel. They dry decorated ware in 1½ minutes, whereas this process formerly took several hours.

Infra-red drying has found its way into many industries and it is likely that in the ceramic industry as well it will, in future, be used to a great extent.

DRYING OF JOLLIED ARTICLES IN MOULDS

The drying of jollied insulators in Plaster of Paris moulds is carried out in a dry but only slightly heated atmosphere. The Plaster of Paris moulds burn if they are exposed to a higher temperature than 50°–69°C. (122°–156°F.) Furthermore, in most cases the jollied plastic body has to be only slightly dried because further shaping processes such as turning have to follow. The moulds in which the insulators are jollied (if they are not too heavy) are put on conveyor trays and slowly moved through drying chambers. The moulds are emptied at the discharge end of the chamber, when the articles are sufficiently dry and the empty dry mould is returned by the conveyor to the jolly-men. If the article, plus the mould, is too large or too heavy to be put on a conveyor, the moulds containing the articles are taken to a room in the workshop near the jolly-men.

N. GLAZING OF PORCELAIN ARTICLES

In porcelain manufacture the glaze may be applied to unfired ware which is either half dry (leather hard) or completely dry, in most cases the latter.

Two methods of applying glazes are used in porcelain manufacture: immersion (dipping) and spraying.

The dipping method consists in immersing the insulator in a glaze slip which is contained in a suitable container. The dry article, owing to its porosity, absorbs some of the water of the glaze slip, so that a thin coating of the solid glaze materials is formed on the surface (Fig. 71). The thickness of the glaze coating depends on the porosity of the article, on the density of the slip and on the duration of immersion. All these factors have to be very thoroughly controlled in order to obtain equal thickness of the glaze layer. Before dipping an insulator, any dust deposited on its surface must very carefully be removed. This is done by applying a jet of compressed air which carries away the deposited impurities. It is important that the compressed air is thoroughly filtered. The glaze slip in the container has to be stirred from time to time, preferably by a mechanical stirring device, in order to prevent "settling" of the solid particles. The addition of a small percentage of plastic china clay helps to keep the particles in suspension. A very small amount of bentonite has the same effect. Settling can furthermore be prevented by the addition of small quantities of organic ingredients, such as flour (previously boiled in water), gum arabic or (in certain cases) a small amount of acid. The dipping of porcelain articles was originally done by hand. Nowadays in most cases where a considerable number of articles of the same type has to be glazed, either semi-automatic or completely automatic mechanical devices are often used. The insulators are temporarily mounted on inclined spindles attached to a rotating turntable. These rotating insulators dip in a bath of glaze, one after the other, until the cycle is completed.

Spraying is the other method used for applying the glaze to porcelain articles. This method is carried out by a pistol (or aerograph). The design works on the air compression principle. The compressed air travels down a tube on the end of which is a fine nozzle. This tube is surrounded by another tube which is connected to the glaze container. By the vacuum effect produced, glaze is sucked into the air stream and is spread on to the articles. Both the flow of the glaze slip and the amount of air pressed into the slip tube can be regulated so that a well-defined amount of glaze spray is pressed through the nozzle of the aerograph.

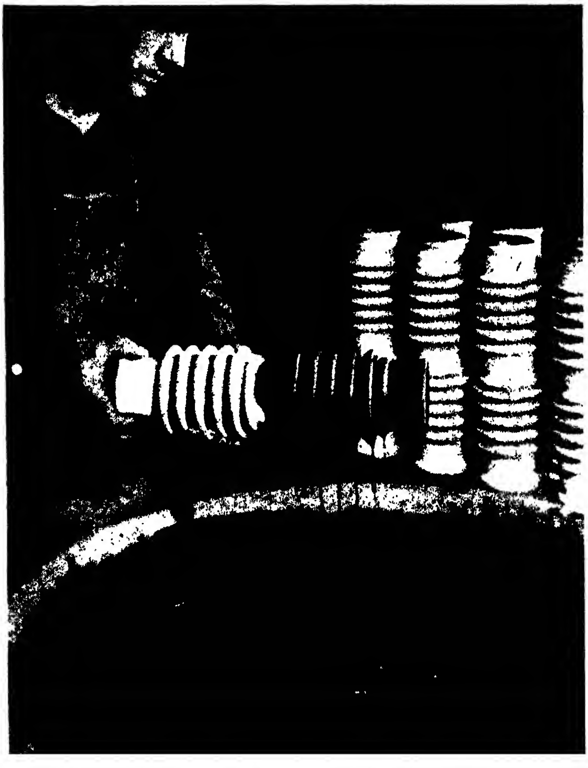


Fig. 71.—Close-up of glazing insulators by hand. (Victor Insulators, Inc.)

Glaze spraying is used in the case of very large articles which would be difficult to immerse in a glaze tank, and also for very thin-walled articles which would absorb too much water if dipped into a glaze slip, thereby losing their mechanical strength and becoming deformed.

The spraying process lends itself very well to automatic glazing.

The articles to be glazed can, for instance, be put on rotating discs fixed on a turntable. Sets of aerographs spray the glaze on the articles from all directions. It has been mentioned that in porcelain manufacture the glaze and the body are often fired in one firing process—the glaze fusing at the same temperature at which the body becomes vitrified and non-porous. Originally, pressed and other thin-walled articles were pre-fired at a temperature of between 800°–950°C. in order to give them the necessary mechanical strength so that they would not be deformed during the dipping process, but with the introduction of the aerograph for mass-production glazing pre-firing of the articles becomes superfluous.

On the Continent pre-firing is, however, still used for pressed and other thin-walled articles. It is carried out on the second floor of the intermittent type of kiln where the waste heat of the oven is used in order to produce the necessary temperature for hardening the articles.

O. FIRING AND KILNS

For firing porcelain articles, intermittent up-draught and intermittent down-draught and continuous tunnel ovens are used. At the time of writing—(Summer 1943)—intermittent ovens are not in favour for new plant construction (but for extension to existing plants they may still be considered). In existing factories there is still a great number of intermittent kilns in operation, except in the United States, where the old intermittent kilns are either lying idle or haye been pulled down.

(*a*) **Intermittent (Down-draught and Up-draught) Kilns.** Intermittent kilns are of various designs (Fig. 72). On the Continent they are of the down-draught type and of circular cross-section, consisting of two chambers, one on top of the other (as far as porcelain manufacture is concerned). The lower chamber, in which the porcelain is fired at about 1,400°C., has on an average a capacity of 60 cubic metres (2,120 cubic ft.). The largest capacity used is in the neighbourhood of 80 cubic metres (2,800 cubic ft.).

Fireplaces (varying between eight and twelve in number) are sunk in the ground at regular intervals around the circumference of the kiln. The distance between any two fireplaces should not be larger than 1·6 metres (5½ ft.). The fireplaces of the down-draught kilns are not interconnected beneath the floor by flues, as is the case with up-draught kilns. The flames enter the interior of the kilns through apertures called " bags " at each fireplace. As the flames enter the kiln they rise and are reflected on the crown. The path of the flame from the fireplace to the chimney is as follows:

1. Fireplace.
2. Bag.
3. Firing chamber. (Interior of the kiln.)
4. Crown.
5. Down to sole of kiln.
6. Through exit holes.
7. Through flues beneath the sole.
8. Through flues in outer wall.
9. Through openings into upper storey.
10. Through crown of upper storey into chimney.

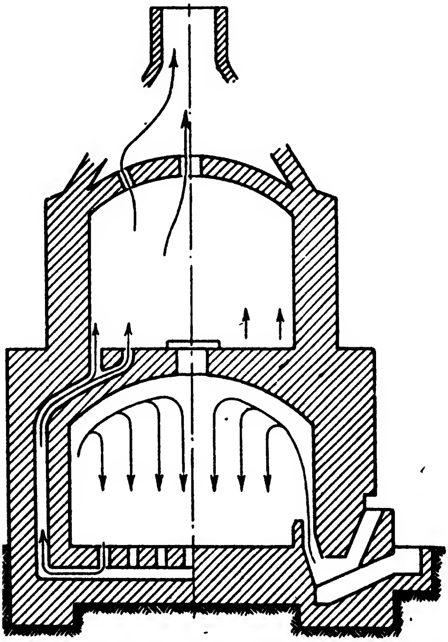


FIG. 72.—Intermittent two-story down-draught kiln. (Continental Type.)

The openings in the sole mentioned above are equally distributed over the circular area of the sole. They are arranged on the circumference of several constructional circles: for instance, 16 on the outer circle, 8 on the second circle, 4 on the third circle, and 1 hole right in the centre of the sole. The flames are consequently fairly well distributed over the whole area of the kiln when they pass downwards from the crown to the openings in the sole of the kiln. The openings in the sole are connected by flues beneath the sole with the series of vertical flues arranged in the walls of the kiln. These flues lead into the upper chamber of the kiln. The second or upper chamber possesses a dome-shaped crown over which the chimney is arranged. In this second chamber a temperature of between 800° and 950°C. is reached. It can be used for hardening articles before glazing and also for hardening " green " saggers in order to give them some mechanical strength. One-storey down-draught ovens are almost unknown on the Continent (as two-storey kilns are generally used). In most cases the upper chamber is however not employed to full capacity. Although the heat distribution in down-draught intermittent kilns is not as good as might be desired, a fairly even heat distribution can be achieved provided the draught conditions in the kilns are carefully watched and controlled. The draught conditions and heat distribution of the kiln are determined by the ratio of the surface area of the fireplaces to the surface area of the outlet openings in the sole and by the manner in which the " saggers " are arranged in the kiln. In England, down-draught kilns for potteries differ somewhat from those on the Continent, in that they possess only one chamber (since there is no need to fire ware in the second floor as pre-firing is not generally practised in Great Britain). They further differ from the Continental type of down-draught ovens by reason of the fact that the flames enter the interior of the kilns not only through the bags behind the fireplaces, but also through an inlet provided in the centre of the sole. Up-draught intermittent kilns are also in operation for pottery manufacture in various places (Fig. 73). The firing chamber of these kilns is also circular. In the case of up-draught kilns, the flames from the fireplace take two separate routes—one directly upwards from the bags to the dome and then to the chimney, and the other through openings in the sole of the kiln, and so on. Dampers in the chimney and in the dome make some sort of draught regulation possible. It is, of course, very difficult to draw as much heat towards the centre and bottom part of the kiln as is drawn from the fireplace direct to the chimney. A temperature variation between the various parts of the kiln not exceeding 120°C. is, under these circumstances, quite a good achievement. The average time for firing and cooling a 60 cubic metre down-draught or up-draught intermittent kiln is about 80 hours.

The principal fuel used in intermittent kilns for firing porcelain and other ceramic articles is coal. On account of the long distance between the firebox and the crown a long-flame coal has to be used.

Short-flame coal and coke may, however, be used to advantage at the commencement of the firing. At the next stage in the firing it may be used mixed with a long-flame (fat) coal, but during the last period of the firing the use of long-flame coal is essential, because it distributes the heat not only by radiation but also to a very great extent by convection and conduction, thus carrying the heat to places in the middle of the oven which would not be sufficiently heated by radiation alone. The firing time of a large oven could be much shorter if it were possible to heat the inner parts of the kilns as quickly as the outer parts. This refers to both down-draught and up-draught kilns. The ware is, in fact, subjected to heat treatment much longer than necessary owing to the difficulties in bringing the inner part of a large kiln to the necessary temperature at the final stages of the firing.

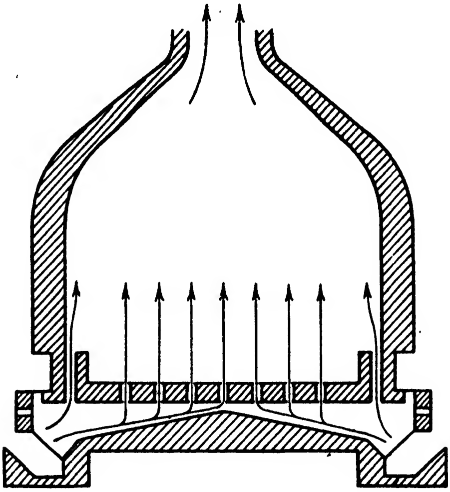


FIG. 73.—Up-draught kiln.

Lignite (brown coal) and lignite briquettes are used on the Continent to a very great extent for firing intermittent kilns, not only at the commencement but also in many cases mixed with coal, throughout the whole firing process, since there are lignites of very high calorific value available, especially in parts of Czechoslovakia.

Oil can also be used for firing intermittent kilns with very favourable results. Very good burners are now available which permit of very accurate mixing of fuel and air, and consequently of good control of the kiln atmosphere. A certain amount of the waste heat of the intermittent kilns can be used for additional purposes. This can be done in the following way: the contents of the kiln, after the firing has been completed, have to cool down to about 700°C. A damper provided in the chimney must then be closed. Strong suction fans are arranged next to the chimney for exhausting the heat accumulated by the ware, the saggers and the brickwork. The heat is conducted through ducts into a temperature mixing chamber at a central point in the factory, from which it may be distributed to all portions of the plant. If in a six-kiln factory one kiln is fired per day, the amount of waste heat available may suffice to make additional heating in certain parts of the factory unnecessary.

Intermittent kilns have, however, very great disadvantages (in spite of several improvements which have been achieved within recent years, and which are the result of experience gained from the use of tunnel ovens). First, the fuel consumption is very high. For firing 100 kg. porcelain insulators at a temperature of 1,400°C. about 100 kg. of coal of best quality is necessary. The reason is that the whole kiln (the sole, chimney, brickwork, etc.), after being used, has to be allowed to cool down to such a temperature as will permit the workmen to enter the kiln and take out the saggers, and has then to be heated up all over again right from the very start. Intermittent operation of the kilns makes the use of recuperators and the use of the waste heat almost impossible (with the exception of the use of the last 600°C. for heating purposes). Secondly, the sagger consumption is very high as a result of the considerable sagger breakage. The saggers filled with porcelain (and in fact all kind of pottery) are placed by hand one on top of the other, ten to twenty saggers high, and are carried up and down ladders. Rough handling of the saggers cannot be avoided, particularly so since both the emptying and filling of the kilns is done when the inside of the oven is still rather hot. Furthermore, in the case of large intermittent kilns, the weight of the saggers placed one on top of the other is rather high, and consequently under the influence of heat and compression a certain percentage of the saggers becomes deformed. Another factor which shortens the life of the saggers is the fact that lime, iron, etc., contained in the ash of the coal drawn with the flames into the inside of the kiln, form a kind of glaze on the surface of the saggers which reduces their resistance to temperature changes. Thirdly, the filling and emptying of kilns are very intricate jobs, requiring great skill and physical strength on the part of the workpeople, who have to carry the heavy saggers filled with ware into the kiln and to pile up high stacks of them. This work is punctuated by considerable breakage of both saggers and ware and is obviously very costly.

(*b*) **Continuous Tunnel Ovens.** The disadvantages enumerated largely disappear with the use of continuous tunnel ovens. The name is self-explanatory and the ware in fact proceeds through a tunnel on a suitable truck, covered with a refractory lining. In this tunnel the temperature rises gradually, and the ware is gradually heated as the trucks are pushed towards the centre of the kiln (in the direction of the combustion zone). At the centre of the kiln the final firing temperature is reached. During the passage through the firing zone the firing process is completed and the ware is then gradually cooled down as it travels to the exit. By this time the ware is sufficiently cooled down for the truck to be removed from the kiln.

Much better use of the calorific value of the fuel is made by the tunnel oven than by the intermittent oven. Once a tunnel oven is heated up to the desired temperature it is kept at this point by a comparatively small amount of fuel. (The types of fuel used are discussed later.) After leaving the combustion (or central firing zone) the ware enters the cooling zone. The air heated during the process of the cooling of the articles is drawn into the combustion zone and is used to raise the combustion temperature. The use of this highly preheated secondary air results in considerable fuel economy. Furthermore, the heat radiated and convected from the ware firing in the cooling zones to the walls (and particularly to the crown of the kiln) is used for heating up a separate air system. This separate air is drawn through ducts provided over the crown and elsewhere in the hot brickwork of the kiln and is exhausted by a fan. This separate air system does not come into contact with the combustion gases and so is absolutely clean and can be used for drying and heating purposes. By this means a great proportion of the calorific value of the fuel burned is usefully employed.

The outer parts of the kiln are lagged with suitably heat-insulating material, in order to avoid loss by radiation and to prevent the room near the kiln getting too hot. It is obvious, however, that instead of lagging the kiln to excess (particularly the cooling zone) it is possible by means of circulating air to control and convect the heat given off into other useful energy.

The life of saggers in tunnel ovens is much longer than in any intermittent kilns, since the placing of the saggers on the trucks can be arranged in such a way that practically no lifting of the saggers is necessary. A height of 5 ft. of the sagger stack is about the maximum height which occurs in connection with tunnel ovens for pottery purposes, particularly for electrical porcelain.

The kiln atmosphere is in most cases free from materials which may attack the saggers and reduce their temperature shock resistance by forming a glaze on the surface. Direct impact of the flames on the surface of the saggers is usually avoided by suitable arrangement of the burners.

The loading and unloading of the saggers is always carried out in the same place, and the truck can be pushed to a place which is most conveniently situated for carrying out these operations. The glazed ware may, for instance, be transported by suitable devices such as conveyors to the place where the filling of the saggers and the loading of the trucks is carried out.

Similarly, a conveyor may transport the ware from the place where it is taken out of the saggers to the inspection or electrical testing rooms. The fact that the same truck carries the ware both in and out of the ovens reduces the cost of transportation.

Fuel. For firing tunnel ovens, the following fuels are used :

(1) Town gas or coke gas.
(2) Oil.
(3) Natural gas.
(4) Producer gas.
(5) Pulverised coal.
(6) Electricity.

The employment of coal is not usual in the case of tunnel ovens. Other fuels offer more advantages particularly with regard to cleanliness.

It would exceed the scope of this book to deal in detail with the special advantages offered by the various fuels. For pottery manufacture, all the fuels enumerated are used very successfully.

A comparison of fuel consumption in intermittent ovens and tunnel ovens showing coal consumption in both systems, and gas and electricity consumption in tunnel ovens may be of interest (Gatzke Kerabedarf Ber. D.K.G., 1936). The Table on p. 210 shows the saving of fuel in tunnel ovens as compared with that in intermittent ovens. For instance, if coal is used in tunnel ovens approximately 1 kg. coal is required for the manufacture of 1 kg. insulator porcelain as against 2 kg. used for the production of 1 kg. insulators in intermittent ovens.

It depends, first of all, on local conditions as to which fuel is the most economical. Of the six fuels listed, three are used mainly in the U.S.A., namely, Town gas or Coke gas, Oil and Natural gas. Oil is, of course, used in places where Town gas, Coke gas or

Class of article	Intermittent Oven				Tunnel Oven					
	Tem-perature	Coal kg. per m.^{3}	Kg. coal per kg. ware	Time for the complete firing-cooling cycle	Coal kg. per m.^{3}	Kg. coal per kg. ware	Town gas, m.^{3} per m.^{3}	m.^{3} town gas per kg. ware	kW. hours kg. ware	Time of the complete cycle
Porcelain dinner sets.	1,410°	190–220	3·20–4·00	hours 76	100–120	1·43–1·71	140–170	2·00–2·42	2·50–4·50	hours 28–40
Electrical insulators .	1,410°	200–230	2·07–2·37	80	100–125	0·95–1·25	125–156	1·20–1·56	2·20–4·00	90–100
Earthenware tableware (bisque) . .	1,280°	80–95	0·85–1·00	72	50–56	0·20–0·23	65–75	0·27–0·31	1·10–1·40	27–37
Earthenware tableware (glost) . . .	1,150°	60–110	1·00–1·80	72	45–50	0·30–0·34	60–80	0·40–0·53	1·00–1·30	17–30

Natural gas is not available. Some factories use oil during one part of the year and natural gas during the other part. Producer gas is not used to a very great extent in the U.S.A. for tunnel ovens, but on the Continent big lignite formations situated near important industrial centres make the use of producer gas very economical for tunnel ovens. The various ceramic factories using producer gas have their own producer plants, and the necessary equipment for removing tar and other materials which may be detrimental to the working of the burners. In English factories town-gas is used almost exclusively as fuel in tunnel ovens. In Switzerland, and in fact wherever it is cheap, electricity is used for heating tunnel ovens in the ceramic industry.

The question of electrical resistors or heating elements has for a long time been the main difficulty connected with electrical tunnel ovens, particularly for temperatures above 1,150°. For temperatures below 1,150°, metal resistors have been, and are being, used which withstand easily such temperatures, their resistivity being almost independent of the temperature to which the resistors are subjected.

For temperatures between 1,150° and 1,250°C. special metal alloys have been developed and manufactured in recent years, such as Kanthal (an aluminium-iron alloy). The resistivity of these is sufficiently independent of the temperature to make possible their use without the provision of special voltage regulators, and which give entirely satisfactory results. For temperatures higher than 1,250°, and particularly for temperatures of about 1,400°C. which are used in Continental porcelain manufacture, non-metallic heating elements have been developed and are being used to a very great extent. This type of non-metallic resistor is called " Globar Resistor " in the United States (made by the Carborundum Company) and " Sillite element " (produced by the Siemens Halske Company in Germany). They consist mainly of silicon carbide (Carborundum). This type of resistor is commonly designated as " ceramic." Whether or not this term is quite correct, in a book dealing with the use of ceramic materials in the electrical industry a description of this type of heating element should not be omitted. Originally, the life of this type of resistor was very limited and the design of suitable metal contacts at its ends caused considerable difficulties, but these drawbacks have been largely overcome in recent years, and the life of this type of resistor has been raised considerably.

During the last few years, new types of Globar elements have been developed to dispense with the water-cooled terminals. This feature eliminates the necessity of a water supply near the furnace; the cost of providing water connection to the terminals is thereby saved, and the cost of furnace operation by eliminating the heat loss reduced. Globar and other carborundum heating elements increase in resistance with use.

The two methods commonly used to compensate for this increase in resistance are either to overpower the furnace, or to increase the impressed voltage across the elements by means of a multiple tap transformer. It is practicable to compensate with a multiple tap transformer for an increase in resistance as great as five times the initial resistance of new elements. It is not practicable to overpower a furnace to compensate for more than 100 per cent. increase in resistance. An element life using a tap transformer is double that which can be expected in an overpowered furnace.

In ordinary practice the voltage increase per step is usually 5–6 per cent. of the calibrating voltage of the element. In cases where fine control is necessary it is desirable to have steps which are only 3 per cent. of the calibrating voltage of the element.

Globar elements are not recommended for use in a vertical position. In those applications where the elements are mounted in a vertical position, they should not be suspended from the top terminal but should be supported at the lower end, so that all the crystals in the element structure will be in compression.

The terminal members used with the new type of Globar elements conserve the heat energy because they operate at temperatures low enough to eliminate the necessity for artificial cooling. This is achieved by using carborundum possessing very high resistivity in the heating section and using a carborundum possessing low electrical resistivity at the ends of the elements.

For instance, heating elements equipped with low resistance ends 5 in. long are used. Of this length 3 in. are of the same diameter as the heating section, whereas the remaining 2 in. are of a reduced diameter. The ends of the reduced section are rounded where they make contact with the terminal rods. The rounded ends of the terminal rod which extend outside the furnace wall are metallized in order to ensure a satisfactory electrical contact between the terminal rod and the terminal metal clamp. The terminal rods are made of the same materials as those used in the ends of the heating element. An alternative arrangement is shown in Fig. 73 (*a*).

The resistor difficulties having been solved, the use of electricity for heating tunnel ovens does not cause other special difficulties and, therefore, electricity is a very economical proposition for heating tunnel ovens where the price of the electrical unit is competitive. The main advantage of electrical heating of tunnel ovens is the absolutely clean oxydizing atmosphere prevailing throughout the whole kiln and the absence of flames and gases. The need for protecting the ware against detrimental effects of smoky flames no longer exists, and saggers are not necessary.

It is obvious that saggers absorb a certain percentage of the heat of the kiln, and increase the fuel consumption. In order to save fuel it has become customary to replace saggers by other means of support, particularly in the case of porcelain articles, if the condition of the kiln atmosphere and the nature of the glazes used allow this replacement.

Glazes fired at temperatures lower than 1,250°C. are, owing to their composition, rather sensitive to changes in kiln atmosphere, and to the influence of impurities contained in the fuel, such as sulphur and evaporated water. Where such low temperature glazes which would not withstand the influence of open flames are used, the articles have to be fired either in saggers, which can be made airtight by glazing the inside of the sagger and by plastic clay placed round the upper rim of the sagger (wad clay) or they can be fired in the muffle or semi-muffle type of tunnel kilns, or in kilns heated by flameless radiant burners or by electricity.

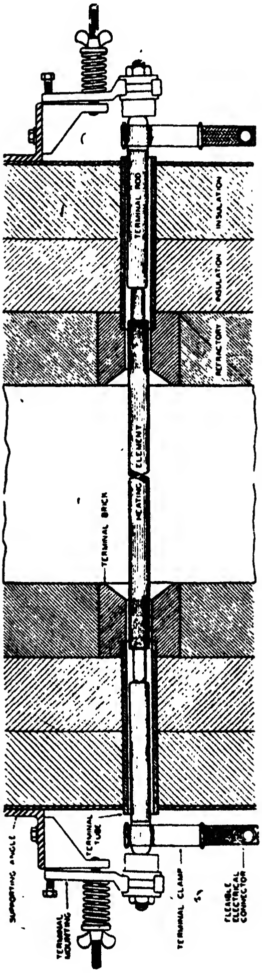
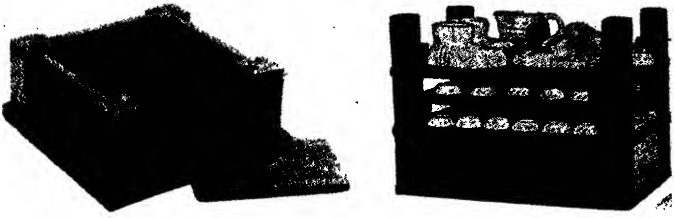


FIG. 73 (*a*).—Arrangement of globar resistor in electric furnace. (*By Courtesy of the British Resistor Company*)

In the muffle type of kiln the flames do not directly heat the ware or the saggers since they are not allowed to enter the inner part of of the muffle oven. The muffle, *i.e.* a kind of shield made of ceramic refractory material, is arranged round the ware. This muffle is heated by flames from both sides, and heats the inner part of the muffle kiln by radiation. There are various types of muffle ovens in use ; the full muffle type embodies a muffle which extends from the entrance all through the kiln to the exit end, and the semi-muffle type kiln where the muffle starts about the middle of the preheating zone and finishes in the middle of the cooling zone, thus protecting the ware in the second half of the preheating zone, in the central firing zone and in the first part of the cooling zone. It is obvious that in the muffle type of tunnel oven it is not ncessary to protect the ware by means of saggers (as the flames do not enter the inside of the muffle). The ware is simply set on plates (slabs or " batts ") made of refractory material. The plates are spaced horizontally above each other at the desired intervals by means of supports, which are also made of highly refractory ceramic material.

In the case, however, of tunnel ovens in which the ware is directly heated by the open flame, the conditions are somewhat different. It depends on the purity of the flame, on the arrangement of the burners, and on the composition of the glaze, whether or not the ware has to be protected by saggers against the products of combustion. The design of burners for oil and gas has so much improved within recent years as to make possible a clean and uniform atmosphere through the whole of the kiln. Furthermore, the burners can be arranged in such a way as to prevent the flames blowing directly on the ware. Provided, therefore, the composition of the glaze is not too sensitive to slight variations of atmospheric conditions in the kiln, there is no need to protect the insulators by putting them into heavy saggers, which consume calorific units unnecessarily. The sagger which surrounds, for instance, a 33 K.V. bushing is about the same weight as the bushing. The sagger into which a 10 in. suspension insulator disc is put, is approximately double the weight of the insulator. The sagger into which a dozen coil formers are put weighs approximately four times as much as the coil formers.

Every pound of sagger consumes approximately the same amount of heat as one pound of porcelain, and, in addition, prevents direct heat rays from reaching the insulator. Although within recent years firms specialising in the manufacture of saggers have introduced improved sectional saggers which offer many advantages (Fig. 74), it is not surprising that the ceramic industry has tried gradually to replace the saggers by other supporting devices, such as posts and slabs. As mentioned previously, these parts must be made of highly refractory material in order to withstand heavy loads, and in order that they may not be deformed at the high temperatures to which they are subjected. Carborundum (silicon carbide), kyanite and sillimanite are,[1] for instance, used as an admixture to clay to impart the desired characteristics to the setting equipment. In kilns possessing a large sectional area saggers are very often used only on the sides of the truck, leaving the inner part of the truck clear for



Sectional sagger with posts cemented to bottom plate.

Sagger as used for open setting.

FIG. 74.—Sectional sagger with post cemented to the bottom plate (Carborundum Company), offering the following advantages: in plants where both open firing and sagger firing is done in the same kiln duplication of kiln furniture is not necessary. Secondly, strains from heating and cooling tend to a very small degree only to crack or break multipart saggers (Ceramic Industry, Chicago.)

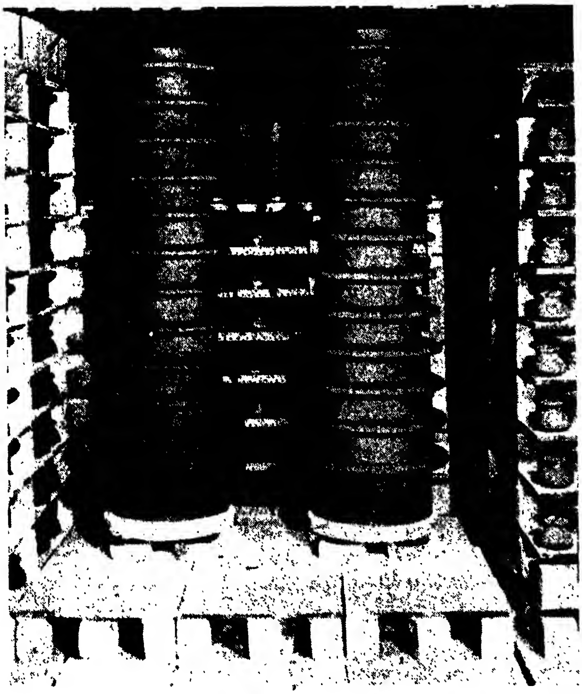


FIG. 75.—Large and small insulators placed in open setting on tunnel oven truck. (General Electric Co., Schenectady.)

open setting. Between the sagger stacks large articles such as bushings are often placed in open setting (Fig. 75). Uniformity of setting is very important. It is, for instance, bad to follow several heavily loaded trucks with lightly loaded trucks. For example, if several trucks were loaded with saggers filled with insulators, followed by other trucks on which all insulators are placed on open slabs supported by posts, the more heavily loaded sagger trucks would absorb and consume more heat than the trucks with open setting

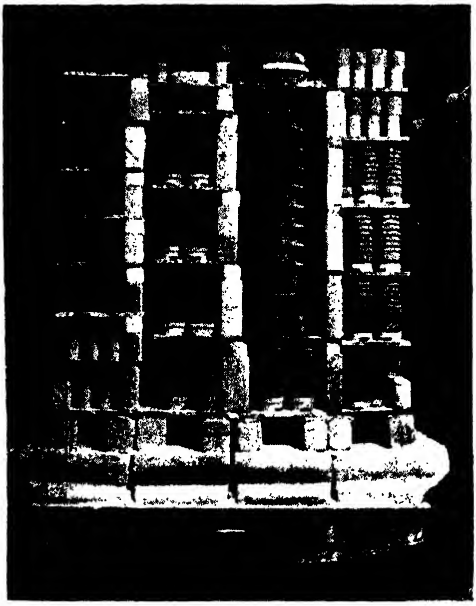


Fig. 76/1.—Variety of articles placed in open setting on tunnel oven truck. (Refractory slabs and supports by Richard Romney & Sons, Philadelphia.)

system and the insulators in the saggers may become under-fired and the insulators on the slabs over-fired.

Very dense ware settings are obtainable if a variety of posts for supporting the slabs is used to suit every size of the insulator to be fired. The space can be better utilized and more ware placed in open setting of each individual truck than if the ware is placed into saggers.

Figs. 76/1–5 illustrate open settings. Figs. 76/1 and 76/2 show articles of different size placed on the same truck by open setting. Figs. 76/3–5 illustrate uniformity of setting of articles which do not vary very much in size.

As far as insulator and other technical porcelain manufacture is

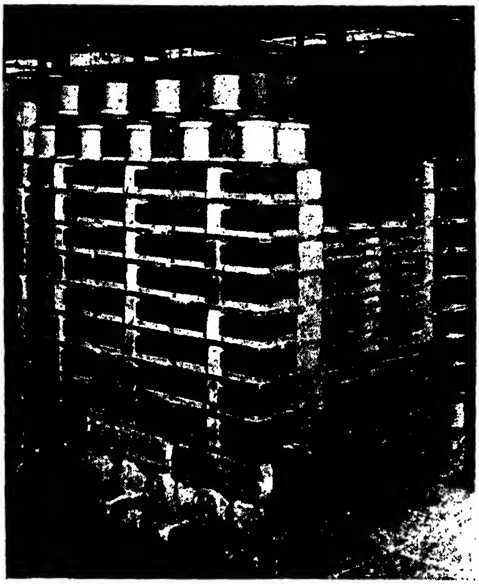


FIG. 76/2.—Open setting of a variety of articles on a tunnel oven kiln truck. (Slabs and posts supplied by Richard Romney & Son, Philadelphia.)

FIG. 76/3.—Typical view of continuous tunnel kiln cars using silicon carbide furniture for shelf-loading. (Victor Insulator Co., Inc.)

concerned, the open flame tunnel kiln offers in most cases, therefore, the same advantages as the muffle or the semi-muffle kiln, particularly

FIG. 76/4.—Two tunnel oven trucks. Great variety of small articles placed in open setting on refractory slabs and posts. (Richard Romney & Son, Philadelphia.)

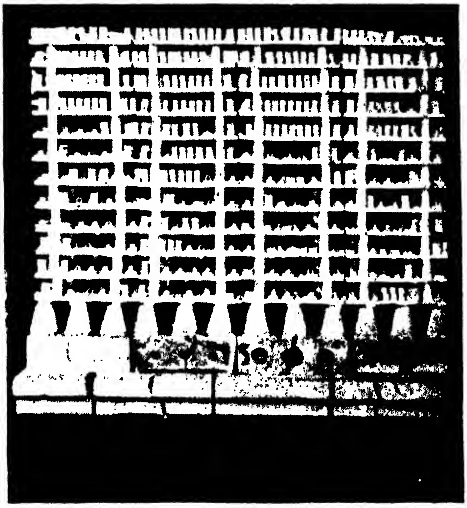


FIG. 76/5.—Open setting of small articles on a tunnel oven truck. (Refractory slabs made by Richard Romney & Son, Philadelphia.)

the possibility of open setting, and requires at the same time less fuel per pound of ware to be fired. It is not surprising, therefore, that for technical porcelain manufacture this type of tunnel kiln is most widely used at the present moment. Figs. 77/1–4 illustrate various open-flame tunnel ovens for insulator manufacture.

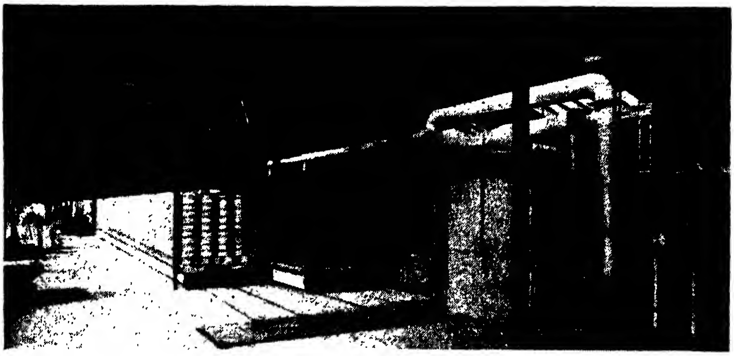


FIG. 77/1.—Locke Insulator Corporation. High tension insulator tunnel oven. Fuel oil. (Supplied by Allied Engineering.)

To give the reader a clear picture of some details of an open-flame tunnel kiln and a semi-muffle tunnel kiln, a description of two tunnel kilns is given by kind permission of Swindell Dressler Inc.

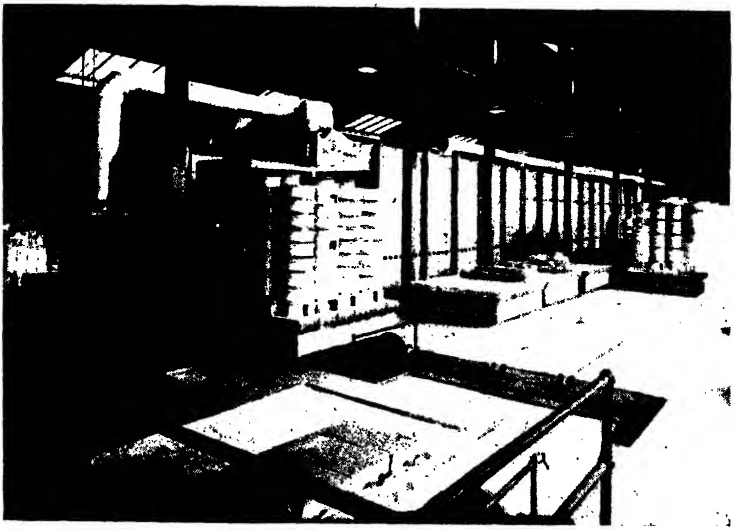


FIG. 77/2.—Locke Insulator Corporation. High tension insulators tunnel oven. Fuel oil. (Supplied by Allied Engineering.)

Description of Typical Open Flame Kiln. The G.E. open-flame kiln at Schenectady has a length of 399 ft. It holds 51 trucks, each 7 ft. 9 in. long. Of the whole length, the firing or furnace zone

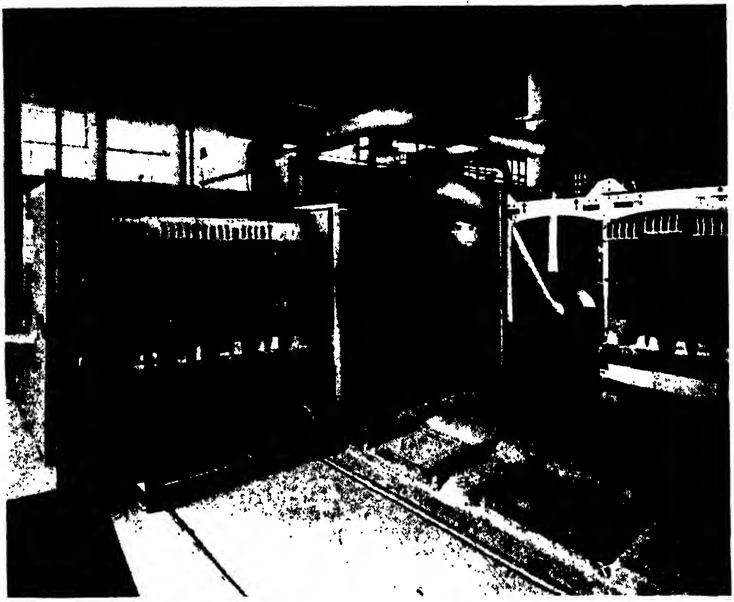


FIG. 77/3.—Tunnel oven. Low tension dry pressed porcelain tunnel oven supplied by Allied Engineering, Cleveland, Ohio. (Akron Porcelain Co., Akron, Ohio.)

FIG. 77/4.—Tunnel oven for electrical porcelain. (Gibbons-Dressler.)

occupies 100 ft. In this region there are 52 burners on each side of the kiln. In addition there are four more burners in the preheating zone on both sides of the furnace extending the length of the firing section by another 40 ft., so that out of a total of 399 ft. about 140 ft. are occupied by the burner zone.

The fuel used is manufactured town gas, having a heat value of 540 British Thermal Units (B.Th.U.) per cubic foot.

The setting space on the truck is 7 ft. 8 in. in length, 5 ft. 8 in. in width and 5 ft. 2 in. in height.

The trucks are moved through the kiln by hydraulic propellers of the vestibule type. A similar propeller is used to return the trucks loaded with fired ware, and the unloaded trucks down the return track to the loading station, near the entrance end of the oven. The main burners are divided into six separate groups, each individually controlled. The first of these groups covers a length of three kiln trucks, whilst the remaining five groups extend over a length of two trucks. Corresponding to the length of each truck in the furnace zone there are four burners on each side (or a total of eight). Of these four are placed at bench level and fired beneath the load. Two are arranged to fire over the top of the loads beneath the kiln crown.

The gases from these burners have no direct impact on the ware. Two other burners are located approximately half-way up the load on the kiln truck and are so placed that they fire into the spaces between the ware on adjacent kiln trucks when the truck train is stationary at the end of the propeller stroke—that means after the whole train has been pushed forward by the length of one truck.

The purpose of these last two burners is to ensure absolute equality of temperature in the height of the load, but the use of these two burners has not been found necessary at Schenectady. The burners are built with nozzles of heat-resisting alloy and are of the low pressure inspirating type. They are fed with gas partially mixed with air. Each group is controlled by an air gas proportioning valve, so as to secure an even distribution of fuel and air.

Air is supplied from a turbo-compressor at constant pressure of 12 oz. The gas supplied is regulated to the same pressure ; about one-third of the air required for combustion is mixed with the gas at the proportioning valves ; the other two-thirds of air required for combustion are drawn through the main hot-air flue (A) (Fig. 78) which connects with the cooling zone of the kiln (see diagram). Each burner has a separate connection to this flue and inspirates through the block (C) the amount of air necessary for complete combustion. The burners are fitted tightly into the kiln wall.

A closed chamber is here formed connected to the flue (A) by the passage (B). The latter is controlled by means of a damper which is kept open when the burner is in use. The combustion air which is drawn in by the burners through the flues (A) is introduced into the interior of the kiln in controlled quantities through a nozzle near the exit end. The flues (A) connect with the interior of the kiln just behind the last burners. The combustion air in its passage through the cooling zone serves to cool the ware and it is self heated to approximately 1,500°F. (830°C.) at which temperature it enters the flues (A) and passes to the burner parts. Each individual burner is equipped with a separate valve and an orifice plate installed in the supply line with connections to a differential gauge. The gauge reading gives the measure of the gas flow at each burner. By this means the fuel consumption at each burner can be controlled and the burner setting quickly determined. Control of the oxidizing, neutralizing or reducing character of the combustion atmosphere is achieved in the following way:

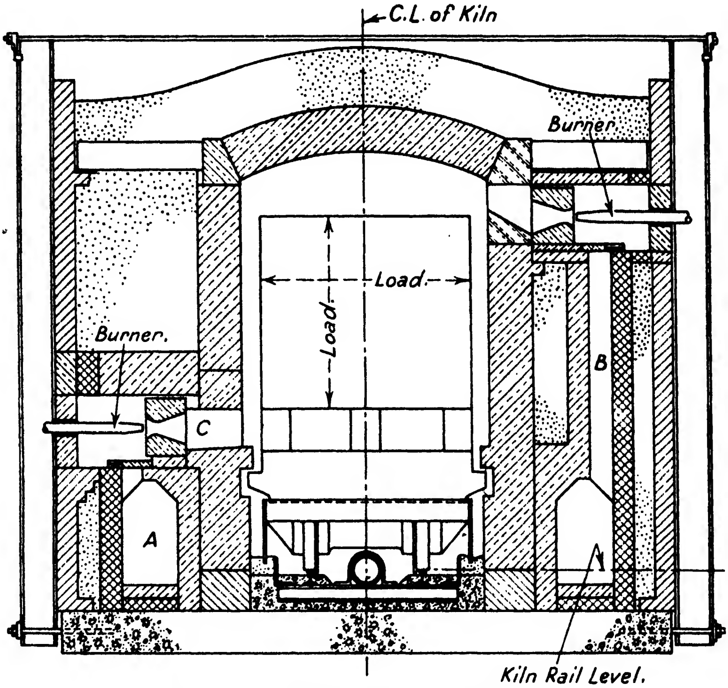


FIG. 78.—Dressler multi-burner kiln.

In the construction of the burners an interior plug is incorporated which permits the velocity of the discharge of the fuel and consequently the suction or inspirating effect to be changed at will.

The kiln atmosphere can be adjusted to different conditions in different sections of the furnace zone controlled by various burner groups. The ware is cooled by two methods: The direct cooling described above, in which the combustion air is preheated, is sufficient to cool the ware. A secondary indirect cooling is effected by drawing air around the inner wall of the cooling zone of the kiln. The cooling zone of the kiln is constructed with cellular side-walls and a thin crown. Suitable controls are provided to regulate the admission of air to the cellular side walls of the kiln at intervals throughout the length of the cooling zone. Hot air is exhausted by means of a cooling fan. This hot air can be used for heating and drying purposes. The final sections of the cooling zone consist of a double wall sealed cooling chamber around which air is circulated and which

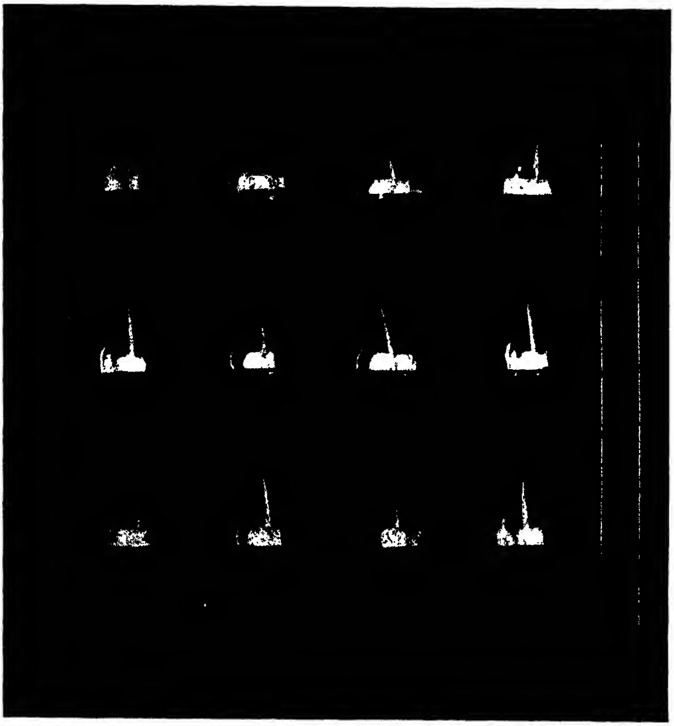


FIG. 79.—Twelve temperature cones to show heat distribution through section of loading space or tunnel kiln car. (Note the equal heat distribution indicated by the cones.) (General Electric Factory, Schenectady.)

permits large pieces of ware to be reduced to a safe temperature before emerging from the kiln.

The heat distribution both in the burner zone and in the preheating zone is very uniform and it has been found practicable to reduce the average temperature difference between the top and bottom of the load to approximately 100° F.

A typical set of test cones is shown (Fig. 79). No greater variation than ½ cone is experienced in practice.

The G.E. kiln is designed to operate on a schedule of 15 trucks per day at a cycle of 80 hours. At an operating condition of 10 trucks per 24 hours the fuel consumption is 190,000 cubic ft. (per 24 hours). The firing temperature is between cone 9 and cone 10.

Description of a Typical Muffle-Kiln. A description of a muffle kiln at the plant of Smith and Stone, Ltd., appeared some time ago in " Clay Products News and Ceramic Record," Toronto, Canada. Since this particular tunnel kiln is an interesting example of all muffle type, a short description is given (Figs. 80 and 80 (*a*)).

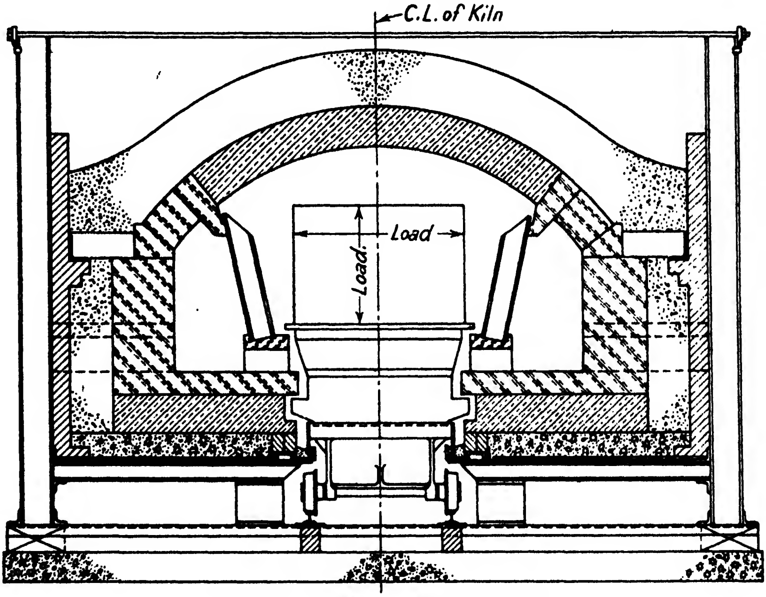


FIG. 80.—Dressler semi-muffle kiln.

The length of the kiln is 110 ft. 6 in. It holds 16 trucks, each 6 ft. 8 in. long, the loading height being 2 ft., the width 2 ft. 6 in. The kiln is a perfect muffle and the atmosphere absolutely pure so that both biscuit and glazed ware are fired satisfactorily in open deck settings, saggers being used only for that portion of the production which consists of small pieces (in which case saggers are often more convenient for placing than the use of decks or slabs supported by posts).

The combustion chamber space is bounded on three sides by the masonry of the bench, haunch wall and base of the kiln arch. The fourth side (facing the ware loading space) consists of a double-walled muffle tile supported upon special bottom pieces of cellular construction. Expansion of the refractory lining which takes place when the kiln is heated up is taken into consideration by providing overlaps of the individual chamber tiles so that the muffle space remains tight at all times : consequently, the ware space is free from products of combustion and the kiln atmosphere is 100 per cent. oxidising.

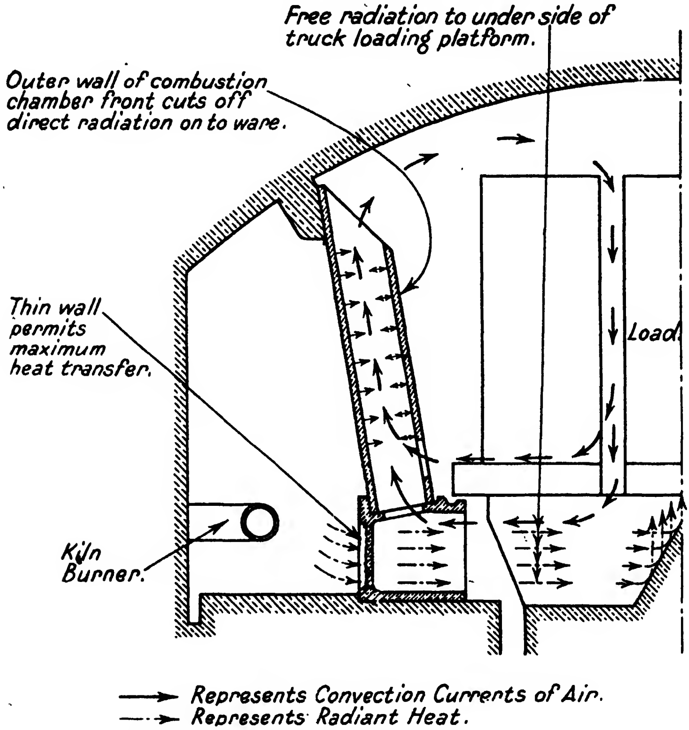


FIG. 80 (*a*).—Dressler " Thrift " muffle-kiln.

The convection air currents between the inner and outer walls of the tile combustion chamber, distribute the heat in a uniform manner throughout the ware space. In some former designs of muffle kilns the lower part of the structure of the kiln truck (when passing through the preheating firing zone of the kiln) absorbed heat continuously. This tended to have a cooling effect on the lower portion of the ware setting. The device adopted in the construction of the tunnel oven under consideration ensures a sufficient excess of heat to the space beneath the ware setting platform to counteract this cooling tendency and to secure a uniform temperature distribution throughout the whole cross-section of the setting space.

The kiln is equipped with two oil burners on each side. In the heating zone carborundum chambers are provided for each burner. In the pre-heating zone the muffles are made of high-grade fire-clay.

The burners are arranged in such a way that the flames are projected down the centre line of the combustion chambers towards the kiln entrance, avoiding direct impact on the muffle and producing an extended zone of heat. The burners are of the low-pressure type. In the cooling zone both direct and indirect cooling of the ware is provided in a similar way to that described in the case of the open-flame kiln.

In order to heat their factory during extraordinarily cold weather Smith and Stone have installed auxiliary fuel fired air heaters feeding into the same system as the waste heat from the kiln. This permits of the entire elimination of steam heat throughout the year and results in considerable savings.

Some Remarks about Dimensions of Tunnel Kilns. Regarding the size of tunnel ovens, it may be said that in the early days the opinion was held that very large units were the most economical ones, that the smaller tunnel ovens did not possess all the advantages of the larger units, and that in particular the fuel consumption of small kilns did not compare favourably with that of the larger kilns. This point of view has, however, been largely abandoned within recent years. The tables on p. 227 give details of the dimensions of tunnel ovens built for insulator factories in the U.S.A. in recent years.

The larger the cross-sectional area of a tunnel kiln the more time it naturally takes for the articles placed in the middle of the truck to follow the rate of temperature increase taking place at the sides of the truck facing the burners.

The trucks cannot, therefore, proceed as quickly through the oven as the outer parts of the ware would allow. They have to travel slowly enough to allow the centre ware, and particularly the lower

Swindell Dressler Corporation, Pittsburgh, Pa.

Name and Location	Kiln length	Setting width	Setting height	Product fired	Fuel	Temperature fired
	ft. in.	ft. in.	ft. in.			
General Electrical, Schnectady (cycle 80 hours 15 trucks per day)	399 0	5 8	5 2	High tension insulators	Gas	Cone 9
General Ceramics Keasbey, New J. (cycle 10–12 hours)	65 0	0 22	0 21	Steatite insulators	Oil	—
American Lava Corpn., Chattanooga, Tenn.	96 0	0 22	0 27	Steatite insulators	Gas	—
Circular Glazing Kiln (cycle 8 ⅓rd hour)	37 0 (mean dia. 14 ft. 6 in.)	0 15	0 18	Steatite insulators	—	Cone 05
Dressler Thrift Muffle Kiln	110 6	0 30	0 24	—	Oil	—

Allied Engineering, Cleveland, Ohio

Name and location	Kiln length	Setting height	Setting width	Product fired	Fuel	Temperature fired
Locke Insulator Corpn., Baltimore (72 - hour cycle capacity, 9 tons in 24 hours)	ft. 265	ft. in. 5 8	ft. in. 5 8	High tension insulators	Oil	Cone 11
Colonial Insulator Co., Akron, Ohio (51-hour cycle—4 tons per 24 hours)	130	in. 42	in. 41	Low and high tension insulators	Gas	Cone 10
Akron Porcelain Co., Ohio (37 - hour cycle—6 per 24 hours)	140	44	44	Low tension dry press porcelain	Gas	Cone 11
Bailey Walker China Co., Bedford, Ohio	46 (mean dia) lengths = 140	55	45	Vitrified china	Oil	Cone 12
Victor Insulators, Inc., Victor, N.Y. (72-hour cycle)	200	53	44	High tension insulators	Oil	Cone 12

part of the centre ware, to reach the same temperature as the hotter parts of the kiln.

In the case of open-flame kilns of large cross-sectional areas, where the heat is convected by long gas flames, the temperature difference between the hottest and coolest parts is smaller than in electric kilns and muffle kilns, in which the heat is only radiated and convected by air currents but not convected directly by the flame. If a certain quantity of calorific units has to be employed solely to keep the hottest part of the kiln for many hours at a given level until the insulators placed in the cooler parts of the truck attain the same temperature, and if this quantity of calorific units does not, at the same time, improve the quality of the insulators placed in the hottest parts, then it is obvious that these calories are not efficiently employed, because they do nothing more than prolong the firing time.

The question arises, therefore, as to how long porcelain articles have to be subjected to that temperature at which vitrification takes place.

This question can be answered experimentally by pushing the trucks at an increasing rate through the kiln and by subsequently investigating how the properties of the porcelain have been influenced by such procedure.

It has been found that acceleration of the speed of travel through the kiln does not detrimentally affect the technical characteristics of insulators and that extremely rapid travel is possible, provided the ware does not emerge from the kiln in too hot a state. In connection with the problem of accelerating the firing cycle, the following considerations have to be borne in mind.

Take the case of a tunnel kiln the design of which provides for the moving forward of a truck every second hour by one truck length. If the speed is increased to one truck length per hour, two drawbacks may be noticed :

Firstly, the ware may leave the kiln red-hot in which case cooling cracks would occur.

Secondly (particularly in the case of kilns of large cross-sectional area) the heat distribution may become less uniform.

The first-mentioned drawback, namely, the ware leaving the kiln before having sufficient time to cool down, can be remedied by making the kiln longer (extending the cooling zone only).

The second drawback mentioned above, namely, that the lower part of the middle of the truck has not sufficient time in which to absorb the same amount of heat as the other parts of the truck, can only be remedied by slowing down the speed of the truck (since it is not possible to decrease the cross-sectional area of an existing tunnel oven).

It can be deduced from these remarks that the ratio of length to cross-sectional area has a very important bearing on the speed at which the ware can be moved through the kiln.

The smaller the cross-sectional area, the quicker a uniform heat distribution can be achieved, and the greater the length of the cooling zone the more time can be allotted for the ware to cool safely down in spite of the increased speed of travel.

As mentioned above, in kilns of large cross-sectional area, a considerable amount of the fuel consumed is not used in properly vitrifying the ware, but it is used in order to ensure a uniform heat distribution.

These conditions explain why, in recent years, kilns possessing small cross-sectional areas and relatively great length have been increasingly installed, particularly for the manufacture of articles of small and medium size. Large insulators, of course, require a kiln of large cross-sectional area.

It is obvious that small tunnel ovens are generally provided in factories where the output is not large enough to justify the erection of large tunnel ovens. In factories with a large production the provision of several smaller units instead of one large unit also offers advantages. It makes production more elastic and adaptable to fluctuating business conditions. If, for instance, orders are coming in very sparsely, and if only one large tunnel kiln is available, the management may be faced with two alternatives : (1) to close down completely ; or (2) to accept orders at risky price-levels in order to get enough work for the large tunnel oven. If, however, several small tunnel ovens are available, it is possible to concentrate on one kiln and to put the remaining kilns out of commission. Although capital expenditure for two small-sized kilns is considerably larger than for one large kiln producing the same amount of ware, the excess expenditure may pay very well under changed market conditions.

Furthermore, a breakdown may occur in a tunnel oven from time to time (fortunately this is rare) and may necessitate the temporary closing down of the kiln. The inconvenience caused by such a happening is, of course, small when several units are in operation.

A kiln may be designed either in the form of a straight-line tunnel or in the form of a circular tunnel. The latter type is a more recent development.

Many circular tunnel ovens are at the present time in operation in the United States, particularly in the china and earthenware industry and also for electrical ceramic materials. Circular tunnel kilns for insulator manufacture were also built in France as far back as 1939.

The answer to the question whether the circular tunnel kiln is more suitable and economical than the straight line kiln depends very much on the local conditions, on the space available and on the lay-out provided for the shaping and drying departments. The principle of design for circular tunnel kilns is the same as that for the straight-line type. The main difference consists in the fact that, instead of trucks carrying the ware through the kiln, the sole of the circular tunnel (like a turn-table lined with heat insulating refractory brickwork) transports the ware through the ovens (Fig. 81).

Fig. 81.—Circular Tunnel Oven (Bailey Walker, Bedford, Ohio), 46 feet mean diameter. Fuel oil. Supplied by Allied Engineering.

Fig. 82 (illustrating a circular tunnel oven designed for firing high frequency ceramics) shows how the ware is placed on the rotating sole.

It is obvious that straight-line tunnel kilns require factory buildings of considerable length. On the other hand, it is frequently easier to link up the straight line tunnel kiln with the flow of production since in the case of the circular kilns entrance and exit ends are very close together.

An advantage of the straight-line tunnel oven is the fact that the trucks required during the week-end can be prepared during the week and it is then only necessary for one worker to stay behind during the week-end to push the trucks into the kiln. This is not possible in the case of a circular tunnel with rotating sole. Here men have to be employed continuously placing ware on the sole as it rotates.

A very interesting new development should be mentioned, viz. the use of radiant burners in connection with gas and oil-fired tunnel

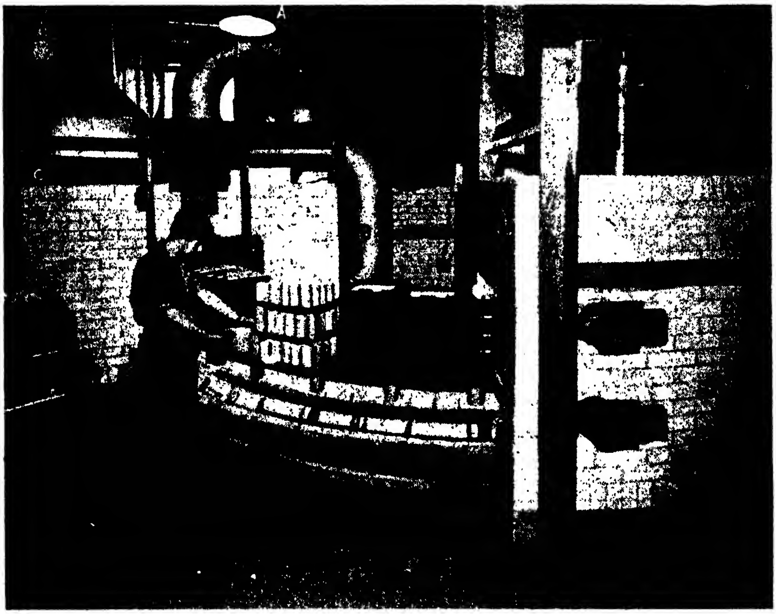


FIG. 82.—Circular tunnel oven.

Fan A, located over the entrance end of the kiln is the exhaust fan. This draws through the insulated duct on each side of the kiln marked B for the right-hand side and C for the left-hand side. The discharge of this fan is marked A. On the cooling side of the kiln is a ware cooling fan, which is not in the photograph. This draws on the bifurcated duct G with a branch to each side of the kiln. Cooling air passes in behind a muffle arrangement in the side walls of the kiln through dampers H, located on both sides near the exit of the kiln. Another set of similar dampers is arranged close to the furnace section of the kiln, the cooling fan exhaust connection being midway between the two sets of inlet dampers on each side of the kiln. The sheet metal pipe I connects from the discharge of the ware cooling fan to a nozzle in the interior of the cooling zone, which serves to push the atmosphere of the kiln towards the entrance end and prevents heat from drifting back from the furnace zone into the cooling zone. (Swindell-Dressler Corporation, Pittsburgh, Pa.)

ovens. The burners are designed in such a way that uniform flameless combustion around the face of the bowl-shaped burner is achieved. Thus the burners heat the ware principally by radiation. A great number of such burners has to be used per kiln. For instance, in a gas-fired circular kiln constructed by Lenox Inc., Trenton, with a mean diameter of 40 ft. (corresponding to a straight kiln length of 125 ft. 8 in.) 104 radiant burners are arranged. The appreciable surface area of these burners produces an effect similar to a muffle heated from outside by long open flames. The advantage of this new design is that a muffle is no longer necessary, since no flame enters the ware space and all the heat is radiated into the inside of the oven by the radiant burners.

For technical porcelain this type of oven may become of importance when glazes have to be used which would suffer under the influence of open flames—where at the present moment muffle tunnel kilns are employed.

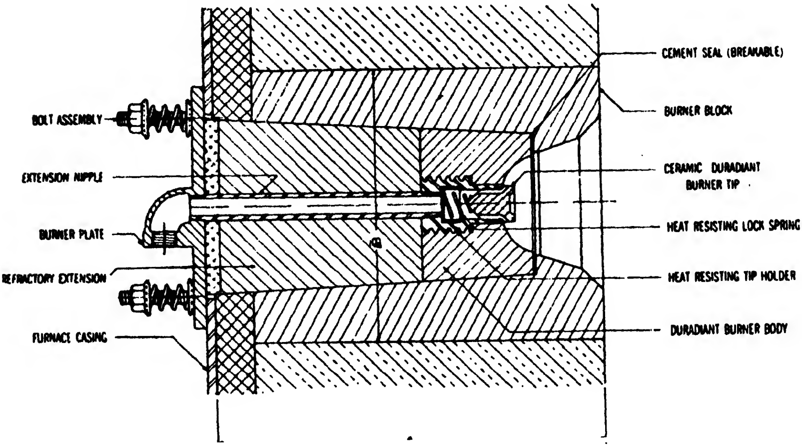


FIG. 82 (*a*).—Duradiant burner assembly Furnace-type ; K510 or K570. (Selas Co., Philadelphia.)

P. TEMPERATURE RECORDING

The temperature control in ceramic kilns is carried out by various means. One has to distinguish between two fundamentally different methods. First, the temperature is measured by pyrometers which indicate the exact temperature prevailing in the kiln at any given moment ; and secondly, the effect of the heat is observed. To appreciate the difference between the two methods, one has to remember that the work done by the heat is not only a factor of the temperature to which the articles are subjected, but is also dependent on the time during which they are subjected to a certain temperature.

Everybody knows that an egg which has been heated for 10 minutes in water at 80°C. becomes much harder than an egg heated, say, for 2 minutes in boiling water at 100°C. Only if heated for the same length of time is the temperature of the water decisive for the hardness of the egg.

With ceramics conditions are very similar. A ceramic body may be vitrified and covered by a transparent glaze when slowly heated to say, 1,300°C., the temperature being increased by 50°C. every hour. It may, however, be still slightly porous and the glaze may still be opaque if the temperature is raised by 500°C. every hour. A pyrometer will in the first case indicate 1,300°C. after 26 hours; in the second case after about 2½ hours. It will, however, not indicate whether the ware has become vitrified. In certain cases it may be of more interest to record the work done by the heat; in other cases it may be more interesting or at least sufficient to record the temperature as such.

It depends, consequently, on the special conditions prevailing as to which method of firing control is the most suitable for the purpose in hand.

(*a*) **Recording of Work Done by Heat.** The work done by the heat may be controlled by observing the deformation of cones or bars or by measuring the shrinkage of unfired ceramic rings caused by the heat.

Seger Cones.—The use of cones made of different ceramic mixtures was introduced by Seger (Staatliche Porzellan, Manufactur, Berlin). They are therefore called "Seger" cones and have the form of a three-sided pyramid. Depending upon their different compositions the cones become soft and bend over at different temperatures. The "squatting" temperature of the cone is reached when its apex is nearly level with its base. The composition of the cones is chosen in such a way that the squatting temperature of one cone having a certain number is 20°–30°C. lower than the squatting temperature of the cone with the next higher number.

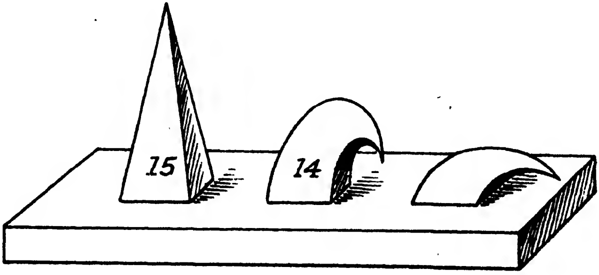


FIG. 83.—Three subsequent cones fired at 13/15.

Fig. 83 shows three Seger cones, numbered 13, 14, and 15, after having been subjected to the temperature of a porcelain kiln. Cone

15 is slightly bent, the apex of cone 14 is level with its base. Cone 13 has become so soft that the number " 13 " which was pressed in it cannot be seen any more, and it lies flat and deformed at the base. The oven temperature was " Cone 14."

The cones have, of course (like all ceramic mixtures), no definite melting or squatting point. The state of softness (called the " squatting " or melting point) is reached after the cone has been subjected for a certain length of time to a certain temperature. Because Seger cones are made of ceramic materials similar to those of which ceramic articles are made and the firing of which has to be controlled, they are very suitable for recording the work done by the heat to the articles to be fired. The shape of the cones when they become soft gives a more reliable indication of the state of the ceramic articles than the reading of the temperature on a pyrometer. As a rule three Seger cones with different numbers are rigidly fixed in vertical position on a ceramic base by means of small pieces of plastic clay, and are then placed in the kiln in such a way as to allow observation of the cones from the outside. One wall of the sagger into which they are placed has to be broken away and the broken sagger placed near an observation hole in the wall so that the cones can be easily observed. Observation holes are arranged in various parts of the kiln, either in the entrance door (in the case of intermittent kilns) or in the walls of the kiln. In tunnel ovens observation holes are made at different places and at various heights in the walls, which allow observation of the various cones, as they pass with the ware.

The following table gives the squatting temperature and composition of the various Seger Cones.

	Composition			Squatting temperature in °C.
022[1]	0·5 Na_2O 0·5 PbO		2 SiO_2 1 B_2O_3	600°
021	0·5 Na_2O 0·25 CaO 0·25 MgO	0·02 Al_2O_3	1·04 SiO_2 1 B_2O_3	650°
020	0·50 Na_2O 0·25 CaO 0·25 MgO	0·04 Al_2O_3	1·08 SiO_2 1 B_2O_3	670°
019	0·50 Na_2O 0·25 CaO 0·25 MgO	0·08 Al_2O_3	1·16 SiO_2 1 B_2O_3	690°
018	0·50 Na_2O 0·25 CaO 0·25 MgO	0·13 Al_2O_3	1·26 SiO_2 1 B_2O_3	710°

	Composition			Squatting temperature in °C.
017	0·50 Na_2O 0·25 CaO 0·25 MgO	0·2 Al_2O_3	1·4 SiO_2 1 B_2O_3	730°
016	0·50 Na_2O 0·25 CaO 0·25 MgO	0·31 Al_2O_3	1·61 SiO_2 1 B_2O_3	750°
015*a*	0·432 Na_2O 0·432 CaO 0·136 MgO	0·34 Al_2O_3	2·06 SiO_2 0·86 B_2O_3	790°
014*a*	0·385 Na_2O 0·385 CaO 0·230 MgO	0·34 Al_2O_3	1·92 SiO_2 0·77 B_2O_3	815°
013*a*	0·343 Na_2O 0·343 CaO 0·314 MgO	0·34 Al_2O_3	1·78 SiO_2 0·69 B_2O_3	835°
012*a*	0·345 Na_2O 0·341 CaO 0·314 MgO	0·365 Al_2O_3	2·04 SiO_2 0·68 B_2O_3	855°
011*a*	0·349 Na_2O 0·350 CaO 0·311 MgO	0·4 Al_2O_3	2·38 SiO_2 0·68 B_2O_3	880°
010*a*	0·338 Na_2O 0·011 K_2O 0·338 CaO 0·313 MgO	0·423 Al_2O_3	2·626 SiO_2 0·675 B_2O_3	900°
09*a*	0·336 Na_2O 0·018 K_2O 0·335 CaO 0·311 MgO	0·468 Al_2O_3	3·087 SiO_2 0·671 B_2O_3	920°
08*a*	0·279 Na_2O 0·038 K_2O 0·369 CaO 0·314 MgO	0·543 Al_2O_3	2·691 SiO_2 0·559 B_2O_3	940°
07*a*	0·261 Na_2O 0·055 K_2O 0·391 CaO 0·293 MgO	0·554 Al_2O_3	2·984 SiO_2 0·521 B_2O_3	960°
06*a*	0·247 Na_2O 0·069 K_2O 0·407 CaO 0·277 MgO	0·561 Al_2O_3	3·197 SiO_2 0·493 B_2O_3	980°
05*a*	0·229 Na_2O 0·086 K_2O 0·428 CaO 0·257 MgO	0·571 Al_2O_3	3·467 SiO_2 0·457 B_2O_3	1,000°

	Composition			Squatting Temperature in °C.
04*a*	0·204 Na_2O 0·109 K_2O 0·458 CaO 0·229 MgO	0·586 Al_2O_3	3·860 SiO_2 0·407 B_2O_3	1,020°
03*a*	0·182 Na_2O 0·130 K_2O 0·484 CaO 0·204 MgO	0·598 Al_2O_3	4·199 SiO_2 0·363 B_2O_3	1,040°
02*a*	0·157 Na_2O 0·153 K_2O 0·513 CaO 0·177 MgO	0·611 Al_2O_3	4·572 SiO_2 0·314 B_2O_3	1,060°
01*a*	0·134 Na_2O 0·174 K_2O 0·541 CaO 0·151 MgO	0·625 Al_2O_3	4·931 SiO_2 0·268 B_2O_3	1,080°
1*a*	0·109 Na_2O 0·198 K_2O 0·571 CaO 0·122 MgO	0·639 Al_2O_3	5·326 SiO_2 0·217 B_2O_3	1,100°
2*a*	0·085 Na_2O 0·220 K_2O 0·599 CaO 0·096 MgO	0·652 Al_2O_3	5·687 SiO_2 0·170 B_2O_3	1,120°
3*a*	0·059 Na_2O 0·244 K_2O 0·630 CaO 0·067 MgO	0·667 Al_2O_3	6·083 SiO_2 0·119 B_2O_3	1,140°
4*a*	0·043 Na_2O 0·260 K_2O 0·649 CaO 0·048 MgO	0·676 Al_2O_3	6·339 SiO_2 0·086 B_2O_3	1,160°
5*a*	0·028 Na_2O 0·274 K_2O 0·666 CaO 0·032 MgO	0·684 Al_2O_3	6·565 SiO_2 0·056 B_2O_3	1,180°
6*a*	0·013 Na_2O 0·288 K_2O 0·685 CaO 0·014 MgO	0·693 Al_2O_3	6·801 SiO_2 0·026 B_2O_3	1,200°
7	0·3 K_2O 0·7 CaO	0·7 Al_2O_3	7 SiO_2	1,230°
8	0·3 K_2O 0·7 CaO	0·8 Al_2O_3	8 SiO_2	1,250°
9	0·3 K_2O 0·7 CaO	0·9 Al_2O_3	9 SiO_2	1,280°
10	0·3 K_2O 0·7 CaO	1·0 Al_2O_3	10 SiO_2	1,300°

	Composition			Squatting temperature in °C.
11	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$1\cdot2\ Al_2O_3$	$12\ SiO_2$	1,320°
12	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$1\cdot4\ Al_2O_3$	$14\ SiO_2$	1,350°
13	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$1\cdot6\ Al_2O_3$	$16\ SiO_2$	1,380°
14	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$1\cdot8\ Al_2O_3$	$18\ SiO_2$	1,410°
15	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$2\cdot1\ Al_2O_3$	$21\ SiO_2$	1,435°
16	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$2\cdot4\ Al_2O_3$	$24\ SiO_2$	1,460°
17	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$2\cdot7\ Al_2O_3$	$27\ SiO_2$	1,480°
18	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$3\cdot1\ Al_2O_3$	$31\ SiO_2$	1,500°
19	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$3\cdot5\ Al_2O_3$	$35\ SiO_2$	1,520°
20	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$3\cdot9\ Al_2O_3$	$39\ SiO_2$	1,530°
26	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$7\cdot2\ Al_2O_3$	$72\ SiO_2$	1,580°
27	$0\cdot3\ K_2O$ $0\cdot7\ CaO$	$20\ Al_2O_3$	$200\ SiO_2$	1,610°
28		Al_2O_3	$10\ SiO_2$	1,630°
29		Al_2O_3	$8\ SiO_2$	1,650°
30		Al_2O_3	$6\ SiO_2$	1,670°
31		Al_2O_3	$5\ SiO_2$	1,690°
32		Al_2O_3	$4\ SiO_2$	1,710°
33		Al_2O_3	$3\ SiO_2$	1,730°
34		Al_2O_3	$2\cdot5\ SiO_2$	1,750°
35		Al_2O_3	$2\ SiO_2$	1,770°
36		Al_2O_3	$1\cdot66\ SiO_2$	1,790°
37		Al_2O_3	$1\cdot33\ SiO_2$	1,825°
38		Al_2O_3	$1\cdot66\ SiO_2$	1,850°
39		Al_2O_3	$0\cdot66\ SiO_2$	1,880°
40		Al_2O_3	$0\cdot33\ SiO_2$	1,920°
41		Al_2O_3	$0\cdot13\ SiO_2$	1,960°
42		Al_2O_3		2,000°

In the above Table the compositions of the Seger cones are given by their molecular formulæ.

Ceramists have the habit of expressing the compositions of glazes by their molecular formulæ. The purpose of this custom is to illustrate the molecular ratio of the several components of the fired glazes.

The formulæ are obtained by bringing the sum of the bases to the total of 1. In other industries the percentage composition of the final products is used to indicate the composition of different materials.

A simple example may illustrate the two methods:

Calcium feldspar (anorthite) has the molecular formula $CaO\ Al_2O_3\ 2SiO_2$.

Its percentage composition is :

20·1 per cent. CaO
36·6 per cent. Al_2O_3
43·3 per cent. SiO_2.

Sodium feldspar (albite) has the molecular formula Na_2O_3 $Al_2O_3\ 6SiO_2$.

The percentage composition is :

11·8 per cent. Na_2O
19·4 per cent. Al_2O_3
68·8 per cent. SiO_2

A mixture of, for instance, 8 parts of Albite with 1 part of Anorthite has then the molecular formula :

$$\begin{array}{l}\left.\begin{array}{l}0{\cdot}8\ Na_2O\\ 0{\cdot}2\ CaO\end{array}\right\}\ 1Al_2O\ 5{\cdot}5SiO_2\\ \hline 1{\cdot}0\end{array}$$

Whereas the percentage composition is :

10·5 per cent. Na_2O
2·4 per cent. CaO
21·5 per cent. Al_2O_3
65·6 per cent. SiO_2

Chemical Composition of Seger Cones and some Remarks on the Usefulness of Ceramic Recipes. Only very few recipes so far as bodies and glazes are concerned are given in this book. The value of recipes for bodies is very limited because the preparation of the raw materials, the fineness of grinding, and the firing temperature and its duration, play such important parts that the recipe is almost meaningless unless full information is given as to all these details.

The value of glaze recipes is very limited because the nature of the body on which the glaze is applied is of great importance and influences the characteristics of the glaze.

Furthermore, it is of great importance whether the body on which the glaze is used is prefired or not, and if prefired at which temperature this prefiring process was carried out. In the case of cones for recording the firing temperature the conditions are not so complicated and for this reason not only the molecular formula but also the percentage composition of the cones is given hereunder.

Knowledge of the composition of the various cones gives very interesting information as to the melting temperature of the various mixtures of those raw materials which are in common use in the Ceramic Industry. Furthermore, it provides Ceramists, who wish to develop glazes for certain maturing temperatures, with a kind of starting point in addition to other interesting information.

For instance, S.C.10 is a suitable glaze for a porcelain body to be fired at S.C.14. At a temperature of 1,300°C. the cone goes down (*i.e.* the apex of the cone touches the base) and at a temperature 110°C. higher, the glaze mixture is viscous enough to cover with a smooth glaze the surface of the porcelain article.

Similar considerations can be applied for other firing temperatures and cones.

For the reasons given above in addition to the molecular composition tabulated on pp. 234–237, the percentage compositions of the Seger cones are given in the following Table, taken from Dr. Singer's Book, " Ceramic Glazes " (Published by Borax Consolidated, Ltd.) :

PERCENTAGE COMPOSITION OF SEGER CONES

No.	Melting point, °C.	Na_2O	K_2O	MgO	CaO	B_2O_3	Al_2O_3	SiO_2
021	650	16·3	—	5·3	7·4	36·86	1·08	33·02
020	670	15·96	—	5·19	7·21	36·03	2·11	33·52
019	690	15·26	—	4·96	6·90	34·5	4·02	34·41
018	710	14·47	—	4·70	6·54	32·67	6·19	35·45
017	730	13·48	—	4·38	6·10	30·41	8·91	36·71
016	750	12·22	—	3·96	5·52	27·59	12·74	38·25
015*a*	790	9·46	—	4·53	8·56	21·3	12·3	43·9
014*a*	815	9·23	—	3·58	8·34	20·8	13·5	44·7
013*a*	835	8·74	—	5·21	7·88	19·8	14·3	44·1
012*a*	855	8·07	—	6·35	7·20	17·90	13·90	46·6
011*a*	880	7·55	—	4·37	6·68	16·7	14·3	50·40
010*a*	900	6·92	0·34	4·17	6·27	15·7	14·30	52·40
09*a*	920	6·21	0·51	3·73	5·61	14·10	14·30	55·60
08*a*	940	5·65	1·15	4·15	6·79	12·80	19·4	53·10
07*a*	960	4·94	1·58	3·59	6·66	11·20	17·20	54·90
06*a*	980	4·49	1·91	3·29	6·69	10·10	16·80	56·70
05*a*	1,000	3·98	2·28	2·92	6·74	8·99	16·40	58·70
04*a*	1,020	3·35	2·72	2·43	6·88	7·52	15·80	61·40
03*a*	1,040	2·90	3·09	2·06	6·82	6·36	15·30	63·50
02*a*	1,060	2·32	3·43	1·70	6·86	5·24	14·80	65·70
01*a*	1,080	1·84	3·64	1·35	6·73	6·38	14·20	66·00
1*a*	1,100	1·45	4·02	1·06	6·89	3·27	14·10	69·30
2*a*	1,120	1·08	4·27	0·80	6·93	2·45	13·60	70·80
3*a*	1,140	0·72	4·53	0·53	6·95	1·64	13·50	72·30
4*a*	1,160	0·51	4·69	0·37	6·96	1·15	13·22	73·20
5*a*	1,180	0·33	4·82	0·24	6·97	0·73	13·10	73·90
6*a*	1,200	0·15	4·93	0·10	6·99	0·33	12·90	74·60

No.	Melting pointing, °C.	K_2O	CaO	Al_2O_3	SiO_2
7	1,230	5·05	7·0	12·75	75·38
8	1,250	4·37	6·22	12·92	76·40
9	1,280	4·3	5·6	13·1	77·30
10	1,300	3·66	5·08	13·3	78·1
11	1,320	3·09	4·30	13·50	79·20
12	1,350	2·68	3·72	13·6	80·0
13	1,380	2·36	3·28	13·7	80·7
14	1,410	2·12	2·94	13·8	81·4
15	1,435	1·82	2·54	13·9	81·8
16	1,460	1·61	2·23	13·99	82·2
17	1,480	1·43	2·0	14·01	82·6
18	1,500	1·25	1·74	14·05	82·96
19	1,520	1·11	1·54	14·10	83·26
20	1,530	1·00	1·39	14·15	83·65
26	1,580	0·55	0·76	14·31	84·39
27	1,610	0·2	0·28	14·42	85·10

No.	Melting point, °C.	Al_2O_3	SiO_2
28	1,630	14·5	85·5
29	1,650	17·5	82·5
30	1,670	22·0	78·0
31	1,690	25·3	74·7
32	1,710	29·8	70·2
33	1,730	36·1	63·9
34	1,750	40·4	59·6
35	1,770	45·8	54·2
36	1,790	50·5	49·5
37	1,825	56·0	44·0
38	1,850	62·9	37·1
39	1,880	71·98	28·02
40	1,920	83·7	16·3
41	1,960	92·88	7·12
42	2,000	100·0	—

Messrs. Harrison & Son (Hanley, Stoke-on-Trent), Manufacture “ Staffordshire Seger Cones,” their numbers correspond to the temperatures given above.

In the United States Seger cones have been modified and are termed Orton Cones. The following table gives the various American Orton Cones and their squatting temperatures :

ORTON CONES

TEMPERATURE EQUIVALENTS OF CONES

	When fired slowly, 20° per hour		When fired rapidly, 150° per hour	
Cone No.	°C.	°F.	°C.	°F.
	The Soft Series			
022	585	1,085	605	1,121
021	595	1,103	615	1,139
020	625	1,157	650	1,202
019	630	1,166	660	1,220
018	670	1,238	720	1,328
017	720	1,328	770	1,418
016	735	1,355	795	1,463
015	770	1,418	805	1,481
014	795	1,463	830	1,526
013	825	1,517	860	1,580
012	840	1,544	875	1,607
011	875	1,607	905	1,661
	The Low Temperature Series			
010	890	1,634	895	1,643
09	930	1,706	930	1,705
08	945	1,733	950	1,742
07	975	1,787	990	1,814
06	1,005	1,841	1,015	1,859
05	1,030	1,886	1,040	1,904
04	1,050	1,922	1,060	1,940
03	1,080	1,976	1,115	2,309
02	1,095	2,003	1,125	2,057
01	1,110	2,030	1,145	2,093
	Intermediate Temperature Series			
1	1,125	2,057	1,160	2,120
2	1,135	2,075	1,165	2,129
3	1,145	2,093	1,170	2,138
4	1,165	2,129	1,190	2,174
5	1,180	2,156	1,205	2,201
6	1,190	2,174	1,230	2,246
7	1,210	2,210	1,250	2,282
8	1,225	2,237	1,260	2,300
9	1,250	2,282	1,285	2,345
10	1,260	2,300	1,305	2,381
11	1,285	2,345	1,325	2,417
12	1,310	2,390	1,335	2,435
13	1,350	2,462	1,350	2,462
14	1,390	2,534	1,400	2,552
15	1,410	2,570	1,435	2,615
16	1,450	2,642	1,465	2,669
17	1,465	2,669	1,475	2,687
18	1,485	2,705	1,490	2,714
19	1,515	2,759	1,520	2,763
20	1,520	2,768	1,530	2,786

The High Temperature Series

	When heated at 100° per hour	
Cone No.	°C.	°F.
23	1,580	2,876
26	1,595	2,903
27	1,605	2,921
28	1,615	2,939
29	1,640	2,984
30	1,650	3,002
31	1,680	3,056
32	1,700	3,092
32½	1,725	3,137
33	1,745	3,173
34	1,760	3,200
35	1,785	3,245
36	1,180	3,290
37	1,820	3,308
38	1,835	3,335
39	1,865	3,389
40	1,885	3,425
41	1,970	3,578
42	2,015	3,659

Holdcroft's Thermoscope. Apart from the cones described above, one can use the so-called Holdcroft's Thermoscopes. These are small rectangular bars which are mounted horizontally and supported at each end. When the squatting temperature is reached, the bars get soft and sag in the middle. The approximate bending temperatures of Holdcroft's Thermoscope bars are indicated in the following Table.

HOLDCROFT'S THERMOSCOPE BARS

(Approximate Bending Temperatures)

	Temperature			Temperature	
Bar No.	°C.	°F.	Bar No.	°C.	°F.
1	600	1,112	22	1,080	1,976
2	650	1,202	23	1,100	2,012
3	670	1,238	24	1,120	2,048
4	700	1,292	25	1,140	2,084
5	730	1,346	26	1,200	2,192
6	760	1,400	26*a*	1,230	2,246
7	790	1,454	27	1,250	2,282
7*a*	810	1,490	27*a*	1,270	2,318
8	840	1,544	28	1,280	2,336
9	860	1,580	29	1,300	2,372
10	875	1,606	30	1,325	2,415
11	890	1,634	31	1,350	2,462
12	905	1,660	32	1,380	2,516
13	920	1,688	33	1,430	2,606
14	935	1,715	34	1,460	2,660
15	950	1,742	35	1,475	2,688
16	960	1,760	36	1,490	2,714
17	970	1,778	37	1,505	2,740
18	985	1,806	38	1,520	2,768
19	1,000	1,832	39	1,535	2,796
20	1,040	1,904	40	1,550	2,823
21	1,060	1,940	—	—	—

BULLER'S RINGS

Buller's Firing Trial Rings indicate the work done by the heat by their radial contraction which is dependent on the temperature. They are manufactured for kiln control for temperatures between 960°–1,300°C. and are made of a body having a regular and uniform contraction. When the unfired rings are subjected to the rising temperature of the oven during the smoking or dehydration period they first expand and then contract until they regain their original diameter. With the further rise of temperature the rings then continue to shrink, the amount of contraction at any given time being dependent upon the temperature reached and the rate at which this temperature is reached. In other words, a given contraction is the result of a certain temperature having been effective over a certain period of time.

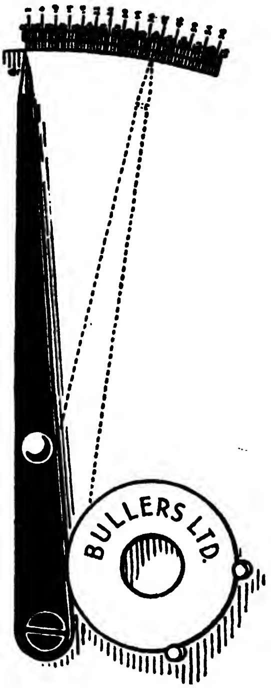


Fig. 84 (*a*).—Gauge for Buller's ring.

A gauge (Fig. 84 (*a*)), indicates which temperature (or more exactly which temperature work) corresponds to the various sizes of the rings after firing and subsequent cooling; it consists of a brass plate upon which is engraved the scale and upon which is mounted the pointer or indicator. The tables on the scale are numbered from 0–60 to the right and from 0–5 to the left. Readings to the left indicate expansion and to the right contraction. Before firing, the ring measures 2½ in. in diameter and registers 0 on the gauge.

The temperature chart below shows the temperatures corresponding to the various gauge readings:

Approximate Temperatures

	°C.
Ring measuring 1 on gauge	960
,, ,, 5 ,,	1,000
,, ,, 10 ,,	1,030
,, ,, 15 ,,	1,065
,, ,, 20 ,,	1,100
,, ,, 25 ,,	1,135
,, ,, 30 ,,	1,170
,, ,, 35 ,,	1,200
,, ,, 40 ,,	1,240
,, ,, 45 ,,	1,275

Buller's rings are more convenient than cones in various respects and have the following advantages :

Firstly, they take up much less room.

Secondly, whereas one has always to use at least two or three different cones in the same sagger, one ring is sufficient for controlling one stage.

Thirdly, the cones have to be affixed very carefully in a vertical position on bases of refractory material, whereas the rings can be put in any position into the saggers or in other places where temperature recording is desired.

Fourthly, they are very cheap.

Furthermore, if in the case of an intermittent oven the firing process (from the soaking period until the conclusion of the firing) has to be controlled at various stages, one can put sufficient rings in one sagger, the front wall of which has to be broken away so that the individual rings can be easily drawn at desired periods with a hooked trial rod (see Fig. 84 (*b*)).

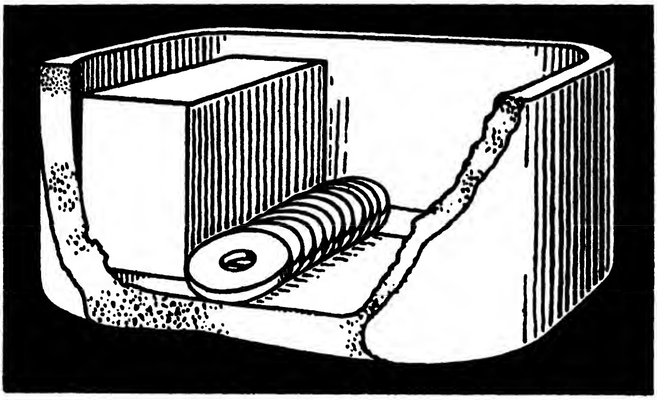


FIG. 84 (*b*).—Sagger with Buller's rings for controlling various firing stages.

(*b*) **Measuring the Temperature.** If the temperature itself (and not the work done by the temperature) has to be measured pyrometers are used, in the ceramic industry, as in other industries. If, for instance, the temperature in the various parts of a tunnel kiln have to be regularly controlled and recorded pyrometers are more convenient than cones or rings.

There are thermo-electric, optical and radiation pyrometers in use. The thermo-electric pyrometer consists of a thermo-couple, a millivoltmeter calibrated in degrees and a pair of connecting leads. The thermo-couple consists of two wires of any two different metals joined together at one end. The junction of the two wires when heated produces an E.M.F. between the junction and the other end. The E.M.F. produced by the thermo-couple is proportional to the difference in temperature between the hot and the cold junctions.

The materials commonly employed for thermo-couples used for ceramic kilns are pure platinum for one wire and platinum-rhodium alloy for the other. This thermo-couple allows of the measuring and recording of temperatures up to 1,600°C. The two wires are surrounded by ceramic insulating beads. The whole is placed inside a ceramic refractory tube and a final sheath, also made of refractory heat-resisting ceramic material or of fused quartz, placed over the whole appliance. The thermo-couple may be connected to a simple indicator, a recorder or an automatic temperature controller.

Optical pyrometers are based on the principle that the intensity of light emitted by the body which has to be measured is compared with the light emitted by a standard lamp. When using the instrument one has to sight it on to the body to be measured and adjust a variable resistor until the brightness of the lamp is exactly equal to the brightness of the body to be measured. At this point the filament becomes invisible against the background formed by the radiant heat of the article to be measured. These optical pyrometers are very handy and portable. No careful setting is required but they cannot be connected with a recording or controlling instrument.

Radiation pyrometers consist of a thermo-couple wire connected to an indicator similar to that used with thermo-electric pyrometers, but the hot junction is not put directly into the kiln as is the case with thermo-electric pyrometers—the junction is heated by radiation from the article to be measured. The heat rays enter through the opening of the pyrometer and are focussed by a concave mirror on to the thermo-couple.

Focussing of the concave mirror is effected by rotating a knob which causes the concave mirror to move backwards and forwards. The pyrometer may be connected as in the case of a thermo-electric pyrometer to an indicator, recorder or automatic controller.*

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* Pyrometers, "The Electrical Encyclopedia," The Waverley Book Co., London.

CHAPTER IX

CERAMIC HIGH FREQUENCY MATERIALS

EVERY insulator coming within the influence of an alternating electric field consumes a certain amount of electrical energy and transforms it into heat. Losses occur.

As mentioned in previous chapters, when the lost energy (N) is only a small proportion of the total energy it is given nearly enough by the equation :

$$N = V^2 2\pi f C \tan \delta$$

where V is the voltage, f the frequency, C the capacity, $\tan \delta$ the tangent of the loss angle or the power factor of the insulating material.

The capacity (C) of the insulating material is determined first by the dielectric constant of the insulating material, and secondly, by the shape and size of the insulator and the electrodes. The dielectric constant at radio frequencies of most insulating materials (with the exception of some ceramic condenser materials referred to later) is between 5–10.

It follows from the above equation that the energy lost in an insulator increases with the square of the voltage and with the frequency. It is furthermore dependent on the loss angle or power factor of the insulating material in question. Each insulating material has its own power factor, which in many cases increases with increasing frequency and with increasing temperature.

It can therefore be seen how very important are the influences of frequency and power factor on the energy lost in insulating materials.

To give a practical example :

A high tension bushing manufactured of porcelain (the power factor of which is about 100×10^{-4} at low frequencies) and having a capacity of 5 p.F. would, at a voltage of 10 kV. at 50 cycles, consume about 1·5 milliwatt. At 50×10^6 cycles it would, however, consume 1·5 kW., which loss would very quickly increase owing to the heat caused by the heavy consumption of energy—energy which is in this case entirely wasted.

It is quite obvious that such a bushing would form a very weak point in a high tension high frequency circuit because the insulating material would soon break down owing to the heat developed by the high power factor of the insulating material. A substance possessing a sufficiently low power factor and (as far as possible) independent of frequency and temperature, should be used instead, in order to keep the high frequency losses of the bushing down.

It has to be borne in mind that for low frequencies porcelain is a highly satisfactory and useful insulating material, suitable at these frequencies for the most severe working conditions. For high frequencies, however, it should, in view of its high power factor, be replaced by other materials having a low power factor and at least the same favourable mechanical characteristics. The power factor is not the only material constant that has to do with the absorption of power. Since air has a smaller power factor than even the best solid insulating material, it is very often essential to use insulators of the smallest possible size. This requirement makes good mechanical characteristics of the insulating material extremely important.

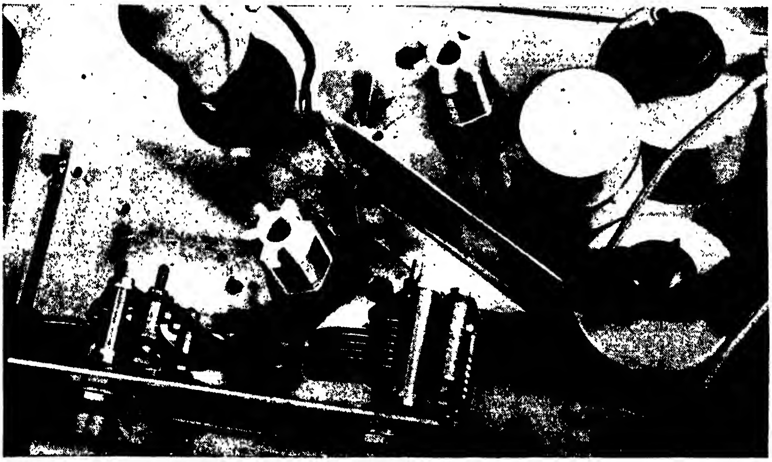


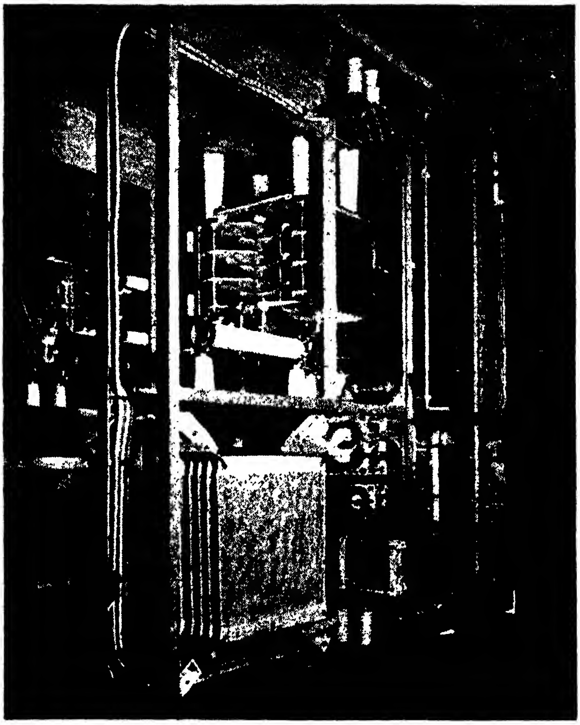
Fig. 85.—Early application of ceramic coilformer in receiving set designed and built by J. E. Nickless. (Bullers, Ltd.)

When considering the example given above for porcelain bushings, it should be noted that porcelain, at both low and high frequencies, has a much lower power factor than most of the insulating materials used in high frequency oscillatory circuits not many years ago.

The foregoing remarks illustrate the importance of the very great improvements achieved by the ceramic industry and by scientific ceramic research work. High frequency ceramics have been developed within recent years which meet all the requirements called for by the high frequency technique.

The various ceramic materials developed within recent years for high frequency purposes may be classified under five groups :

(1) Insulating materials with particularly low power factor, average dielectric constant and high mechanical strength for general use as high frequency insulators and as insulating and spacing parts and for the manufacture of components such as coilformers, bases of trimmer condensers, wave-range switches, crystal holders, air-tuning condensers, variometers, spacers for coaxial cables, etc. (*Clinoenstatite Group*).



(By Courtesy of Marconi's Wireless Telegraph Company, Ltd.)

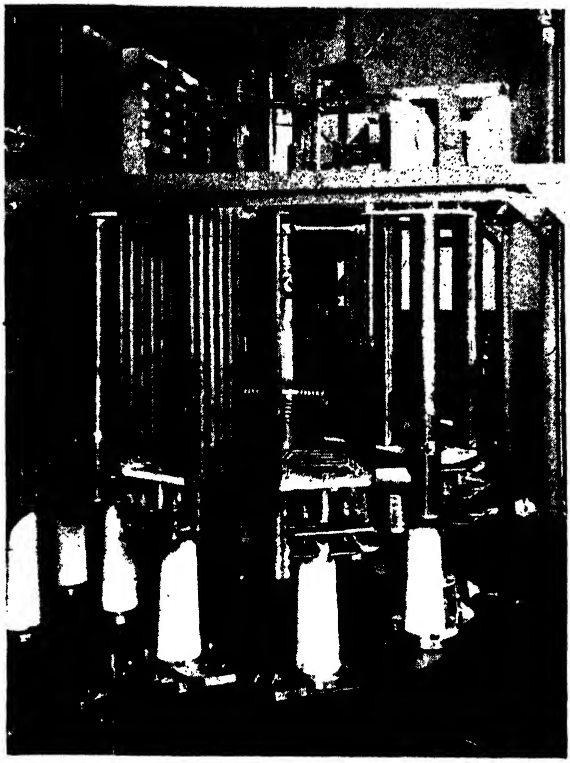
FIG. 85 (*a*).—Part of a transmitter manufactured by Marconi Wireless Telegraph Company, showing the use of high tension insulators made of high frequency ceramic material. (Bullers, Ltd.)

(2) Insulating material possessing unusually low thermal coefficient of expansion, low dielectric constant and relatively low power factor (*Cordierite Group*).

(3) Insulating materials having a particularly low power factor and very high dielectric constant and a negative temperature co-

efficient of the dielectric constant, for the manufacture of high frequency condensers for low and high tension (*Rutile Bodies*).

(4) Insulating material with low power factor, a dielectric constant higher than the Clinoenstatite materials but lower than that of the Rutile group materials, and a slightly negative temperature coefficient of the dielectric constant. The temperature coefficient of the dielectric constant can be graded so that medium and slightly negative temperature coefficients are available (*Magnesium Orthotitanate Group*).



(By Courtesy of Marconi's Wireless Telegraph Company, Ltd.)

FIG. 85 (*b*).—Part of a transmitter manufactured by Marconi Wireless Telegraph Company, showing the use of high tension insulators made of high frequency ceramic material. (Bullers, Ltd.)

(5) Slightly porous insulating materials possessing at high temperatures a low power factor and high Ohmic resistance, which do not release air in vacuo at high temperature for valve spacer and other components used in electronic tubes (*Low loss porous group*).

A. CLINOENSTATITE GROUP

Steatite as manufactured for many years, especially on the Continent, consists mainly of talcum (very often called Soapstone), a hydrous magnesium silicate (3 MgO 4 $SiO_2.H_2O$). Talcum (soapstone) is a plastic material which for many purposes has to be mixed with a small quantity of clay in order to make it more plastic. Clay acts as a flux (this will be explained later) when added in small quantities to talcum. In addition, feldspar is added in order to produce at a firing temperature of about 1,400°C. an absolutely dense and vitrified material.

The structure of the fired Steatite material is much more homogeneous than that of porcelain, and consists to a very great extent of Clinoenstatite crystals—a magnesium silicate of the composition MgO SiO_2 and a feldspatic glass matrix. The power factor of this type of Steatite at Radio frequencies is about 20×10^{-4} tan δ being much smaller than that of porcelain (100×10^{4}). This type of Steatite was, therefore, extensively used as an insulating material in the early stages of short-wave apparatus manufacture, but the increasing technical requirements of the short-wave industry made the development of materials possessing a still lower power factor than Steatite necessary. The structure of these original fired Steatite materials is, as mentioned above, made up as follows :

(1) Clinoenstatite crystals.

(2) Feldspatic glass matrix. This glassy matrix is formed at the firing temperature (1,400°C.) by fused feldspar which dissolves the silica set free by the dissociation of the clay substance and of the talcum. This feldspatic glass to a very considerable extent prevents the Clinoenstatite crystals from imparting their favourable dielectric characteristics to the fired body.

By omitting the feldspar as a flux, and using the fluxes mentioned below, the resultant structure can be made more homogeneous and crystalline, consisting almost exclusively of pure Clinoenstatite crystals. On this principle the improved Clinoenstatite bodies are based. It has been proved that the various dielectric characteristics are more favourable the greater the number of crystals per unit area, and the more equal their sizes. In the case of improved Steatite bodies, feldspar is replaced by fluxes (such as Barium, Strontium, Magnesium compounds) which at the same time act as crystallizers forming more Clinoenstatite crystals than would otherwise be formed.

As previously mentioned, all ceramic materials manufactured mainly of talcum and soapstone were formerly called " Steatite " bodies. Since this word has, however, subsequently been used for all kinds of ceramic materials containing the above-mentioned magnesium silicate, the author prefers to call these improved dense bodies after the crystal which predominates in their structure, " Clinoenstatite bodies."

Resultant electrical properties are entirely a function of the degree and nature of the crystallization. X-ray analyses have proved that there are, for instance, various modifications of the Clinoenstatite crystal denominated α and β. β Clinoenstatite is called " Protoenstatite " by various investigators. Under normal firing conditions, and if the soapstone content of the body mixture is a very high one, primarily Clinoenstatite of the α modification is formed, but a long firing may transform a certain proportion of the Clinoenstatite crystals into the β modification, which causes the power factor to deteriorate, probably because a mixture of various crystals does not give as homogeneous a structure as a single-crystal structure.

The trade names given by the different manufacturing firms to the various improved Clinoenstatite bodies are as follows :

Bodies	Bullers	Steatite and Porcelain Products	Taylor Tunnicliff	Continental	(*a*) U.S.A. Isolantite Inc. (*b*) Lava Corpn. (*c*) Gen. Ceramics
Clinoenstatite	Frequalex	Frequentite	H.F. 20 Ceramic	Calit Frequenta Rosalit	(*a*) Isolantite (*b*) AlSiMag 35 ,, 196 ,, 197 ,, 211 (*c*) Steatite and Ultra Steatite

Figs. 86 (*a*) to 86 (*i*) illustrate various components for High Frequency apparatus made of Clinoenstatite bodies.

Some interesting information about Steatite manufacture in Germany is contained in an article by Dr. E. Albers-Schonberg, Keramische Rundschau (January, 1943).

The article touches on the following subjects :

(1) The jollying of large hollow support insulators used in Wireless Transmitter Stations.

(2) The extrusion (and tolerances) of rod shaped strain insulators for insulating the antennæ at transmitter stations.

(3) Tubes for condensers.

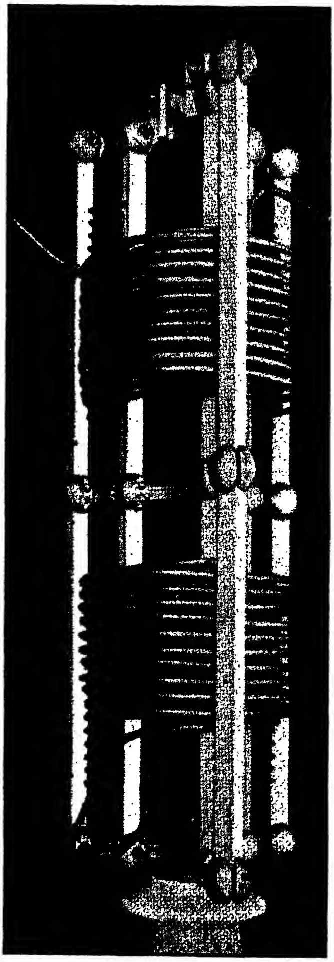


Fig. 86 (*a*).—A coil measuring 3 metres by 1 metre for a short-wave transmitter assembled on a ceramic former.

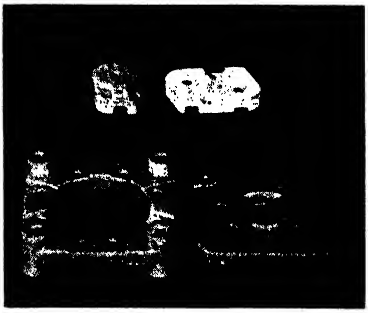


Fig. 86 (*b*).—Ceramic valve holders and (top) parts for trimmer condensers.

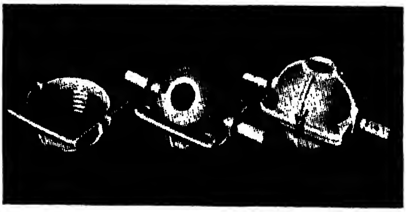


Fig. 86 (*c*).—Variable inductance.

Fig. 86 (*d*).—Metal coil deposited on ceramic coilformer and other components made of ceramic material.

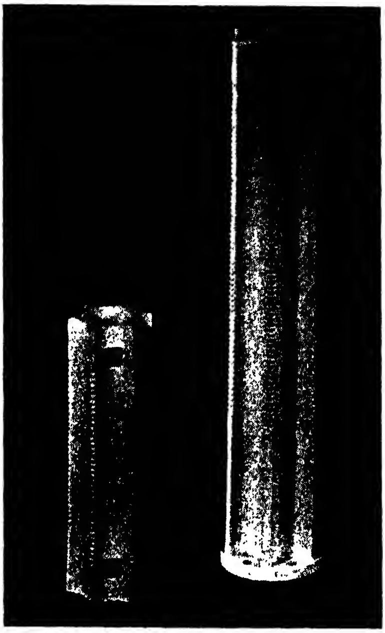


FIG. 86 (*e*).—Long ceramic coilformers.

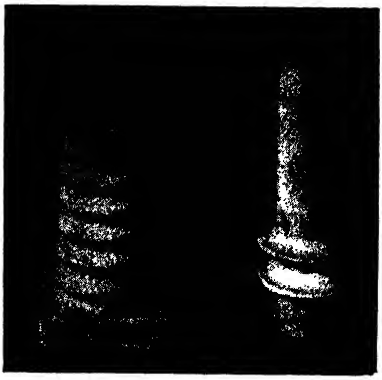


FIG. 86 (*f*).—H.T., H.F. stand-off insulator and shell for condenser.

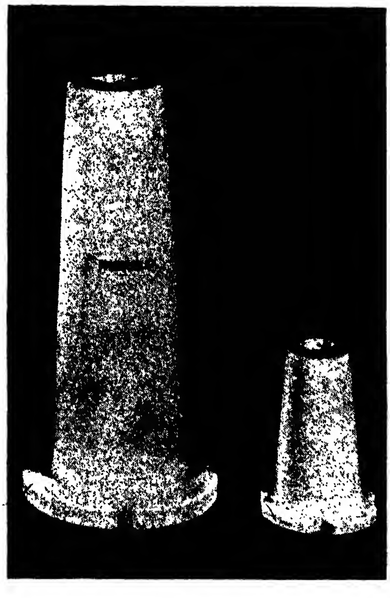


FIG. 86 (*g*).—Stand-off insulators for H.F. transmitters.

(4) Automatic dry pressing for mass production.

(5) Grinding tolerances.

(*a*) It is reported that the largest Steatite articles produced by the jollying process have a height of 1 metre, a diameter of 1 metre and a maximum wall thickness of 190 mm.

Although larger porcelain insulators are manufactured, it is interesting to note that the weight of the biggest Steatite insulators can be as much as 250 kilograms.

(*b*) The thinnest rods which can be extruded in Steatite have a diameter of only 0·3 mm. The largest have a diameter of 80 mm., a length of 2 metres and weigh 30 kilograms each.

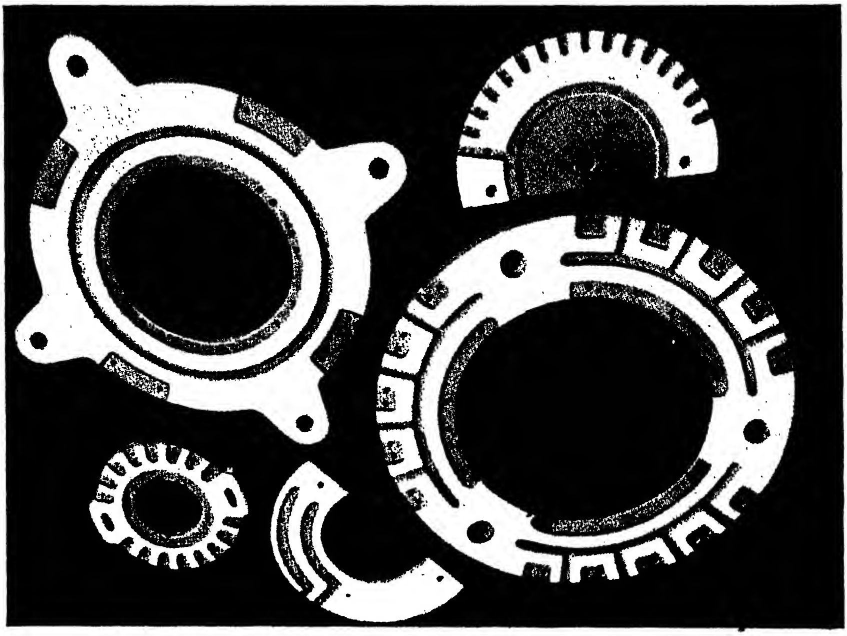


FIG. 85 (*h*).—Ceramic parts for wave range switches with burnt on metal coatings.

Rods having diameters varying from 1·5 mm. to 10 mm. can be ground to an accuracy of 0·01 mm. tolerance, although in certain cases the tolerance has to be as low as 0·003 mm. To achieve such accuracy, centreless grinding is used.

(*c*) Tubes used for condensers are usually made in various diameters and in lengths varying between 20 and 40 mm.

For tubes of outside diameters greater than 5 mm. the minimum wall thickness is 0·4 mm., but for tubes less than 5 mm. outside diameter, the wall thickness can be as low as 0·2 mm.

(*d*) The bulk production of Steatite articles is by dust pressing, and mass production is carried out in automatic presses.

Where single dies are used, as many as 1,000 to 1,200 pieces can be pressed per hour. If the articles are small enough, multiple dies can be used, and in this case the production figure given above has to be multiplied by the corresponding factor.

The dimensions obtained on medium-sized dust-pressed articles are as a rule within ±2 per cent. of the desired figures. For smaller articles the percentage figure is, of course, slightly more, and for larger articles it is slightly less. If the pressing tolerances have to be kept within very narrow limits, subsequent grinding has to be carried out.

(*e*) Most of the grinding methods used at present in the metal and optical industries are also used for grinding Steatite articles.

Plain and parallel grinding is also carried out in mass production. For instance, disks having a diameter of 10 mm. are ground plain and parallel, the deviation from the parallel being only 0·03 mm.

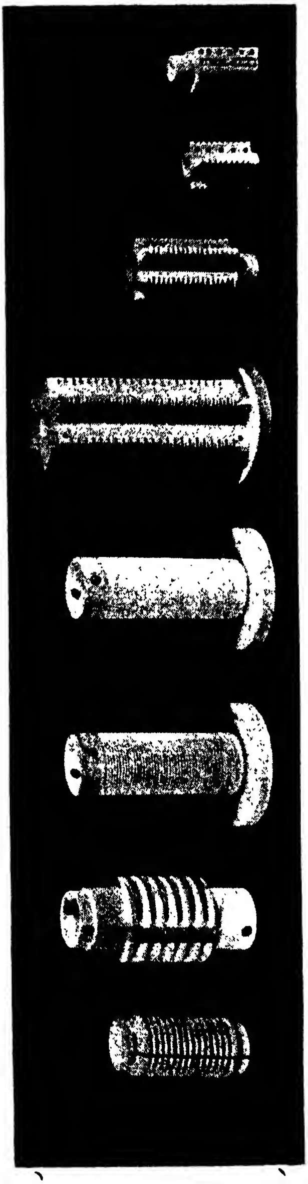


Fig. 86 (*i*).—A set of coilformers in ceramic material. On the left is a former for an H.F. choke. (Messrs. Bullers, Ltd.)

The Technical Characteristics of Improved Clinoenstatite Type Bodies are given below :

Specific gravity	2·6–2·7
Density, lb. per in.^{3}	0·094–0·098
Water absorption in per cent.	0·08–0·00
Softening temperature °C	1,400–1,450
„ „ °F.	2,552–2,642
Linear coefficient of thermal expansion between per °C.	$6{\cdot}2$–$7{\cdot}7 \times 10^{-6}$
Tensile strength, lb. per in.^{2}	7,500–10,000
Compressive strength, lb. per in.^{2}	65,000–85,000
Modulus of rupture, lb. per in.^{2}.	18,000–22,000
Resistance to impact, ft. lb. per in.^{2}	1·8–2·1
Thermal conductivity cal./sec./cm. per °C.	0·006
Dielectric strength (60 cycles test discs ¼-in. thick, volts per mil)	210–240
Volume resistivity at 700°C. (1,292 °F.) in Ohms per cm.^{3}	$2{\cdot}3 \times 10^4$–$4{\cdot}2 \times 10^6$
Dielectric constant 10 M.C.	5·8–6·0
Power factor 10 M.C. per cent.	0·06–0·01
tan $\times 10^{-4}$	6–1
Capacity change per °C. $\times 10^{-6}$	+140–+160

The variations of volume resistivity with varying temperatures of several Clinoenstatite bodies manufactured by the American Lava Corporation is given in Fig. 87. The change of dielectric strength of the same type of bodies per mil thickness for varying thicknesses, and the change of dielectric strength with temperature for test pieces

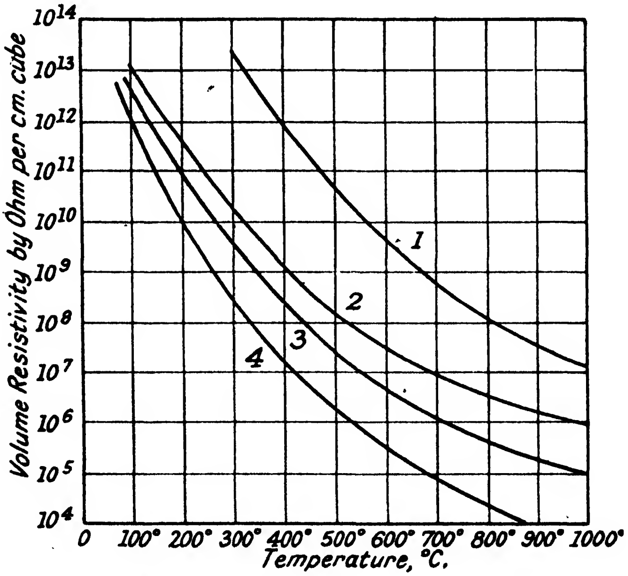


FIG. 87.—Volume resistivity of 4 Clinoenstatite bodies (Alsimag) with varying temperatures, composition 1 has at the same time the lowest power factor (0·01 per cent.), composition 4 the highest power factor (0·18 per cent.) of the four compositions at 10 M.C.

of $\frac{1}{16}$ in. thickness, are referred to in the chapter dealing with breakdown strength of ceramic insulating materials generally.

The figures with regard to the power factor relate to room temperature and dry atmosphere. Fig. 87 (*a*) shows the dependence of the power factor of various dense ceramic materials on varying temperatures between Zero and 100°C. Fig. 87 (*b*) shows the dependence of the power factor of bodies 3, 4, and 5 on varying temperatures between 100°C. and 300°C. The Clinoenstatite bodies (with the exception of feldspar containing Steatite), the rutile and magnesium Orthotitanate bodies (which will be described later on) hardly change their power factor between Zero and 100°C. Between 100°C. and 300°C. the power factor of the improved Clinoenstatite bodies and Magnesium-Orthotitanate bodies rises only very slightly. This is a very important characteristic of these ceramic materials. Organic high frequency materials such as the so-called plastics cannot be used at elevated temperatures.

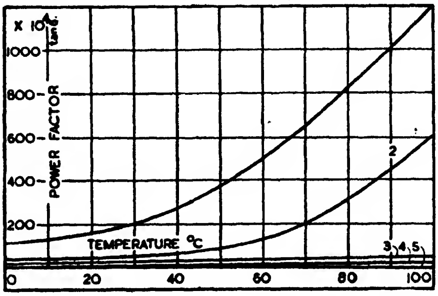
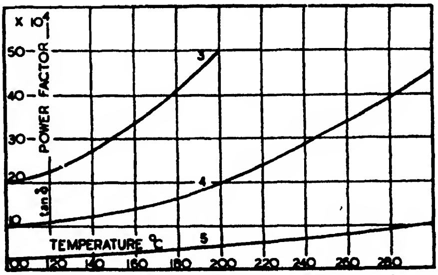


FIG. 87 (*a*).—Temperature-power factor curves of various materials at high frequency (1 to 10 Mc/s). (1) Porcelain. (2) Steatite. (3) Rutile body. (4) Clinoenstatite body. (5) Magnesium-Orthotitanate body.



In Fig. 87 (*b*) curves 3, 4 and 5 have been extended on the temperature scale.

Fig. 12 (*b*) which was described in the chapter dealing with power factor, shows the variation of power factor of a Clinoenstatite group material, with the firing temperature in both a dry atmosphere and an atmosphere of 75 per cent. relative humidity (Robinson, Journ. I.E.E., November, 1940).

The Clinoenstate material tested by Robinson becomes dense at a firing temperature of about 1,290°C. At 1,200°C. it is still very porous, the porosity decreasing with increasing firing temperature until at 1,290°C. all the pores are closed.

When this material is dense, the power factor in a dry atmosphere and that in an atmosphere of 75 per cent. humidity are practically the same. When the same material is, however, still porous (when fired at temperatures below 1,290°C.), the power factor in humid atmosphere is much greater than in a dry atmosphere.

As previously mentioned the A.S.T.M. Standards specify that in all Test Reports the percentage relative humidity of the atmosphere should be recorded. Although it is very important, particularly in the case of porous materials, that the humidity content of the atmosphere should be stated, very often this indication is omitted when figures concerning power factors are given.

Interesting information about the relation between chemical composition and dielectric properties of Clinoenstatite bodies is given in a paper by Rigterink, Grisdale and Morgan, Journal of the American Ceramic Society, November, 1942.

The authors do not differentiate between dense and porous materials. Their conclusions are, therefore, made regardless of porosity and are as follows :

(1) Variations of the ratio of talc to kaolin, within certain limits, have little effect on the dielectric properties of low loss ceramics, the principal constituent of which is talc.

(2) Large variations in the dielectric properties are caused by variations in the proportions and kinds of alkaline earth oxides added as fluxes to a talc-kaolin mixture.

(3) The conditions in ceramics favourable to high specific resistance are not necessarily those favourable to low dielectric loss. (This is particularly true if porous materials are included.) Dense Steatite materials, however, having high specific resistance have at the same time low power factor.

(4) Differences in dielectric properties of Steatite ceramics are more evident if the measurements are carried out at high temperature.

The starting point for all mixtures under review is a talcum body consisting of :

20 parts china clay ;

80 parts talcum (to which various alkaline earth compounds are added in varying proportions).

First of all to this talcum body magnesium carbonate is added in increasing amounts, the best values with regard to power factor being obtained when 20 per cent. magnesium carbonate is added. The specific resistance, however, increases with increasing addition of magnesium carbonate. (Talcum bodies fired at Cone 14 and having a higher magnesium carbonate content than about 20 per cent. are porous. The more magnesium carbonate is added, the more porous they become.)

The substitution of Beryllium oxide for magnesium carbonate decreases Q,* and the substitution of calcium carbonate and strontium carbonate increases Q slightly. The substitution of barium carbonate for magnesium carbonate, however, produces a ceramic with Q almost five times as much at 3 M.c. and more than ten times as much at 100 k.c. The changes in specific resistance are correlated with those for dielectric loss, with the exception of a body containing Beryllium oxide. The substitution of calcium carbonate and strontium carbonate for magnesium carbonate causes only a slight increase in the specific resistance, but the substitution of barium carbonate increases the specific resistance by a factor more than 100. The substitution of Beryllium oxide also improves the specific resistance by a factor of more than 100 times, offering further evidence that conditions favourable for high specific resistance are not necessarily favourable to high Q.

Of the bodies investigated, the best value with regard to power factor is attained by a body consisting of:

80 parts talcum
20 ,, clay
50 ,, barium carbonate

No reference is made as to whether this body fired at Cone 13 or 14, is dense or porous; the author reproduced it, and found it to be porous at Cone 13.

Talcum. The chief raw material of Clinoenstatite bodies.

It has been mentioned above that talcum is a hydro-magnesium silicate. It usually has the formula $3\ MgO\ 4\ SiO_2\ H_2O$, but some talcs have a composition corresponding more closely to the formula $4\ MgO\ 5\ SiO_2\ H_2O$. The mineral talc is very often known as Soapstone or Steatite. In the United States this mineral is, according to

---

* $\left(Q=\frac{1}{\tan\delta}\right)$ has been used, particularly in the United States, in the last few years to indicate the reciprocal of the power factor of dielectric materials. Since Q is the reciprocal of tan δ the greater the figure for Q the better is the power factor of the material.

"Ceramic Industry" January, 1942, found in Maine, Vermont, Massachusetts, Rhode Island, New York, New Jersey, Pennsylvania, Maryland, North Carolina, Virginia, California.

In Europe it is found in such diverse places as Bavaria (Fichtelgebirge), Styria, Scotland, Switzerland, Spain, Roumania, Russia. In Asia in Indo-China; in Africa, in Egypt and Morocco. The MgO contents vary between 29·50 and 32·3 per cent. The SiO_2 content between 58·88 and 61·3 per cent., Fe_2O_3 0·72–4·65 per cent., Al_2O_3 0·07–2 per cent., CaO 0–1·5 per cent.

When talc is gradually and slowly heated it loses its chemically combined water between 750 and 950°C. Between 900–1,000°C. talc dissociates into meta-silicate (3 $MgO.SiO_2$) and Silica (SiO_2). If the temperature is further increased another metasilicate modification "Protoenstatite" and finally "Clinoenstatite" are formed. Many investigations have been carried out in order to ascertain which metasilicate formations are present, if various talcs, having different flux admixtures, are heated at various temperatures. As to this question no complete agreement has been reached. All investigators, however, agree, that the power factor is the better, the more homogeneous the crystal distribution and the smaller the crystal size. The silica set free by this dissociation of the talcum forms cristobalite at a temperature of about 1,100°C.

It has been observed on various occasions by manufacturers of Steatite and other Clinoenstatite articles, that certain overfired articles had good mechanical strength and high density when leaving the kiln, but their mechanical strength decreased and their porosity increased after a certain period of time. The reasons for this strange behaviour were not known and various theories brought forward.

Hans Thurnauer and A. R. Rodrigeuez, published in the Journal of the American Ceramic Society, November, 1942, a report of an interesting investigation which cleared this matter up. A short extract is, therefore, of interest.

Various talcium bodies containing various fluxes were fired, one, two, three, and four times at Cone 14, and examined microscopically and by X-ray method. After each firing, pieces were also checked by immersion in fuchsine dye-alcohol solution under pressure of 2,000 lb. After boiling for four hours in water the moisture absorption was determined.

Boiling in water not only served as a means of obtaining penetration of the dye into existing open pores of the test pieces, but was primarily used as a means of accelerating the possible weakness of structure and of increasing the porosity.

Bodies which by X-ray analysis were found to consist of small crystals retained their low porosity after four firings. Bodies, however, the structure of which was ascertained by the same method to consist of large crystals, exhibited a large increase of porosity after repeated firings. The crystals of certain bodies grew with repeated firings, and it was found that the crystal size controlled the absorption of the dye solution. (This refers only to vitrified bodies.)

The growth of crystals is partially due to the formation of a new phase (namely, the transformation of clinoenstatite into protoenstatite). Clinoenstatite crystals may, however, grow as well but only in such cases when the glassy matrix is not fluid enough to dissolve a substantial part of the crystals. When the matrix, however, has dissolved Clinoenstatite crystals they re-crystallise when cooling down, and form only small crystals.

The large differences in the rate of actual growth are no doubt the result of the differences in the amount and nature of the glassy phases in different bodies. The viscosity or liquidity of the glass at the vitrification temperature plays an important part in conditioning the crystal size ; the greater the liquidity the smaller the crystals.

Provided the crystals are kept small enough (not more than 7μ), the body will remain dense, regardless of the number of firings, each followed by boiling in water.

Talcum when heated does not get soft before fusing like clays, feldspars and many other silicates, but fuses suddenly at about 1,500°C. This is the reason why dense ceramic materials cannot be made of 100 per cent. talcum. Even at a temperature a few degrees below melting point talcum is still porous. It has to be mixed with ingredients which cause the talcum to get dense before reaching its fusing point. A material which serves this purpose admirably is china clay, which, at the same time, has the advantage of improved plasticity. Talc-clay mixtures are, therefore, easy to work.

Interesting information about the fusing temperature, densification, temperature, porosity and thermal expansion of various firing temperatures of clay-talc mixtures were published in 1932 by Rieke and Thurnauer (Ber. D. Keram Ges.). Since these figures are of great interest, a summary is given in the following table.

It can be seen that the bodies 6, 7, and 8 densify and fuse at almost the same temperature. That means, they have no firing range and therefore cannot be used for the manufacture of dense materials. (It was pointed out previously that the range between fusing point and softening point of a ceramic mixture represents the firing range

TALCUM

Table of Clay-Talcum Mixtures

Body No.	1	2	3	4	5	6	7	8	9	10	11
Clay substance, per cent.	100	90	80	70	60	50	40	30	20	10	0
Talcum, per cent.	0	10	20	30	40	50	60	70	80	90	100
Densification temperature, °C.	1,500	1,450	1,350	1,300	1,300	1,300	1,300	1,280	1,300	1,300	—
Fusing temperature, °C.	1,770	1,700	1,520	1,450	1,400	1,310	1,300	1,280	1,410	1,470	1,500
Difference between those temperatures (firing range) in °C.	270	250	170	150	100	10	0	0	110	170	—
Porosity after firing at 1,300°C. per cent.	15·2	4·8	3·6	1·5	1·5	—	—	—	0·4	2·0	42·1
Thermal expansion of body fired at densification temperature per cent (measured between 150–300°C.)	—	0·05	0·06	0·04	0·04	0·05	0·05	0·08	0·10	0·17	0·19

of this body, and that the larger the firing range of a mixture the safer is its firing process.)

Bodies 9 and 10, which contain 80 and 90 per cent. talcum and 20 and 10 per cent. kaolin respectively, have a firing range of 110°C. and 170°C. and are, therefore, suitable for the manufacture of ceramic bodies. The latter mixture (90 per cent. talcum and 10 per cent. kaolin) in particular forms the starting point for the manufacture of the improved type of Clinoenstatite bodies for a firing temperature of 1,400°C.

On the other hand, the bodies 2, 3, 4, and 5, containing between 90 and 60 per cent. kaolin, and between 10 and 40 per cent. talcum respectively, are, as the table indicates, characterized by their low thermal coefficient of expansion. Since their firing range (from 250°C. to 100°C.) is sufficiently large this type of body is used for manufacture on a commercial basis.

The low thermal expansion of these bodies can be explained by the formation of the mineral Cordierite, which has the formula $2\ MgO\ 2\ Al_2O_3\ 5\ SiO_2$, and is characterized by an extremely low thermal coefficient of expansion. The mixtures 2–5 form the basis of the Cordierite bodies.

B. CORDIERITE BODIES

The mineral Cordierite does not occur in nature at least in appreciable deposits. It is, as mentioned above, characterized by an extremely small thermal expansion, and imparts its property to ceramic bodies which are manufactured by mixing talc and clay in a proportion similar to those of the bodies 2, 3, 4, and 5 in the table p. 262. An addition of alumina and certain fluxes facilitates the formation of Cordierite crystals.

Zirkonium oxide is, for instance, one of those ingredients which act as a crystallizer and speed up the formation of the Cordierite crystal.

A considerable percentage of the ingredients of Cordierite bodies consists of plastic materials. It is, therefore, possible to manufacture by the various shaping methods used in the ceramic industry all the complicated shapes which are required.

In high frequency technique it is first of all used for the manufacture of those components, the physical dimensions of which should change as little as possible with varying temperatures. For instance, alterations in the dimension of a coil caused by increasing or decreasing temperature result in a variation of coil inductance and this would, of course, very unfavourably affect the stability of the oscillatory circuit. For this reason Cordierite bodies are used to a very great extent for the manufacture of coilformers. There are many other cases where only small variations of the physical size caused by temperature changes are permissible, and in all such cases the use of Cordierite bodies is indicated.

Trade names for four ceramic materials belonging to the Cordierite Group are as follows :

Cordierex	(Bullers).
H.F. 252	(Taylor Tunnicliff Co., Ltd.).
Ardostan	(German manufacture).
Sipa	,,

Thiess published in the Journal of the American Ceramic Society, March, 1943, a report on a series of experiments which he made to develop self-glazing Cordierite bodies. Two of the best bodies have the following composition :

(1)	Talc	36 per cent.
	Ball clay	29 ,,
	Alumina	19 ,,
	Nepheline-Syenite	16 ,,

This body is dense when fired at Cone 13 and self-glazing, *i.e.* the body develops a glossy surface although the body is not over-fired and, if broken into pieces, the surfaces of fracture have the appearance of those of a normal insulator body.

(2)	Talc	36 per cent.
	Ball clay	29 ,,
	Alumina	19 ,,
	Feldspar	16 ,,

This body is self-glazed at Cone 14.

A great number of experiments were made in order to discover whether other fluxes would develop a self-glazing effect. The fluxes used included zinc oxide, beryllium compounds and spodumene (a lithium feldspar). Although it was possible to obtain vitrified bodies with spodumene and feldspar and with beryllium and feldspar, none of these developed self-glazed bodies. Repeated firing tests furthermore showed that these bodies had too short a firing range for practical application.

For mass production, it is not advisable at all to rely on the self-glazing effect of the bodies, as the appearance of self-glazed articles is not very uniform.

It is very difficult to find a suitable glaze for Cordierite bodies, as the thermal expansion of the body is so low that Thiess, in company with several other authors, found it almost impossible to develop a glaze having an equally low thermal expansion. A dark coloured slip glaze, however, is described by Thiess as giving satisfactory results. The composition is as follows :—

SiO_2	52
Al_2O_3	13·5
MgO	15·5
B_2O_3	3·2
Fe_2O_3	9
Cr_2O_3	6·5

C. RUTILE BODIES

are characterized by the fact that they consist mainly of the crystal rutile—a titanium dioxide (TiO_2). Rutile crystals have an extremely high dielectric constant (89 perpendicular to the crystal axis and 173 parallel). They impart this characteristic to ceramic bodies containing Rutile in proportion to the amount in which it is added. Finely pulverized and prefired Rutile crystals are mixed with a small portion of plastic clay or bentonite for the sole purpose of being made workable.

As the addition of a large proportion of clay would decrease the dielectric constant to a great extent and adversely affect the favourable low power factor, this type of ceramic material is not very plastic and can only be formed into simple shapes such as tubes, caps or discs as required for the manufacture of condensers.

The dielectric constant of Rutile crystals has a strongly negative temperature coefficient (that means that with increasing temperature the dielectric constant decreases). Of this property very much use is made nowadays in the manufacture of compensating capacitors.

Some examples as to how the compensation of the negative temperature dependence of the various components in oscillatory circuits is carried through will be given in the chapter dealing with ceramic high-frequency condensers.

TRADE NAMES FOR RUTILE BODIES

Bullers	Steatite and Porcelain Products	Continental	Taylor Tunnicliff	Lava Corporation
Permalex	Faradex	Condensa Kerafar R. and S.	H.F.3a	AlSi Mag.190, 192

The technical characteristics of Rutile bodies consisting preponderantly of titanium dioxide are as follows :

Specific gravity	4·0
Water absorption	0·05–0·00%
Softening temperature in °C.	1,650
,, ,, ,, °F.	3,000
Linear coefficient of thermal expansion	$7\cdot1–7\cdot3 \times 10^{-6}$
Tensile strength lb. per in.^{2} (American Publications)	7,500
Tensile strength, kg. per cm.^{2} (Continental Publications)	300–600
Compressive strength, lb. per in.^{2} (American Publications)	80,000
Compressive strength, kg. per cm.^{2} (Continental Publication)	6000–12,000
Modulus of rupture, lb. per in.^{2} (American Publication)	20,000
Modulus of rupture, kg. per cm.^{2} (Continental Publication)	1,000–1,500
Resistance to Impact, ft. lb. per in.^{2}	2·4
,, ,, cm. kg. per cm.^{2}	2·8–3·3
Thermal conductivity, kg. cal. m. per h. °C.	7–8
Dielectric strength (60 cycles)	
Test disc ¼-in., volts per mil.	100
Volume resistivity at 700°C. or 1,292°F. (ohms/cm.^{3})	$2\cdot5 \times 10^4$
At 900°C.–1,652°F. (ohms/cm.^{3})	1×10^4
Dielectric constant at 10 M.C.	85
Power factor at 10 M.C.	0·06%
Capacity change per °C.	$-6\cdot8 \times 10^{-4}$

Titanium-dioxide, the main raw material of Rutile bodies, occurs in nature in the form of 2 tetragonal crystals (rutile and anatas) and one rhomboidal crystal, the brookite.

The permittivity of anatas is 31, of brookite 78, and of rutile, as mentioned above, 89, perpendicular to the crystal axis and 173 parallel to the crystal axis. The use of titanium dioxide crystals for the manufacture of condensers possessing high capacity was first mentioned in a Patent in 1925, taken out by Siemens and Halske, but it was almost ten years later that the first condensers in which Rutile was used were put on the market by the ceramic industry. If it were possible to manufacture on a commercial scale discs of pure Rutile powder without any addition of clay or similar plasticizers their permittivity would be 110. But a Rutile powder has to be made plastic and workable by the admixture of plastic clay. This admixture reduces the permittivity as follows :

A mixture of 90 per cent. rutile and 10 per cent. clay has a permittivity of 80
,, ,, 80 ,, ,, 20 ,, ,, ,, 50
,, ,, 70 ,, ,, 30 ,, ,, ,, 40
,, ,, 60 ,, ,, 40 ,, ,, ,, 30
,, ,, 50 ,, ,, 50 ,, ,, ,, 20
,, ,, 40 ,, ,, 60 ,, ,, ,, 18
,, ,, 30 ,, ,, 70 ,, ,, ,, 12
,, ,, 20 ,, ,, 80 ,, ,, ,, 10

(Albers-Schonberg, Hochfrequenzkeramik.)

The temperature coefficient of the permittivity is slightly positive in the case of the mixture containing only 10 per cent. Rutile. It is zero in the case of 20 per cent. Rutile; it is slightly negative in the case of 30 per cent. Rutile. The negative temperature coefficient increases gradually with increasing Rutile content until it reaches 800×10^{-6} for change of permittivity per 1°C. in the case of pure Rutile. The power factor of Rutile bodies is very satisfactory at high frequencies, but increases considerably at lower frequencies. This disadvantage has been largely overcome by the use of Rutile-zirconium-dioxide mixtures. The permittivity of such modified Rutile bodies is still very high and lies between 45 and 63.

The power factor of these Rutile-zirconium-dioxide bodies is almost the same at low frequencies as at high frequencies. Rutile-zirconium-dioxide ceramics are an ideal material for the manufacture of high capacity condensers for both high and low voltages and may prove even more important in the future.

Whereas Rutile bodies not containing zirconium-dioxide have a structure consisting of crystals of considerable but not uniform size, the size of the crystals in Rutile-zirconium-dioxide bodies is very much smaller and of more uniform size. It is assumed that the uniform size and the extraordinary homogeneity of the structure of the Rutile and zirconium-dioxide crystals results in more uniform dielectric characteristics of the insulating material.

D. MAGNESIUM-ORTHOTITANATE BODIES

are characterized by the formation of the crystal Magnesium-Orthotitanate ($2\,MgO.TiO_2$) (other titanates may prevail according to the composition of the bodies). This crystal is formed up to 80 per cent. in certain bodies and imparts its favourable dielectric characteristics to this type of material. The power factor is smaller than that of mica and the temperature variation of the permittivity is negligible. Owing to its high permittivity (three times as great as that of mica) this material is an ideal dielectric for condensers where temperature independence of the capacity, a low power factor and considerable capacity combined with a small size are desirable. Only a very small addition of plastic material is permissible (lest the favourable dielectric properties are adversely affected). This type of body can also be formed only into simple shapes like tubes, caps, and discs. Complicated shapes are, however, as a rule, not required for the manufacture of high frequency condensers.

The technical characteristics of Magnesium-Orthotitanate bodies are as follows :

Magnesium Orthotitanates :

Specific gravity	3·1
Tensile strength, kg. per cm.^{2}	600–700
Compressive strength, kg. per cm.^{2}	5,000–6,000
Modulus of rupture, kg. per cm.^{2}	600–1,100
Resistance to impact, kg. per cm.^{2}	2·3–3·1
Linear coefficient of thermal expansion, $\times 10^{-6}$	6·2–10
Breakdown strength, 50 cycles kV. per mm.	15–20
Permittivity	12·5–19
Change of capacity, per °C. between 20–80°C.	-20–30×10^{-6}
Power factor at 10 M.C. tan ∂	8–15×10^{-4}
„ in precentage	0·08–0·15

(Albers–Schoenberg.)

According to the ratio in which Magnesium Oxide (MgO) and Titanium-dioxide (TiO_2) are present, the following crystals may be formed :

2 MgO.TiO_2—Magnesium Orthotitanates.
MgO–TiO_2—Magnesium Metatitanates.
MgO_2.2TiO_2—Magnesium Dititanates.

(Rieke und Ungewiss—Ber. Dtsch. Ker. Ges. (1936).)

It has been found that preferably Orthotitanate is formed even if in the raw materials magnesium dioxide and titanium dioxide are not mixed exactly in the ratio of 2 molecular weight MgO to 1 molecular weight TiO_2.

The dielectric characteristics of Magnesium-Orthotitanate at low frequencies are not quite as favourable as at high frequencies. This refers especially to the breakdown strength. This disadvantage has been largely overcome (in a way similar to that mentioned with regard to the Rutile bodies), by the addition of zirconium-dioxide (ZrO_2).

It has been found that although the crystalline structure of Magnesium-Orthotitanate bodies is very uniform, the size of the individual crystals is rendered more uniform by the addition of zirconium dioxide. This, in turn, makes the dielectric characteristics more uniform and independent of the frequency applied.

TRADE NAMES FOR ORTHOTITANATE BODIES

Bullers	Steatite and Porcelain Products	Continental
Templex	Tempradex	Tempa
		Kerafar
		T. and U.

E. POROUS CERAMIC BODIES FOR THE MANUFACTURE OF ELECTRONIC VALVES

Dense materials of the Clinoenstatite group and occasionally of the Magnesium-Orthotitanate group are often used in vacuum—for instance, in electronic tubes. In many cases, however, a slightly porous ceramic material is considered to be more advantageous when used in vacuo, and at high frequencies. In certain circumstances, particularly if subjected at the same time to vacuo and to high temperature, dense ceramic materials may release air and spoil the vacuum, and consequently the efficiency of high frequency valves. It has been found that this disadvantage is overcome by the use of a slightly porous ceramic material. It is essential, of course, that ceramic parts used for high frequency valves (for instance, for valve spacers) possess a low power factor and high surface and volume resistivities at high temperatures.

Bodies of the Clinoenstatite type similar to those described above, but containing no flux (apart from a small addition of china clay), have been proved most satisfactory.

F. HIGH FREQUENCY CERAMICS COMPARED WITH BAKELIZED PAPER

The variation of power factor of various materials with frequency is shown in Fig. 88, from which can be seen that all dense ceramic materials have a negative frequency coefficient, the frequency coefficient of the Magnesium-Orthotitanate bodies being negligible over a very wide range, the frequency dependence of the Clinoenstatite and Rutile group being almost negligible at radio frequency. Porcelain and feldspar containing Steatite have a negative frequency dependence also, but the fact that the high power factor causes internal heating at radio frequencies makes the negative frequency dependence a purely theoretical consideration.

It is very interesting to compare the power factor of ceramic materials with that of synthetic resin-bonded paper of relatively good quality. In Fig. 89 the increase of the power factor of resin-bonded paper during the first five minutes is shown. A disc of 80 mm. diameter and 5 mm. thickness was subjected to a strong high frequency field between two electrodes, the voltages being 3 kV. and 5 kV. and the frequency 0·1 Mc/s, 1 Mc/s, and 10 Mc/s respectively. The curves show that with increasing voltage and increasing frequency of

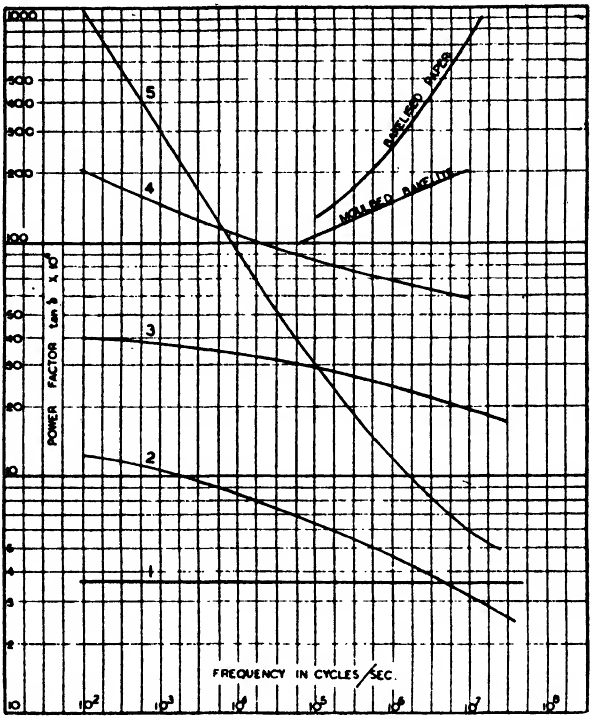


FIG. 88.—Variation of power-factor with frequency.

(1) Rutile body (improved). (2) Clinoenstatite body. (3) Clinoenstatite body containing Felspar (4) Porcelain. (5) Rutile body.

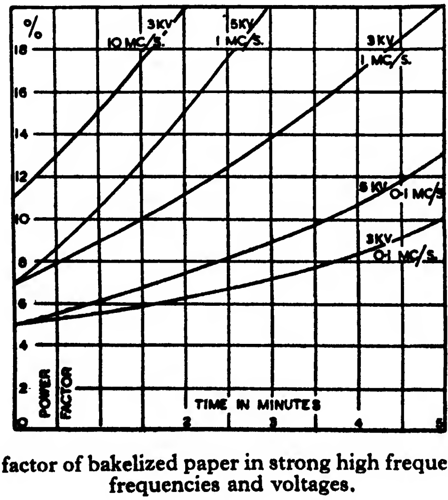


FIG. 89.—Power-factor of bakelized paper in strong high frequency fields at various frequencies and voltages.

the material deteriorates rapidly. The curves also show that resin-bonded or resin-impregnated materials are not so suitable as insulating materials for radio frequency in strong fields. For instance, at a frequency of 1 Mc/s and a voltage of 5 kV., the already very high initial power factor increases almost threefold within the first three minutes and at a frequency of 10 Mc/s, and a voltage of 3 kV., the material deteriorates even more rapidly.

If a component consisting of bakelized paper is not subjected to such a strong high frequency field, as in the test arrangement described above—for instance, in the case of a coilformer—the disadvantages of the high power factor are, of course, not so conspicuous, especially at lower frequencies. The superiority of a ceramic coilformer with regard to the power factor compared with bakelized moulded material is extraordinary and specially marked at frequencies above 1 Mc/s. This is illustrated in Fig. 90.

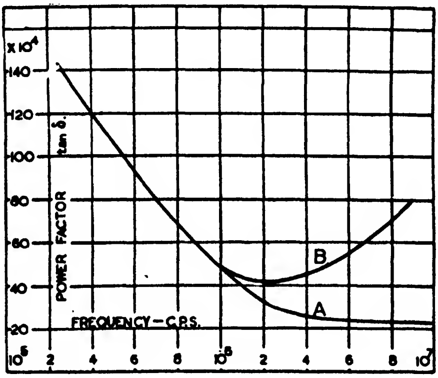


FIG. 90.—Variation of power-factor with frequency.
(*a*) Low-loss ceramic. (*b*) Bakelized paper, coilformers.

Curve (*a*) shows the power factor of a coil, wound on a coilformer of a low-loss ceramic material: whereas curve (*b*) shows the power factor of a coil, wound round a former of bakelized material.

Similar conditions also prevail with regard to other components, used in a high frequency field, and this is one of the reasons why high frequency ceramic materials should be used wherever such losses would otherwise occur. If the permittivity, or its temperature coefficient, is not of special importance, and if a low heat expansion is not required, the type of material most suitable is that of the Clinoenstatite group (see Figs. 86 (*a*)–(*i*)).

CHAPTER X

HIGH FREQUENCY CERAMIC CONDENSERS AND COILS

IN addition to the favourable dielectric and mechanical characteristics set out in the previous chatpers, ceramic materials have another very important advantage of particular importance in connection with the manufacture of condensers compared with organic dielectrics. Ceramic materials can be covered by a silver (or other precious metal) coating by burning on a suspension of silver oxide in an organic medium at temperatures of 700°–800°C. (When fired at this temperature, the silver oxide is reduced and a thin uniform and coherent metal coating is formed.)

In the case of organic insulating materials, condensers are manufactured by using separate sheets of insulating material and metal foils which are pressed together under heat. Interstices of air between the metal foil and the dielectric can hardly be avoided. As a consequence of variation of temperature and pressure, and owing to the different thermal expansion of the metal foils and the insulating materials the individual layers are subjected to slight movements. These movements may not only change the value of the capacity but may also increase the volume of the interstices between foil and dielectric. The method of burning precious metal oxides on the dielectric material at high temperatures makes possible a considerable improvement of high frequency condensers.

The process of pottery decoration by firing on thin films of precious metals has been well known for many years. This method in a slightly modified manner has of late been applied extensively in the manufacture of ceramic condensers.

A suspension of silver oxide, or of another precious metal, or of an alloy of silver and another precious metal in suitable organic medium is sprayed or painted on to the ceramic part.

At firing temperatures between 700–800°C. the silver oxide is reduced to a metallic coating which firmly adheres to the ceramic part.* The electrodes formed in this way are then connected to metallic leads by soldering or welding. The deposit of precious metal may be increased in thickness either by a second spray of the same or a similar suspension of metal oxide as used for the first coating or by electro-plating. If the firing is carried out at the proper temperature and the right metal oxides are employed condensers can

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* In the case of mica condensers the reduction temperature must not exceed 600°C., because otherwise the mica would deteriorate. The higher temperature used for firing metal coatings on ceramics produces a denser silver surface and a firmer adhesion of the coating to the surface of the dielectric.

be produced which remain perfectly stable indefinitely and show a high degree of " cyclicity " when submitted to many temperature cycles.

Capacity adjustment to close tolerances is readily achieved in the following ways : by first covering the ceramic part with a slightly larger metal coating (a slightly higher capacity value than desired is so obtained). The desired capacity is then adjusted by reducing the silvered area by grinding.

The ceramic industry is now able to offer a great variety of dielectrics suitable for the manufacture of high frequency condensers. The most important characteristics by which the various types of ceramic high frequency condenser materials differ are their permittivity and the different temperature dependence of their permittivity.

It has been mentioned that the permittivity of Rutile bodies is about 80 ; that of Magnesium-Orthotitanate between 14 and 16, and that of Clinoenstatite bodies about 6. Consequently, for higher capacitance values, Rutile bodies are more suitable. The capacitance of a Rutile body condenser is about fourteen times greater than that of a capacitor made of a Clinoenstatite body, if the dimensions are the same. Condensers having the shape of a small tube are, for example, made of a Clinoenstatite body for capacitance values ranging from 4 to 250 *pF* and of Rutile bodies for a capacitance value ranging from 25–2,000 *pF*.

If condensers of the same shape were made of the new high capacity body developed recently by the Alsimag (U.S.A.) the capacitance values would range from 500 to 30,000 *pF*.

The American Lava Corporation has recently developed a ceramic material possessing a permittivity of 1,200. This is an astonishing ceramic achievement. Details of the composition of this new high permittivity body are not yet published, but it is mentioned that the power factor and the temperature dependence are not as good as those of Clinoenstatite or Rutile bodies. For this reason, this new material is at present used mainly for the manufacture of by-pass and other condensers which do not call for a particularly low power factor or for temperature independence. It is interesting to note that, owing to its extremely high permittivity, condensers made of this material have a capacity about 200 times greater than that of condensers of the same size made of porcelain, glass, mica or Clinoenstatite bodies and about 15 times greater than that of Rutile condensers.

For manufacturing reasons, the thickness of the dielectric is, as a rule, somewhat greater in the case of high-permittivity bodies than in the case of Clinoenstatite bodies. For smaller capacitance values, condensers having the shape of a disc or small cap are manufactured. Of even greater importance than the permittivity is the temperature coefficient of the permittivity which the various dielectrics possess. In many cases a slightly positive temperature coefficient is desirable, or at least not disadvantageous. In other cases, a permittivity having a temperature coefficient as near as possible to zero is required, but more often a negative temperature coefficient of the permittivity is of special advantage.

Radio and television engineers have become conscious of the ever-increasing importance of greater circuit stability and the importance of making the frequency of the circuit independent of the temperature.

Most circuit components have a positive temperature coefficient. The use of a capacitor having the proper negative temperature coefficient makes it possible to reduce the temperature drift of the whole circuit to a negligible value.

The temperature coefficient of the capacitance C_x expressed in terms of $\mu\mu F$ per $\mu\mu F$ required is given by the following equation:

$$\alpha = t\frac{2\Delta f}{ft} \times \frac{C_o + C_x}{C_x}$$

where C_x is the value of compensating capacitance.
C_o is the circuit capacitance including strays.
Δf is the drift in c.p.s. due to the change in temperature.
f is the frequency in c.p.s., and
t is the temperature change in °C.

The apparent change in capacity ΔC which causes the drift in frequency Δf is assumed small compared with the total capacitance of the circuit. L is assumed constant (Sherwood, Electronics, September, 1940).

The temperature coefficient of the total capacitance of the circuit, and particularly the temperature coefficient of the capacitance value required for compensating purposes, may not be a constant figure and it may therefore in certain cases be desirable to have a special component for regulating the temperature coefficient of the capacitance of a circuit. Various types of temperature coefficient regulators have been developed. One design (illustrated in Fig. 91) consists of a base of Clinoenstatite material (*a*) on one face of which a disc made of a Rutile body (*b*) is arranged, and on the other face of which is another disc made of a Clinoenstatite body (*c*). The thickness of both the rotary discs is proportional to their dielectric constant. Both surfaces of the base-plate and the surfaces facing this base are ground very accurately, and at the upper and lower surfaces of both the rotary discs silver coatings are provided. The coatings of the upper and lower surfaces of the base are connected and face each other. The coatings of both rotary discs are electrically connected by the central pin; they do not face each other but are placed at an angle of 180° to each other. Both rotary discs are firmly coupled by the central pin and they change their relative positions to the base together if the central pin is turned. The capacitance of the component is constant and only the temperature coefficient of their permittivity is changed by turning the coupled discs.

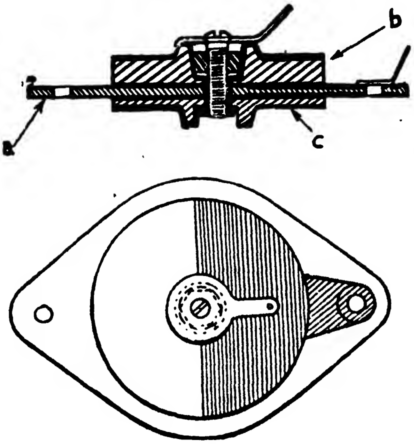

FIG. 91.—Condenser designed for compensating temperature coefficient.
(a) Clinoenstatite base. (b) Disc of Rutile body, the metal coating of which is in electrical contact with that of (c), a Clinoenstatite disc.

Another type of temperature coefficient regulator is designed in a way similar to the trimmer condenser described later on, but the rotor disc (which in the case of the trimmer is made of a Rutile body of high permittivity) is made of a Clinoenstatite body into which a segment of Rutile body is fused, the thickness of the two dielectrics being in the same ratio as their permittivity. In any position of the rotor disc the total capacity is composed of two components, one possessing a positive and the other a negative temperature coefficient of permittivity. If the rotor disc is turned, the total capacity is not changed; only the ratio of the two components having different temperature coefficients is changed. In this way, the temperature dependence of the capacity of an oscillatory circuit can be regulated.

Ceramic trimmer condensers for varying the capacity have been designed and are manufactured nowadays on a very large scale. They consist of a base of Clinoenstatite type material, a segmental area of the upper surface of which is silver-coated, the silvered area of the base forming the stator plate. The rotor disc made of a Rutile body forms the actual condenser, the rotor plate being formed by a segmental area of metal coating fired on the upper surface of the rotor. The connection from this coating is made *via* the adjusting screw and spring, which presses the two ceramic parts together. In order to achieve good electrical properties and stability, it is essential to grind the two meeting surfaces of the two ceramic parts with the utmost accuracy, so that no air interstices are created between the two surfaces, when the rotor is turned for varying the capacitance. (The maximum value of capacitance is, of course, attained when both metal coatings face each other.) This type of trimmer condenser is now manufactured in bulk production, and gives very satisfactory results (see Britton, Electronics Engineering, July, 1941).

Fig. 92 illustrates the temperature dependence of the capacity of

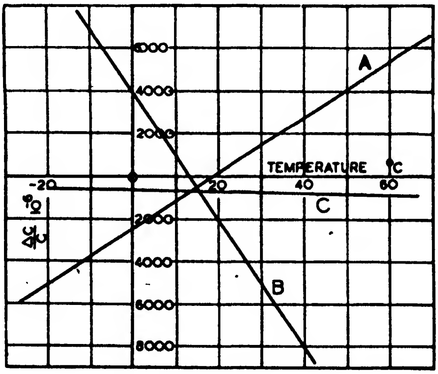

FIG. 92.

a Clinoenstatite body condenser (*a*), of a Rutile body condenser (*b*), and of a capacitor aggregate composed of both types (*c*).

There are, of course, instances where condensers having a temperature coefficient as small as possible are required. For these purposes condensers of the Magnesium Orthotitanate type are most suitable. Compared with mica (which is used extensively for condensers, which do not have to withstand high temperature) low-loss ceramic condensers are less sensitive to the influence of heat, and to electrical discharges or flashovers which may occur in certain instances (*i.e.* in the case of H.T. condensers) and in addition the power factor and capacity are constant and not affected by temperature cycles. For all purposes where a small temperature coefficient of permittivity is required (particularly for higher voltages) condensers made of the Magnesium Orthotitanate type offer the best solution.

HIGH TENSION CONDENSERS

In the case of condensers for higher voltages, the edges of the metal coatings have to be screened by means of suitably shaped ceramic ribs to avoid discharges and flashovers. These protruding edges or ribs can, at the same time, be used to prevent corona losses which would otherwise occur at a high frequency and high voltage (a part of the surface of the rib facing the electrode is covered by the metal coating which thus forms a curved edge with a large radius).

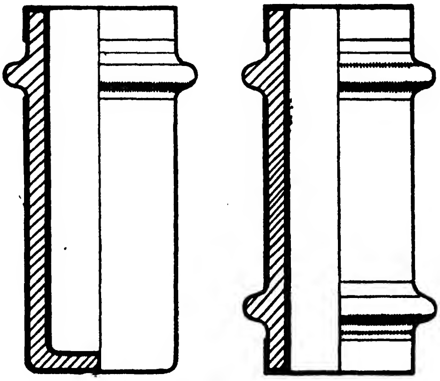

FIG. 93.

For voltages between 1,000 and 5,000 volts tube-shaped condensers, the edges of the metal coatings being screened by ribs, are a very suitable design. The tube shape can be modified into the shape of a bottle with cylindrical walls, one end of the tube being closed (Fig. 93).

For high tension condensers, particularly from 15 kV. test voltage onwards, discs of ceramic low-loss materials are used, both surfaces being covered by metal coatings, the edges of both coatings being again screened by ribs provided on both ends of the ceramic plate (Fig. 94).

In the case of condensers for current carrier telephony on high tension overhead lines, capacitor units for 60 kV. working voltage and 2,200 *pF*. have been designed.

For use in transmitters, a number of condenser plates are assembled on a frame with base or end-plates made of low-loss ceramic material. Such a frame may contain ten condenser plates of about 20 cm. diameter of the Clinoenstatite type material. Such an aggregate designed for 12 kV. test voltage may have 5,000 *pF.* capacitance for 300 kVa.

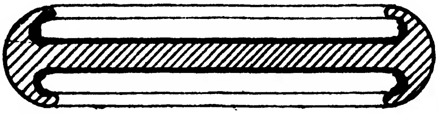

FIG. 94.—Ceramic H.T. condenser disc.

If Rutile bodies having dielectric constant of about 80 are used as a dielectric, the corresponding design is suitable for 6 kV. high frequency test voltage only, since the dielectric breakdown strength of Rutile bodies is somewhat lower than that of the Clinoenstatite type, but the capacitance amounts to 50,000 *pF.* owing to the higher permittivity of the dielectric.

(Some finished metal coated H.F. condensers showing the protruding ribs for reducing flashover and corona losses at high voltages are illustrated in Fig. 95 by courtesy of Dubilier Condensers.)

FIG. 95.—Typical metal coated high-tension high-frequency ceramic condensers showing the protruding ribs for reducing corona losses at high voltages. (Dubilier Condenser Co.)

CERAMIC COILS

Temperature instability of the oscillatory circuit is, of course, not only caused by the temperature dependence of the permittivity of the condensers and other components, but also by the variation of the dimensions of the coils which change with increasing and decreasing temperatures, and cause alterations of the coil inductance. Coils, the inductance of which is practically independent of the temperature, can be wound on a coilformer made of a ceramic material which possesses a very small thermal expansion, *i.e.* of a low loss material of the Cordierite type.

Coils can be manufactured by burning on the ceramic coilformer a silver coating into which a spiral of the desired pitch may be ground. By this means coils can be produced which practically do not change their dimensions with rising or falling temperature, since the thin metallic coating follows elastically the alterations of the dimensions of the ceramic coilformer. Consequently, the metallic coating has practically the same thermal expansion as the ceramic former, and if the thermal expansion of the ceramic material is very small, a coilformer is thus produced, the inductance of which is practically independent of the temperature.

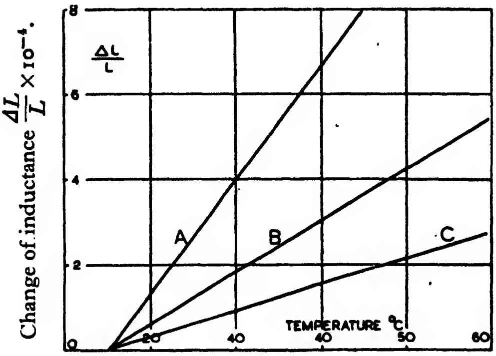

FIG. 96.—Shows the variation of the inductance of three types of coil, with increasing temperature, (A) being a coil consisting of a ceramic coilformer of the Clinoenstatite type, the wire being wound in. (B) Clinoenstatite coilformer with burnt-on metal spirals. (C) Cordierite body with burnt-on spirals.

Fig. 96 shows the variation of the inductance of three types of coil,

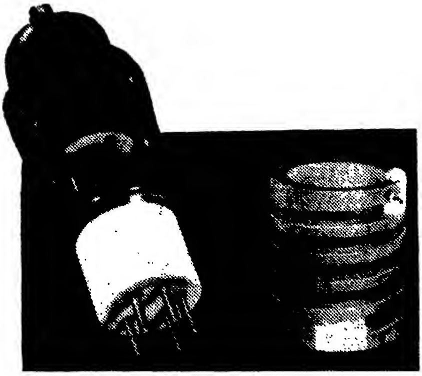

FIG. 97.—Cossor valve with ceramic base and, on right, a coil (Bullers) of which the conductor consists of a silver coating deposited on a ceramic former.

with temperature : (*a*) being a coil consisting of a ceramic coilformer of the Clinoenstatite type, the wire being wound in the usual way ; (*b*) a coil consisting of a coilformer of the same type of ceramic material the coils being formed by burnt-on metal spirals, and the third (*c*) being a coilformer of a Cordierite body with burnt-on metal coils. The improvement is demonstrated by the fact that the temperature coefficient of inductance is 40×10^{-6} for coil (*a*) and 8×10^{-6} for coil (*c*). (Albers-Schoenberg.)

A coil of which the conductor consists of a silver coating deposited on a ceramic former having the form of a spiral is illustrated in Fig. 97 on the right. The inductance value can be adjusted within narrow limits by compressing the coil. (By courtesy of Messrs. Bullers, Ltd.)

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