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Refractory Materials for Marine Boilers

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The chief functions of the refractory material in marine boilers are outlined. Defining a refractory as a solid able to maintain its shape at high temperature, it is pointed out that failure may result from liquefaction, fracture or shrinkage. Each of these causes is of importance in the failure of marine boiler refractories.

Liquefaction may occur simply through exposure of the refractories to temperatures sufficient to melt them or some of their constituents. For oil firing maximum temperatures of 1,650 deg.-1,700 deg. C. have been quoted. Liquefaction may also occur through the action of fuel ash. For example soda, commonly found in the ash of fuel oil, is a vigorous flux of alumino-silicate refractories. Fracture of marine boiler refractories is most commonly caused by severe temperature gradients, especially below 1,000 deg. C. These are usually caused by rapid temperature fluctuations due, for example, to manœuvring and are aggravated when the refractories are of complex shape. Shrinkage of boiler refractories is objectionable in itself and it aggravates destruction brought about by the causes previously mentioned.

The properties of firebricks, aluminous firebricks, mullite and high alumina refractories, plastic and insulating refractories are briefly described.

INTRODUCTION

It is perhaps pertinent to ask at the outset whether any refractory materials are really necessary in marine boilers. Could not a boiler be designed in which the transfer of heat from flame to boiler was direct as when heating water on a gas ring? While such a boiler is a theoretical possibility, in practice it is found necessary to liberate so much heat and burn so much fuel in so limited a space that direct contact of the flame with the water-cooled metal surfaces could not be maintained. It would lead to incomplete combustion of the fuel and to steam pockets in the system because the water could not be circulated sufficiently rapidly.

The amount and disposition of the refractory, however, are matters of design, subject to variation within wide limits. To some degree the trends to be noted in large power installations have been reflected in designs for marine boilers. About 1900,[1] boilers were of the Lancashire, Cornish, Scotch and the locomotive types and therefore utilized water-cooled fireboxes and the minimum quantity of refractory material. Then followed watertube boilers of larger capacity. At first the heating surfaces were comparatively close to the flame; this led to difficulties with smoke and incomplete combustion. Subsequently higher settings with refractory arches and higher furnace temperatures were employed; this introduced difficulties from ash and slag. The modern treatment is to revert to the use of a certain amount of heat absorbing surface in the furnace by the judicious use of water cooled walls. This type of treatment is to be found in marine boilers. Water tubes may be closely packed and let into the furnace wall, or bare tubes or tubes protected by a thin coating of plastic refractory may be used. At all times a balance between overheating of the refractory and undue cooling of the furnace must be achieved.

THE FUNCTION OF THE REFRACTORY MATERIAL

The refractory material in a marine boiler serves several purposes which may be summarized as follows: —

(1) It protects the furnace casing from flame impingement and prevents heat from reaching the stoke-hold.
(2) It defines the combustion chamber and permits the attainment of sufficiently high temperatures to ensure the complete combustion of the fuel.
(3) It protects furnace tubes from overheating and damage through formation of steam pockets.
(4) It acts as a reservoir of heat.

The boilers on individual ships are generally designed as an integral part of the ship to suit a particular duty. Ships' boilers, therefore, vary considerably. The design of boiler and the kind of work undertaken by a ship are rarely completely duplicated in another. Thus the service conditions encountered by the refractories on a particular ship tend to be peculiar to that ship. Standards of performance by the refractory linings are in consequence difficult to establish, since strict intercomparisons are so seldom possible.

CAUSES OF FAILURE OF REFRACTORIES

A refractory material may be defined as a solid able to maintain its shape at high temperature. Fundamentally,

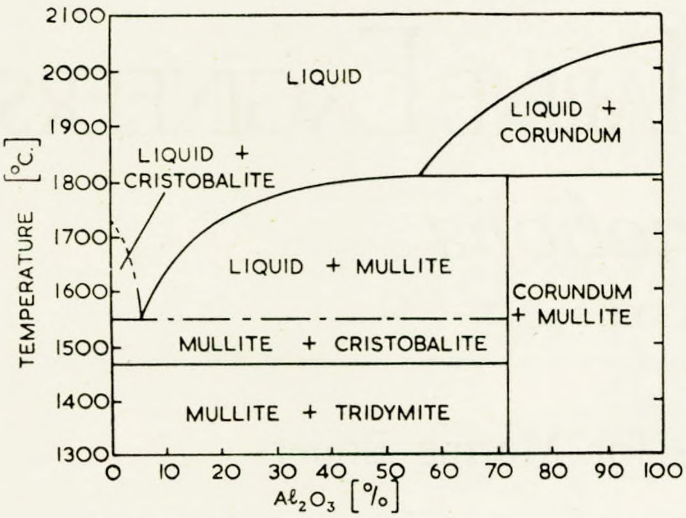

FIG. 1—*The Al_2O_3–SiO_2 phase diagram (Bowen and Greig[2])*

therefore, the causes of failure are few. It will cease to be a refractory when it loses its shape through (i) liquefaction; (ii) fracture; (iii) shrinkage.

(i) Liquefaction

(a) Refractoriness and Refractoriness-under-load

At sufficiently high temperature all solids will melt (or vaporize) and refractory materials are only exceptional in requiring high temperatures for the change in state to occur. Melting point is dependent on composition. The relationships between solid and liquid phases, the composition and the temperature are governed by the phase rule and are perhaps most conveniently shown by means of phase diagrams. The most fundamental phase diagram of refractories technology is the silica-alumina diagram, because alumino-silicate refractories constitute over ninety per cent of all the refractory material manufactured. The proportion is probably greater if marine boiler refractories only are considered. The SiO_2-Al_2O_3 diagram[2] is shown in Fig. 1. Refractories of almost any $SiO_2 : Al_2O_3$ ratio are now manufactured, but only a relatively small proportion contain more than 42 per cent alumina in the fired state. This is solely because of the comparative scarcity of raw materials for, and cost of manufacture of, high alumina products. As the diagram indicates, the liquefying points of these materials are high and they are valued for positions where the temperature conditions are extremely severe. The majority of alumino-silicate refractories, however, are made from natural fireclay having in the fired condition from 20 to 42 per cent of alumina. The diagram gives an indication of the way in which the $SiO_2 : Al_2O_3$ ratio affects the liquefying temperature. The silica-alumina eutectic at 1,545 deg. C. and the composition 5·5 per cent Al_2O_3, 94·5 per cent SiO_2 is of prime importance.

The diagram, as it stands, gives an unduly favourable representation of the softening temperatures of fireclay refractories because the effect of the presence of minor quantities of other oxides is ignored. If, for example, a small percentage of soda is also present in addition to silica and alumina, Fig. 2 by Schairer and Bowen[3] indicates a definite lowering of refractoriness; indeed a eutectic of 740 deg. ± 5 deg. C. occurs in the diagram. The effect of small amounts of other fluxing oxides is similar, and a total of at least 5 per cent of oxides other than SiO_2 and Al_2O_3 is usual. The result is probably that at least 300 deg. C. below the eutectic given in Fig. 1 some liquid will tend to form, solely under the influence of heat in a fireclay refractory. The amount of liquid formed will depend very considerably on the alumina : silica ratio.

Liquefaction of course entails flow and loss of shape under the action of gravity or other forces. Flow can therefore be accelerated by increasing the forces acting. In fact most fireclay refractory materials at a sufficiently high temperature

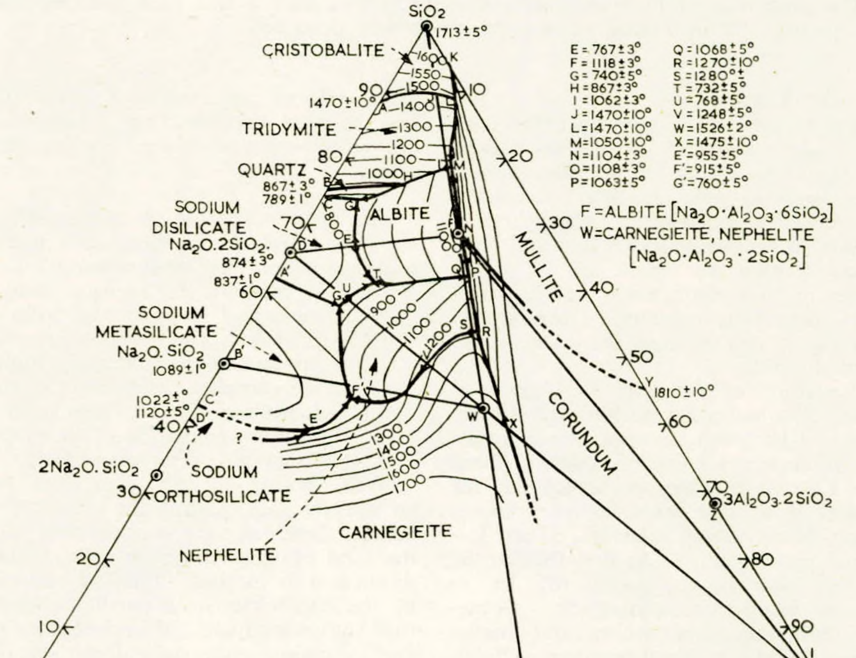

FIG. 2—*The Na_2O–Al_2O_3–SiO_2 phase diagram (Schairer and Bowen[3])*

develop the plastic properties of a mixture of solid and liquid phases. They thus can be deformed by a load in a short period at a given temperature, whereas the same material unstressed or subjected to only a small force would retain its shape indefinitely. The two technical terms "refractoriness" and "refractoriness-under-load" are used in this connexion. The first is applied to the time temperature conditions necessary to make a test-piece of a defined shape deform in a definite manner under the small forces of its own weight and surface tension. Fig. 3 illustrates the completed refractoriness test. The test piece is the central pyramid which has deformed until its tip is level with its base. The smaller "cones" placed round the circumference are standard reference cones which for a standard heating schedule define the temperature attained. The second is also applied to the time-temperature conditions required to make a test-piece of a defined shape deform in a definite manner but under a defined comparatively large external force. In this case the test-piece in this country is usually a prism 2½-in. tall and of 1¾-in. square cross section or a cylinder of the same height 2-in. in diameter. An external load of 28lb. per sq. in. is applied through a thrust column of rigid refractory material while the test-piece is heated at a uniform rate of 10 deg. C. per minute. The alteration in height of the test-piece is recorded and for firebricks and alumino-silicate refractories usually takes the form indicated in Fig. 4, when the expansion of the supports and thrust column is determined and allowed for. It will be seen that

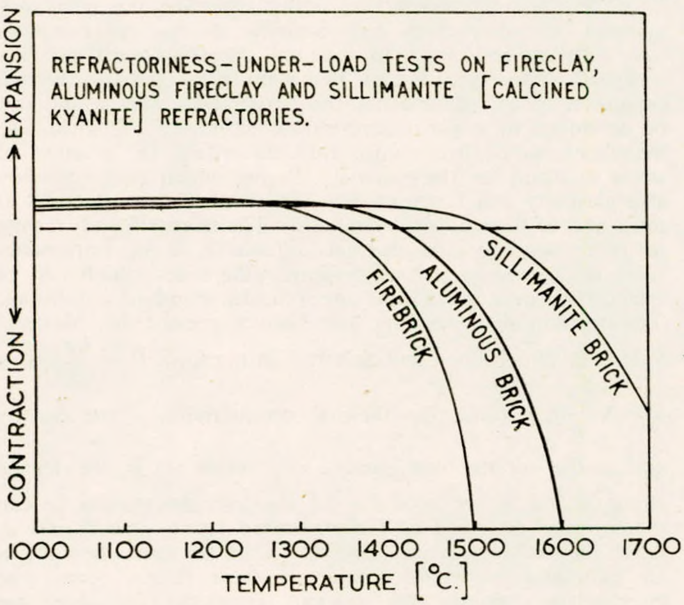

FIG. 4—*Typical refractoriness-under-load curves*

the thermal expansion of the test-piece is neutralized at a temperature not much in excess of 1,100 deg. C. and that contraction sets in at a slightly higher temperature (depending on the material) and proceeds at an increasing rate as the temperature rises. Five per cent deformation is regarded as failure. It may occur at a temperature 100 deg. to 150 deg. C. below that indicated by the refractoriness test of Fig. 3.

These two aspects of liquefaction of refractories are of paramount importance since it frequently happens that in high temperature installations large forces, such as the weight of a considerable number of overlying courses of brickwork or of expansion stresses, are operating in addition to the prevailing high temperature.

In marine boiler practice the refractoriness of the furnace lining must be adequate. In specifying the material for the lining it is therefore necessary to have some knowledge of the maximum temperatures which are likely to be encountered. It is clear that wide variations in maximum temperature can occur depending on the type of service, the size and design of boiler and the nature of the fuel. For oil firing, maximum temperatures of 1,650 deg. to 1,700 deg. C. have been quoted.[4] Lambertson[5] in tests with an experimental naval boiler in the U.S.A. employed temperatures from 1,300 deg. to 1,600 deg. C. Under such severe conditions, and on the score of temperature alone, blocks of high refractoriness are required, but the 40 to 60 per cent Al_2O_3 bricks based on aluminous fireclay, or calcined kyanite, possess the necessary margin of safety in refractoriness.

In most forms of construction used in marine boilers the refractories are not called on to support large stresses at high temperatures. The weight of the lining is generally taken by the bolts holding the blocks to the metal casing. Apart from stresses caused by expansion, deformation under load is not therefore likely to be serious.

(b) Slagging and Corrosion

It seldom happens that refractories are employed under clean conditions; almost always some contamination of the refractory material takes place and almost always the contamination results in products of lower melting point being formed. In boiler installations the contamination arises from the fuel ash.

The phase diagrams relevant to the application and use of a particular refractory are not therefore merely those based on the composition of the refractory including its own natural impurities, but also those based on the composition it acquires in service when contaminated with fuel ash and other impurities. Even from only ten of the most commonly occurring oxides that are of interest in the present connexion, say: SiO_2, Al_2O_3, CaO, MgO, K_2O, Na_2O, Fe_2O_3, FeO, V_2O_5, Cr_2O_3, it would be possible to select 252 different five-component systems and 1,023 systems having from one up to ten components. Of these, only the simpler two and three component systems have so far been investigated, together with a few of the more important four and five component systems, although probably most of them would be of value. At present, therefore, *ad hoc* testing for slag resistance must continue.

Today oil is most commonly used to fire ships' boilers. Although the quantity of ash present in commercial fuel oils can be quite low, it tends to accumulate in the furnace; its composition is therefore of importance. The analysis in Table 1 is quoted from Bailey.[1] It will be seen that the main constituents are soda, sulphur trioxide, vanadium pentoxide, with moderate amounts of iron and aluminium oxides. Of these constituents the action of the vanadium is not known. Very few systems involving vanadium oxide have been investigated. The action of the sulphur trioxide may be ignored as a first approximation since it is probably volatilized at temperatures above 1,200 deg. C. in contact with silicates. The soda will undoubtedly act as a severe flux, as Fig. 2 indicates. In fact it becomes clear that the ash of any of the fuels of Table 1, in virtue of its soda content, could attack alumino-silicate refractories containing 40 or 50 per cent Al_2O_3 to form pro-

TABLE 1.—COMPOSITION OF ASH FROM BUNKER "C" OIL (E. G. BAILEY[1])

	H	R	No. 1
Ash, per cent	0·104	0·050	0·06
SiO_2	5·0	2·6	9·5
Al_2O_3	0·5	0·4	13·9
Fe_2O_3 (equiv.)	5·8	19·5	
CaO	0·5	1·8	
MgO	1·9	2·2	trace
SO_3	20·8	24·2	61·8
Na_2O+K_2O	16·1	18·8	
Group II metals	4·9	11·4	
V_2O_5	35·9	11·0	
Undetermined	—	—	14·8

ducts melting at 1,000 deg. C. or lower. Such blocks would therefore become progressively thinner by reason of the liquid products draining down from the hot face and probably accumulating as slag on the furnace floor (see Fig. 6).

Iron oxide, especially when it is in the ferrous state, is also a fluxing oxide towards fireclay refractories. Table 1 shows that notable amounts of iron oxide may be present in the ash from fuel oil. The bolts used for anchoring the blocks to the casing are a potential source of danger, since the protective covering of brick or refractory cement may fall out of position or be worn back and the bolt head become exposed to the direct heat of the furnace. Under these conditions ferrous oxide is likely to be formed. According to Schairer[6] in the system $FeO-Al_2O_3-SiO_2$ the eutectic between mullite, hercynite and tridymite ($3Al_2O_3.2SiO_2-FeO.Al_2O_3-SiO_2$) occurs at 1,205 deg. C. and between hercynite, tridymite and fayalite ($FeO.Al_2O_3-SiO_2-2FeO.SiO_2$) at 1,073 deg. C. Ferrous oxide is therefore a powerful flux of firebrick refractories. The iron content of the bricks and fuel ash should preferably be low, and accidental contamination such as that just outlined should be guarded against.

The progress of these fluxing reactions, however, is dependent on other factors besides chemical composition. The physical condition of the refractory, the surface area of its pore system, and the size of the capillaries influence the rate of attack, probably to a considerable degree. Thus for maximum resistance to corrosive action, refractories should be as dense and close-textured as possible. Sometimes recrystallization products hinder the progress of reaction. This is often the case with firebricks where a felted mass of mullite crystals, sometimes seen as a white layer some little distance beneath the working surface of the brick, acts as a partially protective barrier to the unattacked material below. This is in spite of the fact that mullite crystals are unstable[3, 7] in contact with a soda-rich melt and decompose to form corundum crystals and yield more silica to the melt.

(ii) Fracture

Most refractories are weaker in tension than in compression or shear. Furnaces and other high temperature installations are generally designed so that the refractories shall be under compression rather than tension. The mechanical strength of fired alumino-silicate refractories rises with increase of temperature to a maximum of about 700 deg. C.[8] In these circumstances simple mechanical failure of refractory materials in correctly designed structures is comparatively rare.

Under certain conditions, however, stresses can be developed which exceed the limiting strength of the material. Some of these are listed and discussed below. They are most readily produced at temperatures at which the material is rigid (e.g. below 1,000 deg. C.). At higher temperatures the presence of some liquid in the refractory mass allows stresses to be accommodated by viscous flow.

(a) Expansion Stresses

The thermal expansion of fired fireclay products is dependent on the composition and the severity of the firing received but the expansion to 1,000 deg. C. is of the order of 0·5 per cent of the original length. In structures measuring several feet it becomes necessary, therefore, for expansion cavities of appropriate size to be left, otherwise severe stresses can be produced when the brickwork is hot. In some cases corners and ends of bricks may become detached because the shear breaking stress has been exceeded. To some degree the porosity of the bricks, and particularly of the joints, affords a means of accommodating the stress but with well fired bricks laid with thin joints definite expansion spaces are a necessity.

(b) Thermal Shock

Whatever the rate of heating, expansion stresses arise if provision is not made for the increase in volume of the refractory lining, but even with this provision serious stresses can develop when the rate of heating is rapid or is local and uneven. Indeed, any set of circumstances which produces a steep temperature gradient through the structure will produce corresponding stresses in the structure. If, for example, there is a large rate of fuel consumption and heat liberation in the combustion chamber, as may easily occur when a ship is manœuvring, the temperature difference between the hot and cool faces will increase considerably and the shear forces developed may cause bricks to crack. Similarly, if a burner is badly positioned so that the flame impinges directly on the brickwork a severe temperature gradient may be set up between the position where the flame impinges and the cooler surrounding area. Sudden cooling can produce stresses more serious than sudden heating since analysis shows that cooling tends to cause tensile stresses and refractories are generally weaker in tension than in shear. Protruding portions of brickwork in the path of hot gases are liable to rise in temperature above the general level of the hot face, and even the corners of bricks or blocks exposed by the falling out of jointing cement may become much hotter than the adjacent parts where the cement is intact. These gradients and the stresses to which they give rise may induce cracking or spalling. The tendency of the block to crack will be all the greater if its shape is not simple. Complications such as tongues and grooves, re-entrant angles, bolt holes, etc., predispose to temperature differences and reduce the strength of the block as a unit. As far as possible, therefore, the units of the refractory lining should be as simple as possible and the design of the furnace chamber should be clean and free from obstructions and protuberances.

The above considerations apply whatever the refractory material of construction, but naturally the various materials have different resistances to spalling. Spalling resistance is a composite property; it is clear that it must be related to thermal expansion as this determines the maximum strain which can be developed by a given temperature difference. It must also be related to elasticity since this determines the relation of stress to strain for the material. Bodies which have considerable elasticity can accommodate considerable deformation. It must also be related to the strength. The thermal conductivity, or more precisely the thermal diffusivity, is of importance since it determines the temperature differences which can be established for a given heat input under standard conditions. The resistance to spalling has been expressed by Norton,[9] following Winckelman and Schott[10], in the form $R = \frac{he}{\Delta}$ where $h = \sqrt{\frac{k}{\rho c}}$, k being the thermal conductivity, ρ the density and c the specific heat, and $e = \frac{T}{E}$ where T is the tensile strength and E the modulus of elasticity in tension (e can therefore be described as the maximum tensile strain) and Δ is the thermal expansion. This applies to the case when cracks are produced by tensile stress. If shear failure occurs the appropriate strength and elasticity constants for shear are required.

(c) Structural Spalling

In service most refractories undergo some continuous alteration. These changes may be simply the effect of temperature causing decrease in porosity, shrinkage, and crystal growth, or they may be more deep-seated changes brought about, for example, by reaction of the fuel ash with the refractory. The alteration is necessarily more pronounced on the working face than elsewhere and it sometimes happens that accretions of slag emphasize the differentiation. Occasionally a fairly sharp delimitation of altered from unaltered brickwork can be recognized. In slag-attacked firebrick a thin white zone of mullite crystals may serve as a boundary separating the slagged from the unslagged portions of the brick, but usually the transition is more gradual. In cases where the transition is abrupt, spalling or cracking is liable to occur because the modified layer has not the same coefficient of expansion as the comparatively unaltered material beneath. In this kind of spalling the fracture may not occur exactly in the interface but it usually occurs in its vicinity.

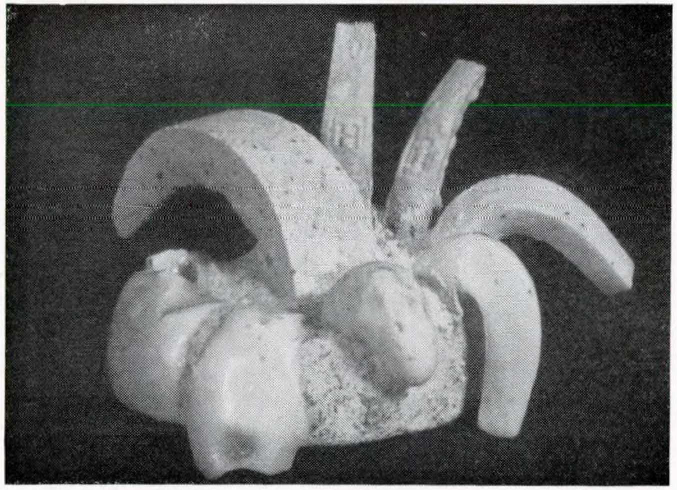

FIG. 3—*Appearance of completed refractoriness test*

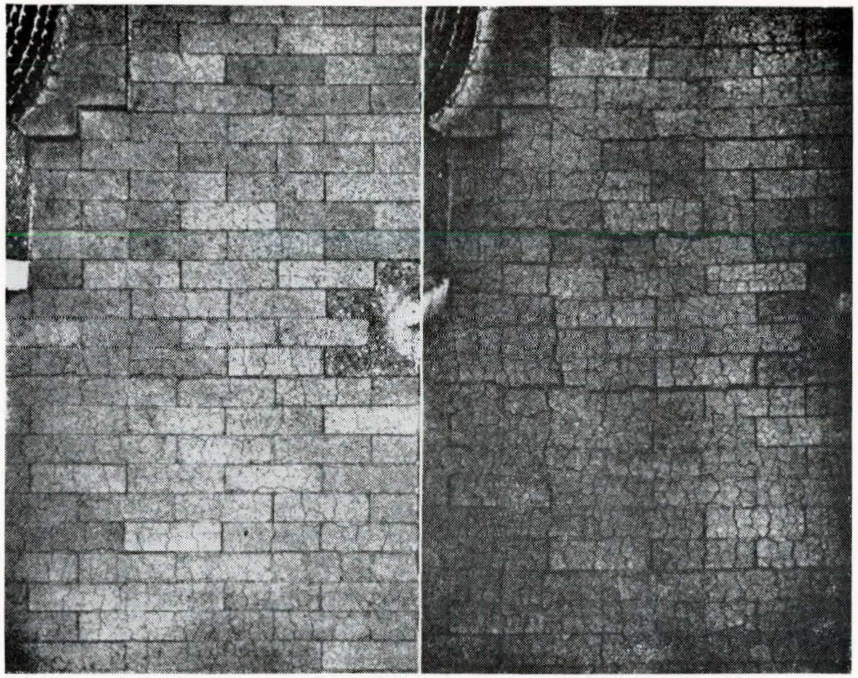

FIG. 5—*Shrinkage of bricks in naval oil-fired boiler after 112 and 420 hours steaming (Tredennick, Kelly and Burt*[15]*)*

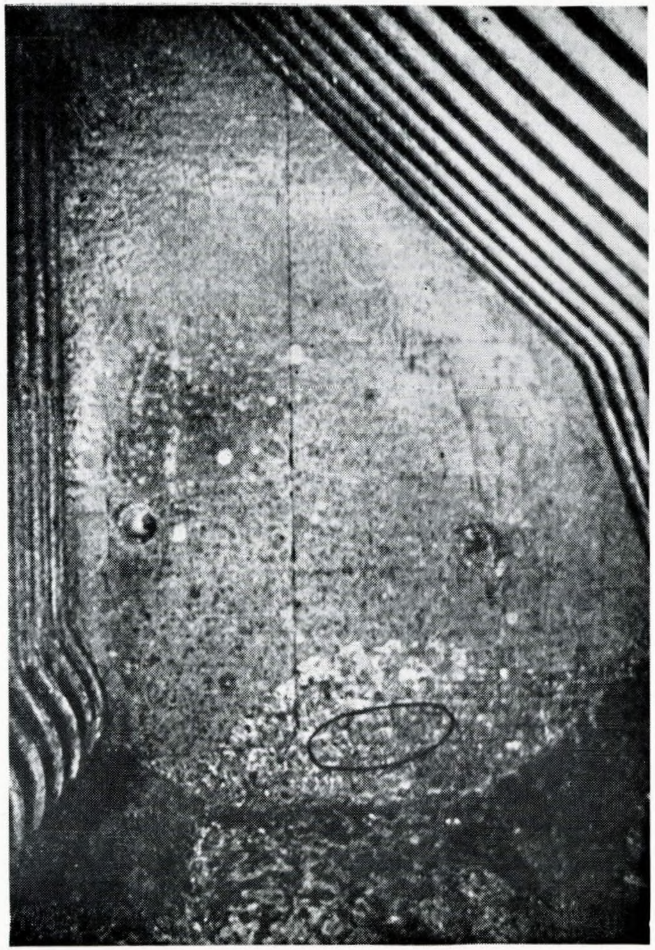

FIG. 6 *(above)—Slag on floor of naval oil-fired boiler after 4,291 hours steaming (W. A. Lambertson[5])*

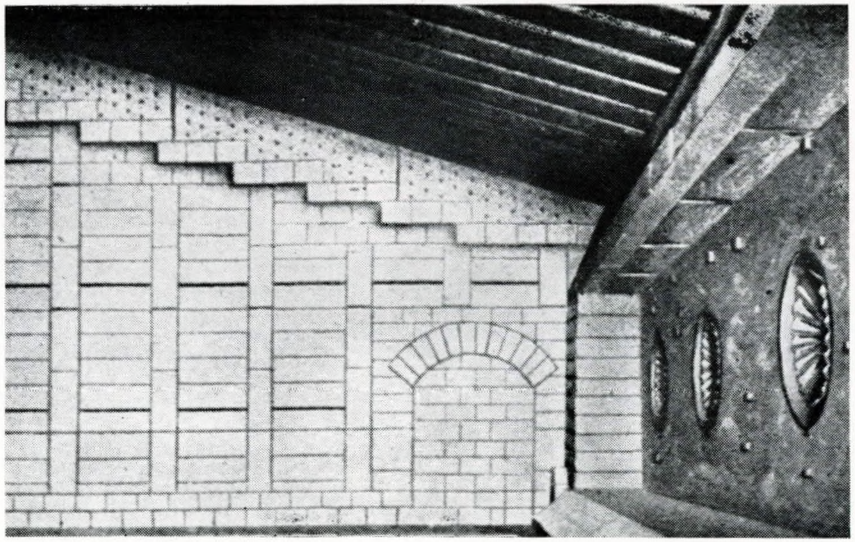

FIG. 7—*Illustrating use of plastic refractory in boilers of EC2 vessels (from "Brick and Clay Record"[21])*

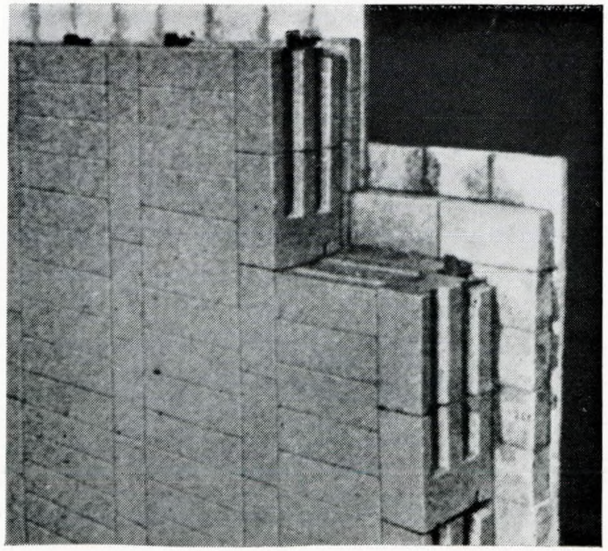

FIG. 8 *(right)—Illustrating use of insulating refractories in boilers of EC2 vessels (from "Brick and Clay Record"[21])*

Oil fired furnaces are subject to this kind of action. The high temperatures reached and the fusibility of the fuel ash which impinges on and is absorbed by the furnace walls tend to convert the hot face for a depth of about an inch into a vitrified and glassy layer adhering to the more porous unchanged refractory beneath. Owing to the differing expansion characteristics, heating and cooling (especially if rapid) tend to detach the glassy layer.

For the same reason refractory cement washes applied to brickwork are not effective if the coefficients of expansion have not been carefully matched. Indeed they may be definitely harmful since when spalling occurs a proportion of the underlying refractory may be lost at the same time as the applied layer.

(d) Abrasion

In blast furnaces and coke ovens, abrasion of the refractory walls by the charge can be a cause of breakdown but in the case of refractory boiler furnace linings, loss of shape through abrasion is not usually serious. Under certain conditions of firing with pulverized coal, the ash can have an abrasive action. In hand-fired coal-burning boiler furnaces the necessity for removal of clinker inevitably arises. In carrying out this operation it is difficult to avoid some mechanical damage to the refractory surfaces.

Very little is known concerning the effect of temperature on abrasion resistance. Of course, at a sufficiently high temperature gases moving at high velocity can displace refractory material that has become softened. This, however, is not abrasion but liquid flow. At a rather lower temperature, when the glassy bond is in the condition of a very viscous liquid, the resilience which this condition affords enables the solid grains to move slightly without being torn loose.

To resist abrasion, bricks should (in general terms) consist of uniformly hard grains so graded as to produce a close-packing mixture which is well-bonded in a firm resilient matrix.

(e) Crumbling

In service, refractories sometimes suffer a loss of strength, which may declare itself in a crumbly condition of the surface. It may be brought about through different causes. Sometimes the heat treatment is itself responsible. For example, the crystallization of the glassy bond of a fireclay refractory by long exposure at a temperature a little lower than that at which softening takes place, may induce the condition.

Sometimes chemical actions are responsible. For example, alkali compounds react with fired clay products to produce alkali alumino-silicates. Some of the eutectics in the Na_2O–Al_2O_3–SiO_2 and K_2O–Al_2O_3–SiO_2 systems are at comparatively low temperatures, so that the reaction is frequently accompanied by slagging and loss of shape through fluxing. At moderate temperatures, between 800 and 1,000 deg. C., it sometimes happens that alkali vapours are absorbed by the fireclay material to form alkali-alumino-silicates in the solid state. When free from restraint, this action is accompanied by an expansion[11] of the clay material, but under service conditions when the refractories are built into a structure, flaking and crumbling may be observed. As fuel oil ash is rich in soda it is possible, but not very probable, that effects of this kind may occur in marine boilers when the conditions of temperature are favourable. Again, chemical reaction between fired clay products and sulphur dioxide and sulphur trioxide in the range of temperature 600-1,000 deg. C. has been demonstrated and in some cases loss of strength has been reported.[12] Here again, it is feasible with some fuel oils that the sulphur dioxide produced on combustion may react with the firebrick to produce sulphates of aluminium, iron, calcium and magnesium in positions where the temperature falls within the reactive range. The formation of the sulphates does not appear in itself to have very disruptive effects but these may develop on hydration which could occur during periods when the boiler was not in use. Or again, with temperature cycles in which sulphates were alternately formed and decomposed again the structure of the bricks must of necessity be broken down.

Another type of disruptive action, to which firebricks are subject, arises from the growth of carbon around the ferruginous spots of the firebricks. In these reactions the iron spots act as catalysts to a reaction in which carbon is produced.

e.g. $$2CO \rightarrow C + CO_2$$
$$CH_4 \rightarrow C + 2H_2$$

Only a proportion of the iron spots in firebricks are capable of promoting such reactions and in these cases it appears that the iron compound present in the bricks is first activated by being reduced to metal or carbide. In general, well-fired firebricks are less susceptible to attack. The carbon monoxide decomposition[13] occurs most readily around 450-500 deg. C., but the hydrocarbon decomposition[14] (methane is only given above as an example) generally proceeds more vigorously around 800-1,100 deg. C. Obviously, such reactions can only occur in marine boilers under exceptional conditions, e.g. with incomplete combustion of fuel oil maintained over a considerable period.

(iii) Shrinkage

It is of the nature of clay and some other refractory materials such as diaspore and bauxite to shrink when they are dried and fired. Linear shrinkages of the order of 10 per cent are commonly met with. Allowance is made for this in the manufacturing process, the bricks, blocks and shapes being made from the mould oversize by a predetermined amount so that when the drying and firing shrinkage shall have taken place the article shall be of the correct dimensions. The rate of shrinkage at a particular temperature of firing decreases exponentially with time, but when it has virtually come to an end, renewed shrinkage will occur if the temperature is raised. It is therefore important that the kiln firing which the refractories have received shall have been appropriate to the use to which they are subsequently put, otherwise further shrinkage will occur in service. Shrinkage of the units of which a furnace wall has been built may result in cracks in the working face (as in Fig. 5), but more commonly certain of the joints open and there is then a tendency for jointing material to be lost. Unfilled joints provide a lodgment for fuel ash and increase the severity of slag action. They are also very undesirable because the bricks are thereby more exposed to sudden changes of temperature and to spalling. In large structures shrinkage in use can cause serious loss of alignment.

To ensure that clay refractories have been sufficiently well fired, standard reheat tests have been instituted. In this country it is customary to measure the linear shrinkage on reheating small $2\frac{1}{2} \times 2 \times 2$in. test-pieces at 1,410 deg. C. for two hours. Other higher temperatures can be employed for more severe duty. In the U.S.A. the corresponding A.S.T.M. reheat test requires three full sized bricks to be heated at 1,200 deg. C., 1,350 deg. C., 1,400 deg. C., 1,600 deg. C. for five hours, according to the duty required of them. Some clay products may expand irreversibly when reheated. This is also undesirable, but inasmuch as a small applied pressure can generally reverse the expansion of clay products, expansion is usually of less moment than shrinkage under service conditions.

For the severe duty required of the boiler refractories in certain ships of the U.S. Navy, W. T. Tredennick, J. F. Kelly and R. C. Burt[15] have argued that the period of time involved in the A.S.T.M. test is too short. For successful service as regards shrinkage, a refractory which does not shrink more than 1 per cent or expand by 3 per cent in volume in the first reheat at 1,600 deg. C. and which does not change more than 1 per cent in volume after two further similar reheats, is required. This conclusion is reached after correlating the condition of bricks in a naval boiler operating continuously for 600 hours and that of test bricks repeatedly submitted to the most severe of the A.S.T.M. schedules of reheating. The illustrations which accompany the paper by Tredennick, Kelly and Burt emphasize the defects which may develop in brickwork which has been insufficiently fired (see Fig. 5). At the same time it should be realized that the 60 per cent Al_2O_3 refractories used by the U.S. Navy for this duty, largely on the score of slag resistance, are of the type in which continued slow shrinkage at high temperatures is particularly liable to occur.

TYPES OF REFRACTORY

The demand for a material which will be sufficiently refractory, slag resistant and spalling resistant for use in ships' boilers and not unduly expensive can generally be met out of the alumino-silicate range of refractories.

(a) Firebricks and Aluminous Firebricks

These products are generally made from naturally occurring clays usually without other additions except perhaps some of the same clay, prefired and crushed. In this country most of the useful fireclays are located with the coal measures. The fireclays generally immediately underlie the seams of coal. Mineralogically the fireclays generally consist of fine grains of the clay mineral kaolinite, $Al_2O_3.2SiO_2.2H_2O$, with more or less quartz. Other minerals occur as impurities in minor amount. When the clay is fired it is partially converted to mullite, $3Al_2O_3.2SiO_2$ and cristobalite and the quartz present is also partly converted into cristobalite.

Some of the commonly measured properties of this kind of material are indicated in Table 2. It will be seen that the ratio of alumina to silica can vary over a wide range. Other factors equal, the refractoriness of the product increases with the proportion of alumina. The resistance to the action of fuel ash also rises with the alumina content. The thermal expansion increases with increase in the silica content; indeed the expansion up to 1,000 deg. C. is largely dependent on the proportion of free silica in the product and the various forms —quartz, cristobalite, tridymite—in which it is present in the fired brick. The resistance to thermal shock is largely governed by the physical texture, particularly the porosity, and the proportion and size of the clay grains and the prefired clay (grog) which may be included in the mix, since these factors influence the elasticity considerably.

TABLE 2.—SOME PROPERTIES OF FIREBRICKS

	25-30 per cent Al_2O_3	30-35 per cent Al_2O_3	35-42 per cent Al_2O_3
Refractoriness, Cone	27-29	28-31/32	32-34/35
deg. C.	1,610-1,650	1,630-1,700	1,710-1,760
Temperature of failure under load of 28 lb. per sq. in., deg. C.	1,380-1,440	1,440-1,520	1,550-1,620
Bulk density, gm./cc.	1·8-2·0	1·85-2·05	1·9-2·1
Crushing strength, lb. per sq. in.		2,500 - 5,500	
Thermal conductivity at mean temperature 400 deg. C., British units		coarse texture 6·7; fine texture 4·9	c 7
Specific heat, 400 deg. C.		c 0·2	
Thermal expansion 0-1,000 deg. C., per cent	0·6-0·7	0·55-0·65	0·5-0·6

(b) Mullite and High Alumina Refractories

Clay is the commonest of refractory materials and for most refractory purposes and for most marine boilers the purer kinds of clay containing, after calcination, between 32 and 42 per cent of alumina are adequate. For more severe duty, especially in respect of maximum temperatures to be withstood and resistance to slagging, more aluminous refractories are to be preferred.

All clays when strongly heated are converted into mullite and associated silica in the form of cristobalite. Mullite can be produced with less cristobalite contamination from other alumino-silicates, e.g. kyanite, andalusite, sillimanite, all of ideal formula, $Al_2O_3.SiO_2$; dumortierite $H\,Al(AlO)_7(BO)(SiO_4)_3$; or topaz $SiO_4(AlF)_2$. Of these, kyanite is the most abundant and of most importance; it is not a hydrated mineral and it is not plastic like clay. All the above minerals are converted into mullite on calcination. In the case of kyanite the conversion entails an increase in volume of about 18 per cent and the change is fairly rapid at temperatures over 1,350 deg. C. Precalcination of the raw materials is therefore essential, otherwise bricks would disrupt in service. The usual practice is to calcine the kyanite at about 1,500 deg. C., to crush and grade the product, to mix with 10 or 20 per cent of a good quality plastic clay and perhaps an organic bond, to shape by pressing or pneumatic ramming and to fire again at about 1,450-1,500 deg. C.

Bricks of approximately the mullite composition and of still higher alumina to silica ratios can be obtained by firing mixtures of clay with calcined alumina minerals such as diaspore $Al_2O_3.H_2O$ or bauxite $Al_2O_3.2H_2O$. This type of product is manufactured in America, rather than in England, since suitable deposits of diaspore and clay are found in Missouri and elsewhere in the U.S.A. On ignition at a high temperature these minerals are converted to corundum. The increase in crystal size of the corundum with increased severity of firing is usually accompanied by a considerable shrinkage. Hence the necessity for converting part at least of the aluminous mineral to a dead-burned condition. When crushed and rebonded with clay and refired it is not likely that mullite will be formed uniformly throughout the brick even if the overall composition corresponds roughly to $3Al_2O_3.2SiO_2$. Rather the diaspore grain is converted to corundum with a reaction rim of mullite in contact with the clay bond, which has itself converted to mullite and cristobalite (W. J. McCaughey).[16]

The properties of mullite and high alumina refractories are very dependent on the firing treatment received and the manufacturing technique employed. The values in Table 3 are indicative. The bricks are characterized by a high refractoriness and spalling resistance. The thermal expansion of mullite bricks is rather less than of bricks consisting mainly of corundum but the thermal conductivity is also less.

TABLE 3.—SOME PROPERTIES OF MULLITE AND HIGH ALUMINA BRICKS

	Calcined kyanite bricks	70 per cent Al_2O_3 bricks	95 per cent Al_2O_3 bricks
True specific gravity	2·9-3·1	3·5	3·9
Temperature of failure under load of 28 lb. per sq. in., deg. C.	>1,700	>1,700	>1,700
Thermal expansion 0-1,000 deg. C., per cent	0·4-0·5	0·65-0·75	0·8
Bulk density	2·0-2·2		
Thermal conductivity at mean temperature 400 deg. C., British units	c 10	c 14	

Mullite refractories were recommended by Y. Letort[17] and A. F. Robillard[18] for use in ships in the French Navy where the temperature and spalling conditions must be rated as severe. The U.S. Navy has employed 60 per cent Al_2O_3 bricks for such duty. W. A. Lambertson[5] has examined a diaspore (60 per cent alumina) firebrick from the vertical rear wall of a naval boiler after it had undergone 4,291 hours steaming. The analyses of the hot face, cold face and unused brick are given in Table 4, and a photograph of the site of the sample is given in Fig. 6.

It will be seen that during service there has been an appreciable increase in the impurities at the hot face sufficient to lower the refractoriness from Cone 36-Cone 37 to Cone 8 and that even at the cold face there has been some increase in the content of fluxing oxides, probably caused by the migration of low melting glass. The mineral phases identified were mullite, corundum, with small amounts of magnetite and spinel. The petrological observations were interpreted as indicating the conversion of the corundum and cristobalite of the original brick into mullite in the hot zone with the crystallization of the mullite favoured by the presence of some fluid melt. Later, as alkali corrosion developed at the hot face, the mullite was partly decomposed to reform corundum and spinel.

TABLE 4.—ANALYSES OF SLAGGED BRICK TAKEN FROM NAVAL BOILER (W. A. Lambertson[5])

	Unused brick	Cold face	Hot face
SiO_2	36·2	34·22	36·2
Al_2O_3	58·6	59·67	54·36
Fe_2O_3	1·38	2·79	4·66
TiO_2	3·76	2·02	1·62
CaO		0·55	1·80
MgO		0·70	1·40
K_2O+Na_2O	0·89	1·85	4·33
V_2O_5		0·18	0·18
Cr_2O_3		0·10	0·13
NiO		Trace	0·60
SO_3		Trace	Trace
$SiO_2:Al_2O_3$	1:1·62	1:1·74	1:1·50
Refractoriness, Cone	36-37	36-37	8
deg. C.	1,810-1,820	1,810-1,820	1,225

(c) *Plastic Refractory Mixtures*

For most purposes refractory materials are supplied in the form of fired bricks or blocks of prescribed dimensions. This is the case with marine boiler refractories except that a large proportion may be blocks of special shape. This arises because blocks may have to be bolted to the furnace casing or may have to be of a shape to suit the particular dimensions of the combustion chamber. Blocks of complicated shape are more expensive to make, and are not stocked in large quantities by the manufacturers. In some situations the difficulties encountered in placing blocks in position cause the contiguous surfaces of interlocking blocks not to be readily coated with jointing material so that joints are sometimes only partly filled, and the blocks are therefore more subject to the destructive processes of slag action and temperature fluctuation, as has already been outlined. In view of all these considerations there has been a tendency in recent years to make increasing use of plastic refractories, if not for a complete new lining at least for particular situations such as the burner walls, or for repair work (see Fig. 7 for a particular application).

Plastic refractories may be regarded as a development of the jointing material used in standard construction. Many proprietary compositions are on the market.

Plasticity is generally achieved by including a proportion of plastic clay in the mix. Since a large proportion of plastic clay would entail considerable shrinkage and cracking when high temperatures were attained in service, the amounts used are generally low and a large amount of non-plastic and non-shrinking highly refractory granular material is included in the mix. This usually consists of calcined fireclay, or kyanite crushed and graded so as to pack closely together. Richardson, Clews and Green[19] obtained satisfactory results in laboratory trials from a mixture containing 30 per cent calcined kyanite ($-8+16$ mesh), 10 per cent calcined kyanite ($-16+40$ mesh), 40 per cent calcined kyanite (-60 mesh), and 20 per cent of Scotch fireclay. Subsequently it was found that even the small shrinkage which occurred when this mixture was strongly heated could be reduced by including about 10 per cent of -60 mesh uncalcined kyanite in the plastic mixture. The amount of moisture included in the mixture is of importance since mixes moulded in a very wet state tend to shrink more and are more porous than mixes in which the water content is at a minimum and considerable force has to be applied when moulding them into position. Mixes may be conveniently moulded by means of a wooden mallet. Sometimes it is desirable to use a mixture which sets hard in the unfired state. This may conveniently be achieved by adding a proportion of sodium silicate. If more than 2 per cent of Na_2O is introduced in this way the effect on the refractoriness may be serious. With cold-setting cements of this kind it is necessary to allow for the ready escape of moisture which will be evolved at temperatures up to 900 deg. C. This can be done by puncturing the set surface with a pointed tool at intervals. Some provision must also be made for the reversible thermal expansion of the plastic refractory since after the first period of use the surface will be rigid. This can be done by scoring the surface to a depth of about an inch with a knife, while the refractory is still slightly plastic. The properties of plastic refractories may vary considerably; much depends on the nature of the main ingredients. Perhaps it may suffice to say that preparations can be obtained of comparable refractory properties to fired refractories of similar composition and with good spalling resistance and small firing shrinkage.

A plastic chrome preparation is sometimes used to coat over a set of closely packed water tubes to form the so-called water wall. Such preparations generally consist of finely ground chrome ore bonded with a little clay and/or sodium silicate, or the bond may consist of ciment fondu. Chrome plastic is refractory, and has a higher thermal conductivity than alumino-silicate refractories. It is also resistant to attack by iron oxide scale up to temperatures around 1,200 deg. C-1,300 deg. C. It is therefore suited to the sort of application just outlined.

The U.S. Navy has employed plastic refractories in their boiler furnaces and has laid down specifications[20] to which they must comply in respect of workability, strength and firing shrinkage. The assessment of workability was carried out by compressing 300 gm. of the test material in a steel cylinder 2in. in diameter by twenty blows (10 from each end) from a 14lb. weight falling through 2in. This is conveniently achieved in the American Foundrymen's Association sand rammer. The moulded, but unsupported, sample is then subjected to three further blows and the percentage decrease in height measured. Good performance was obtained from materials which suffered a 22 per cent decrease in height. The modulus of rupture prescribed was 100lb. per sq. in. at 1,500 deg. F., 200lb. per sq. in. at 2,000 deg. F. and 300lb. per sq. in. at 3,552 deg. F. The change in dimensions must not exceed 2 per cent contraction or 1 per cent expansion at any two temperatures between 230 and 2,552 deg. F.

(d) *Insulating Refractories*

One of the functions of the refractories in boilers is to confine the heat within the furnace. This is highly desirable, firstly because it ensures the more efficient use of the fuel and secondly because it contributes towards equable conditions in the stoke-hold.

Low thermal conductivity in refractories, however, can rarely be achieved without some sacrifice of durability. This is because the textural properties required for low conductivity, viz. high porosity and large internal surface area of the pores, are precisely those which tend to give high shrinkage on reheating, susceptibility to slag attack and to thermal shock, and low mechanical strength. Hence the practice is general of providing a refractory lining, chosen to resist the temperature and action of fuel ash, and to insert between it and the furnace casing one or more layers of material chosen on account of their resistance to heat flow. Despite the inherent and inevitable susceptibility of high porosity refractories to attack and disruption, considerable progress has been made in the last twenty years in increasing the temperature to which highly porous refractories may be safely exposed, at least under clean conditions.

When insulation of kilns and furnaces was first practised, the material generally employed was diatomite. Diatomite is the accumulated siliceous skeletal remains of diatoms. It owes its insulating properties to the extremely small sizes of the pores that are present, which are in turn derived from the small size and highly developed form of the original diatoms. Diatomite may be used as a powder, or bonded with clay and made into bricks, or, in favourable circumstances, cut from the natural deposit in the form of blocks.

Insulating firebricks are made by including a proportion of fine combustible material such as sawdust, anthracite powder, coke dust in a refractory fireclay mix, shaping by extrusion, hand moulding or semi-dry pressing and firing in kilns. Since one of the difficulties of manufacture with all highly porous refractories is the low load the goods will sustain while being fired, it is fairly common practice to fire a few courses of porous refractories on the top of a normal firebrick setting.

Another material which has come into prominence as an insulator is expanded vermiculite produced by quickly heating natural vermiculite (magnesia iron mica) to about 900 deg. C. The sudden evolution of the steam separates the crystal planes and produces grain of a low density consisting of thin slightly separated parallel plates. It can be used in grain or brick form.

The range of some of the more important properties is indicated in Table 5.

TABLE 5.—SOME PROPERTIES OF HIGH TEMPERATURE INSULATING BRICKS

Material	Thermal conductivity at 400 deg. C. mean temperature, British units	Maximum safe temperature	Cold crushing strength, lb. per sq. in.	Porosity, per cent	Bulk density, lb. per cu. ft.
Diatomite bricks	0·6-3·0	800->1,200 deg. C.	100-250	55-80	27-70
Fireclay bricks	1·5-3·0	<1,200->1,400 deg. C.	200-700	58-72	48-68

In general the maximum safe temperature of use is determined by the shrinkage which the material undergoes on exposure to heat. This is affected in turn by the purity of the raw materials, the size and number of the pores and the severity of the kiln firing already received. There is a considerable range in the values given above, but it is generally found that low thermal conductivity is linked to low bulk density and high porosity and relatively low maximum safe temperature of use. The fine pore structure of diatomite products limits the maximum temperature of use in most cases to about 950 deg. C.; it is only the exceptionally pure or the exceptionally dense varieties which can be used above 1,200 deg. C. In consequence, diatomite is nearly always used as a backing material whereas in suitable circumstances (not marine boiler furnaces) fireclay insulators can be used on the hot face. The type of construction illustrated (Fig. 8), which is that adopted on the American EC2 vessels, shows orthodox use of insulating material.

CONCLUSION

So many considerations enter into the design of a ship as a composite unit and of the individual components, including the boilers, that it would be improper to submit views on matters of design merely from the standpoint of ensuring good performance from the boiler refractories. It has therefore been the aim of the author to indicate what are the chief causes of deterioration of refractories in use and more particularly which of these are of prime importance in the raising of steam aboard ship. The aim of the boiler designer will naturally be to design the furnace so as to expose the refractories to as little rough usage as possible. Sometimes hard conditions for the refractories are unavoidable but to meet all usage effectively and economically some knowledge of the characteristics of the main types of refractory material is necessary. The second half of the paper has therefore been devoted to this aspect of the problem.

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Discussion

MR. W. KILLNER said Mr. Clews had covered a wide and troublesome field and given to the refractory world, both maker and user, much very useful information.

Although the author had stated that the causes of failure of refractories were few, they were nevertheless very serious. Experience had shown that the refractory materials which formed the walls of a boiler only too readily found their way to the furnace floor by spalling and/or slagging, and frequent re-bricking was necessary.

The firebrick manufacturer could produce from clays mined in this country a refractory to withstand the maximum temperatures likely to be encountered and leave the necessary margin of refractoriness which safety demanded and, as the author had stated, and for reasons he had given, the deformation under load was not likely to be serious.

It would be interesting to know whether the Bunker "C" oils referred to in Table 1 were water free and whether the constituents of the ash were from the fuels themselves or from water in the fuels. The figures given for the soda content were higher than one would expect to find in the natural ash of a fuel oil and they corresponded to those which would be expected from a fuel oil containing of the order of 1 per cent of sea water. Such an oil would give an ash where the sulphur compounds in the fuel had replaced the chloride to form sodium sulphate.

It was fairly safe to say that boiler fuel oil today always contained some water and in general this water was salt water.

There was room for much work in connexion with the behaviour of ash of fuel oils used to fire ships' boilers. Did the ash under all circumstances tend to accumulate in the furnaces, or, in cases where the ash content was of the order of 0·05 per cent, would the small globules of molten ash be airborne throughout their passage and be emitted from the funnel? There was evidence to suggest that the ash from fuel oils was to be found in various places, depending upon the extent of the contamination of the fuels by sea water; heavy contamination, resulting in a high ash and larger molten particles, deposited on the back and side walls and on the fire rows and superheater tubes, whilst where the contamination was lighter the ash accumulated in small spheroids in the economizer.

It was certain, however, that if the ash contained sodium salts and these found their way on to the brickwork in the early stages, they accumulated to form an encrustation. Further heating resulted in reaction with the constitutents of the firebricks with the formation of a glass-like slag, which ran down the walls and on to the furnace floor. Analysis of such encrustations showed them to have a high percentage of matter soluble in water which consisted of sodium sulphate, whilst the glass-like slags had practically no matter soluble in water and no sulphates.

Alkali sulphates volatilized at high temperatures without decomposition and it might be that the constituents of the firebrick turned out the SO_3 radical from the sodium sulphate and combined with the sodium to form the glass-like slag.

Even with a relatively dry oil, one could not neglect the salt carried in sea air supplied to a boiler, which increased the sodium salts entering the boiler.

There was, of course, a difference in the thermal expansions of fireclay products, and experience had shown that in many cases where the kiln firing temperature had been considerably below that to which the firebrick was submitted in use an undue difference had been found.

The disadvantages which accompanied firebricks of troublesome shapes was realized, and it would be an advantage to turn over to standard rectangular bricks, without bolt holes, similar to those enumerated in B.S.I. 1758:1951, any irregular shape being filled in with plastic. Such a brick could be machine made and it might be that pressure moulding would produce a homogeneous brick which might stand up to thermal shock much better than the present hand-made brick. The type of brick visualized would also avoid the danger of iron slagging due to anchor bolts becoming exposed.

Operational differences might have a bearing on the type of firebrick which gave the best service. It was questionable whether a 60 per cent alumina brick would withstand the action of the ash from sea water contaminated fuel oil as well as a 40 per cent alumina brick. There was an indication that the life of a 60 per cent alumina brick was lengthened considerably by the application of a 40 per cent alumina wash as a protection against slagging.

The factors which influenced slagging and slag penetration and the resistance to spalling appeared to be diametrically opposed. While a close grained brick might be better from the slag resistance angle than one of open texture, it would seem that the latter was more resistant to thermal shock and the spalling which it caused.

There was at the present time little information in this country to guide the user on resistance to spalling and slag attack. The simulative service test might provide some information on spalling characteristics and it would be useful to correlate the results obtained in this test with the behaviour of furnace refractories under Service conditions.

It would seem to be desirable to carry out the laboratory testing as far as possible on whole firebricks and not on test pieces cut from them.

Whilst it might be wise on the part of the author to avoid submitting views on matters of design, he could not help feeling that much good would result from closer co-operation between the firebrick makers, the users and their scientific staffs.

MR. W. R. HARVEY (Member) said that refractory materials were becoming more and more important to the watertube boiler user. Despite the custom today of providing a considerable amount of water cooled surface in boiler furnaces there was an urgent need for a really high class refractory material at economic cost which would withstand not only the somewhat higher boiler ratings now common practice, but also what might be termed the wear and tear due to more contaminated fuels in use today.

On page 271 under the heading, "The Function of Refractory Material", the author suggested (item 3) that one of the functions was to protect the furnace tubes from overheating and damage through the formation of steam pockets. I would suggest that this could not be the case as the avoidance of the formation of steam pockets was a necessary part of the design of the boiler.

The author had dealt very fully with the chemical properties of various refractories and their effect on the life of the brick, but the speaker was rather sorry that more detailed information as to the manufacture and firing of bricks had not been given, as he felt that the process used and the care taken in making the bricks was as important as the chemical analysis.

It would have been the experience of all users that often a brick which had been unsatisfactory in service had practically the same chemical analysis as a brick used in exactly the same position which would give a long trouble-free life, and he sugggested that the cause of the failure of the first brick was either imperfect firing or bad moulding. Due probably to the vast increase in output which had been required from the brickmakers over recent years, it was often found that bricks were of poor shape and this necessitated using thick jointing material between the bricks, which in the speaker's opinion was one of the most prevalent causes of wall failures; he felt that the author had this in mind when he referred on page 274 to the bricks or blocks being exposed by the falling out of the jointing cement. In his experience the only satisfactory way of building a furnace wall was to dispense entirely with any cementing of the brick joints, only permitting the bricks to be dipped in a slurry of the correct fireclay, made to the consistency of thick cream.

On page 273 the author stated that in marine boilers the refractories were not called on to support large stresses at high temperatures; with this he entirely agreed and could not recollect any trouble from this cause.

On page 274 the author suggested that the bolts used for anchoring the blocks to the casings were a potential source of danger, but he would point out that this type of anchoring had been obsolete for some years now.

The author very rightly pointed out the importance of allowing for the expansion of brick walls, and in his (Mr. Harvey's) opinion this could not be stressed too strongly, particularly with the men who actually carried out the construction of the wall. Too often it had been his experience that after careful arrangements had been made for the provision of expansion, this had been entirely ignored when the wall had been built up, with consequent trouble almost immediately the boilers had been fired. It was also his experience that thermal shock was the cause of many brick failures, and here the constructor or designer depended almost entirely on the operating staff who did not always realize what ultimate damage would be caused by bad operation, such as leaving the air inlets open after an oil burner had been shut off, or the malalignment of an oil burner.

In Fig. 5 the author illustrated two samples of shrinkage after only 112 and 420 hours' steaming. He would suggest that in the case shown there must have been something radically wrong with the brick material or the manufacture of the brick.

Figs. 7 and 8, illustrating the refractory furnace of the boilers of EC2 vessels, were most interesting, but it should be pointed out that the construction utilizing tongued and grooved bricks was special and was not the usual construction used in these vessels. It was also suggested that the plastic front shown was not good practice as it left what appeared to be a large overhang on the top which could easily be a source of considerable trouble.

Regarding slag attack, the author's opinion would be appreciated as to the advisability of the makers using finer grinding of the grog and higher pressure moulding in order to obtain a denser brick and thus make the brick more resistant to penetration.

Fig. 6 was also interesting and he would suggest that the general condition of the furnace could be considered quite good after 4,300 hours' steaming, which probably represented twelve months in service. With regard to the section on p. 275 headed "Abrasion", to withstand abrasion in marine stoker-fired boilers a few courses of air cooled silica carbide or carborundum bricks immediately above the grate level had been found very satisfactory.

Some further explanation of hydration on the formation of sulphates when the boilers were not in use would be appreciated.

The author had pointed out that unfilled joints provided a lodgement for fuel ash and increased the severity of slag action. This was certainly the case, but if the bricks were a good shape there would be no need to use jointing cement and therefore no chance of such material falling out.

Plastic refractory mixtures were excellent for use in place of special shapes, but it was suggested that these should be only of ramming quality and great care should be taken to see that the plastic was properly applied, as badly formed plastic was worse than badly shaped brick. Plastic chrome ore on stud tubes was most satisfactory, but it was suggested that the sentence used by the author on page 277, "coat over a set of closely packed tubes", was misleading. The chrome had to be rammed and was no use unless properly applied. In his own experience, insulating refractories properly designed and protected with firebrick gave practically no trouble. It could be confirmed that in certain cases refractory cement washes had proved satisfactory but it was most important that only a very thin wash should be applied.

LIEUT. COM'R(E) A. P. MONK, D.S.C., R.N.(ret.) (Member) said that the paper would be of great value to sea-going engineers because, in his view, the junior members who usually looked after the boilers were very ignorant so far as general refractory materials were concerned.

The serious effects of soda and iron oxide contamination acting as a flux and causing the brick face to melt at a lower temperature than the original brick was most interesting, particularly as the contamination might be caused by the oil fuel being burnt. With modern oil fuels the high standard of distilling, cracking and the latest catalytic cracking employed in order to obtain larger quantities of petrol and the higher volatile products, meant that the Bunker "C" fuel was getting progressively more coarse, and that was probably giving a concentration of impurities. In the last ten to fifteen years, the yield of petrol produced by modern methods of "cracking" the crude oil had improved by something like 50 per cent. Contamination would therefore appear to be left in the fuel, which would give further impurities and lead to slagging action or fluxing of the firebricks.

It was a pity that the effects of vanadium had not yet been fully investigated, because already trouble was experienced at high temperatures with vanadium. It would be interesting to learn whether this element caused excessive brick troubles as well.

A previous speaker stated that brick-bolts were obsolete, but Commander Monk did not entirely agree because quite a number were still being used. However, it was appreciated that the failure of a brick-bolt was serious in that the iron oxide contaminated the brick and lowered its refractoriness to the higher temperatures.

The question of protecting the bolt head by "stopping" should have far more attention paid to it than had been the case in the past. It would be interesting to hear what the author considered to be the ideal "stopping" for brick bolt heads. Presumably it should be a mixture of fireclay and the crushed brick; could Mr. Clews suggest the percentage mixture?

With regard to thermal shock so far as refractories were concerned, furnace temperature changes when manœuvring could not be controlled by the sea-going engineer although flame-impingement should be checked. A serious error which some sea-going engineers made was the practice of cooling the brickwork deliberately by opening up the air registers in order to cool the boiler quickly so that repair work might be expedited. Such practice should be condemned unless it was absolutely essential.

It was becoming the practice in some designs to provide for a means of water washing the superheater tubes. Presumably it was the intention that this should be carried out when the brick setting was cold, although there was still the danger of the washing being commenced whilst the setting was hot by an ardent operator desirous of getting ashore! Even if the job were done whilst the setting was cold it would be interesting to know the author's views on bricks which were wet when it came to lighting the boiler again. In a certain power station the practice for the past four years had been to water wash the superheater daily whilst the boiler was still on the line, and the claim was made that no insulating tiles had suffered as a result of that operation. Demonstration trials were carried out and the results on local insulating tiles appeared to be satisfactory. Therefore it would appear that the effect of water on the bricks, so far as thermal shock damage was concerned, was at variance with statements in the paper.

Plastic refractories had become increasingly popular in the last few years, and boiler designers were being asked whether they could be recommended. The author's comments were welcome and should certainly inspire confidence in anyone wishing to use those materials, but one practical point should be emphasized. Experience had shown that the plastic materials must be applied exactly as recommended by the makers, provision being made for venting during the drying out process and for expansion during its use. Some materials called for slow atmospheric drying whilst others required slow fire drying, and importance should be attached to those points.

On the question of the application of cement washes being applied, it was presumed that the author meant proprietary brands of materials for sealing bricks. Before using cement washes, an assurance should be obtained that the expansion of the material used was equal to that of the brick to which it was applied.

MR. B. TAYLOR, B.Sc.(Eng.) pointed out that refractory technology was not a subject which normally came within the scope of the marine engineer, and the paper was of particular interest since the question of deterioration of merchant ship boiler refractories was one which was engaging the attention of the British Shipbuilding Research Association at the present time.

Both slagging and spalling were serious problems met with in boiler operation, but he was inclined to think that spalling was the more important factor, particularly in the case of quarl blocks which often had a life of only a few months. In addition to harmful inclusions in the fuel and other factors which were outside the control of the fireman, much of the wastage of brickwork could be attributed to inadequate design and faulty operation of the oil-burning equipment.

On reading through the paper a number of points arose upon which the author might enlarge with advantage. First of all, referring to the statement on p. 273 in which temperatures of 1,650-1,700 deg. C. were mentioned, it was not clear whether that referred to furnace temperature or brick-face temperature. Those values seemed particularly high in view of the statement made in the recent paper by Ingram and Peile† that in a Naval boiler where the furnace rating was more than twice that of a highly rated merchant ship boiler, brick-face temperatures were of the order of 1,300 deg. C. In merchant ship boilers it was the normal practice to employ thicker linings, so that air cooling would not be so effective as in Naval designs. That would, of course, lead to an increase in brick-face temperatures. However, surprisingly little published information appeared to be available on the question of working temperatures.

With regard to slagging, it was noted that the author had not considered the effect of seawater inclusions in the fuel oil, which was quite probably one of the main factors causing that type of wastage. The introduction of seawater might be due to the use of fuel tanks for ballasting or leaky seams or, of course, seawater might be present when the fuel was loaded. In connexion with that point, it had been suggested by some authorities that the sodium chloride reacted in the furnace with sulphur dioxide from the fuel to produce sodium sulphate, which attacked the brickwork; but in the paper by Gray and Killner,* it was stated that the sodium chloride reacted with the constituents of the bricks to produce the well-known glass-like slag. The author's views on that would be interesting.

In some fuel oils, particularly of Venezuelan origin, the ash contained a high proportion of vanadium—of the order of 80 per cent—the total ash percentage being about 0·1. If vanadium pentoxide were a severe fluxing agent, it seemed that slagging troubles when using that oil were likely to be serious. Even when oils of Middle East origin were used, it was not unusual for slag to run down the walls, and after a number of years of service might attain several inches in thickness on the floor.

Fracture of the bricks commonly occurred, particularly where there was flame impingement. It also seemed probable that such damage might often result from cold air blowing on to the brickwork when a sprayer was shut off. Flame impingement also often caused carbon to build up on the brickwork, and it would be interesting to know whether that had an adverse effect on the performance of the refractory.

Another point which probably had some influence on spalling was that in many cases bricks were damaged when set in place, corners and edges being broken off in the many handlings to which they were subjected before finally reaching the boiler combustion chamber. When bolted blocks were used, it was very often impossible effectively to seal the joints between adjacent blocks.

In the section devoted to structural spalling, the author pointed out the way in which damage might result when there was a layer of vitrified material on the surface. Products were on the market, however, which were designed just to produce that effect. It would appear from the author's remarks that he did not advise the use of materials which were applied to the surface of the brickwork, but on the other hand it would appear desirable if the coefficients of expansion of the refractory and coating were carefully matched. By the use of such a coating it should be possible to use a more porous brick which was resistant to spalling while preventing the ingress of fluxing agents which caused slagging.

Shrinkage of the type shown in Fig. 5 and also opening up of the joints was fairly common. The author pointed out that this was due to incorrect heat treatment of the refractories during manufacture. At the present time, however, the supply position was so difficult that shipowners were more or less obliged to use whatever materials were available, and while that state of affairs existed there did not appear to be much possibility of obtaining bricks having the requisite properties.

In connexion with the question of specification for firebricks it was interesting to note in the paper by Ingram and Peile† that the Admiralty had discontinued the practice of specifying quality of firebrick by the alumina content, and had substituted the pyrometric cone equivalent with limitations on the porosity and contained fluxes. That would appear to be a much more satisfactory procedure in view of the author's statement regarding the great reduction in refractoriness which might result from small percentages of fluxing oxides which might be present. It was noted that the resistance to the action of fuel ash rose with the alumina content, but in the paper previously mentioned it was stated that increase in the alumina over 43 per cent led to a reduction of slagging resistance in the presence of sodium chloride.

It was understood that the objection to the use of higher alumina refractories was the fact that materials for their manufacture had to be imported, but it was probably correct to say that there were considerable deposits of kaolin in this country. Bricks made of that material had been used to a considerable extent in the United States, and were reported to have given very good results. It would be of interest to know whether such bricks were manufactured in this country.

Plastic refractories had the great advantage that they could

* 1948. C. J. Gray and W. Killner. "Sea Water Contamination of Boiler Fuel Oil and its Effects". Trans.I.Mar.E., Vol. LX, p. 43.

† 1951. L. F. Ingram and L. A. B. Peile. "Boiler and Turbine Testing". Trans.I.Mar.E., Vol. LXIII, p. 179.

be moulded to any shape and they were being used to a greater extent in recent years. The boilers of at least one ship had been completely lined with that material. Such linings often appeared to be more resistant to slagging than the standard 42 per cent alumina bricks, but unless great care was taken during installation of the material, cracking was liable to occur.

MR. G. A. PLUMMER (Member) said that all who were concerned with the operation of steam boilers would have experienced serious difficulties, failures and heavy maintenance of refractories, resulting in considerable expense and, in some cases, adversely affecting the service availability of the plant. The paper provided a valuable reference which adequately covered the reasons for those difficulties. Explanations and examples had been given proving how refractories could be affected by contamination of many of the constituents of the ash and by gaseous attack.

Table 4 showed how the refractoriness of high quality (60 per cent Al_2O_3) firebrick was reduced from 1,800 deg. C. to 1,225 deg. C. as a result of fluxing oxides from the fuel oil ash. Some of the difficulties might be reduced by attention to design and operation. Other difficulties might be avoided by the provision of special refractories, particularly where the makers were informed beforehand of any peculiar conditions of service or fuel. Unfortunately, however, many of the causes of refractory trouble were unpredictable, fortuitous, and beyond the control of the designer or user of the plant, and whilst it might be of some comfort for the cause of the trouble to be known, it would be of greater value to eliminate the trouble.

His own experience had led him to consider the desirability of reducing exposed refractory to the minimum; in fact, the ideal boiler, in his opinion, would have no exposed refractory, and in that connexion he was unable to accept the statements in the first two paragraphs of the paper. The author suggested that the elimination of exposed refractory would result in smoke and incomplete combustion, and to steam pockets in the water system of the boiler, due to inadequate circulation. Given sufficient temperature to cause ignition, any further heat developed was the result and not the cause of combustion. He had designed and operated a number of boilers having very little exposed refractory and, subject to well designed oil burners being fitted and under proper control, he had never experienced any difficulty with smoke. The combustion chamber must, of course, be designed in conjunction with the oil burners, and the atomization must be such as to enable the flame to be propagated within the confines of the combustion chamber without direct impingement of the fuel on to the furnace tubes.

With regard to the formation of steam pockets in the boiler tubes, the author's attention was drawn to the La Mont system of forced circulation which was at present employed in a number of British built and British owned vessels. In several cases, heat release rates of 340,000 B.Th.U. per cu. ft. per hr. had been employed and in one case the system operated at a heat release rate of 750,000 B.Th.U. per cu. ft. per hr. He had been to sea with several of these boilers and over some fourteen years had never yet had a case of overheating or failure of a boiler tube where forced circulation had been maintained.

(Mr. Plummer then showed a slide [reproduced as Fig. 9] illustrating a La Mont forced circulation combustion chamber.)

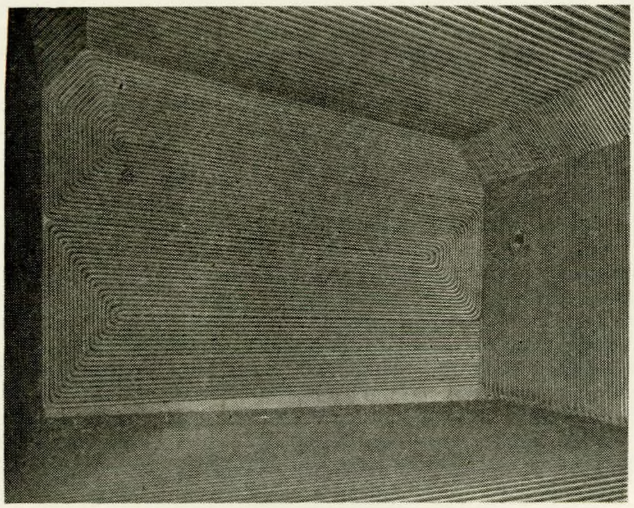

FIG. 9—*La Mont forced circulating combustion chamber*

It would be seen that the sides, rear wall and floor were formed entirely of bare, close pitched tubes, the only refractory in this case being the burner front wall.

Refractory material was undoubtedly necessary in many parts of boilers, but in his opinion should be used with discretion and not exposed unduly to the often severe duties and unsuitable atmosphere of the oil-fired combustion chambers of marine boilers.

MR. R. L. J. HAYDEN said that the paper was of great interest to him because most of the types of failure of refractories had come to his attention over the last five or six years. The cause of those failures had not always been apparent at the outset and it had only been during the slow collection of data on deposits on brickwork and tubes and on analysis of brick materials which had failed, that some inkling of the causes of failure had been brought to light.

The deposits which had been analysed contained the exact materials which the author enumerated as being destructive of refractory materials. In other words, they contained sodium sulphates, iron oxide and vanadium oxide.

The first assumption made when a brick failed was that it had been too hot and the paper well demonstrated that there were very many more factors than temperature alone which contributed towards the failure of refractories. It was usually possible in a marine boiler to provide for sufficient water cooling in the furnace to prevent refractories reaching their melting point. Over the last two years they had begun to realize that in addition to providing sufficient water cooling to reduce the furnace temperature it was also necessary to provide the maximum of water cooling to prevent actual impingement of the fuel and ash particles on the refractories. Presumably, there was a limit to the amount of water cooling which could be included local to burners without the combustion having to suffer.

Penetration of the refractories by constituents in the fuel ash happened to be one of the main causes of deterioration and it would be interesting to learn the author's opinion of the various coatings which were marketed and which appeared to preserve a non-porous face on the bricks. It was said that the coatings were supposed to be in a semi-plastic form when hot. If those methods were effective one wondered why firebricks were not supplied with such a non-porous face baked on. It would also be interesting to have the author's opinion on the effect of moisture on firebricks during storage, and whether it was harmful if the brickwork were slowly dried out after installation.

Plastic refractories were originally used as a makeshift when a preformed tile or brick could not be made for the service involved, or could not be obtained in time for repairs. Recently complete settings had been successfully carried out, and the difficulty with firing those settings seemed to have been overcome. It was difficult to understand how a sufficiently high temperature was reached in some places in the setting actually to fire the material, but apparently no serious difficulties had arisen afterwards so it must be assumed that the temperatures reached were satisfactory to fire the material. Those settings appeared to show some advantages in life over individual tiles, but the initial cost of the installation had to be borne in mind.

Brick bolts had been used very largely for securing individual tiles in marine boilers in this country. The American practice over the last twenty years had been to hold the bricks in contact with the water wall tubes by the insulation and casing. That did not appear to have given rise to the abrasion of the tubes or bricks which was anticipated, and the elimination of the brick bolts was a definite advantage in avoiding iron oxide contamination.

COM'R(E) J. I. T. GREEN, R.N. (Associate Member) said he was sure that boilers without bricks would be welcomed by all concerned and a previous speaker had drawn attention to the almost brickless furnace of the La Mont boiler. It might be of interest to consider from the theoretical point of view what was the function of the refractory and what sort of temperature it should be required to withstand. In general, it might be stated that for a fixed quantity of fuel burned in a given size of furnace, the less the brick area the lower the average temperature of combustion. The highest average figure obtainable at atmospheric pressure with a furnace completely surrounded by bricks, would be of the order of 2,000 deg. C., whereas the figure obtainable under comparable conditions in a furnace completely surrounded by water cooled tubes would be only 1,100 deg. C. As, however, combustion could not be properly sustained within the furnace at the lower figure quoted, the situation was that with atmospheric combustion some brickwork was essential. If pressure combustion were employed, brickwork would not be necessary except for the protection of uncooled surfaces.

As to the temperature reached by the brick surface, this depended again on the proportion of brick surface to total envelope surface; the smaller the relative area of brickwork, the lower would be its temperature on account of its high rate of radiation to the cooled surface.

Thus, a reduction in the amount of brickwork had a doubly beneficial effect on the temperature it had to withstand and this was of importance in comparing results of trials of bricks in furnaces of different design.

Regarding the figures in Tables 2 and 3 concerning thermal conductivity, could the author please give the detailed units employed?

Finally, with regard to item 4 of the list of functions on p. 271, surely a "reservoir of heat" would cause a marine boiler to blow off whenever the engines were stopped!

Correspondence

MR. L. BAKER, D.S.C. (Member of Council) had noticed that the author posed the question of the necessity of refractories before outlining their uses in the design of marine boilers; perhaps it would be better to admit from the outset that they were necessary but undesirable.

They were necessary because, by virtue of their peculiar combination of resistance to deformation by heat with a relatively low thermal conductivity, they could be used where no other material commonly available could be used. They were undesirable because they were always a potential source of weakness and, to a lesser extent, because their use implied a failure—however limited—of the boiler designer in achieving his object.

In modern boilers for mercantile service, the uses of refractories were:—

(a) to form the throats of the oil burning registers;
(b) to line the wall through which the oil was fired;
(c) to back up the water walls;
(d) to break down the temperature of uptake casings to values within the capabilities of insulating materials;
(e) to form dividing or protecting walls or to form corbels.

The requirements of these various applications were different, for example, the throat bricks had to withstand the maximum changes of temperature without spalling, whereas resistance to abrasion was of greater importance in the case of corbel bricks.

The requirements for each case could all be enumerated with fair accuracy but from the users' viewpoint it would appear that the development of refractories had not taken this possibility into account. Certainly, the information available to marine engineers gave no clue as to the desirable specifications for the various needs.

Until recently, the most usual refractories in service had been those with 33 per cent SiO_2, which had been due primarily to the fact that clays suitable for higher percentages were rare in Great Britain. Due to the impurities contained in them, many of these bricks were unsuitable for use in marine boilers, consequently renewals were expensive and frequent.

The two main impurities in marine boiler fuels were inorganic ashes and sea water; of the two, probably sea water was the more important as it could rise as high as 10 per cent without the operator becoming aware of any untoward circumstance. The boiler fuel ash appeared to be so finely dispersed that the particles remained airborne in the hot gases until they were deposited in the tube nest or uptakes, or on deck. Any ash deposit carelessly removed during cleaning operations might with some boilers fall into the furnace and cause the slagging described by the author, but his company's experience was that the greatest percentage of slagging was caused by sea water contamination of the fuel, allied with slagging of brick bolts due to extraneous air leaks in the casing.

It must also be appreciated that a most serious effect of slag accumulations on the floor of the boiler was the loss of clearance between the flame and refractory surface. In many cases this was so far reduced as to interfere with combustion when, of course, the disintegration of the refractory proceeds at an increased and increasing rate due to bad combustion.

Many defects in marine boilers, however, were not attributable to the material. The most common causes were:—

(a) failure to provide sufficient freedom for expansion;
(b) overtightening brick bolts;
(c) failure to ram and vent plastic refractory correctly or failure to fire it adequately.

These were design or maintenance defects that should no longer be necessary. With attention to these points and to the elimination of sea water from fuel, most refractory troubles would be eliminated.

REAR-ADMIRAL(E) F. E. CLEMITSON (Member) thought it would be apparent that the Royal Navy must be deeply interested in the question of boiler refractories, as being one of the many factors on which the extent of fully-operational periods of warships depended. It was of prime importance that H.M. ships should be fitted with the most durable boiler bricks, since, besides having to resist the causes of failure mentioned in the paper, they had to withstand physical shock, both from enemy action and the vessel's own armament.

Perhaps the most serious trouble encountered with Naval brickwork in recent years had been the effects of sea water in the furnace fuel. Experience had shown that a fuel contaminated with as much as 12 per cent water, in the form of a stable emulsion, could be burned without the boiler room staff being aware of its presence. Such contamination had led to rapid and serious deterioration of the boiler refractories.

Although it was expedient to guard against the presence of sea water in the fuel and in this respect frequent tests could be made using the apparatus referred to in the paper by Gray and Killner,* nevertheless its absence could not be always guaranteed or, on discovery, the fuel might have to be used.

It was felt, therefore, that every effort should be made to develop refractories which would withstand the effects of this contamination.

With reference to the little known effects of vanadium derivatives, it was considered that studies in this field should be pursued.

MR. D. HORSBURGH (Member) considered that it was most important that the firebrick for any particular boiler should be chosen carefully as to refractoriness and good shape so that the bricks could be laid up with thin joints and so had a better chance to stand up to the work they were called upon to do, with a little in hand in case the boiler might have to be forced. In many cases bricks were obtained locally, possibly due to the present difficult situation as to delivery of good quality firebricks; they were not suitable for the work and entailed heavy expenditure in renewals.

To find the cause of failure of furnace brickwork, it would be extremely useful to know the actual brick temperatures in various parts of the furnace in order to assess the damage due to chemical attack and that due to the refractories not being of a sufficiently high quality. From Table 2 it would seem that refractories would not fail owing to excessive heating but rather from chemical attack from the fuel oil ash, together with the stresses put on the brickwork by too rapid heating and cooling.

Great care should be taken of the fuel oil burners during operation and, especially in cleaning, no hard instrument should be used to remove carbon from the tips, possibly damaging them by altering the shape of the hole in the diaphragm and resulting in less perfect atomization of the oil or even spraying the refractories with partly consumed oil which burned on the bricks and contributed to their failure. He agreed with the author that adequate expansion spaces must be allowed for in the brickwork, especially with thin joints, or spalling would occur and so expose another surface for penetration of heat and gases. Some furnace back walls had been observed where the bricks had fused badly, so much so as to fuse on to the side walls and prevent normal expansion and contraction, with resulting bulging and spalling of the walls. Many plastic refractory mixtures were on the market, but these were mostly only plastic while being made up and when fired they became hard and non-plastic and so were liable to failure like ordinary firebrick. There was a glaze refractory coating on the market which, at its vitrifying temperature and above, was semi-plastic and gave with the expansion or contraction of the bricks coated. It prevented the entrance of the gases of combustion into the pores of the brick and sealed up any slight cracks which might occur in the brickwork beneath; also, by covering the joints between the bricks, it rendered them less likely to spalling, which usually commenced along the edges of the brick, giving rise to the well-known "cobblestone" effect.

Walls could also be laid up with one of these glaze coatings of the correct vitrifying temperature and the face of the brick coated with a glaze of a higher vitrifying temperature to suit the furnace conditions and so, by its semi-plastic nature under working conditions, gave a monolithic wall. Had the author had any experience of these glazes?

MR. JOHN LAMB, O.B.E. (Member) thought that the subject of gas turbines, while not strictly within the scope of the paper as defined by its title, was of increasing interest to marine engineers and it was hoped that a few remarks on the use of refractory materials in gas turbine combustion chambers would not be regarded as irrelevant, and might induce the author to give his views.

The flame zone of a gas turbine combustion chamber was similar to the furnace of a boiler in that air-fuel ratios were near stoichiometric and thus flame temperature was high. Otherwise, the two systems were noted for their differences rather than their similarities. The gas turbine combustion chamber might receive preheated air at 400 deg. C. and, in the flame zone, raise the products of combustion to an average temperature of 1,900 deg. C. Coupled with this was the high heat release rate per unit volume of combustion space. Thus, ratings of 280lb. fuel per hr. ft.^{3} were normal and might be exceeded in some installations. Subsequent to complete combustion in the flame zone, the products were diluted with preheated air down to the turbine inlet temperature (600-700 deg. C.).

The use of refractories to line the primary zone was an early development and the first technical problem was to maintain moderate brick inside surface temperature by the correct choice of cooling air (i.e. diluent air) velocities, brick thickness and thermal conductivity. After succumbing early on to the temptation of using continuous annular rings of material, it was realized that hoop stresses would prohibit this form of construction. The result was a segmented construction with its attendant complication in brick profile for keying.

From the material standpoint the author's criteria had been found to be extremely important. The arduous conditions necessitated good resistance to spalling and ash attack and, broadly speaking, the most promising materials had belonged to the alumina-silica group with alumina contents not less than about 70 per cent. As inferred by the author, it had been discovered that an open structure material, although beneficial for spalling resistance, offered increased opportunities for slag attack and to some extent there had to be a compromise in the grain size chosen for a satisfactory material. Outside the alumina-silica group, experience on magnesite showed it to have low spalling resistance; zircon was slightly inferior to alumina bricks on the score of spalling and more so on ash attack; silicon carbide, although possessing very high strength, was oxidized rapidly in the atmosphere of the combustion chamber; recrystallized alumina (of high purity) was expensive and difficult to grind to shape after firing, although slight experience showed it to have high strength and resistance to ash attack. It would be instructive if the author could comment on these experiences, possibly indicating materials of better performance under the given conditions.

In the case of the gas turbine built for the tanker *Auris* the hot face temperature was estimated for design purposes as 1,400 deg. C.; during shop trials of the unit the actual temperature was 1,200-1,250 deg. C. The condition of the bricks, which contained 70 per cent alumina, was satisfactory after 680 hours' running but it had been decided to replace them with bricks made of an 80 per cent alumina material. It was hoped that this might further improve slagging resistance.

It was possible, of course, that refractory lined combustion chambers would be superseded by the all-metal type but it should be pointed out that the amount of flame cooling was much greater in the absence of a refractory lining, and while this did not prevent such combustion chambers from dealing satisfactorily with light fuels it might prove an obstacle to obtaining good combustion with boiler oil. The problem was somewhat analogous to the amount of water wall surface which could be incorporated into a boiler furnace without introducing combustion difficulties.

MR. J. W. E. STANLEY proposed to contribute something extra to that part of the paper dealing with refractory plastics; or rather, more specifically, to the subject of complete "full-monolithic" marine boiler settings, in the hope that it might prove of value.

The author had stated some of the inherent disadvantages in the use of "special shapes" and had indicated the tendency to make increasing use of refractory plastics.

He (Mr. Stanley) suggested that there were four principal reasons why, in their earlier stages of development, refractory plastics were limited in their application:—

(1) They were not good enough in quality;
(2) the engineering technique had not been sufficiently developed;

* 1948. C. J. Gray and W. Killner. "Sea Water Contamination of Boiler Fuel Oil and its Effects". Trans.I.Mar.E., Vol. LX, p. 43.

(3) the necessary mechanical devices had not been invented and perfected;
(4) innate conservatism and prejudice had to be overcome.

Meanwhile, due to the continually increasing severity of conditions to which the refractory linings were exposed, refractory bricks were greatly improved in quality and dimensional accuracy and their range extended.

However, the inherent defects in the structures built with standard bricks and special shapes, namely the weakening joints and the lack of attachment of the brick lining or, alternatively, its rigid attachment to the outer supporting structure, could not be overcome. Further brick and tile constructions were not sufficiently flexible to enable the designer to provide the most suitable refractory and insulating enclosure for optimum combustion, bearing in mind that the gases were not only at high temperature but were travelling at high velocity.

By the time he had at his disposal a useful range of quality refractory plastics, the engineer had got busy, conceived the idea of the "full-monolithic" structure and invented the devices necessary to its success. The rest was a process of evolution and improvement. Thus, the application of the engineering mind to the structural problems, coupled with the advances made by the refractory scientist in the materials, gave birth to the full-monolithic boiler setting and furnace lining—an engineering, not a brick job, and eliminating the inherent defects of the latter. Hence the term "refractory engineering", coined by the writer, who was the first refractory engineer in the country and who had been in close contact with all the developments over the past twenty years.

Today there were endless land boilers with "full-monolithic" settings constructed with refractory plastics, boilers of all types and sizes, including the very largest. There were also quite a few ships sailing the seas with similar boiler settings and a great many more, whose settings had been partially reconstructed, and which were well on the way towards complete settings.

The latest designs of marine boilers imposed even more severe conditions on the refractory settings than did their predecessors and a refractory plastic had to be specifically evolved to meet this heavy duty successfully. As a result these modern methods and materials were being adopted more and more; they were already standardized by some of the best known shipping and tanker companies in the world.

Further, some of the marine boilermakers were now allowing his organization to co-operate closely with them. They were already finding that they could modify their steel casings, cut down weight and save steel.

As to the future, his organization neither designed nor made boilers but it was his belief that, in some respects, the boiler designer had been hampered by the restrictions in design imposed on him by the brick and tile settings. When he had rid his mind of these restrictions and proceeded to design anew, it was his belief that the "full-monolithic" refractory engineering setting would give him scope for at least some improvement in efficiency and service.

Author's Reply

In reply to Mr. Killner the author said that the composition of the ash from Bunker "C" oil was quoted and used by way of illustration. From the quantities of the different oxides which were listed in the analyses it seemed likely that certain amount of sea water was present in the fuel.

The author agreed with Mr. Killner regarding his description of the manner in which the ash from fuel oils behaved in ships' boilers. It was probable that the larger particles (liquid or solid) would be retained in the furnace but that the smaller particles would pass further through the flues and the finest would be emitted from the funnel.

The author also largely agreed with the description given by Mr. Killner of the action of sodium salts on the brickwork.

Mr. Killner had referred to the use of bricks similar to those enumerated in B.S.I. 17, 58; 1951. If designers could use such simply shaped bricks it would be all to the good in the performance of the refractories in the boiler furnace.

The comment to the effect that 40 per cent alumina bricks resisted the fluxing action of soda rather better than 60 per cent alumina bricks was quite interesting. There was a certain amount of theoretical confirmation of that in the case of a ferruginous slag approximately 34 per cent Fe_2O_3, 17 per cent Al_2O_3, 44 per cent SiO_2, 5 per cent $CaO + MgO$,* but not, so far as he could make out, for slags rich in soda.

Mr. Harvey raised an important issue when he referred to methods of shaping and firing bricks. In the old-fashioned method of making bricks by hand, a good brickmaker could produce a very good brick because he paid attention to the particular positions in the mould in which defects were likely to arise; if this were not done with complicated shapes, defects would be present in the finished article. Some products were prepared by extrusion and were sometimes re-pressed to give them more accurate shape. Bricks could also be shaped by semi-dry pressing using clay-water mixtures in which the water content was lower and the pressures employed in shaping were higher. Another method sometimes used for blocks other than the simple shapes, was to use a pneumatic ramming process to consolidate the contents of the mould. In all cases, the accurate shape of the finished brick was very important; this enabled the joints to be quite thin. If desired, the method of dipping the bricks in a fireclay slurry could then be applied.

In reply to Mr. Harvey's question concerning slag attack, the author said the importance of brick texture in giving resistance to fluxing was referred to in the paper. It would probably be true to say that, in general, the larger the proportion of solid matter in the brick, the greater would be the resistance to the solvent action of the slag. That principle was made use of in making glass tank blocks of almost zero porosity. In the case of marine boilers, of course, corrosion was not the only thing which had to be considered; resistance to spalling was probably even more important. Manufacturers achieved some control over spalling resistance by varying the elasticity of the brick, which in turn was accomplished by adjusting the porosity.

* 1939. Endell, Fehling and Kley. Jl.Amer.Ceram.Soc., Vol. 22, p. 113.

Commander Monk asked for a suitable composition for a brick bolthead stopping. The author's opinion was that it would probably require the sort of composition which was given in the section of the paper devoted to plastic refractory mixtures. The author agreed with Commander Monk in condemning the practice of cooling the brickwork deliberately by opening the air registers. Similarly, the practice of washing the superheated tubes should certainly be carried out when the brick setting was cold. One of the standard tests for measuring the resistance of bricks to thermal shock was to withdraw them from a furnace at 1,000 deg. C., then to lower the ends an inch or so into cold water and to repeat the process until the bricks cracked. In practice, bricks might survive an occasional spraying or washing with water even while hot, but unless there was good reason for it, the practice was to be avoided.

Several questions had been asked on the value of cement washes. If a cement wash matched in thermal expansion that of the brickwork on which it were placed, it was difficult to see that it could do much harm. On the other hand, it was difficult to see how effective would be a very thin layer of material, basically similar in composition to the brick, in retarding the action of the slag. If the thermal expansion of the cement wash on the brick were not satisfactorily matched, then the cement layer would flake off, probably carrying with it a certain proportion of the underlying brick. On the other hand, if a serious attempt were being made to combine slag resistance and spalling resistance in one unit, then it would be theoretically possible to design a brick having a front face composed of, say, $1\frac{1}{2}$ inch of slag resisting material, and the back portion porous and spalling resistant. In fact, that kind of brick had been evolved for heat insulation, the working face had been made slag resistant and the rear portion resistant to the flow of heat. It was, however, expensive to produce and brick manufacturers had not adopted the idea to any considerable extent.

The author was interested in Mr. Taylor's remarks, particularly the statement that in his experience spalling was the trouble to which marine boilers were subject, especially the quarl blocks. Mr. Taylor queried the temperatures which were quoted for the hot face of the furnace refractories. They were certainly high, but all the author could do was to quote from the literature because he had no personal experience of what were maximum brickface temperatures in these circumstances. One of the difficulties in writing a paper on the subject of refractory materials for marine boilers was to obtain all the facts; it was possible that the temperatures quoted were obtained under exceptional conditions.

Experiments on the action of sodium chloride on firebricks had shown that under certain conditions some of the constituent oxides of the bricks could be volatilized; for example, the alumina, iron oxide and lime tended to be volatilized to some extent as chlorides according to equations such as:—

$$CaO + 2NaCl = CaCl_2 + Na_2O$$
$$Al_2O_3 + 6NaCl = 2AlCl_3 + 3Na_2O$$

Any soda liberated in this way, or by direct hydrolysis of the sodium chloride, would combine with the brick constituents to form alkali alumino silicates, which might be fluid at the temperature of the furnace.

The chemical action of sodium sulphate on brickwork was similar, alkali alumino silicates being formed and sulphur trioxide liberated. Both sodium salts reacted more readily with hot brick material in the presence of steam. At temperatures of the order of 1,000 deg. C., however, the reactions were not particularly rapid and sodium chloride and sulphate could persist unchanged in contact with firebrick material for some hours.

As to the carbon which was built up and its possible deleterious action, this would occur if it adhered very tenaciously to the brick and if the expansion of the carbon were different from that of the underlying brick. A sudden rise or fall in temperature might be responsible for the flaking off of the carbon with a certain amount of brick attached to it. Of course the carbon might have a chemical action in bringing about reducing conditions locally and enhancing the fluxing action of iron oxides. The author agreed that it was more satisfactory to specify refractories on the basis of their refractoriness rather than solely on their alumina content.

Mr. Taylor referred to kaolin bricks; a certain amount of china clay from Cornwall was being used for making refractories in the form of grain and was also made up into bricks. One application of the latter had been in connexion with blast furnaces, but limited supplies only of such bricks were available.

Mr. Plummer referred to the question of the amount of refractories which were required in marine boilers. This subject was of particular interest to the author when he commenced to write the paper. Subsequently, the problem had been fairly stated and answered by Commander Green.

In reply to Mr. Hayden, the amount of damage sustained by firebricks stored in a damp atmosphere was comparatively slight, provided they were not exposed to the action of frost. They should, of course, be put into use quite slowly. A certain amount of hydration could take place and, as some of the pores in the bricks were very small, if the temperatures were raised quickly the water which was retained in the fine pores escaped with difficulty and might even cause an explosion.

In reply to Commander Green, the units in which thermal conductivity was expressed in Table 5 were B.Th.U. per sq. ft. per hr. per deg. F. temperature difference per in. thickness.

The author wished to thank Mr. Baker for his contribution, but did not think that it called for much comment from him, except to express general agreement with his statements. It was, of course, necessary to construct and operate correctly plant containing refractory materials, before complaining of the length of service that had been obtained.

The author thanked Rear Admiral Clemitson for his contribution. His view reinforced that of several previous speakers, that sea water contamination of fuel oil was the chief source of fluxing of boiler refractories. A refractory which could withstand completely the action of alkali salts had yet to be found and it was probable that greater success might be obtained in ensuring that the fuel was as free as possible from contamination from sea water. The action of oxides of vanadium on refractories would be a useful subject for investigation.

The author agreed with Mr. Horsburgh on the need for investigation of the actual brick temperatures in various parts of the furnace. It would probably be true to say that boiler refractories failed more from the chemical action of the fuel ash and from spalling through rapid heating and cooling than through excessive temperature. Regarding the use of plastic refractories, it was, of course, necessary to appreciate that while they were plastic at the outset, as soon as they were exposed to high temperature in use the portions so heated became rigid.

The author was interested in the contribution sent by Mr. Stanley. There was obviously a considerable field for the application of plastic refractories in marine boilers and particulars of the service to be obtained from boilers having the full monolithic furnace structure would be awaited with much interest. The author thought that they were likely to achieve considerable success. The use of plastic refractories certainly removed some of the restrictions in design imposed by the more usual fired refractories.

The contribution of Mr. Lamb on the subject of gas turbines was most interesting; it was certainly a subject closely allied to that of the paper under discussion although the author had excluded it from consideration. It was generally agreed that refractories for gas turbines would require to have good resistance to spalling and corrosion by fuel ash, and it was very interesting to have Mr. Lamb's experience on the relative performance of alumino-silicate refractories, magnesite, zircon, silicon carbide and re-crystallized alumina. These were in line with the known properties of these materials. Gas turbines for marine propulsion were not subject to the same restrictions of weight as gas turbines for aircraft propulsion; it was therefore interesting to read Mr. Lamb's conjecture that