

General Developments in Ceramics for Marine Engineering

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A general review is presented of developments which have taken place in ceramics, in the last decade, in so far as they affect:—

Marine Boilers
Gas Turbines
Diesel Engines and
Nuclear Power Plant.

The development of the Super Duty bricks and mouldable and castable materials used extensively in marine boilers is referred to and developments aimed to provide ceramic materials suitable for gas turbine combustion chamber linings and turbine blades are described. Mention is made of ceramic coatings for Diesel engine pistons and valves and ceramic materials which may possibly be employed in nuclear reactors are reviewed.

INTRODUCTION

The Oxford English Dictionary defines "ceramic" in the following terms:

"Of or pertaining to pottery especially as an art; as a noun in the plural—the ceramic art."

It is quite obvious to anyone with even a superficial knowledge of ceramic technology that this definition is far too narrow to cover present day usage of the word.

There have in fact, in this century been several papers devoted entirely to attempts to define the term ceramic and one of them (11) concludes that Ceramics should be defined as an inorganic technology in which cold moulding is followed by consolidation by the action of heat. Although this has met with wide acceptance, in some directions it would seem to be too wide a definition, in that, for example, it could include sintered metals, but on the other hand it excludes hot-pressing which is now an established ceramic technique.

The American Ceramic Society includes among its interests; pottery, clay building materials, refractories, hydraulic cement, vitreous enamel ware, glass, abrasives and electro ceramics. The interests of the British Ceramic Society are not so wide, in that it has four sections; Pottery, Heavy Clay Ware, Refractories, and Basic Science. The first of these sections embraces industrial porcelains and electrical ceramics as well as true pottery.

Taking even the more restricted British interpretation of ceramics these are involved in the marine industry in many ways such as:

- (a) In the metallurgical industries, which represent the biggest tonnage consumption of refractories.
- (b) In the fabrication of metals, e.g. refractories in furnaces, ceramic welding nozzles, ceramic sand blast nozzles.
- (c) In heat engines, not only in traditional boiler plants but in gas turbines and nuclear power plants.
- (d) In electronic equipment, which includes a wide range of ceramic materials chosen usually for specific electrical properties.
- (e) Lastly, ceramics of course are used in the "domestic" sense in sanitary ware, tiles, and pottery.

It is proposed to limit the present paper to the use of ceramic materials in heat engines, and to cover not only established uses but also work which is still in the very early develop-

ment stages and may or may not ultimately have commercial impact on marine engineering.

MARINE BOILER LININGS

Firebricks

At the end of the last war it was apparent that the refractories available in Great Britain for lining marine boilers were inadequate to meet the increasingly severe operating conditions in boilers of new design. The choice of materials was almost entirely confined to firebricks made from Scottish clays, having analyses in the range 35 per cent Al_2O_3 , 60 per cent SiO_2 to 42 per cent Al_2O_3 , 54 per cent SiO_2 , the balance in each case being made up of fluxes such as mica, feldspar and the oxides of iron and titanium.

These grades were kilned to temperatures of the order of 1,350—1,400 deg. C. resulting in limiting service temperatures up to about 1,450 deg. C. in the case of the 42 per cent alumina grade and 1,350—1,400 deg. C. in the case of the 35 per cent alumina grade. The majority of these bricks were moulded by either soft mud or stiff mud processes, which, because of high drying and kilning shrinkages, leave much to be desired in shape and dimensional accuracy.

Improved service results were obtained by the introduction of dry and semi-dry moulding techniques which produce bricks of a much improved dimensional standard. Troubles still arose however, from bricks, especially quarl brick, spalling after quite short periods of steaming and from slagging which generally attacked the joints to a greater degree than the remainder of the lining. This joint attack was aggravated by brick shrinkage in parts of the boiler where temperatures (14) were near the safe limit for the refractory and by the use of clay jointing materials which were inadequate for the purpose.

It was apparent that there was a need for refractory bricks which had even better thermal shock resistance and greater volume stability than the best quality Scottish firebricks and development of suitable products was undertaken by several manufacturers.

It appeared desirable to develop bricks based on indigenous raw materials and here the first problem was to find a suitable clay which would withstand the higher kilning temperatures required to give adequate volume stability. Two possibilities were open, either the beneficiation of the 42 per cent Al_2O_3 Ayrshire clays in order to reduce the flux content or the use of china clays which have low flux contents and are generally more refractory.

The manufacture of bricks from china clays represented

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quite a new departure and one of the major problems facing the manufacturers was the very high linear shrinkage associated with the kilning of these clays when temperatures of the order of 1,600 deg. C. are used to confer stability. This was overcome by employing as the main constituent of the refractory, china clay which had already been calcined to a sufficiently high temperature virtually to eliminate shrinkage. This calcined material, usually termed "grog", formed up to 80 per cent of the final product. By careful size grading of this grog, bricks were produced which on laboratory test had very much better thermal shock resistance than the best quality Scottish firebrick. These results have been fully confirmed in service.

At the same time, development proceeded with refractories based on imported raw materials. Sillimanite ($Al_2O_3 \cdot SiO_2$) and bauxite were employed, the development following a similar pattern to that with china clays, and products were evolved ranging from 55-65 per cent alumina content, having excellent volume stability at temperatures well in excess of 1,500 deg. C. These products also showed excellent resistance to thermal shock.

Typical properties of the bricks which have resulted from this development work and which are now in service in marine boilers, are shown in Table I, compared with a typical Scottish firebrick.

TABLE I.—PROPERTIES OF BRICKS FOR MARINE BOILER LININGS

	Scottish firebrick	China clay Super Duty	Bauxite based 60 per cent. Al_2O_3	Sillimanite based 55 per cent. Al_2O_3	Sillimanite based 63 per cent. Al_2O_3
Per cent Al_2O_3	42	43	60	56	63
Per cent SiO_2	51	53	36	39	34
Per cent total flux content	7	4	4	5	3
Bulk density gm/cc.	1.92	2.15	2.15	2.31	2.35
Apparent porosity, per cent	28	17	23	25	22
Reheat shrinkage 2 hrs. at.	0.3 per cent. (1,410 deg. C.)	0.8 per cent. (1,500 deg. C.)	0.8 per cent. (1,600 deg. C.)	+0.5 per cent. (1,500 deg. C.)	0.2 per cent. (1,500 deg. C.)

Almost all the china clay and high alumina refractories are manufactured by dry pressing methods ensuring consistency and accuracy of size. Air setting cements especially developed for use with these grades are recommended for use in marine boilers, and eliminate the jointing troubles referred to earlier.

Thermal Shock Testing

In all developments it is necessary to have some means of assessing the product in the laboratory, and whilst reasonable test procedures existed for determining physical properties, the only test for thermal shock resistance in use in this country consisted of heating a 2-in. prism to 1,000 deg. C. repeatedly until it fractured. This test has obvious shortcomings especially for applications where it was anticipated that there would be rapid temperature fluctuations up to 1,400 deg. C. In the United States, the American Society for Testing Materials developed a panel spalling test which tests a panel of bricks built in a similar manner to normal construction and tested by heating on one face as would be the case in service (1 and 15).

The panel spalling test for Super Duty bricks is a two part test comprising a preheat test in which the face of the panel is heated to 1,650 deg. C. for 24 hours to simulate the effect of prolonged heating in service followed by a spalling test in which the face of the panel is heated to 1,400 deg. C. for 10 minutes and cooled by means of a controlled air and water blast for a further 10 minutes. The heating and cooling cycle is repeated 12 times and the loss in weight of the test bricks at the end of the test is taken as a measure of the resistance to spalling.

Fig. 1, illustrates a panel of 42 per cent Al_2O_3 Scottish firebricks which lost 9 per cent by weight, after testing on the A.S.T.M. panel spalling test.

Fig. 2 shows a panel of china clay Super Duty firebrick which lost 3 per cent by weight on test, and Fig. 3, a 60 per

cent alumina bauxite based high alumina brick which showed no loss on test.

Insulation

Insulating firebricks capable of withstanding temperatures in excess of 1,500 deg. C. and having thermal conductivities of about one third that of normal firebrick, have also been developed. These are based on various clays which in manufacture are blended with a combustible material such as sawdust or coke. The combustible burns out during kilning leaving a very porous light-weight refractory. These products permit higher interface temperatures between the solid grade lining and the insulation so that either thinner hot face linings or a greater amount of insulation can be employed.

Monolithic Refractories

The other major refractory developments affecting marine boilers have been in the field of mouldable and castable refractories. In the furnace chamber the use of mouldables has become widespread and for lining superheater chambers, castables have been used with very satisfactory results.

Pre-1950 mouldable refractories were simply firebrick recipes supplied in the unfired state and used for patching spalled or eroded brickwork. These patches frequently gave

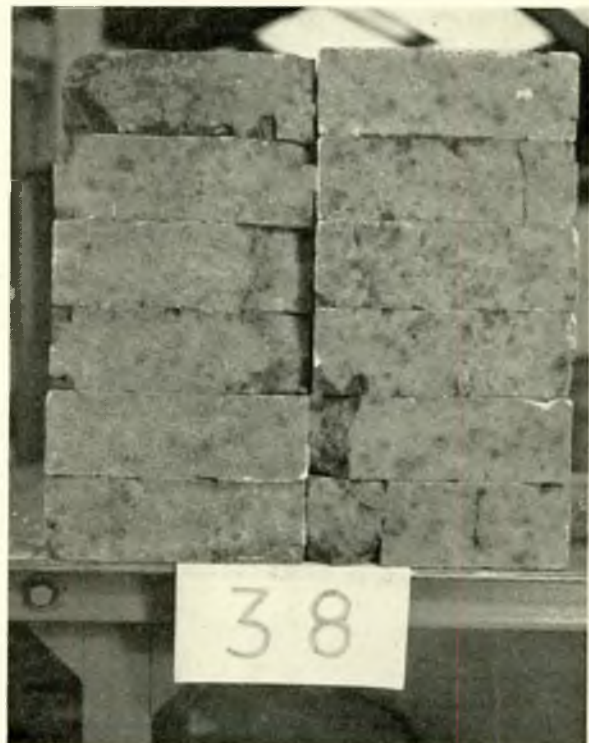


FIG. 1.—Scottish firebrick after panel spalling test

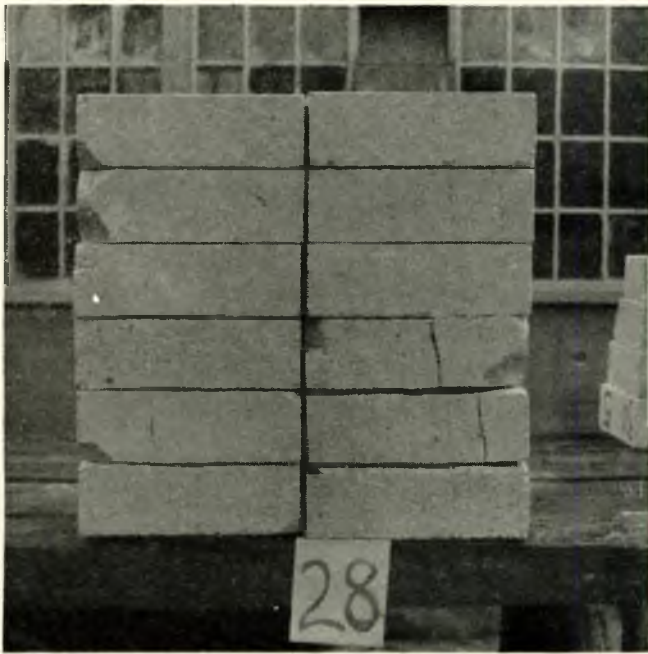


FIG. 2—China clay brick after panel spalling test

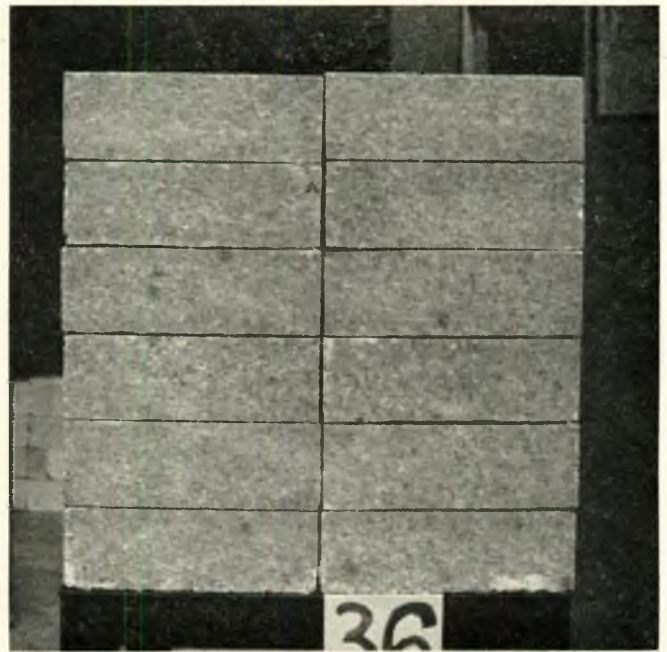


FIG. 3—High alumina brick after panel spalling test

very good results in service and so steps were taken to modify the recipes so that the products could be used for massive installations. The important step in the development was to increase the grog content of the mix substantially which necessitated replacing the fireclay bond with a more plastic ball clay in order to retain good moulding properties. Higher temperature plastics were developed based on the same raw materials as the aforementioned bricks. Those having 40-45 per cent Al_2O_3 are usually suitable for service temperatures up to 1,450 deg. C.—1,500 deg. C., whilst others having alumina contents of 60 per cent or more are suitable for temperatures of the order of 1,600—1,650 deg. C.

Mouldable refractories have better resistance to thermal shock than can be obtained in almost any prefired refractory. Although prefiring a mouldable refractory reduces its resistance to thermal shock in proportion to the degree of vitrification of the bond, the thermal gradient through a structure ensures that a large part of the refractory retains this excellent resistance.

At first, mouldables were used only for forming the burner quarls but their use spread rapidly to the whole of the front wall and in many boilers, to side and rear walls as well. As the use of mouldables extended it became necessary to devise methods of providing effective anchoring throughout the lining thickness while retaining free movement between the furnace

casing and the lining. Fig. 4 illustrates a method which has proved effective for walls of varying thicknesses.

Refractory castables have also been developed for application by methods similar to those employed with structural concretes. These materials have good resistance to thermal shock but are less flexible than mouldables. They generally find use in the superheater sections of boilers where the freedom from joints ensures that hot gases are kept away from the casing. Anchoring for the castables can usually be effected with metal anchors and where temperatures on the anchoring do not exceed 300—350 deg. C. mild steel expanded metal can be used safely. Where temperatures are higher, it is necessary to use heat resisting steel studs which should be wrapped with paper before placing the castable. The paper will char away leaving space for the greater expansion of the metal than that of the castable.

THE MARINE GAS TURBINE COMBUSTION CHAMBER

In the immediate post war years, intensive research was directed towards developing gas turbines for commercial marine application. From the outset it was considered that the metal combustion chamber, as used in aircraft type gas turbines would corrode too rapidly to permit economic marine application particularly if heavy grade fuel oil was used. It was necessary therefore to devise some means for protecting the metal by a

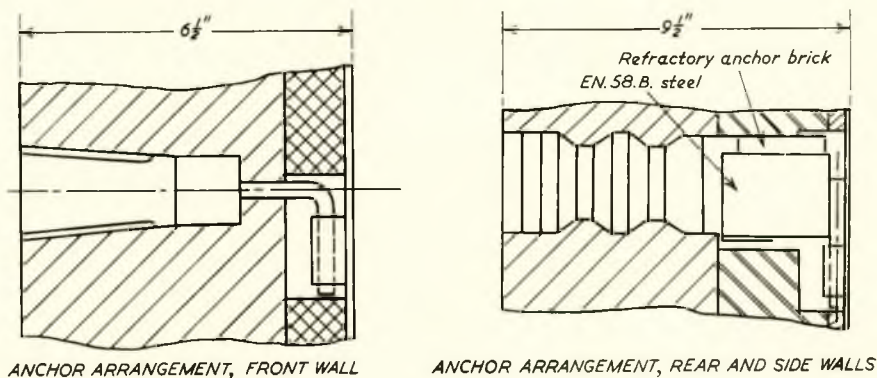


FIG. 4

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refractory material. The use of such a lining would have the added advantage of increasing radiation so improving combustion conditions.

The requirements of the refractory were:

- 1) The ability to withstand temperatures up to 1,750 deg. C. for prolonged campaigns.
- 2) The ability to withstand severe heating and cooling shocks.
- 3) Strength enough to withstand mechanical vibration.
- 4) The ability to withstand the action of oil fuel slags without spalling or peeling.

All these factors were considered to be of extreme importance because any breaking up of the refractory could prove costly in damage to the turbine rotor and blades.

Trials were made in the late 1940's using three materials, silicon carbide, a 70 per cent alumina body based on fused alumina and an 80 per cent alumina body kilned to both intermediate and very high temperatures. The trial linings consisted of tongued and grooved segments approximately 6in. \times 6in. \times 3in. thick.

These trials indicated that the 70 per cent alumina body was insufficiently refractory to withstand long operating campaigns. The silicon carbide oxidized and broke up and the high temperature fired 80 per cent alumina body spalled. The intermediate temperature fired 80 per cent alumina body showed the most promise. In order further to improve the shock resistance of the lining, it was decided to reduce the thickness of the refractory to about 1in. and to suspend each tile on lugs welded to the combustion chamber shell.

The modifications proved effective and a great many test starts and shut-downs were carried out with only very minor cracking. A few very small pieces did in fact, break off the refractories during trials but no damage to the turbine resulted and it was concluded that gas velocities were not sufficiently high to carry pieces of refractory large enough to damage the blades.

Since these trials, several gas turbine combustion chambers have been lined successfully with this type of refractory although only short periods of their service have been on heavy grade fuels (12).

There are still many problems to be overcome in combustion chamber linings, particularly as the addition of fuel oil additives to reduce blade corrosion has introduced other complications which may be more difficult to overcome than the earlier problems. Magnesium salts have proved to be very effective in reducing corrosion but at temperatures above 1,250 deg. C. these severely flux alumino-silicate refractories. In one case known to the authors, the refractory lining was almost completely eroded away during 100 hours operation. The final solution may be in the use of magnesia-alumina spinels but very much work remains to be done in order to produce refractories from such a body that will meet the other requirements of thermal shock and mechanical strength.

GAS TURBINE BLADES

General

The fuel economy of the gas turbine, as is well known, improves as the gas inlet temperature to the turbine increases. It has, for example, been stated that a temperature of 1,200 deg. C. is required to achieve a fuel economy comparable with that of a marine Diesel engine (5).

It seems unlikely that metals can operate at this temperature for long periods such as those required of a marine engine unless some technique of cooling is used, so that for some years there has been an incentive to develop other materials for the purpose.

Ceramic materials naturally come to mind in this connexion and certain of them have the necessary resistance to temperature and corrosion in good measure. However, they are brittle materials readily damaged by mechanical shock and by rapid temperature changes (thermal shock), and are, in general, unreliable when subjected to tensile stress.

At the end of the last war a considerable amount of work was initiated to develop improved ceramics for use as gas

turbine blade materials. After the first flush of enthusiasm it was realized that there was little hope of using these materials for rotor blades so that attention was concentrated on the still difficult problem of application to stator blades.

As far as the authors are aware there is no non-metallic material at present in use, even for stator blades, but there appear to be at least two special ceramics of the non-oxide type, silicon carbide and silicon nitride, which come near to fulfilling the requirements for stator blades in a high temperature gas turbine and which might, with further development, be applied in practice.

Some of the research which has been reported is described here, exemplifying the search for improved ductility (while retaining good creep strength) high thermal conductivity and low thermal expansion, all of which associated with high breaking strain lead to an improvement in thermal shock resistance.

Metal-ceramic Compositions

Following early work in Germany towards the end of the last war, a considerable amount of research has been carried out in many countries in an attempt to combine a metal and a ceramic so that the final composition has the ductility of the metal combined with the high temperature strength and creep resistance of the ceramic.

It has not in the event proved possible to combine the best properties of the two components. In general, starting from a metal and adding a ceramic material in increasing proportion, where the ceramic particles are relatively large there is at first little effect on the properties of the metal. There may be some improvement in creep resistance in special cases, where the ceramic is finely dispersed. With increasing addition of the ceramic material, there is transition from a continuous metal phase to a continuous ceramic phase, and the composition then has properties little different from those of the ceramic. This is well exemplified by the effect on electrical resistivity

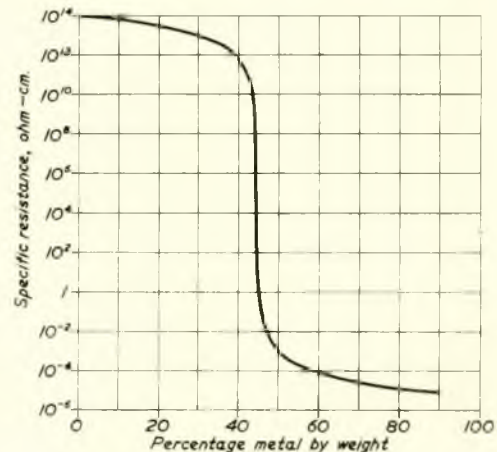


FIG. 5—Composition and specific resistance of silver-alumina cermets

shown in Fig. 5. Much ingenuity has been expended to produce metal-ceramics in which the properties of both phases are retained but little practical success has been achieved. The research has however led almost directly to new techniques used to manufacture the special ceramics referred to below.

A test, in a gas turbine test rig, of one of these metal-ceramic compositions is reported by Blakeley and Darling (5).

The resistance to thermal shock appeared quite promising, but this had obviously been obtained at the expense of the high temperature properties of the ceramic phase, since the blades were reported to be weak in creep and distorted appreciably in 2 or 3 hours testing at 1,200 deg. C.

Ceramics of High Thermal Conductivity

Another class of ceramic considered for turbine blades includes those of high thermal conductivity. For example at

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1,000 deg. C. beryllia has a conductivity of 0.046, and silicon carbide 0.072 compared with 0.014 cal/cm. sec. deg. C. for alumina. These two former values are as high as those of many metals at high temperature.

Beryllia is extremely toxic and it may be for this reason that no work appears to have been done on it for this application. Silicon carbide in many ways is an excellent ceramic material, though limited in application by its proneness to oxidation and its reluctance to sinter. Of recent years much research is known to have been done on it to improve both these properties, but little has been published. Some work by Popper at the British Ceramic Research Association is an exception (17).

A set of stator blades in one of the commercially developed materials ("IC" silicon carbide) has been tested in a gas turbine test rig and showed promise of running for thousands of hours without cracking or distortion (5). Further work (6) has confirmed this promise and overcome some of the fabrication difficulties referred to in the 1957 paper.

Low Expansion Ceramics

Fused silica is well known to have excellent thermal shock resistance, mainly by reason of its low coefficient of thermal expansion (0.5×10^{-6} /deg. C.). Unfortunately, this material has poor creep resistance and with prolonged heating at temperatures approaching 1,200 deg. C., devitrifies and loses its thermal shock resistance. It is equally true that other low expansion oxide ceramics such as the lithium silicates and cordierite (magnesium aluminium silicate) have relatively poor creep resistance. The search for other materials of low thermal expansion has led to an investigation of non-oxide materials, particularly silicon nitride (16).

Silicon nitride is manufactured by a new technique known as reaction sintering. A compact of silicon powder is first made, best results being obtained by isostatic pressing. This is then heat-treated in a nitrogen atmosphere so that the compact is converted to silicon nitride and simultaneously sintered. In practice this nitriding is carried out in two stages which has the added advantage that the intermediate material is easily machinable. Since there is only very slight shrinkage in the final heat treatment, articles can readily be made to close tolerances. This eliminates one of the problems of conventional ceramic manufacture where the high shrinkage on sintering renders dimensional control difficult.

The thermal shock resistance of silicon nitride is reported to be excellent and approaching that of metals, and it is dimensionally stable and resistant to oxidation up to 1,400 deg. C. The creep resistance of "pure" silicon nitride is not as good as that of some oxide ceramics, but it can be improved by incorporating a proportion of silicon carbide into the structure.

DIESEL ENGINES

General

The brittleness and poor resistance to tensile stresses typical of ceramic materials do not commend these to the designer of reciprocating machinery such as Diesel engines. Against this the excellent abrasion resistance of ceramics is attractive, and there have been some attempts to use them in, for example, fuel injector nozzles. However, the good abrasion resistance also implies that these materials are difficult and expensive to machine; in particular the machining of fine holes to close tolerances presents serious difficulty, and it may be this which is the limiting factor in this connexion.

Attempts have also been made to use ceramic coatings to protect metal components from the effects of high temperature corrosive gases, initially with limited success, but new techniques appear to have given fresh impetus to this work.

Ceramic Coatings

Early attempts to use ceramic coatings were based on enamelling techniques, and achieved only limited success. Broadly speaking, an enamel is a ceramic type composition of fairly low melting point and usually of a glassy nature (known as "frit"). This is finely ground, suspended in a

liquid and applied to the metal. Subsequently the coated metal article is baked or stoved when the liquid volatilizes and the enamel frits together, and also bonds to the metal. Many refinements are of course involved, in the form of multiple coatings and pre-treatment of the metal.

One limitation of the process is immediately apparent from the above description; the metal has to be heated to a temperature at which the coating will frit or sinter. Thus, if the metal is to be enabled to work at a temperature above its normal working limit, the coating must be designed to frit at a temperature below this limit and yet be serviceable at a higher temperature. This difficult, though not impossible feat, severely limits the range of ceramic compositions which can be employed and usually one advantage of the true enamel is lost in that the coating is not impervious to gases and liquids. Thus, at best, it acts as a thermal barrier only, reducing the surface temperature of the metal.

Recently, techniques known collectively as flame spraying have been introduced and alter this situation to some extent. In flame spraying, ceramic material in the form of rod or powder, is fed through a high temperature flame and a blast of hot gas directs the material in the form of molten droplets on to the surface to be coated, which is not heated to any great extent. Again, however, the coatings are not completely impervious but it has been claimed (8) that they can be made so by the use of sub-coatings or by impregnation.

These coatings have been proposed (8) for:

- 1) Inhibition of oxidation.
- 2) Protection against wear.
- 3) Control of heat radiation.
- 4) Fireproofing.
- 5) Electrical insulation.
- 6) Thermal insulation.
- 7) Protection against corrosion.

In particular the application of flame sprayed coatings to Diesel engine pistons and valves has been reported (2 and 4). The ceramic materials used were the oxides of rare earth metals such as cerium, lanthanum praseodymium and neodymium, and these are reported to localize heat in the combustion chamber and also to have a catalytic effect ensuring more complete combustion and a cleaner engine. Claims are also made that oil changes are less frequent and that the decreased content of carbon monoxide and unburned hydrocarbons in the exhaust gases contributes to the reduction in atmospheric pollution at present being sought in most civilized countries. The effect of cheaper oxide coatings, such as alumina, does not appear to have been reported upon.

NUCLEAR PROPULSION

General

One of the more recent technological developments of potential interest to the marine engineering industry is the generation of power by nuclear fission and its application to ship propulsion.

As is now well known the nuclei of certain heavy atoms when bombarded by neutrons split into roughly equal parts; a considerable amount of energy is released and several neutrons are ejected. These are also capable of producing fission in other heavy nuclei so that under suitable conditions a self-perpetuating chain reaction can be formed. The fissile materials are U^{235} which occurs naturally as 0.7 per cent of natural uranium, U^{233} which is formed by neutron absorption in thorium and Pu^{239} which is derived from uranium. Unlike the fossil fuels the release of nuclear energy does not require air for combustion and the energy potentially available in one pound of U^{235} is equal to that obtainable by burning 1,500 tons of high grade coal. The attractions for ship propulsion, particularly in the case of submarines, are obvious.

Since the nuclear energy is released initially in the form of heat, and this has to be converted into other forms of energy, the overall efficiency of nuclear power generation increases as temperatures are raised. There is thus a demand for materials which will have appropriate nuclear properties and which will be resistant to corrosion by specific gases and liquids used for

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heat transfer, while also withstanding relatively high temperatures.

The thoughts of designers again turn towards ceramics and much research and development has been done to produce materials suitable for specific application in nuclear reactors, with such success that these materials are already in use in some installations.

Nuclear Fuels

The obvious material for use as a nuclear fuel is natural uranium, but this has a number of disadvantages (7). Briefly, because of phase changes and anisotropy, the metal distorts on thermal cycling and in addition its maximum working temperature is limited to approximately 450 deg. C. by swelling under irradiation. Attempts to produce alloys free from these effects have been partially successful, but there appears to be a trend towards ceramic fuel both for high and low temperature systems.

Uranium has four oxides; UO , UO_2 , U_3O_8 , UO_3 of which UO_2 is the most stable and has a melting point of approximately 2,800 deg. C. compared with 1,130 deg. C. for the metal. This oxide shows a range of non-stoichiometry ($UO_{2.0} - UO_{2.1}$)* and on being heated in air at 450—500 deg. C. forms U_3O_8 with an increase in volume (13). These effects have a profound

Another ceramic material which can be classed as a nuclear fuel is thorium oxide. Thorium absorbs a neutron and, by a process of radioactive decay forms U^{233} which is fissile. Thoria is one of the highest melting oxides (3,200 deg. C.) and is difficult to sinter to high density. It has been found that the addition of lime increases the density on firing at 1,700 deg. C. from 86 per cent to 96 per cent of the theoretical density (10) while similar densities are now being achieved commercially by the authors' company without additions, the resulting material analysing 99.9 per cent ThO_2 .

Many other ceramic materials have been suggested for use as nuclear fuel and brief reports on them have appeared. Examples are an Fe — UO_2 composition (13) and a plutonium oxide—uranium oxide mixture (7) which would make use of the large quantities of plutonium which should shortly become available from the operation of land based nuclear power stations. Undoubtedly much work is in hand in many laboratories to provide materials for high temperature fuel elements, and it appears that much of this work has a ceramic flavour.

Thermal Barrier Discs

Current reactor techniques involve encasing the fuel element in a can, which separates the fuel element from the coolant to prevent corrosion of the former and contamination of the

TABLE II.—PROPERTIES OF VARIOUS NUCLEAR FUELS (7, 13, 18)

Property	Uranium	Uranium Dioxide	Uranium Monocarbide
Coefficient of thermal expansion (10 ⁻⁶ /deg. C.)	(a) † 20.3 (b) † -1.4 (c) † 22.2	10.0	11.4
Thermal conductivity (cal./sec. cm. deg. C.)	0.071	0.017	0.060
Ultimate tensile strength (lbs./sq. in.)	approximate 100,000	—	—
Bend strength (lbs./sq. in.)	—	16,000	50,000

†Crystalline axes.

influence on the fabrication of uranium dioxide and much work has been done to obtain a material having the high density (95 per cent of theoretical) desirable for nuclear reactor use.

Fabrication must be carried out in a non-oxidizing atmosphere and higher densities can be obtained with non-stoichiometric oxide than with the stoichiometric. For example, a particular oxide of composition $UO_{2.03}$ gave a density of approximately 7.1 gms/cc when sintered to 1,400 deg. C. but this was increased to 8.75 gms/cc when the powder was oxidized to $UO_{2.17}$ (13). As is usual in ceramic technology, high surface area also favours sintering to high density.

Many ceramic oxides can be sintered to high densities by "hot pressing", a technique in which pressure and temperature are applied simultaneously in graphite dies. In the case of uranium dioxide chemical reduction of the surface of the compact takes place giving differential shrinkage and cracking (13).

A disadvantage of uranium dioxide as a nuclear fuel is its low thermal conductivity, which leads to a high temperature at the centre of the element. Interest has therefore been aroused in the uranium carbides, UC and UC_2 , particularly the former, since the dicarbide tends to be unstable in moist atmospheres. Some properties of uranium monocarbide compared with uranium and uranium dioxide are shown in Table 2.

Uranium monocarbide is pyrophoric so that considerable precautions are necessary in handling fine powders, quite apart from radiation hazards. It is difficult to fabricate into a dense material of fine grain size and good mechanical properties. Arc melting of a mixture of uranium and carbon followed by casting has been used to prepare UC , in addition to the more usual techniques of compacting and sintering (18).

latter. Additionally the can acts as a structural unit. Once again there is an obvious trend towards higher can temperatures.

The use of ceramics as canning materials would involve considerable technological advances since the can must be reliably impervious in long periods of operation, during which thermal and possibly mechanical shocks could occur. Since most ceramics are of relatively low thermal conductivity heat transfer problems would also arise.

TABLE III.—PROPERTIES OF OXIDE CERAMICS (19)

Material	Neutron absorption cross-section (cm. ² /cc.)	Coefficient of Thermal conductivity at 100 deg. C. (cals./sec. cm. deg. C.)
Beryllia	0.00074	0.500
Alumina	0.0101	0.069
Magnesia	0.0032	0.082
Zirconia	0.0057	0.004
Hafnia	3.18	—

However, ceramic materials are already being applied in connexion with fuel element cans, in one of their traditional roles as thermal insulators. If the uranium metal fuel element is in direct contact with the can the contact temperature is limited by metallurgical considerations. Consequently in some designs ceramic discs are interposed between the element and the can to act as a thermal barrier. The ceramic must have low neutron absorption and good long term stability under irradiation, in addition to as low a thermal conductivity as possible. The relevant properties for a number of materials are shown in Table 3.

Of these materials, beryllia, although having a low absorption cross-section, has an exceptionally high thermal conductivity for an oxide while zirconia would seem to have the best

* i.e. can contain oxygen in excess of the theoretical amount.

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combination of thermal conductivity and neutron absorption. The usual commercially obtainable zirconia however contains approximately 2 per cent of hafnia which markedly increases its neutron absorption. While separation of the hafnia is possible it is a costly procedure and this, coupled with some doubts about the irradiation stability of zirconia, has kept this material in the background as a thermal barrier ceramic. In fact little development appears to have been done on materials for this comparatively minor component of the reactor, and established dense high alumina, or less commonly magnesia, ceramics have been used.

There would appear to be scope for investigation of the long term stability of other low conductivity ceramics, such as those having porous structures or those having intrinsically low conductivity. One example of the latter class is forsterite ($2 \text{ MgO} \cdot \text{SiO}_2$) which the authors have prepared in high purity form with a thermal conductivity of $0.008 \text{ cal/sec. cm. deg. C.}$ at 100 deg. C. and a measured neutron absorption cross-section of $0.0036 \text{ cm}^2/\text{cc.}$ In view of its purity this material may have better long term stability than the conventional forsterite ceramics. Techniques for controlling the porosity of alumina and magnesia ceramics are also known, and enable materials of somewhat reduced thermal conductivity to be manufactured.

Control Rods

A further example of research in the ceramic field designed to meet the requirements of the nuclear reactor is provided by the problem of controlling the reactor. This is carried out by adjusting the position of rods of neutron absorbing material in the reactor core, the material in common use being boron, in the form of boron steel. Some other elements having a high neutron absorption cross-section are shown in Table 4.

TABLE IV.—THERMAL NEUTRON ABSORPTION CROSS-SECTIONS

Element	Cm. ² /gms.
Cadmium	12.8
Europium	17.9
Samarium	26.0
Boron	42.0
Gadolinium	169.0

It is not possible to incorporate a very high percentage of boron in steel so that control rods of boron steel are heavy and necessitate expensive and bulky electrical control gear for their operation. Additionally natural boron breaks down under irradiation with release of helium, which at the higher temperatures of operation can cause swelling of the control rod.

For these reasons there is interest in the use of the three rare earth metals, samarium, gadolinium and europium in various forms including oxide ceramics. It is believed that these materials will enable much lighter control rods to be made, and that these will be stable under irradiation.

The three oxides, samaria, europa and gadolinia have high melting points, and initial research showed that they are comparatively easily fabricated into low porosity ceramics. However, the geometrical requirements of the control rod are such that these simple materials would require to be fabricated into impossibly thin sections to avoid the system having too high an absorption. Research has therefore continued on mixtures of the rare earth oxides with readily available low absorption ceramics so that the absorbing nuclei are distributed over a larger volume. This has necessitated some quite fundamental research and, for example, phase diagrams have been determined (3). A typical example is shown in Fig. 6; the other combinations of rare earth oxides and common ceramic oxides give similar diagrams. If compositions near the eutectic are required severe ceramic problems arise, which are intensified if un-separated mixtures of rare earth oxides are used for economic reasons.

Other materials which have been developed in the search for new and improved ceramic materials may also be of value in controlling nuclear reactors. For example, boron nitride

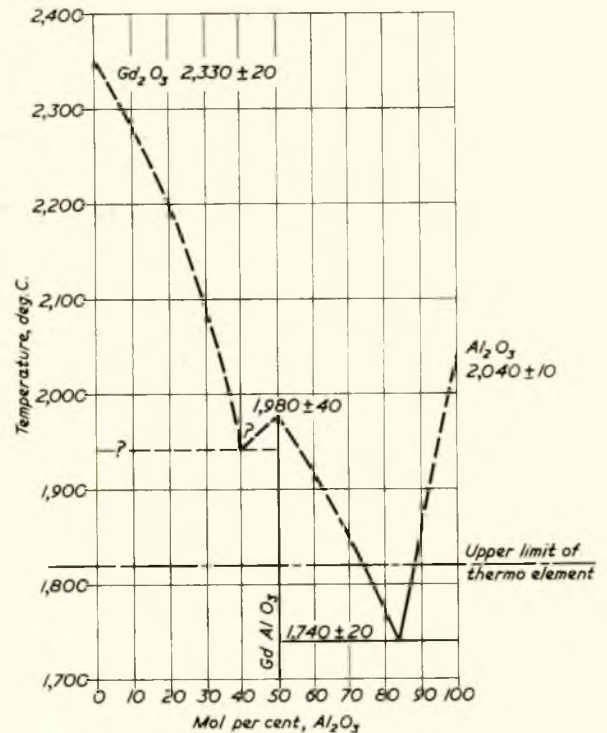


FIG. 6—Tentative diagram for the system $\text{Gd}_2\text{O}_3 - \text{Al}_2\text{O}_3$

has been described (9) and boron carbide is commercially available.

Of just as much importance as the initial neutron absorption cross-section of the control rod is its total capacity for absorbing neutrons and the changes which take place on irradiation, since these will determine its life. This necessitates a knowledge of the properties of the daughter products of the absorption process, and this type of work is being undertaken by nuclear physicists to enable the choice of the most suitable control rod materials to be made. If these materials prove to be "ceramic" the problems involved in the use of brittle materials of limited thermal shock resistance will need consideration.

CONCLUDING REMARKS

It has not been possible in the space of this survey to deal in detail with the many ceramic developments which may be of significance to the marine engineer. It is hoped that sufficient has been said to indicate the enormous increase in the scope of ceramic technology in the last decade and the extent to which ceramic materials are being increasingly considered for applications which are conventionally reserved for metals.

The engineer will detect a common thread through all the apparently diverse developments reported; ceramics are all, to some extent, brittle materials and are liable to failure by shock effects, both thermal and mechanical. The best efforts of the ceramic technologist are unlikely, in reasonable time, to permit modification of this statement other than in a matter of degree so that the engineer must, if he wishes to use these materials, design accordingly. This point of view has been accepted by nuclear design engineers and it may not be many years before ceramics are as familiar as components in marine nuclear reactors as they are now in marine boilers. The problems involved in reciprocating and rotating machinery are, of course, rather different, and here the time factor may be longer but, in the authors' view, by the joint efforts of ceramists and designers, materials which fall within the wider definition of the word "ceramic" will ultimately take their place as engineering materials.

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ACKNOWLEDGEMENT

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Discussion

MR. H. M. RICHARDSON, opening the discussion, said that he must have been crazy when he agreed to open the discussion, because, having read the paper, he found he was very ignorant on more than half of it, and the opener of a discussion was supposed to talk about the paper and not just one small section.

He thanked the authors for their paper because it had made him realize again what an increase in the potential applications of ceramic materials there had been in the last few years. He had noted that workers in that field often talked about "special" ceramics, but they had still got ceramic properties, and he was glad that the authors had pointed that out in their conclusion, and that it was very difficult to alter those properties very appreciably. The materials were still hard, they were not ductile, and they failed from thermal shock, but he was pleased to note that engineers and designers were taking particular note of that and were designing accordingly.

Commenting on the section of the paper on special ceramics, he said he had noted that, in the section on marine gas turbines, silicon carbide and high alumina tiles had been used, and it was suggested that a magnesium alumina compound, or a spinel, might be tried in these tiles one inch thick? Did the authors think that the magnesium chromite might be used—the conventional basic refractory or one made from magnesia and finely ground chrome ore to give a spinel bond. That material would resist magnesium salts although it might not withstand thermal shock sufficiently. Basic bricks had been used in tunnel kiln roofs at 1,700 deg. C. for long periods.

He also noted that it was mentioned in the paper that silicon carbide was liable to oxidize. A reference by Popper at the laboratory at Stoke mentioned that a self-bonded silicon carbide could be obtained by heating a mixture of silicon carbide and carbon in an atmosphere of silicon, and he understood that that material had more resistance than the conventional material to oxidation. Mr. Popper also believed that silicon nitride might be a useful material for the stator blades. It had a fairly good resistance to thermal shock.

Mr. Richardson said he was interested in the section on ceramic coatings because the joint committee of the British Ceramic Research Association and the British Shipbuilding Association, dealing with marine boiler refractories, had been asked to do work on the protection of superheater supports, and they were thinking in terms of flame spraying alumina on to the metal. They had tried small specimens in the laboratory and had found that after two methods of flame spray they could easily chip that material away by heating and cooling. He wondered whether Mr. Aldred was referring to the plasma gun in his talk, or whether he believed that that method would form a denser coating of alumina than the normal flame sprayed alumina?

In another part of that section, talking about uranium oxide, UO_2 , hot pressing tended to give cracking and differential shrinkage. Had the authors noted a paper by Scott which was in the Ceramic Society's Transactions, in which he claimed that that material could be pressed at relatively low temperatures?

He was really a conventional ceramic man and was very interested in that part of the paper dealing with boiler linings. He agreed with the statements about monolithic materials, the

mouldable and castable refractories; those were very useful in quarl blocks and linings because the material did resist thermal shock more than firebrick. He believed that the ceramic anchors shown on the slide were good and gave better support than certain metal anchors.

When he had first read the paper he was very disturbed about the section which referred to Scottish firebricks. He felt that it was very critical of Scottish firebricks—but he was glad to note that the verbal presentation was not so critical as the written word. He was glad Mr. Aldred noted that the bricks had been made by dry press methods for a long time and that they were a good shape and could be kilned to a high temperature. A sentence in the paper stated that china clay was more refractory than Scottish firebrick. That was not always true. It was possible to get china clays which were less refractory than Scottish fireclay. Scottish fireclay could be very refractory, and more refractory than some china clay bricks. He did not like the slide which had given the conventional Scottish brick with a porosity of 28. A Scottish firebrick could be made with a porosity of 17, the same value as given for the china clay brick on the slide, and Scottish firebrick these days could also be had with very low porosity just as one could get china clay bricks with low porosity, of say 10 per cent.

The slide had shown alumina and silica added up to 96 and 93, with a 7 per cent flux in the Scottish firebrick and 4 per cent in the china clay. That was not a fair statement. There were fluxes and fluxes, and the flux in the china clay could be much more deleterious than that in fireclay, because there was usually a high content of alkali in the china clay. It could be from 1.5 or over 2 per cent in china clay whereas in the Scottish firebrick, the alkali would be down to 0.6, and often, the titania was bracketed with alumina. Titania was not a very dangerous oxide, and iron oxide could be present in discrete spots. So it was not right to say there was 7 per cent in one and 4 per cent in the other; it did not give a true picture. The alkali from the mica, although a lot of the mica was removed, was still present in the china clay to a much greater extent than in the fireclay.

Mr. Richardson said he just had to get that off his chest and he apologized!

He was interested in the spalling test and agreed that the standard prism spalling test at 1,000 deg. C. was not a good test, when bricks were being heated in service at one end to a much higher temperature. He was not entirely happy with the panel spalling test, mainly because of the high temperatures in the preliminary heating of the panel. Were the authors completely happy with that test? In the paper, Scottish firebricks were seen badly spalled and china clay not very badly spalled. He suggested that with other brick samples, that answer could be reversed. It depended on the firing temperature, on the composition of the material, the grading, etc., and there were bricks and bricks in both classes. The initial high temperature heating completely changed the structure of the brick, and, during service, that structure change might not take place. Therefore, he was not happy with that test.

He thanked the authors for the paper and hoped that he had not been so critical that their friendship was endangered.

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MR. R. F. DARLING said it was very appropriate that a paper dealing with a particular class of materials should be read before an engineering institution. Engineers were limited at all points by the properties of the materials at their disposal, and as good a definition as any of an engineer was one who made the best use of the materials available to him. It was often said that the predominant position of Britain in such fields as jet engines was due largely to the efforts of her metallurgists in producing superior materials, and this was undoubtedly true. Tonight's paper told of another field in which equally creditable progress had been made, although with less publicity.

Where ceramic materials were employed it was usually for the sake of their high temperature properties. In nearly all other respects they were inferior to metallic materials and it therefore followed that they were used as sparingly as possible and usually mounted inside metallic structures. The difficulty was to mount them in a manner which allowed for their undesirable properties and still permitted them to work as they were meant to work—resisting the high temperature but having freedom to distort. Distortion was inevitable, as there was always a temperature gradient through the ceramic leading to differential expansion and a change of shape. He proposed to describe two applications of ceramics, one in which the problem described above had been overcome quite successfully, and another which was rather less successful.

Fig. 7 showed a ceramic lined flame tube which had been used in a high temperature gas turbine. The bricks were grooved along their sides and fitted into suitably shaped sheet metal channel pieces which were rigid in the longitudinal direction but flexible circumferentially. The channel pieces were bolted to a steel skeleton, and the whole assembly was surrounded by further sheet metal covers with lines of small holes in way of the gaps between the bricks. These holes permitted a controlled quantity of air to pass between the bricks and prevent the flame from impinging on the metal channel pieces.

This was an example of a successful use of ceramics, because the ceramic parts were free to distort and yet were held firmly in their correct position. At the same time the metal parts were completely shielded from the high temperatures,



FIG. 7—Ceramic lined flame tube

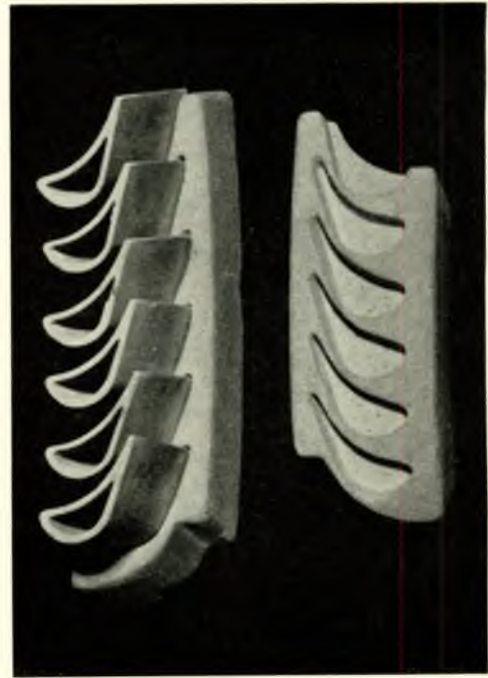


FIG. 8—Section of ceramic nozzle blades

so much so that flame tubes could be made with all the metal parts in mild steel.

A further development of the same idea had been carried out by Thermal Syndicate Limited, who, at their own suggestion, tried manufacturing the bricks by an extrusion process which would obviously be very suitable for large scale production. They had made up an experimental batch of bricks which were of absolutely superb quality, some of the best he had ever seen. Unfortunately, the extrusion process could only be used to make bricks of a rather small cross-section and they had had to use about 20 to make up a circle, whereas previously they had used six. That was a disadvantage. He asked the authors whether they had used extrusion techniques to make bricks and what they thought about the idea in general.

A different example was illustrated in Figs. 8 and 9. These showed the construction of a ring of ceramic nozzle blades for the same high temperature gas turbine which had an inlet temperature of 2,200 deg. F. (1,200 deg. C.). The blades themselves had given little trouble, and their strength and thermal shock resistance were quite adequate for this particular application. As would be seen, however, the method of mounting was to fit them into recesses in segmental shaped mounting bricks, twelve of which fitted together to form a complete circle. They were supported in a water cooled casing, and had therefore to be a slack fit when cold so as to allow for differential expansion. Some of this slackness was bound to persist at the working temperature, and the result was a leakage of gas between and behind the mounting pieces, which represented a serious loss of turbine efficiency and was quite unacceptable. This turbine had been running intermittently for experimental purposes for over three years, and was in fact running that very day.

The blades illustrated were in an early grade of silicon carbide made by the author's company. Later grades had been found to have greater creep strength at high temperatures, and were much superior to any form of silicon nitride which had yet been offered to Pametrada for test.

Finally, he referred to the remark at the top of the second column on page 84 regarding the hopelessness of using ceramic materials for rotor blades. This was undoubtedly true at the end of the last war, but is not necessarily still the case. The best materials now available gave promise of having a very extended life at 2,200 deg. F. (1,200 deg. C.) under stresses

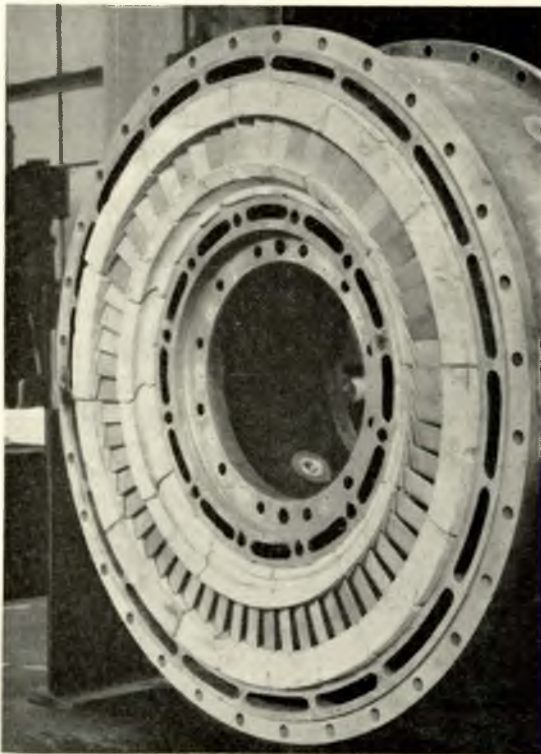


FIG. 9—Construction of ring of ceramic nozzle blades

of the order of 2-3 tons, and when it was realized that their densities were less than $\frac{1}{3}$ those of metallic blade materials, it would be realized that this gave the designer considerable scope. Much more creep testing would of course be required before such a project could be embarked upon, and the design of root fixings whereby the blades could be supported in a much cooler metallic rotor would be a major problem. He merely wished to call attention to the possibilities without in any way minimizing the difficulties involved.

MR. E. G. HUTCHINGS (Associate Member) said that the authors were to be congratulated on their clear statement of the progress made in the ceramics industry in recent years, but wanted to take them up on one point.

In their concluding remarks, the authors inferred that ceramics were very common in marine boilers. He felt that that might be a case of familiarity breeding contempt. It was perfectly true that a large amount of ceramic material was used in a marine boiler, but that had been so for many years, and, as far as he could see, there had not been very much increase in the extent to which ceramics were used in marine boilers.

He felt that there were several possible applications for ceramics in marine boilers which had received less attention than some of the more exotic items such as gas turbines mentioned in the paper. Was it not possible for the ceramics industry to assist the boiler-maker with such problems as the corrosion and burning of superheater supports? Also, to find a means of protecting such items as economizers and air heater tubes from corrosion?

He would appreciate the authors' remarks particularly on the suitability of silicon nitride for superheater supports. Also, he would appreciate their comments on whether flame spraying techniques developed for Diesel engines could be used with advantage on economizers and air heater tubes to eliminate sulphuric acid attack, or on sootblower elements to eliminate vanadium attack and oxidation?

A further point which occurred to him was that that it might not be either impossible or impractical to develop a ceramic which would have sufficient strength to provide not

only the insulation but the casing itself in the lower temperature parts of a boiler.

Another feature which would greatly simplify the problem of automatic ignition would be a ceramic insulator which could be incorporated in the tip and barrel of a load carrying oil burner, so that spark ignition could be applied directly to the main burners of a marine boiler, instead of merely to the small output igniters which usually had to be withdrawn as soon as possible after the main flame was established. In that connexion, he understood that the problem was that although there were ceramic insulators available capable of withstanding the temperatures involved, they could not, as yet, be made in large enough pieces for load carrying burners.

The authors' reactions to those remarks would be most interesting to those involved in the marine boiler industry.

MR. J. F. BEGLEY'S contribution to the discussion was given by MR. R. C. APPS, who apologized for Mr. Begley's absence, due to another business engagement.

He congratulated the authors on the presentation and neat preparation of the paper. It was noted, however, that in their reference to monolithic refractories, the authors stated that, prior to 1950, mouldable refractories were in a very undeveloped state and consisted of firebrick recipes in the unfired state. There was an impression that the development of monolithic refractories for marine application had only taken place gradually since 1950. In actual fact, the company which pioneered monolithic refractories used substantially the same type of mix today as it had when it introduced those products over 45 years ago. Certainly, high temperature plastic refractories such as were currently used in marine boilers were available in this country 20 years ago. Authors and members might be interested to know that a complete plastic burner wall was installed in a Babcock and Wilcox boiler in 1948. So much experience had been gained with monolithic refractories after that work that Shaw Savill decided to install complete monolithic linings that included the burner wall, hearth, rear wall, side walls and roof in two Foster Wheeler boilers in a ship that went on trials early in 1950 and which was still in service. Complete monolithic linings had been installed in the Foster Wheeler boilers of s.s. *Brighton*, in 1951, and in 1953 complete monolithic linings were also installed in Foster Wheeler boilers in the *Arcadia* and *Iberia*. Refractory castables were used not only for superheater linings but also for complete side walls, rear walls and roof of certain types of boilers where protected by tubes. In that respect, it might be mentioned that anchorage was invariably mild steel, and within one inch of the hot face of the castable, and although protected by tubes, the temperature of mild steel anchorage would be higher than 300 to 350 deg. C.

In conclusion, could the authors state the precautions required to be taken to avoid breakage or incipient fracture of ceramic anchors during the course of pounding the mouldable refractory round them?

MR. G. E. DARWIN congratulated the authors on the wide scope of the paper. With regard to the nuclear side, which was the side he wished to discuss, he felt it had been cut down to such an extent that a great deal of amplification could usefully be carried out, and he proposed to fill in some of the gaps for the authors. He did not wish them to take that as a criticism of their paper, which was an admirable summary.

His first remarks would concern that extremely useful material, uranium dioxide. The main reason that reactor designers had first considered that material as a fuel was not, as suggested, because they wanted higher temperatures but because they wanted a fuel which was resistant to corrosion by water. Development work was first started in America where it was found that most uranium alloys oxidized very rapidly and that meant, that even a small hole, meant loss of the fuel element. Even now, there was no certainty that one out of 100,000 fuel elements would not have a hole in it. The Americans looked round for an alternative material

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and chose UO_2 , which had admirable corrosion resistance and was also volumetrically stable: under radiation it did not increase in volume. Uranium metal increased in volume very considerably. There was now a great deal of experience of UO_2 , principally in America and Canada, and a growing volume of experience in this country. It was used in the Shippingport reactor which started operation in 1957, and would be used in the n.s. *Savannah* when it started off in the next few months.

In general, not very much could be done about the properties. It had very poor conductivity and it was desirable to improve it. People had tried various additions which did not seem to have a great deal of effect. Perhaps the authors could discuss, in their summing up, the use of additives to UO_2 to improve its thermal conductivity. A designer who had to specify UO_2 would, in general, specify two things apart from purity. High density was required firstly for nuclear design reasons and, secondly, because high density usually meant good thermal conductivity, and that was important to keep temperatures down. He would also specify stoichiometry—that it should be $UO_{2.0}$ and not $UO_{2.9}$, or $UO_{2.25}$. Stoichiometry was important because non-stoichiometric oxide was nothing like such a good retainer of fission product gases possibly due to the presence of a volatile component, possibly U_2O_6 . The fission process produced a certain number of atoms which were gaseous and a good fuel would hold those gases in its body; a bad fuel released them all as gases, and for that reason, a stoichiometric oxide was specified.

In general, high density material could be made in three ways. Firstly, non-stoichiometric powder could be pressed and sintered in argon and then reduced at a lower temperature. That had the advantage that the sintering temperature was only 1,600 deg. C. Alternatively, stoichiometric powder could be pressed and sintered in hydrogen at temperatures of 1,650 to 1,700 deg. C. to give high density. Modern methods were also being developed in which a powder was loaded direct into a stainless steel tube, the caps were welded in and the whole thing swaged down, there being no firing process. It seemed that with the latter process, quite high densities could be achieved.

His next remarks referred to uranium carbide. He agreed with the statement that UC was better than UC_2 . They were both horrible materials. Even UC oxidized extremely rapidly in CO_2 and in water and was only of interest in sodium cooled reactors with rather specialized uses such as the Dounreay fast reactor.

Mr. Aldred had made interesting points on thorium dioxide. He would mention that the Babcock and Wilcox Company had recently fabricated 23,400 pins each about 100in. long containing thorium dioxide-uranium dioxide pellets each about $\frac{1}{2}$ in. long by 0.3in. diameter. He would be grateful for comments on the probable effect of uranium dioxide on the sinterability of thorium dioxide. Mr. Aldred mentioned that lime had been added.

On the question of thermal barriers, there was rather a misleading discussion in the paper on how it was desirable to separate the can from the coolant. In general, it was highly desirable to keep the can in good thermal contact with the coolant in order to keep the fuel temperatures as low as possible. It did happen that, in certain particular parts of the fuel elements, at the ends for instance, it was in ones interest to keep the temperatures down: For example, to use a situation in the British gas-cooled reactor, the can was in good thermal contact on the barrel, but at the end, there was an end cap welded to the can, supporting the cone piece, and the weight of the next fuel element above came on to it. There was not the extended surface, and it was desirable to keep the heat away from the end cap, otherwise, the weight of the element above would distort it; so insulators were put in. Alumina was used, largely because it was a well developed material, and was known to have good irradiation resistance. Also, designers were not really interested in having very low thermal conductivity. In a typical fuel element, one had temperatures of 450 deg. C.

on the cylindrical surface of the uranium bar and as high as 600 deg. C. on its axis. It was necessary to get the heat away. The idea was to get it into the insulator and then radially out; hence the use of an array of alumina discs was a good solution because of the temperature drops between the discs. Similar situations applied in pressurized water reactors. With marine applications also, there were certain cases where it was required to keep certain specific parts cool. The paper mentioned Forsterite, a material which contained silica: from the point of view of use with magnesium cans, he would frown on it, because all experience suggested that silica-containing refractories were not compatible with magnesium alloys.

He confirmed what Mr. Aldred had said on the need for an alternative control material. Boron-containing material was relatively unsatisfactory and there was certainly a need for something better. Ceramics had been used in control rods and the present control rods of the *Savannah* which contained boron stainless steel as the control part, also had a follower having dual functions, one of location and the second of occupying water space in the reactor when the control rod was out. That follower was made of zirconium alloy cruciform with a round hole in the middle which was filled with alumina pellets.

With regard to the choice of rare earths for control rods, for nuclear physics reasons, he would prefer europium, but it was expensive, and he would like to see some more commercial development of mixed rare earths, which he hoped to get for a reasonable price.

He had heard that people had made quite a lot of progress on the development of ductile magnesia and would be grateful for any comments on that.

DR. T. H. BLAKELEY, said that he had known Mr. Aldred for many years, and would like to compliment him. He proposed to deal first with thermal insulation, to which no other speaker had so far referred.

Thermal insulation covered the whole gamut of applications from cold storage through steam pipe insulation to furnace construction, which were problems well known to marine engineers. Most frequently, thermal insulation was of importance under steady state conditions, but somewhat different considerations applied when temperatures fluctuated, so that diffusivity was the dominant factor; and diffusivity was compounded of thermal conductivity and thermal capacity. For a rapid response to fluctuating conditions, low thermal capacity was important, a fact which was well recognized in land installations. He was sure that the same applied to marine practice.

He turned next to a point other speakers had dealt with, concerning design. It was encouraging to find a growing appreciation of the need to design to suit the inherent properties of ceramics. The best ceramic in the long run was not always the cheapest in first cost. Design for the best use of ceramic materials could be considered under the two heads of thermal and mechanical factors. Thermal properties of major interest were strength and thermal conductivity, and the variation of both those properties with temperature. The balancing of those factors, and the cost factor, and the fuel cost could be quite complex, and deserved careful consideration if the most economical structure was to be achieved. When numerous problems of a similar type had to be solved in that way, they had found it worth while to construct an analogue computer for that purpose.

Mechanical factors of design were equally as interesting as the thermal factors. There, the best approach was to design so as to use the desired good properties of ceramics and to minimize their undesirable features. That might sound platitudinous, but it was worth repeating. They were continually being asked to produce ceramic components which were geometrically similar to metal components and were expected to do the same job as the metal component under the same conditions except at a much higher temperature. It had to be remembered that those metal components were initially designed to suit the properties of metals, and that the geometrical forms which had been evolved and to which designers

Discussion

were accustomed, depended on that fact. Once that was realized, it was possible to do something with ceramics. He paid tribute to Mr. Darling for the interesting work he had done.

Before the fullest advantage could be taken in the mechanical designing of ceramic structures, more needed to be known about the fundamental properties involved, such as strength, expansion, and modulus of elasticity over the temperature range concerned, as well as about the less readily definable factor of texture, which could be vitally important. They had come a long way in the past decade, but much remained to be done by designers and ceramic technologists in association.

Dr. Blakeley said that he had a contribution from Mr. E. S. White, who apologized for his absence.

MR. WHITE'S main connexion with the work, and the only one on which he felt qualified to express an opinion was the use of ceramic materials for gas turbine blades.

He agreed with the authors' view that the two most promising materials at the moment for gas turbine blades were silicon carbide and silicon nitride. In the 1,000 deg. to 1,200 deg. C. temperature range, those materials combined good thermal shock resistance with excellent strength and creep resistance, especially silicon carbide. Their most serious disadvantage was their relatively poor impact resistance, which could only be overcome partly by suitable design. What was needed was a material with very much better resistance to mechanical shock. It was well known that ceramics were relatively poor in that respect.

Surface effects (e.g. Griffiths cracks) were very important here and the value of surface pre-stressing as in toughened glass was obviously great, while general textural effects were also important in the propagation of cracks, once started. The main material factor governing impact strength was resiliency which for brittle materials was proportional to maximum stress by maximum strain. Thus, as expected, maximum strength was desirable, but also so was maximum strain. It was very noticeable that breaking strain was surprisingly consistent at around 0.1 per cent for all ceramics. Possibly, if more were known about the reasons for that low value, some improvement might be possible. Graphite was an exception to that generalization—if graphite could be called a ceramic, which was debatable. Its maximum breaking strain was three or four times as great. Coupled with other desirable properties of graphite,

such as very good thermal shock and creep resistance and easy machinability, that meant that graphite was a very good potential material for turbine blades. Its major drawback, and a serious one, was that it needed protection from oxidation, and some success had been achieved in recent years by development and use of silicon carbide coatings on graphite both in this country and the United States.

Finally, one other application—a small one—of ceramics which was possibly worth mentioning, was the silicon carbide thermocouple for temperature measurement. It consisted of two different forms of recrystallized silicon carbide run against each other, which gave a high e.m.f. of the order of 50 microvolts per deg. C., which was about five times that of a rare metal couple. It was usable to about 1,600 deg. C. for long periods and, for short periods, up to about 2,000 deg. C., and might be useful in the future.

MR. F. JARRETT said that in the last 20 to 25 years there had been obvious developments in marine boilers in the direction of power/weight ratio and related performance. In this direction it was important that the heat from combustion should pass as quickly and direct as possible into water and the increasing use of extensive water walls was of major value in this direction. Boilers had been built with very small quantities of refractory or ceramic and it would appear that in the future less and less brickwork would be used in marine boilers, but those who operated boilers with little or no brickwork realized that refractory or ceramic had a stabilizing effect upon combustion, not only when water was present in the fuel but under normal conditions. Merchant Marine boilers of today were also required to use fuel which was becoming increasingly inferior, with the resulting increasing heavy deposits on tubes; a problem which might become gradually worse. Thinking of these things, it occurred to him that the future use of the refractory might possibly be to assist in combustion at sufficiently high temperature which might reduce deposits.

Mr. Aldred had mentioned catalytic effect (under heading "Ceramic Coatings") and it had occurred to him that there might be a possibility of making use of such an effect to assist in the combustion of some of those difficult oil fuels. He would like the authors' comments on that with reference, if possible, to research that may have been carried out in that direction; in other words, the development of the ceramic to assist fundamentally in combustion, not in the normally accepted use of the ceramic.

Correspondence

MR. E. F. BARTON (Member) wrote that he would declare his interest as a user of refractories and confine his remarks to the first section of the authors' comprehensive paper.

The authors had emphasized the improvement that had been made in shape and dimensional accuracy of firebricks following improved techniques of manufacture. He would ask for factual details of the improvement in linear tolerances and the limits now acceptable to manufacturers as normal specification requirements. Tolerances on shape were less simple to define but information on this aspect would be helpful. Reference had been made to joint attack by slags because of brick shrinkage and inadequate jointing materials, in this respect it was clearly advantageous to lay joints as "close" as possible and for this dimensional accuracy was a pre-requisite. Examination of Figs. 1, 2 and 3 inferred dimensional differences of 1 per cent for the pairs of stacked bricks with measurement made to minimize any perspective effect.

Referring to Table I, it would be of value for reference if cost relative to Scottish firebrick were stated for the higher

alumina grades. It was also observed that sillimanite based 55 per cent alumina exhibited a reheat permanent expansion whereas the 63 per cent alumina showed reheat permanent shrinkage and an explanation of this was requested.

Details given, and results, of the A.S.T.M. panel spalling test were valuable, he would, however, question whether the bricks involved had been laid up in "header" construction which was generally the normal method, and what influence header or stretcher lay would have on this test. Assessment of loss in weight by separated fragments over a fixed number of cycles was thought to be unsatisfactory and a better basis would be the number of cycles to specified percentage weight losses. Service performance of china clay bricks personally observed indicated at first a superior spalling resistance but later spalling to a greater depth than Scottish fireclay brick. In the overall analysis comparisons of time elapsed to a limiting reduction in wall thickness indicated that any advantage of the china clay brick was marginal only.

It was observed that no mention has been made of coatings

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which were offered for the treatment of installed refractory brick walls. Did this reflect the opinion of the authors as to their value?

MR. P. F. P. HORNE, B.Sc. (Associate Member) thought that in discussing ceramic nuclear fuels the authors implied that there was an advantage to be gained from the use of non-stoichiometric UO_2 as a nuclear fuel. Any advantage in ease of sintering must be weighed against the poorer thermal conductivity of non-stoichiometric UO_2 . This lower conductivity would give rise to poorer fission gas retention and increased central temperatures, leading to a lower fuel element rating if central melting was to be prevented. This was further aggravated by the relatively poor conductivity of the fission gases compared with helium which was usually used as a filler gas in oxide fuel elements.

He understood that in the case of fuel for n.s. *Savannah* a limit of $UO_{2.03}$ was set and it was determined that the conductivity of $UO_{2.13}$ was one-third of that of stoichiometric UO_2 .

MR. W. MCCLIMMONT, B.Sc. (Member) wrote that he was interested mainly in the section which dealt with marine boiler linings and referred to the first paragraph concerning fire-bricks, where it was stated that at the end of the last war it was apparent that the refractories available in Great Britain were inadequate to meet the increasingly severe operating conditions in boilers of new design. The authors might not be aware that most of the trouble in the immediate post-war years did not occur on new designs but on the more conventional types. The use of burners avoiding flame impingement, in many cases achieved by the use of higher burner pressures, has had the effect of reducing refractory wall temperatures in new designs. In addition, the more widespread adoption of water walls has also had the effect of easing the burden on refractories. As against this, of course, there had been some increase in forcing rates but distinction should be drawn here between merchant navy practice and the more arduous conditions adopted by the Admiralty. One question, therefore, whether the authors were correct in the implication that service temperatures above 1,450 deg. C. were required in merchant ship boilers in the years immediately after the war, except perhaps, in the case of cross-channel vessels.

The observation concerning the use of clay jointing materials which were inadequate for the purpose was worthy of emphasis because even today much of the jointing material in use, particularly in header type boilers, was still sub-standard and gave rise to much avoidable attack at the joints.

One trouble which had been encountered with high alumina bricks, used as quarls, had been what could be described as "exfoliation" or "peeling" of the surface, leading to a loss of shape and dimensional accuracy of the face of the cone and he would welcome the authors' comments on this. Was it possibly a very shallow form of spalling?

Monolithic refractories had undoubtedly made a valuable contribution to the solution of boiler furnace lining problems but they had their disadvantages. One of those was the need for an accurate knowledge of the temperature to which they were going to be subjected. If the temperature were too high for the grade selected, the refractoriness would obviously be insufficient but, on the other hand, if the service temperature were too low, the full strength of the material would not be developed. One of the troublesome phenomena in this case was low abrasion resistance.

Mention might profitably be made here of the paper which appeared in the June 1960 issue of the Supplement to the Institutes Transactions, which set out recommended methods for the application of mouldable and castable refractories. This report was prepared by the Marine Boiler Refractories Committee, set up by the British Shipbuilding Research Association and the British Ceramic Research Association to bring together representatives of the marine engineering, refractories, boiler-making, petroleum, and shipowning industries to study problems and requirements pertaining to the use of refractories

in their marine application. The Committee prepared this report because it considered that it was essential that the correct procedure was used in the application of these materials if satisfactory results were to be obtained.

Finally, he would like to express the view that, although the use of high-temperature mouldables and, to some extent, castables appeared to have consolidated itself in preference to pre-fired quarls, there was good reason to believe that if the refractory manufacturer could produce a sufficiently spalling-resistance pre-fired quarl at a reasonable price, there was still room for it and it might indeed prove advantageous.

MR. J. R. MICHAELIS (Student Member) wrote that he had read the above paper and found it most interesting. At a time when ceramics were gaining greater acceptance as a standard engineering material it was most opportune to have such a survey of their uses, but nevertheless he was rather disappointed that the authors had not given any indication of the maximum stresses which a component made of these materials would be expected to withstand.

The authors had pointed out that the cermet, the combination of a metal and ceramic, had not fulfilled the hopes placed in it of combining all the desirable qualities of both constituents, but there was one field in which the cermet had really come into its own, and that was for fuel elements for nuclear reactors. In such elements the fuel in ceramic form was finely divided and randomly dispersed in a metal matrix. When fission occurred on or near the surface of the fuel particle some of the fission products recoiled into the matrix damaging it. Therefore, that this damage might be minimized, a particle size must be chosen that was large compared with the recoil range of the fission products so that only those originating at or near the surface would leave the particle. Another reason for choosing a relatively large particle size was to make the distance between adjacent particles greater than twice the range of the fission fragments. This ensured that throughout the fuel element there was a continuous network of undamaged matrix.

The elements could be made with up to 40 per cent of ceramic dispersion but prolonged burn-up with such a high loading might cause swelling due to the collection of the fission products in the matrix, although in the U.S.A. experiments to find a means of overcoming this distortion had shown that by applying a tensile elongation of 15 per cent, 20 per cent voidage was introduced in which the fission gas could collect. A layer of cladding was still required for a cermet element, but as it did not have to provide structural support neither did it need to be strong enough to withstand the full pressure of all the fission gas generated, it could be fairly thin. A further advantage of such an element was that a rupture in the cladding only resulted in the coolant coming into contact with a very small portion of the fuel phase and only a small fraction of the fission products would be released.

The retention of fission products in the event of a rupture occurring in the cladding was one of the most desirable characteristics of the cermet element, but from a nuclear standpoint it would be advantageous to reduce the amount of steel present. He would be interested to know whether the authors could prophesy the development of an impervious ceramic which could be used to supplant the steel matrix.

MR. W. G. ROBINSON felt that the authors had drawn attention to the great increase in the scope of ceramic materials in recent years which had taken them into the field of many branches of engineering.

The reason for the wide range of properties obtainable in ceramics lay in their structure. The materials consisted of an agglomeration of crystals which were bonded either by a glassy phase which developed during firing or by sintering and crystal growth during firing. By varying the bonding and the nature of the crystalline material present ceramists could produce materials having a wide range of mechanical, thermal, electrical, and other properties.

The authors had intentionally confined their remarks to

Discussion

the use of ceramics in heat engines, but it might not be inappropriate to mention the already considerable use of ceramics in other apparatus used in marine engineering. A number of different ceramic materials were used in the electronic equipment for radio communications and navigation, radar and echo-depth recorders for example.

The use of ceramic refractories in boiler construction went back for a long time but even so the paper was able to record considerable progress in recent years in the thermal shock resistance and thermal insulating properties of refractories, and in their application in castable and mouldable form.

Looking into the future, mention was made of the possible uses of ceramic coatings in gas engines and as materials in gas turbine construction. The authors quite rightly drew attention

to the lack of ductility and rather low resistance to thermal and mechanical shock of ceramic materials when compared with metals. Progress was however, possible if those factors were recognized by engineers and allowed for in design.

Another factor which required consideration was dimensional tolerances. In general there was a considerable shrinkage during the firing of any ceramic product and even with the best control this resulted in some variation in the fired dimensions. Many ceramic materials were so hard that machining was impractical and grinding was the only means of controlling dimensions after firing. Expensive grinding operations could often be reduced or avoided if the dimensional tolerances were taken into account when designing equipment containing ceramic components.

Author's Reply

The authors were very pleased that the paper had provoked so much discussion because that, after all, was where progress was made. It was very enlightening to hear of experiences with ceramic materials in some of the more difficult applications because the paper was written from the point of view of the ceramic manufacturer who often supplied materials for applications, the details of which were not known to him. It was appreciated by the authors that it was not possible to go into any great detail as far as the applications and uses of some of the products mentioned were concerned and they were particularly pleased to hear from the valuable and comprehensive contribution made by Mr. Darling that ceramics were having some success in gas turbines.

With regard to Mr. Richardson's remarks on the panel spalling test, the authors agreed that no spalling test was 100 per cent fool proof and that some criticism could be directed at every spalling test. The A.S.T.M. panel test had been the subject of extensive development and attempted, by incorporating a pre-heat schedule, to test the bricks in the condition they would be in after a period of service. Other tests known to the authors test bricks in new conditions. The temperature of the pre-heat in the panel test could be varied according to the duty required from the product and in developing grades for marine boiler combustion chamber applications, it was considered that the pre-heat of 1,650 deg. C. was required in order that the refractory should be subjected to the worst conditions likely to be presented in a marine boiler. While therefore accepting that the test was not ideal the authors considered it the best available for the application.

The authors accepted Mr. Richardson's view that the porosity of the Scottish firebrick grade shown in Table I was higher than that of many Scottish firebricks but the figure of 28 per cent was typical of a particular grade which was widely used for marine boiler burner quarls because of its resistance to spalling. A panel spalling test had been carried out on Scottish firebricks having differing porosities, using the high heat duty pre-heat of 1,600 deg. C. with a result that a 23 per cent porosity brick showed 3.8 per cent loss in weight whilst a 28 per cent porosity brick showed 1.6 per cent loss in weight.

Mr. Richardson suggested that magnesium chromite was a possible material for lining gas turbine combustion chambers and the authors agreed that this should certainly be suitable from the chemical point of view but a considerable amount of work might have to be done in order to develop such a material having adequate thermal shock resistance. A spinel material based on pure materials had been tried in a small experimental rig using fuels with a very high additive content and had shown very little corrosion but had spalled readily. No further work had been done on this as yet.

The authors were grateful for Mr. Richardson's comments on silicon carbide and uranium dioxide, which added to their own brief remarks. They had no direct experience of flame spraying ceramics and could not say whether the coatings on Diesel engine components had been applied by a plasma gun.

The authors were interested in Mr. Darling's comments on extruded ceramics but did not consider that this method of manufacture was satisfactory for manufacturing heavy sections of very high duty refractories in order that the finished

body would be sufficiently uniform in texture and composition across the section. It was their opinion that for the small sections used in this particular application extrusion was a satisfactory method of production but for the larger segments normally used in combustion chamber linings variations in texture could result in premature failure.

The problem of improved corrosion resistance of super heater supports and economizer tubes raised by Mr. Hutchings was one that was comparable with the general corrosion of metal parts in many oil burning applications such as Diesel engines and whilst some good results were claimed, the ceramic coatings were generally of a brittle nature as Mr. Richardson had noted, so that they readily suffered from mechanical damage, and also the coatings which had been claimed to be successful were very expensive, perhaps much too expensive for widespread use in boilers.

Both silicon carbide and silicon nitride were possibilities for super heater supports both being strong materials and having excellent thermal shock resistance but both were brittle materials and this might preclude their use in this application.

The possible use for ceramics not only as backing behind the furnace tubes in a boiler but also as the boiler casing was an interesting thought but the authors doubted whether such a ceramic would have the mechanical properties to withstand normal usage in such an application.

Mr. Hutchings comments regarding the small size of ceramic insulators for spark ignition were surprising. The authors knew of one proprietary ceramic material in use for this application; if the manufacture of this material could not make larger pieces they were certain that there were other manufacturers of similar material who could do so.

The authors agreed that, as Mr. Begley had said, monolithic refractories had been available for many years, in fact their own Company was using them in crucible furnaces over 50 years ago, but they maintained that there had been extensive development over the last decade and that it was only in recent years that monolithic materials had been used with complete confidence. The authors could not comment on the point about fracture of ceramic anchors on installation; they had not met this and believed no hazard existed.

Mr. Darwin had made an excellent contribution from the nuclear point of view, amplifying the authors' remarks as Mr. Darling had done in another connexion. In reply to Mr. Darwin's questions, they were unable to comment on the sinterability of thorium dioxide-uranium pellets, having no experience of this. There seemed to be no reason, at least in theory, why the thermal conductivity of uranium dioxide should not be improved to some extent at least, by additions, but this could involve the problems referred to in the paper in connexion with metal-ceramic compositions.

The authors were of course aware of the work on ductile magnesia but had excluded it from the paper on the grounds that it was at present a piece of fundamental research involving specially prepared magnesia specimens and unlikely to be applicable to ceramic technology for some time to come.

In answer to Mr. Jarrett's query regarding the use of ceramic catalysts for improving combustion the authors were aware that such a claim had been made in the case of a ceramic coating on the piston of a Diesel engine but knew of no such

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claims with regard to general boiler applications. However, it was generally accepted that a hot refractory provided a good radiation surface which assisted in combustion under the more difficult conditions.

Dr. Blakeley had been right to raise the question of thermal insulation and might be interested to know that a high temperature insulating firebrick had been used behind the main tubes in the boilers of s.s. *Windsor Castle*. This had been chosen because it was a material of low thermal conductivity capable of withstanding the full furnace temperature if need be. As far as the authors were aware this was the first time that a material of this nature had been used in this way but it was an interesting idea which might well develop in future boilers.

The comments by Mr. White on some recent developments in ceramic-type materials were noted with interest.

Mr. Barton's point concerning actual tolerances on refractory bricks could not be satisfactorily answered by representatives of only one manufacturer. However, the improved manufacturing techniques had resulted in more consistent shape with flatter faces so that tighter joints could be formed. It was not correct to measure stacks of bricks as shown in Figs. 1, 2 and 3, which had been subjected to extensive testing, cleaning and subsequent reconstruction for photographing.

Reheat expansions of high alumina grades were not uncommon and were usually associated with the formation of mullite from its constituents. Other mineralogical changes could, however, produce similar effects.

The panel spalling test did not differentiate between header and stretcher constructions and was only intended as a comparative guide to the thermal shock resistance of various materials. It was unlikely that differences in thermal shock

resistance between header and stretcher constructions would materially affect service performance in marine boilers.

The authors did not consider the use of wash coatings over brickwork offered any advantages in the majority of instances. These coatings invariably contained fluxes which must attack the surface of the refractory if they were going to stay in position. Any such attack might lead to premature spalling.

The position regarding wash coatings for monolithic refractories was even more serious and several cases of serious damage to the refractory had been reported.

Mr. McClimont questioned whether refractory temperatures in merchant marine boilers after the war were significantly above 1,450 deg. C. The authors believed that some were substantially above this temperature and there were many instances where 1,600 deg. C. materials in both mouldable and brick form have given much better service than 42 per cent Al_2O_3 grades which should be satisfactory up to 1,450 deg. C. The authors believed that there was a considerable lack of information about refractory temperatures in marine boilers and the situation was certainly no better immediately after the war.

In response to Mr. Michaelis the authors considered that impervious ceramics were available which would withstand normal operations but there were many manufacturing problems to be overcome before cladding of suitable dimensional accuracy could be produced in quantity. Furthermore, the brittle nature of the ceramic cladding would increase the risk of rupture compared with metallic cladding.

The authors' thanked Mr. Robinson for his contribution, emphasizing that close co-operation between designer and manufacturer is necessary if advances in the use of ceramics materials are to be made.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting Held at The Memorial Building on Tuesday, 11th October 1960

An Ordinary Meeting was held by the Institute on Tuesday, 8th November 1960 at 5.30 p.m., when a paper entitled "General Developments in Ceramics for Marine Engineering" by F. J. Aldred, B.A., and N. W. Hinchliffe, B.Sc., was presented by the authors and discussed.

Mr. W. R. Harvey (Chairman of Council) was in the Chair and fifty-five members and visitors were present.

Eight speakers took part in the discussion which followed.

A vote of thanks to the authors, proposed by the Chairman, was warmly supported. The meeting ended at 7.15 p.m.

Section Meetings

Scottish Section

A joint meeting with the Aberdeen Mechanical Society was held at Robert Gordon's Technical College on Friday, 24th February 1961 at 7.30 p.m.

Mr. J. Forbes, Vice-President of the Aberdeen Mechanical Society, asked Mr. T. W. D. Abell, Chairman of the Scottish Section to preside. Mr. Abell then called on Mr. C. A. Creber (Associate Member) to read his paper "Apprenticeship and Ministry of Transport Examination Requirements for Junior Marine Engineers".

A lively discussion followed, which was ably dealt with by the author.

A vote of thanks to Mr. Creber for his instructive paper and to the committee members of the Scottish Section who attended the meeting, was proposed by Dr. A. C. West, Local Vice-President for Aberdeen.

Seventh Annual Dinner

The Seventh Annual Dinner was held at The Central Hotel, Glasgow, on Friday, 17th February 1961 at 7.15 p.m.

Mr. T. W. D. Abell was in the Chair and some 385 members and guests were present.

The toast to "The Institute of Marine Engineers in Scotland" was proposed by Lord Polwarth, T.D., and was replied to by the President of the Institute, Viscount Simon, C.M.G., who also incorporated in his speech, the toast to "Our Guests". Sir William Lithgow, Bt., replied to the latter toast.

The top table party consisted of representatives from local shipowners, shipbuilders, the Admiralty, Survey societies, and sister institutions.

Mr. W. R. Harvey (Chairman of Council) and Mr. J. Stuart Robinson (Secretary) were present from London Headquarters.

The Dinner was followed by a *Conversazione* until about 11.30 p.m.

The President and Chairman formally received the guests at a Reception prior to the Dinner.

West of England Section

An ordinary meeting of the West of England Section was held at the University of Bristol on Monday, 13th February 1961 at 7.30 p.m., when a paper entitled "Recent Developments in Pump Auxiliaries for Ships" by T. McAlpine, B.Sc. (Member) and I. S. Paterson, B.Sc., was presented and discussed. Mr. W. John, M.B.E. (Chairman of the Section) presided and twenty-five members and visitors including the Local Vice-President, Mr. D. W. Gelling, were present. Seven speakers took part in the discussion that followed.

A vote of thanks to the authors, proposed by the Chairman was accorded with acclamation. The meeting ended at 9.25 p.m.

A Junior Meeting of the West of England Section was held at the City of Bath Technical College, on Thursday, 2nd March, at 7.30 p.m. There was an audience of twenty-one, which included the Local Vice-President, Mr. D. W. Gelling.

Mr. Cotterell, Head of the Department of Electrical Engineering, conveyed the apologies for unavoidable absence of Mr. Yates, the College Principal, and on behalf of Mr. Yates said that he had very great pleasure in welcoming the Section on this their first meeting to be held at the college. Mr. W. John, M.B.E. (Chairman of the Section) replied suitably to the address of welcome, and in declaring the meeting open introduced Dr. J. E. Garside, M.Sc., who gave a very interesting and instructive lecture entitled "Metallurgy in Marine Engineering" illustrated with numerous lantern slides. Dr. Garside concluded his lecture by showing a coloured film on the Argon Arc welding process.

A vote of thanks to the author for his excellent paper, proposed by the Chairman, was accorded by enthusiastic applause.

The meeting ended at 9.20 p.m.

West Midlands Section

A meeting of the West Midlands Section was held on Wednesday, 22nd February 1961 at 7.0 p.m. at the Engineering Centre, Birmingham. A paper entitled "Development of Medium Speed Diesel Engines for Marine Auxiliary Uses" was read by Mr. C. J. Hind.

Mr. H. E. Upton, O.B.E., Chairman of the Section, presided at the meeting which was attended by 36 members and guests. With the aid of slides, Mr. Hind described the developments which have taken place over the last few years in the design and standardization of medium Diesel engines, emphasizing the problems which have been associated with bearings, etc.

Mr. Hind also mentioned the problems associated with maintenance and felt that the time may arrive when small high speed engines which can be withdrawn and replaced as a complete unit and returned for complete factory overhaul, may be supplied. The affect of pressure charging and intercooling was also fully discussed.

After the lecture a lively discussion took place in which all questions were ably dealt with.

On behalf of the members and guests present, the Chairman thanked the speaker for a most interesting paper.

The meeting closed at 9.0 p.m.

Student Section

A meeting of the Student Section was held at the Memorial Building, 76 Mark Lane, London, E.C.3, on Monday, 6th March 1961, at 6.30 p.m., when a panel of senior members discussed "Watchkeeping and Maintenance in a Steam Ship".

Mr. F. A. Everard (Member) was in the Chair.

Twenty-five members and visitors were present and took part in a question period.

A vote of thanks to members of the panel proposed by the Chairman was carried by acclamation.

The meeting ended at 8.15 p.m.

Institute Activities

Election of Members

Elected on 13th March 1961

MEMBERS

Charles Robertson Cain
Edward Caine
Robert William Carson
J. Leon Dion
Albert Michael Edward Dooley
Edwin Fairfax
Sydney Alick Harrison-Smith, Captain, C.B.E., R.N.
Cecil Joseph Hind
Moteelal Khubchand Jagtianie
John James Kinley
Cecil Adrian Logan
Michael Alfred Lonsdale Morgan-Giles, Captain
John Alfred Platt
David Purves
Vittorio Reverberi
J. Chandrashekar Simon
Ronald Dickinson Sutherst
Harold Alfred Thornton
Donald Edward Wilson

ASSOCIATE MEMBERS

Dennis Bateman
Thomas Henry Berry
Jan Blaasse
Peter C. Bulgarides
David Christison
George Robert Cowap
Peter Dominic Fernandes, Lieut., I.N.
Anthony Michael Ford, Lieut., R.N.
John Leslie Longman Gadsby, Lieut., R.N.
David Green
George Clarke Gudgeon, Lieut., R.C.N.
David William Hills
Edmund John Kulin, Lieut., R.C.N.
Michael Edward Lambert, Lieut., R.C.N.
Francis William Lea
Lai Lo
Norman Lyall
Norman Douglas Merry
Neil James Moir, Lieut., R.C.N.
John Dominic Oswald
Shavak Maneckji Poonawala
James Reid
Alan Jardine Rogerson
John Russell Sandars, Lieut., R.N.
John Scott
Alan Smalley
Douglas Thaw
Shaligram Gangaram Vichare, Lieut., I.N.
Harold Arthur Webster
Lawrence White
Raymond White
Dereyk Wright

ASSOCIATES

Robert Pleasant Brown
James Callf
C. N. Venkita Chalam, Cd. Eng., I.N.
Stanley Gartland
Kunnath Peter George, Cd. Eng., I.N.
Albert M. Goosney
Brian James Jenner
Martin Kent O'Grady
George Petley
Harjit Singh Sidhu, Cd. Eng., I.N.
Alexander Simpson
Bhola Nath Singh, Cd. Eng., I.N.

GRADUATES

Donald Ashenden
Navin Chandra, Sub. Lieut., I.N.

Colbert William Charles, Sub. Lieut., I.N.
Barry Trevor James Coles
Anil Dabir, Sub. Lieut., I.N.
Karl Jacobson George Andrew Fraser, 2nd Eng., R.F.A.
Rajendra Kumar Gupta, Sub. Lieut., I.N.
Nitte Prasanna Kumar Hegde, Sub. Lieut., I.N.
Ian Geoffrey Johnson
S. F. Jokhi, Sub. Lieut., I.N.
Norman A. Nicolson
John David Panakal, Sub. Lieut., I.N.
John James Pinkney
A. Sabherwal, Sub. Lieut., I.N.
Swaraj Kumar Sabherwal, Sub. Lieut., I.N.
Colin Shakespeare
Roy Henry Smith
Christopher Charles Edward Wilkins

STUDENTS

Henry Vaughan Griffith
Colin George Marsh
Anthony Odukwé
Patrick Neill Perioli
Anthony Merriman Tye
Stephen Warren
Christopher Wilks
Dimitris George Zeppos

PROBATIONER STUDENTS

Charles MacFadyen Houston
Guy Lindley Morris
Alec Mottram
Roderick Michael Nash
John Anthony Share

TRANSFER FROM ASSOCIATE MEMBER TO MEMBER

Andrew David Hunter
Arthur Wanless Hurst
James Milne
V. S. P. Mudaliar, Cdr., I.N.
Thomas Ollerton
William Phillips Robinson
William Brian Weston

TRANSFER FROM ASSOCIATE TO MEMBER

James Bruce Goodier
James Mahony
John Embleton Waugh

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER

William George Barnett, Lieut., R.C.N.
D. S. Tomar

TRANSFER FROM GRADUATE TO ASSOCIATE MEMBER

Brian Peter Bloudele
Victor George Bridge
Leslie Ronald Hyatt
John Pearson Ireland
Donald Adrian Mieras
Jemi Pirojshaw Mistry
Maneck Pirojshaw Motawara
Peter Munro
Elijah John Stevens
John Travis
Ronald Albert William Webber
Rex Young

TRANSFER FROM STUDENT TO GRADUATE

Demetrios Boucoyannis, B.Sc., Sub. Lieut., R.H.N.R.
Thomas Arthur Johnson
John Mason
George Ralph Anthony Metcalfe, B.Sc.
David Llewelyn Morgan
Ian Philip Wall
Peter Roland Whitehead

Institute Activities

TRANSFER FROM PROBATIONER STUDENT TO ASSOCIATE MEMBER

Terence Byrne

TRANSFER FROM PROBATIONER STUDENT TO GRADUATE

Paul Frederick Spires

TRANSFER FROM PROBATIONER STUDENT TO STUDENT

Keith Evans

David William Auckland

Anthony Peter Coleman-Wilson

Richard Graham

Donald Stewart Greenfield

John Roger Hollerton

Wilfrid Michael Jolley

William John George Noble

Brian Ovington

Ernest Reynolds

David G. Sutton

Richard Wall

Roy Kenneth Young