The Institute of Marine Engineers Transactions

1952, Vol. LXIV, No. 2

Ductile Cast Iron

M. M. HALLETT, M.Sc., F.I.M. (Member)

Spheroidal graphite cast iron depends for its good properties on the complete replacement of the weakening graphite flakes present in normal cast iron by spheroids of graphite, which do not interrupt the continuity of the metallic matrix nearly so sharply as do the flakes of graphite. The change in graphite type can be made to coincide with changes in the matrix of the iron. It is thus possible to produce an iron which in the "as cast" condition combines a tensile strength of 40 tons per sq. in. with three times the toughness of engineering cast iron. The same material, annealed to produce a ferritic matrix, will show a tensile strength of about 32 tons per sq. in. with an elongation of 10 per cent or more. The characteristic behaviour of a ductile material is exhibited by the annealed iron in torsion and compression tests as well as in tensile tests. In fatigue, the endurance ratio varies from 0·4 to 0·5, a value higher than that of most high strength cast irons, while the notch sensitivity is closer to that of mild steel.

The spheroidal graphite structure is associated with interesting physical properties. Under conditions of good lubrication, the "as cast" material may show a wear-resistance superior to that of grey cast iron, but the latter is better when lubrication is poor or lacking. Resistance to heat is also improved.

The introduction of spheroidal graphite into austenitic iron has similar beneficial effects, doubling the strength and greatly increasing ductility. The endurance ratio in fatigue remains high.

In the concluding sections, the production properties are discussed from the point of view of the foundry and of the machine shop and the probable lines of application of this new family of irons in marine engineering are considered briefly.

INTRODUCTION

During the past three years a spectacular development has taken place in the field of cast iron, resulting in a range of materials which possesses considerable ductility and a tensile strength exceeding that of mild steel. These irons have received such names as nodular iron, spheroidal graphite cast iron and ductile cast iron. The process is associated with the addition of one of two metallic elements, either cerium or magnesium. The cerium process was first described by Morrogh and Williams[1] and the magnesium process by Gagnebin, Millis and Pilling.[2] Since the original papers, there has been a flood of information, varying in reliability, describing both the production and the properties of the resulting products. The purpose of the present paper is to review the situation in the light of the author's own experience and to provide a practical summary of the information on the characteristics of the irons, paying particular attention to those properties likely to be of interest to the marine engineer. Where possible, original experimental evidence is furnished, and is supplemented by published data.

The information is confined to iron treated by the magnesium process. This is because the magnesium process is easy to apply in the foundry and can be made to work on normal types of cast iron melted in the customary manner in cupola furnaces. The cerium process, on the other hand, as stated in the original description, necessitates the use of an iron high in carbon and silicon and unusually low in sulphur. Such a combination cannot readily be achieved in the cupola and it is necessary to employ some special form of melting, such as high-frequency induction furnaces. Where this equipment is available, good nodular iron can be produced, but in the present stage of development the method is of limited application.

MICROSTRUCTURE

It is desirable first to consider the changes in microstructure on which the great improvement in mechanical properties depends.

All grey cast irons contain graphite which varies greatly in quantity, in size and in distribution. Typical flakes of graphite in a normal soft grey iron casting are shown in Fig. 1,

Plate 1, at a magnification of 100 diameters. It is apparent that the graphite flakes seriously interrupt the continuity of the metallic matrix and offer an easy path for fracture, as the strength of the graphite is negligible in comparison with that of the metallic matrix. It will also be noted that the ends of the graphite flakes tend to be sharp, providing a large number of sites for severe stress concentration throughout the material. Improvements in the mechanical properties of cast iron were effected ten to twenty years ago by reducing the quantity of the graphite and by decreasing the size and ensuring an even distribution of the flakes. The result was a series of high duty cast irons with tensile strengths ranging from about 18 to about 28 tons per sq. in. The magnesium process, however, leads to the complete elimination of the normal graphite flakes and to the substitution for them of graphite spheroids, as illustrated in Fig. 2, Plate 1, at the same magnification as used in Fig. 1. The improvement in the continuity of the metallic matrix is obvious. In addition to greatly increasing the length of the metallic bridges extending from one piece of graphite to the next, the spheroids of graphite do not introduce the points of stress concentration characteristic of flake graphite.

The graphite spheroids can be combined with any form of metallic matrix, but it is likely that most of the demand will be for one of two conditions. The first is that illustrated in Fig. 3, Plate 1, at 650 diameters magnification, where the matrix is entirely pearlitic, while the other is that shown in Fig. 4, Plate 1, where the matrix is entirely ferritic. The pearlitic matrix is characteristic of the iron in the "as cast" condition, while the ferritic matrix is attained by annealing, usually at a temperature of about 725 deg. C. for four to sixteen hours, depending on circumstances. Other types of matrix consisting partly of pearlite and partly of ferrite, or entirely of martensite, austenite or the so-called acicular structure, can be readily achieved, each conferring its characteristic properties.

The actual level of mechanical properties achieved depends to a considerable extent on the perfection of the graphite structure. It is very easy indeed to produce structures in which, for example, half of the graphite is in the form of spheroids and half is in the form sometimes referred to as "quasi-flake graphite". For the purpose of this paper, the use of the term "spheroidal graphite cast iron" is intended to convey that at least 80 per cent of the graphite (preferably at least 90 per cent) is in the form of spheroids. This degree of perfection can be readily achieved by careful metallurgical control, but the figures quoted below are thoroughly conservative. The use of the term "ductile cast iron" should be restricted to the material in the annealed condition, when it shows appreciable ductility.

MECHANICAL PROPERTIES

Tensile tests

The characteristics of the two major types can best be understood by considering the normal stress-strain curves obtained in the course of a tensile test. Two typical curves are given in Fig. 5 which also includes a comparison curve on a medium strength flake graphite cast iron and the detailed mechanical properties obtained on these test pieces are quoted in Table 1. In the "as cast" condition the material shows a

TABLE 1—*Mechanical properties of specimens giving the stress-strain curves shown in Fig. 5*

	Grey cast iron	Spheroidal graphite iron "As cast"	Spheroidal graphite iron Annealed
Limit of proportionality, tons per sq. in.	—	14·0	16·0
0·1 per cent proof stress, tons per sq. in.	—	31·5	24·8
Yield point, tons per sq in....	—	—	27·0
Maximum stress, tons per sq. in.	15·8	37·0	32·0
Elongation per cent	—	1	21
Reduction in area per cent ...	—	1	21
Modulus of elasticity, $\times 10^6$lb. per sq. in.	16·7	24·0	24·0
Vickers diamond hardness ...	229	296	190

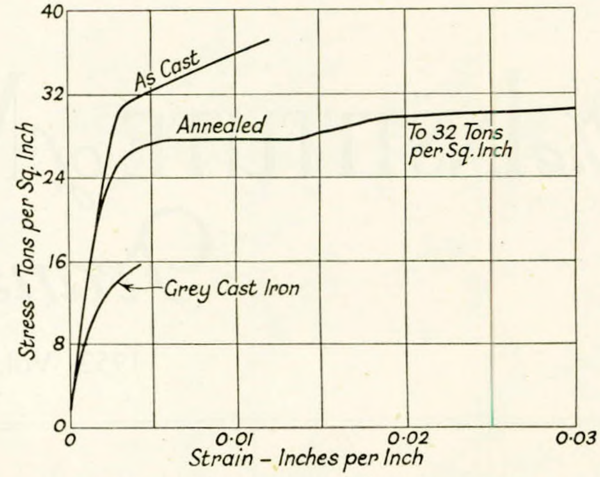


FIG. 5—*Effect of heat treatment on stress-strain curves in tension*

type of stress-strain curve different from that of normal cast iron, in that over a wide range of stress there is a close approximation to proportionality between stress and strain. At very high stresses the curve does bend over as an indication of somewhat greater ductility, but fracture occurs with a total elongation of only about 1 per cent.

The annealed specimen, on the other hand, shows a stress-strain curve very much more like that of normal mild steel. Again, there is an initial period of elastic extension, followed by a gradual departure from proportionality and then a definite yield point, after which a steady extension occurs under gradually increasing stress, persisting to the point of fracture. Referring to Table 1, the limit of proportionality is about 15 tons per sq. in. in each case, and the modulus of elasticity is also unaffected by the heat-treatment. The value of 24×10^6lb. per sq. in. is considerably higher than that of the grey cast iron at 16×10^6lb. per sq. in. The annealing operation has lowered the proof stress and the tensile strength and introduced a definite yield point and a definite elongation. Even in the ductile condition there is no necking of the specimen, reduction in area being approximately the same as the elongation.

The results quoted are typical of those obtained in production.

The two conditions cited differ sharply in their characteristics, the "as cast" condition conferring properties similar to those of a normal grey cast iron, but at a much higher level, while the annealed specimen has many more of the characteristics of mild steel or malleable cast iron. In the "as cast" state, the tensile strength will vary from 35 to 45 tons per sq. in. and the annealed material will generally be between 29 and 34 tons per sq. in., with elongation ranging from 10 to 20 per cent.

Torsion tests

The ductility of the annealed material is well illustrated

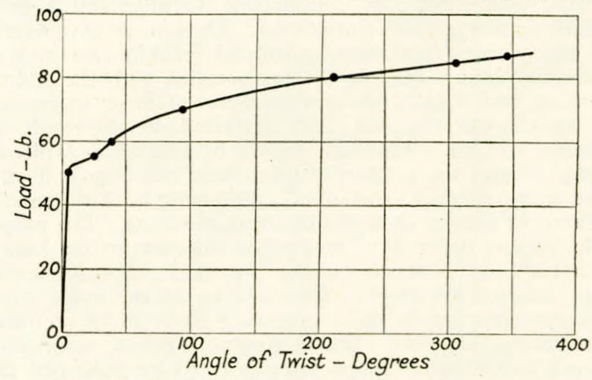
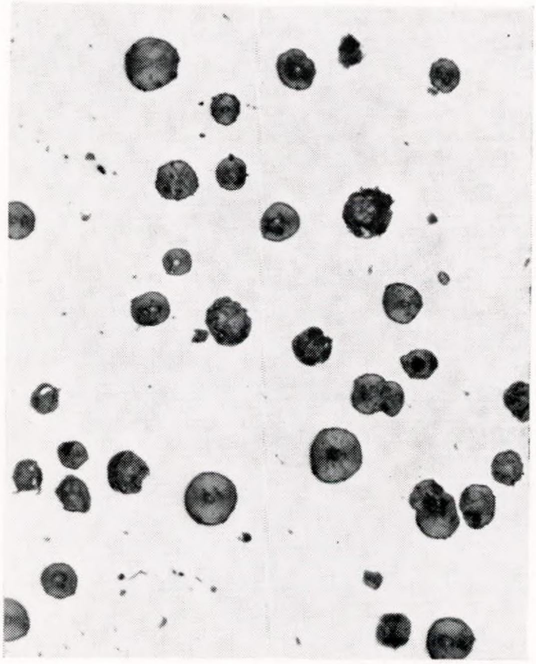
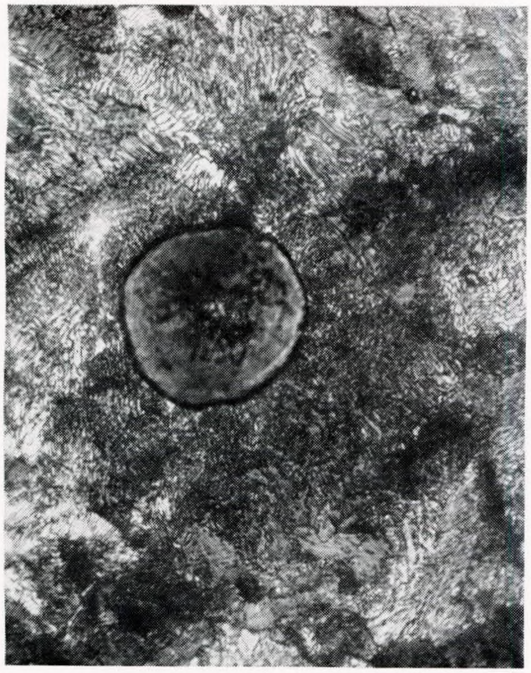


FIG. 6—*Typical stress-strain curve in torsion*

× 100
FIG. 1—*Unetched. Graphite flakes in grey cast iron*

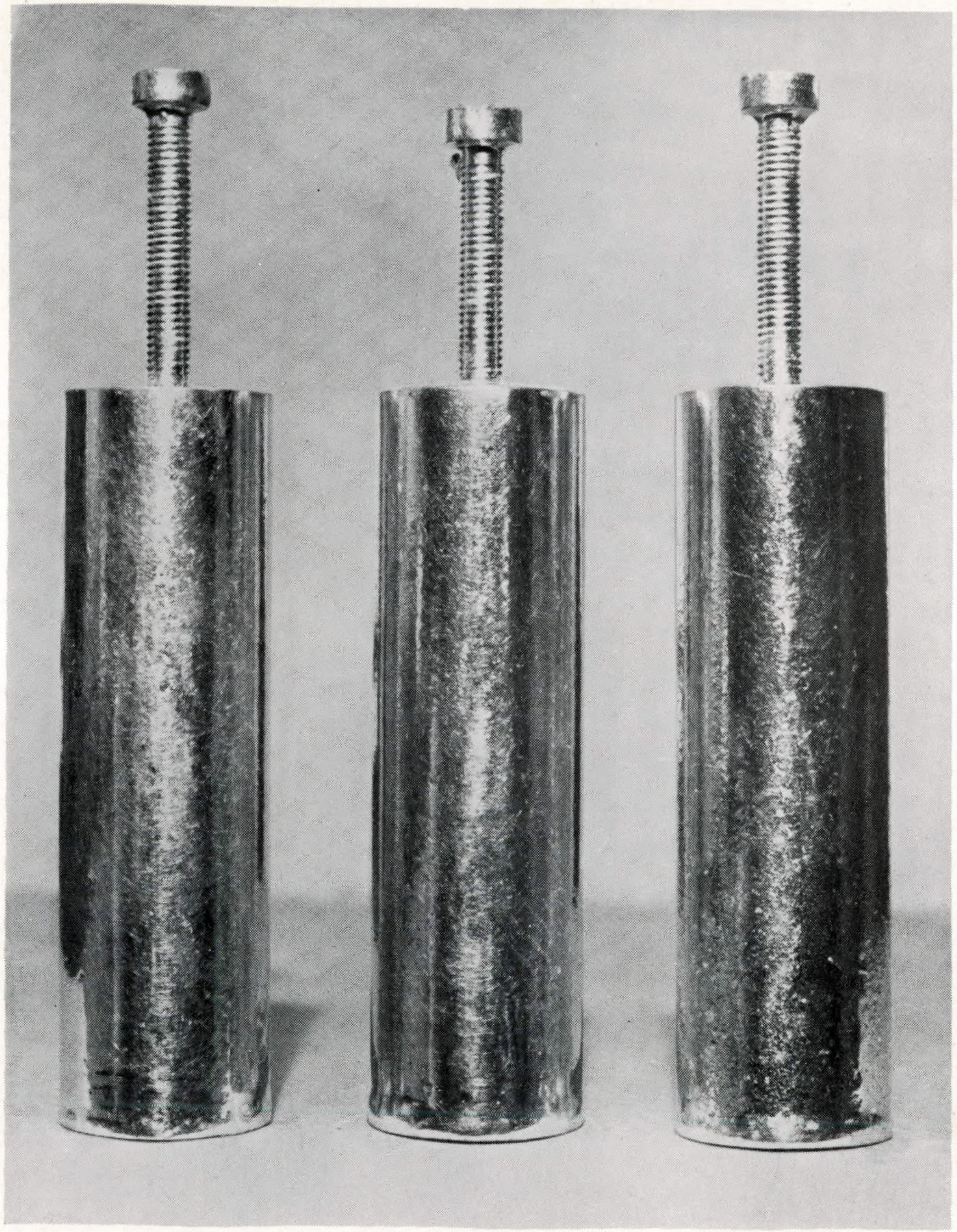


× 100
FIG. 2—*Unetched. Graphite spheroids in ductile cast iron*



× 650
FIG. 3—*Etched. Spheroidal graphite cast iron "as cast"*

× 650
FIG. 4—*Etched. Spheroidal graphite cast iron annealed*



Sample 1 *Sample 2* *Sample 3*

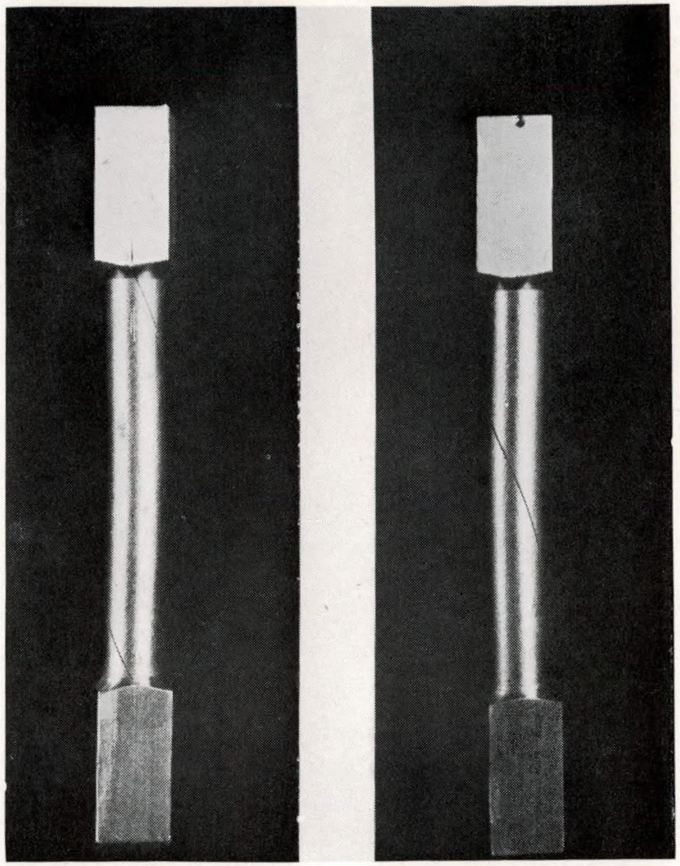


FIG. 7 *(above)—Test piece after torsion test (approximately two-thirds full size)*

FIG. 9 *(left)—Tin coated spheroidal graphite cast iron (approximately $1\frac{1}{3}$ full size)* by torsion tests. For example, a specimen with a parallel portion 0·5in. diameter and 3·125in. between shoulders, was twisted through 360 deg. without fracture occurring. The graph of this curve, illustrated in Fig. 6, again shows the yield point and the same sort of behaviour as in the tensile stress-strain curve. The actual specimen, on which a straight line was scribed before the start of the test, is illustrated in Fig. 7, Plate 2. From the same bar a tensometer test piece was prepared, which gave a yield point of 25 tons per sq. in., a maximum stress of 31 tons per sq. in., an elongation of 10 per cent and a reduction of area of 13 per cent. For the results of these torsion tests the writer is indebted to Mr. W. E. Woodward of the Department of Engineering of the University of Cambridge.

Impact tests

The expression of impact value in cast iron is a troublesome problem, as the ordinary Izod impact test piece in a customary flake graphite iron gives extremely low values. For this reason, a 0·798in. diameter unnotched impact test piece was standardized in B.S.1349. On this type of test piece an engineering flake graphite grey cast iron gives an impact value of about 20ft.-lb.; the spheroidal graphite cast iron, even in the "as cast" condition, frequently gives impact values of over 100ft.-lb., while the annealed material is invariably unbroken after being struck with the full blow of 120ft.-lb. There has, therefore, been a tendency to use either an unnotched bar of 0·45in. diameter or even the normal notched Izod impact test piece, when testing the ductile material. Using the unnotched bar, Braidwood and Busby[3] reported values of 12ft.-lb. for the "as cast" material and 52ft.-lb. for the annealed material, corresponding to about three times and twelve times the impact strength of normal cast iron. More recently, Grant[4] has quoted values for Izod impact tests using the normal notched bar. In the annealed condition on material of satisfactory microstructure, values of 9 to 11ft.-lb. were obtained.

In the author's experience, the impact value is more dependent on the thoroughness of the annealing operation than are the other mechanical properties. Impact values of 50 to 75ft.-lb. are regularly determined on completely ferritic unnotched 0·45in. diameter bar samples and up to 13ft.-lb. on notched Izod impact test pieces of the same microstructure, but if there are traces of residual pearlite due to incomplete annealing, the values fall abruptly, particularly the Izod impact values. The silicon content is also important and the impact value falls as the silicon content rises, particularly above 3 per cent silicon.

Fatigue tests

The first data on fatigue properties reported by Gagnebin, Millis and Pilling[2] indicated a fatigue strength of 18·3 tons per sq. in. and an endurance ratio of 0·43 on the cast material while in the annealed condition, a fatigue strength of 16·5 tons per sq. in. and an endurance ratio of 0·49 were reported. The most complete account of experiments on fatigue has been published by Grant of The British Cast Iron Research Association.[4] This work indicates a fatigue strength of 16 to 18 tons per sq. in. with an endurance ratio of about 0·38 in the "as cast" condition, and a fatigue strength of 13 tons per sq. in., with an endurance ratio of 0·43 to 0·46 in the annealed condition. Grant presents some interesting data on the relation between tensile strength and endurance ratio in cast iron. In all types of cast iron, there is a tendency for the endurance ratio to decrease as the tensile strength increases, but the value of the endurance ratio is much higher at a given tensile strength in an iron with spheroidal graphite than in one with flake graphite.

There is practically no information on the notch susceptibility of nodular cast iron. One result on a bar with a notch of 0·05in. radius suggests a relatively small notch susceptibility (Eagan and James[5]), while Grant[4] quotes a few figures for cerium-treated nodular iron, in which the ratio was lowered from about 0·5 on a plain test piece to about 0·25 on a test piece with a 45 deg. notch of the Izod impact test piece type. This degree of notch susceptibility is greater than that of a normal engineering grey cast iron with flake graphite but it must be borne in mind that the tensile strength of the latter is considerably lower. This conclusion would perhaps be expected, since the properties of nodular cast iron are intermediate between those of grey cast iron and of steel.

Compressive strength

The behaviour of the spheroidal graphite cast iron in compression is parallel with its behaviour in tension and torsion. Gagnebin, Millis and Pilling[6] have reported that in the "as cast" condition, only a small plasticity is displayed and the yield strength approaches more closely the ultimate strength. In the annealed or ductile material, the yield strength is lower at about 29 tons per sq. in., while the ultimate strength is about 55 tons per sq. in. It is interesting to note that in the ductile material considerable work-hardening takes place. For example, a specimen 0·5in. diameter × 0·375in. high was compressed to a height of 0·26in. without any signs of cracking. The Vickers diamond hardness rose from 185 before compression to 215 after compression.

Consistency of properties

In all cast irons the mechanical properties tend to decrease with increasing size of castings. Spheroidal graphite cast iron is no exception, but the amount of decrease is less than with many other types of cast iron. The mechanical properties which have been described above are typical of those obtained on castings with a sectional thickness of 1 to 2in.

At this thickness, tensile strength values ranging from 35 to 45 tons per sq. in. in the "as cast" condition and an average value of perhaps 40 tons per sq. in. may be expected. After annealing, the tensile strength will drop to 30 to 34 tons per sq. in., and elongation values ranging from 10 to 20 per cent with an average of at least 12 per cent, will be obtained. On test bars representing a section of from ⅜in. to ¾in. thickness, tensile strength values in the "as cast" condition usually range from 40 to 50 tons per sq. in., with an average of about 45 tons per sq. in. The impact value seems to be particularly sensitive to section. In the annealed condition, the 1in. to 2in. thick castings have an average value of about 35ft.-lb., while the ⅜in. to ¾in. castings average about 60ft.-lb., both determined on the 0·45in. diameter unnotched bar. Results have been reported in the American literature which, taken together, show that, even in extremely large sections, the mechanical properties of the spheroidal graphite cast iron are well maintained at a value at least double that of normal grey cast iron. Thus, in a section of about 8in. diameter, a tensile strength of 30 tons per sq. in., with an elongation of 10 per cent can be expected.

In addition to the effect of the size of the casting, the heat-treatment conditions play an extremely important part

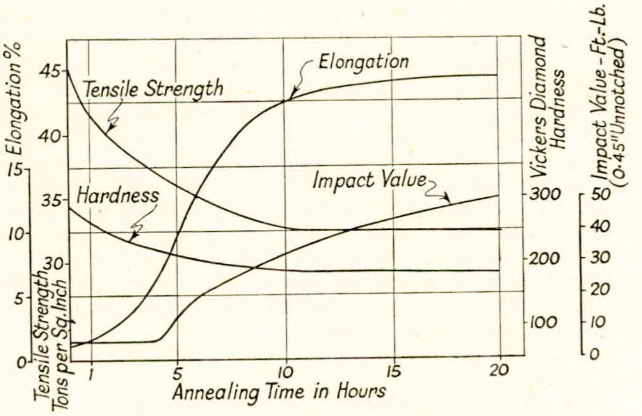


FIG. 8—*Effect of time of annealing at 725 deg. C.*

in controlling the final properties. The annealing operation is usually carried out at the relatively low temperature of 725 deg. C., and Fig. 8 gives the results of determinations on a typical spheroidal graphite iron. This figure, which helps to emphasize the essential differences between the "as cast" and the annealed conditions, indicates the relatively rapid change in the early stages of annealing, and the steady conditions attained in longer periods. Changes in the composition of the iron will displace the curves in one direction or another, but should not alter their general form.

PHYSICAL PROPERTIES

It might be expected that the substitution of spheroidal graphite for flake graphite would also have a profound influence on the magnetic properties and the electrical resistance. This is indeed the case. Since the material is usually required in the magnetically soft condition, annealing is used to induce the ferritic structure. The maximum permeability then rises to about 1,400 as against a value of about 450 for normal flake graphite iron. The material approaches saturation at considerably lower field strengths and the coercive force is also reduced, a value of 2·0 having been quoted by Everest[7] as against 3·3 for a flake graphite iron. The electrical resistivity is also sharply lowered, values of 57·6 and 54·8 microhms per cm. cube having been found as against 106·6 for flake graphite iron. This combination suggests possible applications for electrical purposes, such as the pole pieces of electro-magnets.

PROPERTIES DEPENDING ON SURFACE CONDITION

In many cases the service performance of engineering grey cast iron is influenced by the outcropping of the graphite flakes on a machined surface. The change from flake graphite to spheroidal graphite has a profound influence on those properties controlled by the flake outcrops.

Heat-resistance

Oxidation of cast iron at high temperatures often proceeds by the preferential passage of oxidizing gases along the graphite flakes, so that the scaling extends relatively deeply into the iron. The much shorter path offered by the graphite spheroids improves the resistance to scaling. It has been reported by Gagnebin[2] that at 870 deg. C. ductile cast iron behaved as well as a flake graphite iron alloyed with 1·3 per cent of chromium, the growth of the specimen and the depth of oxide penetration being only one-sixth to one-twentieth of that of unalloyed iron of otherwise similar composition. A substantial decrease in growth at 550 deg. C. and at 900 deg. C. has also been reported by Ko,[8] but in this case the unalloyed comparison sample differed greatly in composition from the spheroidal graphite sample.

Corrosion-resistance

Under conditions of mild acid attack, evolution of hydrogen takes place from the graphite flakes which are cathodic to the surrounding matrix. Everest[7] has shown that in dilute hydrochloric acid and sulphuric acid at room temperature or slightly elevated temperature, the spheroidal graphite iron shows a great improvement in corrosion resistance as compared with flake graphite iron, though the overall rates of corrosion are still very high. In corrosion depending mainly on absorption of oxygen, the differences in rate of attack between spheroidal graphite cast iron and flake graphite cast iron are probably not significant. Nevertheless, the fact that resistance to corrosion is likely to be better under mild acid attack and not worse under other types of attack, indicates that there need be no apprehension with regard to the use of spheroidal graphite iron in mildly corrosive conditions where flake graphite iron has been successfully employed.

Wear-resistance

One of the most valuable features of normal flake graphite cast iron is its self-lubricating capacity, which is a function of the graphite. The much greater areas of the metallic matrix which are left relatively remote from graphite in spheroidal graphite cast iron naturally raises a doubt as to the ability of spheroidal graphite cast iron to run in contact with other material or with itself as well as does flake graphite iron. Reports in American literature have suggested that, under lubricated conditions, the wear-resistance of nodular iron compares very well with that of grey cast iron, and this is borne out by the rather limited service experience at present available to the author.

At the request of the owners a set of piston rings in spheroidal graphite iron in the "as cast" condition were installed in No. 2 cylinder of the airless injection supercharged four-cycle Hawthorne-Werkspoor engine of m.s. *Auricula*, running on boiler oil of 3,500 secs. viscosity (Red. No. 1 at 100 deg. F.). The piston was fitted with five compression rings and one scraper ring, all in the same material. The rings were of standard type, 650 mm. diameter and 21 mm. radial thickness. The stroke of this engine is 1,400 mm. and it operates at 114 r.p.m. After working for 6,195 hours, during which 4,127,550 revolutions were performed, the rings were removed for examination. The working surfaces were good, showing only normal very slight signs of scoring. The radial wear on the five compression rings did not differ very much, and averaged 1·29 mm. as compared with 1·85 mm. mean wear on normal grey iron rings running at the same time in No. 7 cylinder. Expressed in terms of mean radial wear per 1,000 hours, the figures were 0·208 mm. on the spheroidal graphite iron and 0·300 mm. on the standard grey iron. It was also found that the wear on the two cylinder liners (Nos. 2 and 7) was practically the same. Subsequent microscopical examination showed that 95 per cent of the graphite was in the form of rather coarse spheroids in a pearlitic matrix. The Vickers diamond hardness was 273.

This favourable result is not put forward as indicating that spheroidal graphite cast iron is necessarily a good piston ring material under all conditions, but is intended to indicate that, where lubrication is satisfactory, as in the engine concerned, the wear-resistance of the "as cast" form of spheroidal graphite iron is not likely to be much, if at all, inferior to that of normal grey cast iron. The author is indebted to Mr. John Lamb, O.B.E. and The Anglo-Saxon Petroleum Co., Ltd., for their kind co-operation in carrying out these tests, and in providing detailed information on wear rates.

Under conditions of dry loading, Gagnebin and his colleagues[6] have studied the resistance to galling by oscillating a cylinder against an annular ring under a load increasing with each oscillation. They showed that the pearlitic spheroidal graphite iron appeared to be rather better in resistance to galling than normal grey cast iron, and even the annealed material did not suffer much more.

On the other hand, some tests under virtually unlubricated conditions which were kindly carried out for the author by Mr. J. Arnott of G. and J. Weir, Ltd., did not fully support this conclusion. In these tests a small rectangular specimen was reciprocated across a large rectangular specimen under a load of 200lb. per sq. in. at a speed of 160ft. per minute. The total swept area was 7 sq. in., and the stroke was 3½in., the duration of the test being 100,000 double strokes. For these tests the lubricant was boiling water since it was desired to imitate the conditions arising in boiler injection pumps. Tests were carried out on an ordinary grey cast iron, on "as cast" spheroidal graphite cast iron and on annealed spheroidal graphite cast iron. The results are given below, the wear being expressed in each case as a loss in thickness calculated from losses in weight:—

Material	Condition	Loss in thickness/inches Small specimen	Large specimen
Grey iron	"As cast"	0·002	0·0004
Spheroidal graphite iron	"As cast"	0·015	0·0007
Spheroidal graphite iron	Annealed	0·032	0·0026

After the conclusion of the tests the grey iron specimens appeared smooth and polished, the "as cast" spheroidal graphite iron showed slight scoring, whereas the annealed spheroidal graphite iron showed severe scoring and heavy wear, the test having to be discontinued after only 20,000 double strokes.

These figures suggest that, while "as cast" spheroidal graphite cast iron may function perfectly satisfactorily under normal lubrication, care should be taken before applying the annealed material under conditions in which lubrication is virtually absent.

Surface coating

Flake graphite iron is usually regarded as troublesome to coat with tin and the process is avoided in practice. Methods for improving the tinning capacity of cast iron have been worked out and a fused chloride treatment has been described by Cresswell.[9] Following some very promising indications in an industrial application, three samples were submitted to the Tin Research Institute for treatment by them. One sample was tinned direct on to the fine turned surface, while the second was shot blasted prior to the tinning, each being passed through the fused chloride treatment. The third was pickled and tinned in the conventional way without fused chloride treatment. The coating of all three appeared to be satisfactory, though the first two were superior to the third, as would be expected. The improved ability to take a tin coating shown by these three samples is illustrated in Fig. 9, Plate 2. The subject is difficult to photograph, but the illustration does give some idea of the perfection of the surface. It is particularly interesting to note that even without the fused chloride treatment, the third sample is clearly better than with a normal cast iron. Similar conclusions are to be expected from other forms of plating operation, e.g., nickel and chrome plating, though these processes have already been improved so much that normal cast irons can be handled satisfactorily.

AUSTENITIC IRON WITH SPHEROIDAL GRAPHITE

The examples quoted above have all been on low alloy material with a pearlitic or ferritic matrix. By the addition of large amounts of alloys, the matrix can be rendered austenitic while the iron remains amenable to the spheroidizing treatment. Table 2 gives details of duplicate mechanical test results obtained on an iron of this type in two conditions (1) "as cast" and (2) after heating to 1,000 deg. C. for one hour and cooling in air. The latter treatment is designed to break down free carbides which often occur in iron of this type. The composition of this material ("Ni-Resist") is approximately 2·7 per cent carbon, 1 per cent manganese, 14 per cent nickel, 7 per cent copper and 2 per cent chromium, with low phosphorus and sulphur.

TABLE 2—*Properties of "Ni-Resist" with spheroidal graphite*

	"As cast"		Air cooled 1,000 deg. C.	
Limit of proportionality, tons per sq. in.	3·8	3·6	3·6	3·8
0·1 per cent proof stress, tons per sq. in.	16·2	15·7	16·0	16·0
0·2 per cent proof stress, tons per sq. in.	18·9	18·5	18·0	18·3
Maximum stress, tons per sq. in.	24·0	24·9	26·7	26·6
Elongation per cent	2·5	2·5	5·0	4·0
Reduction in area per cent ...	4·0	4·0	7·0	7·5
Modulus of elasticity, $\times 10^6$lb. per sq. in.	21·3	21·0	20·6	20·3
Brinell hardness	177	179	176	179
Fatigue limit (reversed bending —plain specimen) tons per sq. in.	± 15·0		± 12·5	

The above results were obtained on material supplied by the author, who is indebted to Mr. E. R. Gadd of the Bristol Aeroplane Co., Ltd., for permission to publish them. The ductility is a little lower than would have been expected (private information has indicated elongation values up to 13 per cent), but the properties are interesting in that they show a doubling of the strength of an iron which has a useful resistance to heat and to corrosion.

PRODUCTION CHARACTERISTICS

However good the inherent properties of a material, it is of no interest to the engineer unless it can be produced in practice. Spheroidal graphite cast iron possesses many of the desirable foundry characteristics of grey cast iron. It requires only the use of normal foundry melting equipment. Its fluidity is satisfactory and it can be cast with a good skin. Careful metallurgical control is required and, on account of the high shrinkage, very careful attention is needed to ensure the most economical gating and feeding practice, but, provided these facilities are available, sound castings of a high level of mechanical properties can be regularly produced. As in the case of any new material undergoing development, consultation between the engineer and the founder in the design stage will almost invariably save much time and effort later on.

Machinability is generally good. It will already have been noted that in the pearlitic state the hardness is higher than that of flake graphite irons. No difficulty whatever is experienced in machining spheroidal graphite cast irons with a pearlitic matrix and a hardness approaching 300, as it appears to machine more easily than flake graphite iron of the same hardness. Tool life is satisfactory, though because of the high strength of the iron, the power consumption in machining may be 40 per cent greater than when machining grey iron. In the annealed ductile condition machinability is excellent and is superior to that of normal cast grey iron. In both conditions a very smooth surface is left after machining, having much more the appearance of mild steel than of sand cast grey iron.

POSSIBLE APPLICATIONS

The applications of the new type of iron in marine engineering are likely to fall into three major fields:—

1. Those in which use is made of its improved shock-resistance.
2. Those requiring high strength often combined with wear-resistance.
3. Those in which heat-resistance is combined with other properties, such as wear-resistance.

It is well-known that, in recent years, and particularly as a result of war-time experiences, the use of grey cast iron has been abandoned in many applications because of the liability of the castings to fracture by shock from underwater explosions. Typical applications range from large castings, such as engine bed plates, to a variety of smaller fittings. Instead of cast iron, welded steel assemblies are widely used, and in some cases tougher cast alloys have been employed. Ductile cast iron should find a definite field of application in meeting these conditions, in view of its combination of satisfactory foundry properties with great toughness in the annealed condition. Experiments are already in hand, but it is not possible yet to provide any service data.

The combination of strength and wear-resistance, particularly apparent in the "as cast" spheroidal graphite iron, has already caused much experimental work to be undertaken in various engine components; such parts as crankshafts are an obvious example. The higher modulus of elasticity alone gives the material a great advantage over ordinary cast iron by promoting greater stiffness, while the good fatigue properties should give it ample strength for most conditions.

What is at first sight a slightly different application, but which probably calls for similar properties, is that of propellers. The resistance to cavitation erosion seems to be dependent to some extent on the tensile strength when comparing alloys of a similar type. On this basis the "as cast" material should be advantageous and laboratory tests have tended to confirm this conclusion. The greater shock-resistance should reduce the incidence of tip breakage, and it is possible that this aspect might be regarded as of prime importance, leading to the use of annealed material.

Although service data are lacking, one would imagine that the resistance of the iron to heat shock is good, and this may well lead to interesting possibilities in the Diesel engine field. At the moment the inability of grey cast iron to withstand more severe conditions of combined pressure and heat shock, forms a definite limitation in Diesel engine development. Spheroidal graphite iron is attracting attention in this field. Already large pistons of 750 mm. diameter have been cast and are undergoing service tests. Not only is resistance to heat shock important here, but the pistons must have good wear-resistance and be able to maintain the piston ring groove dimensions. The thermal conductivity of the spheroidal graphite iron suggests some advantage over the more complex type of pistons involving heat-resisting steel heads and cast iron skirts.

All such applications take time to develop, and it is the purpose of this paper to provide the data on which work may be initiated.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the Directors of Sheepbridge Engineering, Ltd., for permission to publish this paper and acknowledges the guidance of the Mond Nickel Co., Ltd., and the help of his colleagues in the foundry and in the laboratory in overcoming the problems naturally associated with the development of the iron.

REFERENCES

1. MORROGH, H. and WILLIAMS, W. J. 1948. Jl. Iron and Steel Inst., Vol. *158*, p. 306.
2. GAGNEBIN, A. P., MILLIS, K. D. and PILLING, N. B. 1949. "The Iron Age", 17th Feb., Vol. *163*, p. 77.
3. BRAIDWOOD, W. W. and BUSBY, A. D. 1949. "The Nickel Bulletin", Vol. *22*, p. 126.
4. GRANT, J. W. 1950. Jl. of Research and Development, British Cast Iron Research Association, April, Vol. *3*, p. 333.
5. EAGAN, T. E. and JAMES, J. D. 1949. "The Iron Age", 15th Dec., Vol. *164*, p. 77.
6. GAGNEBIN, A. P., MILLIS, K. D. and PILLING, N. B. 1950. "Machine Design", January, Vol. *22*, p. 108.
7. EVEREST, A. B. 1950. Proc.Inst.British Foundrymen, Vol. *43*, p. A35.
8. KO, T. 1950. "Foundry Trade Journal", 20th April, Vol. *88*, p. 433.
9. CRESSWELL, R. A. 1945. Jl. Iron and Steel Inst., Vol. *152*, p. 157P.

Discussion

DR. A. B. EVEREST said that he had very great pleasure in opening the discussion on the paper by Mr. Hallett, who was one of the pioneers in cast iron metallurgy in this country, and in particular one of the pioneers in spheroidal graphite (or ductile) cast iron. He would not say a great deal about the subject matter of the paper except to compliment the author on the most clear and delightful way in which he had presented his subject. There were, however, one or two minor points to which he desired to draw attention. The author had referred to the question of wear and had quoted some comparative results on spheroidal graphite and ordinary flake graphite cast irons. The speaker wished to emphasize that these new cast irons could be made with many different matrix structures, and that the wear resistance would vary greatly from type to type. Some of the grades of spheroidal graphite cast iron were giving excellent resistance to dry wear, especially when it was possible to chill the wearing face. The example quoted by the author should not be taken in any way as indicating the general unsuitability of the new iron in service involving dry wear.

The author had quoted figures showing the properties of Ni-Resist with spheroidal graphite. Many of these properties were impressive, but since the date when the author had made his tests, a great deal more had been learned about this grade of iron, in particular on the influence of copper. When copper-free compositions of Ni-Resist were treated by the magnesium process, even better results could be attained and, in particular, a much higher ductility. Figures from commercial production showed that a tensile strength of 28 tons per sq. in. combined with an elongation of 15 per cent was easily achieved.

With regard to the uses of spheroidal graphite cast iron, it was well to recall that this new material was very young. Our knowledge of ordinary cast iron and its behaviour in service had been built up during the past 150 years, but this new iron was invented only three years ago so that it was still in the development stage. When questions relating to the behaviour of the iron under different conditions were asked as, for example, when its behaviour as a Diesel engine liner material was raised, the answer must of necessity be that data were being collected as fast as possible. There was no short cut to service data, quick laboratory tests often being, if anything, misleading and enquirers could only be asked to await

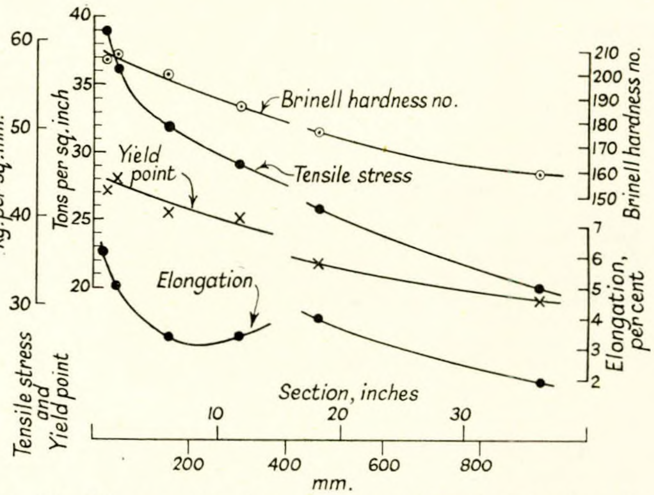


FIG. 10—*Diagram showing the properties of S.G. iron in sections up to 36 inch. The curves show respectively Brinell hardness, tensile strength, yield point and elongation*

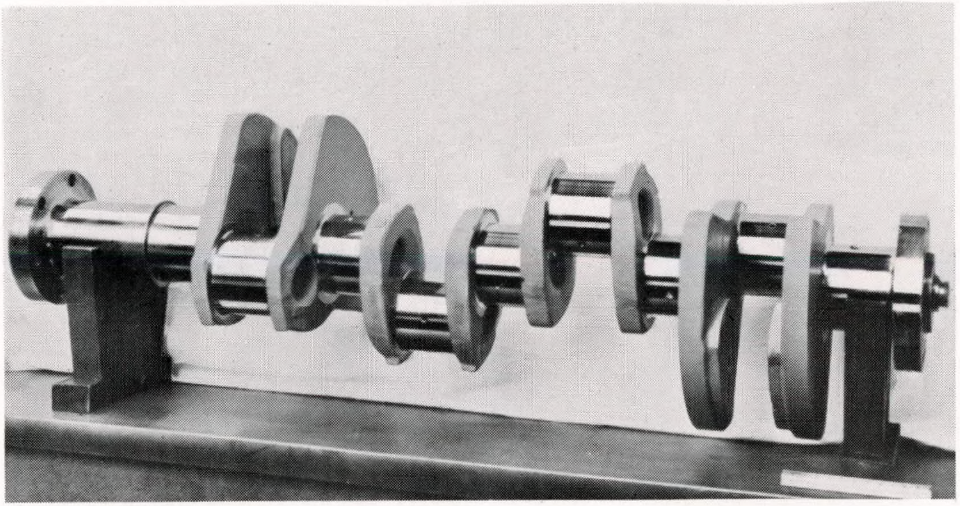


FIG. 11 (*above*)—*Four-throw crankshaft in S.G. iron—overall length 7ft. 1in., journal diameter $7\frac{1}{4}$-in.*
By courtesy of Cooper-Bessemer Corporation, Mount Vernon, Ohio, U.S.A.

FIG. 12 (*right*)—*5-ton flywheel in S.G. iron*
By courtesy of Escher Wyss A.G., Zurich, Switzerland

FIG. 13—*Part of oil burner in S.G. iron with casting heads attached*
By courtesy of Mario Pensotti, S.p.A., Milan, Italy

FIG. 14—*Centrifugally cast S.G. iron pipe, after bursting tests on welded sections*
By courtesy of Lynchburg Foundry Company, Lynchburg, Va., U.S.A.

undertake service tests for themselves.

Of special interest from the marine point of view was that in the new iron a material was available combining the corrosion resistance of ordinary cast iron, which was good, with mechanical properties approaching those of steel. In this connexion, a typical application of current interest was for heating coil pipes and fittings in oil tankers. One firm abroad had already equipped two or three ships with such fittings made in the new iron and high hopes were held for it, in that it would withstand the jerks and twistings of the ship in rough weather, whilst having the corrosion resistance of ordinary iron. In this application ordinary cast iron was too weak, and steel had a relatively short life, due to rapid corrosion, but with the new iron it was expected to obtain four or five times the life.

The speaker then showed some pictures of castings in the new iron; these were not necessarily all castings for marine service, but they were directly related to marine requirements. The pictures covered castings produced in all parts of the world, interest in the new iron being universal. The first slide, Fig. 10, showed a diagram indicating that the new iron was, if anything, less section sensitive than was ordinary cast iron, and that the new iron maintained its properties well, even to the largest sections. The diagram showed the properties obtained in varying sections up to 36 inches, and it would be noted that in all sections the properties were at least double those previously attainable in ordinary cast iron under similar conditions.

In connexion with engine castings, the author had quoted some figures in a paper presented to the International Internal Combustion Engine Congress* last May which indicated the possibilities of the new iron for crankshafts. Fig. 11, Plate 3, illustrated a crankshaft with 7¼-in. diameter journals in S.G. iron now on trial in the U.S.A. Shafts up to 12 feet long with 8 or 10 inch journals had now been made and were under test. It was too early to say just how these shafts were going to behave, but the preliminary indications were very good indeed, and important economies were envisaged by their adoption for crankshafts in place of conventional forgings.

Fig. 12, Plate 3, showed a 5-ton flywheel in the new iron where it could replace steel for intermediate loadings.

The author in his paper referred to propellers. The speaker did not feel happy about his reference to the annealing of these castings. There was clearly a practical difficulty in annealing large propellers and, further, the preliminary indications were that the as-cast condition was to be preferred to the annealed state from the point of view of resistance to cavitation erosion. It was likely that with suitable control over composition, propellers in the as-cast spheroidal graphite iron would give good strength and toughness at, of course, a fraction of the cost of ordinary bronze propellers.

In considering the new iron for castings for steam engineering to replace steel or other metals, the question of creep assumed importance. Considerable time was involved in determining the creep properties of any metal and unfortunately little data was yet available on which to base any recommendations as to how far the new iron could be used for superheated steam.

Another useful property of the iron was its heat resistance. In this connexion it was of value for furnace parts, tube supports and furnace doors and frames. It had already justified itself for many of these items and had a promising future in this type of service. Fig. 13, Plate 4, showed part of an oil burner—an application typical in this field.

For Diesel engine heads, the new iron had already proved itself much superior to ordinary iron where heat cracking was troublesome. The author referred to this in his paper and recent test records showed increased life and reliability for the spheroidal graphite iron as compared with the normal type.

* "Cast Iron Crankshafts, with special reference to Acicular and Spheroidal Graphite Cast Irons". A. B. Everest. Congrès International des Moteurs, Paris, May 1951, Groupe IV—1. See also "Foundry Trade Journal", 6th December 1951, pp. 643-650.

Other applications in which the new iron had proved itself included rotary compressor shells and even for connecting rods on reciprocating compressors. It presented interesting possibilities for pumps of all types, particularly in view of its success for pressure resisting castings. Already the new iron had been accepted by Lloyd's and associated authorities abroad for ships' side fittings.

Fig. 14, Plate 4, was of interest in showing test lengths of centrifugally cast S.G. iron pipe. As would be noted, some of the sections included welds illustrating the weldability of the iron. It should be particularly noted that after pressure test, failure had taken place at positions remote from the welds and, further, that the pipes had split, like steel, instead of shattering, like cast iron.

Other applications of interest in the marine field included parts for winches, hoists, dock fittings, such as bollards, etc., in many of these cases replacing steel.

In passing, it should be noted that in addition to its many other unique features, the new iron had shown a measure of forgeability. This was not put forward as of immediate significance in connexion with marine components, but was mentioned as further evidence of the extraordinary possibilities of the new iron.

Mr. S. Archer, M.Sc. (Member) said that the author had presented a most useful survey of the properties of this highly interesting material which had been hailed as one of the most revolutionary advances in ironfounding in our time, and marine engineers, usually chary of sudden innovations in the materials they were used to handling, should be quick to appreciate the potentialities of spheroidal graphite cast iron.

It was noted that only the magnesium-treated process was considered in the paper and its advantages were clearly portrayed. It was understood, however, that in the presence of certain metallic impurities which were not uncommon in cast irons there might be considerable difficulty in ensuring a spheroidal structure using the magnesium process, but that this difficulty did not apply to the British cerium-treated process. Could the author comment on this?

The most obviously desirable characteristic of spheroidal cast iron was, he thought, not so much its strength but rather its astonishing ability to withstand shock and deformation successfully. After all, there were plenty of good high strength alloy irons capable of achieving tensile strengths equal to that of the "as cast" spheroidal iron, but to be able to obtain elongations of 10-15 per cent even at the expense of a heat treatment process and still retain tensile strengths comparable with mild steel castings made this new material worthy of the closest examination by marine engineers.

The author had referred to the abandonment of ordinary cast iron in recent years in many marine applications on account of the dangers of underwater explosion. Obvious examples were Diesel engine bed-plates, entablatures and scavenge trunks and steam turbine stator casings. In regard to the latter the use of rigid/resilient mountings had been common practice in certain classes of war-time merchant ships under both fixed and sliding feet of the main turbines, and this, in the absence of adequate inspection and servicing, had been found to result in serious misalignment in one or two cases, leading to cracked gear cases and fractured claw-coupling teeth. The supporting of the fixed feet of turbines on other than solid chocks was fundamentally undesirable and it might well be that by careful design and the use of ductile cast iron adequate protection might be afforded to the turbines without the possible sacrifice of alignment. Other applications which came to mind were to ships' side fittings, sea connexions, etc., which were such a frequent source of trouble during the late war.

On the possible use of ductile cast iron for crankshafts, although lighter scantlings could be achieved in the "as cast" condition, the advantages of higher ductility and impact resistance weighed largely in favour of the "annealed" material even though the wear resistance would be reduced and despite the reduction in bending fatigue strength from about ±17 t.s.i.

to about ±13 t.s.i. While there was some merit in increased stiffness for crankshafts of given dimensions, it must not be forgotten that the 50 per cent higher modulus of elasticity of spheroidal cast iron as compared with ordinary cast iron would entail correspondingly higher bending fatigue stresses due to misalignment arising from unequal wear-down of main bearings. However, it was probable that the higher fatigue strength of the new material would more than take care of this factor despite its higher notch sensitivity.

To facilitate torsional vibration frequency calculations, it would be useful if the author could state the value of the modulus of rigidity, G, for spheroidal graphite cast iron.

It was rather a pity that no direct experimental evidence on the resistance of spheroidal cast iron to thermal shock was yet available since doubtless many Diesel engine designers would welcome this material as a "heaven-sent" solution to the problems of cracked piston heads and cylinder covers and the possible benefits would, in time, be passed on to harassed superintendent engineers and surveyors as an easement of their daily load. Since time was necessary before service results could be assessed, might it not be possible to devise a test method which would simulate actual cylinder conditions but under greatly accelerated rates of application of the thermal shock?

Could the author give an estimate of what would be the highest temperature at which spheroidal cast iron was likely to be used successfully under conditions of high pressure and superheat, that is, before it would be necessary to go to cast steel?

On the subject of cavitation erosion in cast iron propellers, experimental evidence to date would seem to suggest that spheroidal cast iron might prove beneficial mainly by enabling lighter blade sections to be used, thus avoiding cavitation itself, and incidentally, of course, carrying with it the premium of higher efficiency.

Finally, could the author give an estimate of the comparative present-day costs of an identical casting of sizeable dimensions in cast steel and in spheroidal cast iron?

MR. R. N. RICHARDSON (Member) considered that this interesting paper had painted rather too rosy a picture. He was well aware that this new material was only three years old, and, of course, the author could not be expected to deal with all the multitudinous aspects of it. He himself had no personal practical knowledge of nodular iron, but he was very much interested in the subject and he would like to ask the author—if it was a fair question (it might be a pretty one)—why was nodular iron made nodular? A percentage of magnesium or cerium was added to grey cast iron. We would like to know why that resulted in nodularity.

His second point had been made already by a previous speaker. Was there any particular reason why the author had limited his remarks to the magnesium process and had not included the cerium? He was told—he did not know whether it was true or not—that the magnesium process worked nine times out of ten, or it might be ninety-nine times out of a hundred, but the tenth time or the hundredth time it did not work, and nobody so far knew why. He would like to know whether that was true.

Furthermore, he was advised that there were advantages to be gained by using a combination of the two processes. Would the author comment on that point? Some figures were given for the fatigue limit in the two conditions. Could they have the equivalent corrosion fatigue limit, by which he meant the figures obtained in salt water or salt spray?

One was often told—and personally he had never known how much authority was behind it—that there was a virtue in maintaining the original skin of grey cast iron. He would like to know whether that was true and whether there was any particular virtue in maintaining the original cast skin of nodular iron.

The previous speaker had referred to deformation on annealing. It had also been mentioned that superior properties could be obtained by quenching and tempering. He imagined that the deformation resulting would be pretty serious, but he would like some further information on that point.

Finally, the author had referred to cavitation erosion resistance and its relationship to the tensile strength of a material. He thought he had stated that cavitation erosion varied directly with tensile strength. In his own view that was not correct, or not always or necessarily correct. Perhaps the author would enlarge on the subject.

MR. A. F. EVANS (Member) asked whether spheroidal graphite cast iron was, in the opinion of the author, likely to find a large place in crankshafts and in general engine structures.

MAJOR GENERAL A. E. DAVIDSON, C.B., D.S.O. (Member) asked about the machining properties of the new material. Could it be machined at a higher cutting speed without detriment to the surface condition?

Correspondence

MR. E. V. MATHIAS considered that the author of the paper had given an excellent review of the properties of spheroidal cast iron and had presented a very clear picture of the advantages of this new material over those of normal grey cast iron. When one studied the figures that had been presented it was evident that they had a readily cast material of great promise.

A matter which perhaps called for some comment was the author's suggestion that the use of the term "ductile cast iron" should be restricted to material in the annealed condition. This distinction between the "as cast" and annealed irons had been followed in the text, but it would be noted that the title of the paper which dealt with both these types was "Ductile Cast Iron". In keeping with the author's proposal, a more appropriate title would have been "Spheroidal Cast Iron", but the author had wisely avoided the use of such a cumbersome expression. One wondered, therefore, whether the simpler expression would in fact suffice for both these irons. The term "ductile" was, of course, not strictly true for the "as cast" iron, but when standard specifications were drawn up for these irons it should be possible to solve the difficulty by grading, as was now done for grey iron castings to B.S. 1452. Until such time as a suitable British Standard became available, however, it would be appreciated if the author could give some guidance to materials engineers who might wish to specify either or both of these spheroidal irons. At present, if pearlitic iron were required for wear resistance it would be necessary, presumably, to specify "as cast spheroidal cast iron".

One very important point which the author had discussed was the effect of section thickness. While the strength level, in common with other cast irons, would be expected to fall with increasing thickness, it was gratifying to note that satisfactory values had been obtained on section thicknesses of about 8 inches. In this connexion, however, it would be interesting to know whether in the author's opinion any change in the spheroidal shape of the graphite would be expected in practice with the very slow rates of cooling which might be encountered in large castings.

A matter which naturally arose out of the paper was the possibility of making practical use of the appreciable ductility of the annealed iron. When required, it should be possible to deform or bend the material either in the cold or the hot condition. If this could be done readily, for example in pipe alignment, it would be a very real advantage in shipbuilding. The author's views on this aspect would be appreciated.

With regard to the wear resistance of spheroidal cast iron it was probable that, other factors being constant, a difference in graphite form was of less importance than the total area of the graphite exposed. In the case of the Anglo-Saxon Petroleum Company's tanker m.s. *Auricula,* the favourable results obtained so far were given in the paper. These trials were still proceeding and it would be interesting to see in due course whether the good behaviour of the spheroidal iron rings was maintained. It was suggested that the results obtained might be due partly to the greater hardness of the spheroidal iron compared with that of the normal grey iron, and it would be useful to have the author's comments on this point.

A brief statement regarding present day costs would add to the value of the discussion. For a fair comparison, costs should be based on castings of equal strength and not equal size or weight, since it would be obvious that, within limits, a definite weight saving might be effected by the use of a higher strength iron. Perhaps the author would be able to give some idea of the relative costs of the various irons available today compared with that of, say, cast carbon steel.

Finally, in connexion with the possibility of effecting weight reduction through the use of the higher strength irons, it would also be helpful to designers if some information could be given on the maximum thickness which would be practicable for, say, 3-in. bore pipes, either in the form of sand or centrifugal castings.

PROFESSOR J. A. POPE, Ph.D., commented that the production of spheroidal graphite cast iron had virtually given the engineer a new material and Mr. Hallett's survey of its properties was most timely.

There seemed little doubt in his mind that this nodular iron derived its strength, and to some extent its ductility, from the fact that the stress concentration due to the spheroidal graphite flakes was much less than those produced by the long sharp ended flakes of normal cast iron. This was revealed by the value of the apparent Young's Modulus for the various cast irons. When a stress was applied to a grey cast iron, say, then the stress concentrations at the ends of the graphite flakes caused deformations in excess of those obtainable in a notch free steel. Thus, roughly speaking, the amount the Young's Modulus was less than 30×10^6lb. per sq. in. was an indication of the stress concentrations existing in the iron. For example, Young's Modulus for grey cast iron was 16×10^6lb. per sq. in. and for nodular iron 24×10^6lb. per sq. in.

It was interesting to note that no neck was formed during the tensile test of annealed ductile cast iron. Seeing that the structure of this iron was mainly ferrite, at first sight, one would have expected "necking" similar to that which occurred in a tensile test on mild steel. Necking was produced when the rate of work hardening was less than the rate of reduction in cross-sectional area due to the longitudinal extension. The fact that this did not occur would suggest that fracture due to stress concentration at, and crack propagation from, the spheroidal graphite took place before the surrounding ferrite was fully work hardened. If this were the case, then spheroidal cast iron would be very susceptible to brittle fracture produced by either triaxial stress or low temperature. Some experiments on this metal at low temperature would be most interesting.

This new iron, which was really half-way between a cast iron and a mild steel, might have some new form of criterion of failure under compound stress. For normal grey cast iron the criterion of failure was taken as the maximum principal tensile stress and for mild steel the maximum shear stress. As spheroidal cast iron in the annealed condition was mainly ferrite, one would anticipate that, to a first approximation, the maximum shear stress criterion held. More experimental evidence was wanted on this point. In this respect it was unfortunate that on the curve shown in Fig. 6, the load on the machine had been plotted as the axis instead of the applied torque. As the curve stood, the dimensions of the testing machine, as well as those of the specimen, were required before any calculations could be made from this diagram. Mr. Hallett, however, gave the tensile yield stress as 27 tons per sq. in. and the compressive yield stress (on a different batch of material) as 29 tons per sq. in. If the maximum shear stress were the criterion, these two yield strengths should be equal. A knowledge of the yield strength in torsion would be valuable.

With regard to the use of nodular cast irons for crankshafts, it should be remembered that a crankshaft was a component in which the damaging stresses might be produced by vibrational forces rather than by the applied load. For this reason, a material having good damping capacity could be as beneficial as one having high mechanical properties. One would expect the damping capacity for nodular cast iron to be much less than that for grey cast iron. He wondered whether Mr. Hallett had any information on this point.

In this contribution to the discussion, Professor Pope had endeavoured to outline where he considered more information to be required before nodular cast iron could be used with confidence. It might be that Mr. Hallett would be able to supply this information when replying to the discussion. A considerable amount of research was being carried out at Nottingham University on the mechanical properties of cast iron and he would be glad, if required, to co-operate in further investigations into the properties of nodular iron.

MR. G. M. SMIBERT was particularly interested in the paper because of a discussion he had had two years ago with the author when it was decided to put in hand a nodular iron piston for a large two-stroke Diesel engine. This piston had been in service for several months; there had been no adverse reports so far but it was too early for reliable performance data to have been obtained and, in particular, its resistance to wear, scaling and oxidation which, of course, could not be expected to be as good as that of a 13 per cent chromium piston crown, for instance. It was confidently expected that this nodular iron piston would supersede the more costly type where a special steel crown was screwed or bolted to the ordinary cast iron ring carrying skirt.

The piston as fitted was in the "as cast" condition with a tensile strength a little lower than that of a special steel crown; it was hoped that in this condition it would have a high wear resistance and thereby retain the ring groove dimensions.

In view of the experiments on m.v. *Auricula* with nodular iron piston rings, it would be interesting to have the author's comments on the possibility of using this type of ring on a nodular iron piston.

Author's Reply

MR. HALLETT, replying, said that in his very interesting and useful introduction to the discussion, Dr. Everest referred to one or two points which gave him the opportunity of making some further remarks. He would agree that any problem of wear resistance could be settled only by direct test under operating conditions, though this would take a long time. It was very difficult to predict wear resistance from first principles, and he was not at all surprised that there were some discrepancies in the reported tests.

In this connexion, all the results set out in the paper were carried out on iron with a total carbon content of about 3·2 per cent, but tests carried out, for example, with a higher carbon iron, say 3·6 per cent, giving correspondingly more graphite, might present entirely different results and that would explain some of the discrepancy.

The annealing of propellers obviously presented difficulties and could be applied only to relatively small cases. Actually, in the casting of fairly large propellers it was quite probable that a certain amount of ductility would be developed in the casting without any heat treatment at all, and a moderately small amount of ductility might be quite adequate to give the sort of shock resistance needed. He agreed that it was unlikely that annealing would be, or need be, applied to large propellers.

Mr. Archer had raised a number of interesting points, starting with a reference to cerium. The cerium process, unfortunately, suffered from serious limitations and could be applied only to iron which was high in carbon, high in silicon and very low in sulphur; that combination could not be achieved by ordinary cupola melting as operated in the average foundry. Therefore one was thrown back on special methods, so that the cerium process could not be applied nearly as widely as the magnesium process. That was one of the basic reasons for the choice of the magnesium process. The other was that the magnesium process itself was a much better one, giving better mechanical properties. It was true that certain metallic elements, present in small amounts, could interfere with the magnesium process. Much more was being learned about the reasons behind these interferences, and as time went on methods would undoubtedly be evolved for overcoming the effects and the process would be applicable to wider ranges of pig iron than it was at the moment. This country seemed to be in a less fortunate position from the point of view of pig iron supplies than almost any other country in the world.

As for the use of annealed material for crankshafts, he believed that it would generally be better not to use the fully annealed material. He did not really see why a considerable shock resistance was wanted in a crankshaft. What was needed was the ability to accommodate itself to slight misalignment, but it would be generally true to say that, coupled with a moderate degree of ductility, fatigue strength and wear resistance were two more important factors.

A recent determination of the shear modulus of elasticity had been quoted by Majors* as $9{\cdot}5 \times 10^6$lb. per sq. in. as determined on annealed ductile cast iron treated by the magnesium process.

The question of thermal shock resistance had been raised. Much metallurgical attention had been paid to devising a good test for thermal shock resistance, but he would not like to say that anybody had as yet evolved a thermal shock resistance test which classified the older heat resisting materials in the right order, let alone the new material. Service tests had to be performed. Research work was being organized at one of the universities on this very question, and one of the materials which was being tested was spheroidal graphite cast iron.

The question of the highest temperature of application opened up a series of problems. If it were purely a question of creep it was necessary to await the results of creep tests, and there was no published information on this point concerning spheroidal graphite cast iron at the moment. Ordinary cast iron was satisfactory from the creep point of view up to a temperature of about 400 deg. C., above which it deteriorated rapidly. It was reasonable to guess that spheroidal graphite cast iron would raise that ceiling temperature, but to what extent was not known. If it were a question of oxidation resistance the picture was a little clearer, though there again the data were not very extensive. The scaling resistance of spheroidal graphite cast iron was at least as good as that of ordinary cast iron alloyed with 1 per cent of chromium, and there were indications that it was better than that. Therefore, from the oxidation point of view he thought the ceiling could be placed at something of the order of 600 or 700 deg. C., though this would depend on the amount of scaling which could be tolerated in a given application.

As to relative costs, no very clear answer could be given. If the casting were relatively complicated, then the good founding properties of spheroidal graphite cast iron in relation to steel became of predominant importance. The actual raw material costs—the costs of the metal at the furnace—were if anything in favour of steel, so that the more complicated the casting the more one was likely to turn to spheroidal graphite iron rather than steel.

Mr. Richardson complained that he had painted too rosy a picture, but had not indicated in what way this was so. The paper was intended to be entirely factual, and he had left his audience to draw their own conclusions. In spite of an enormous amount of research all over the world there were many points in doubt on the mechanism of the process. Of the essential conditions, the most important was the virtual elimination of sulphur from the iron. Ordinary cast iron contained about 0·1 per cent of sulphur, and the first function of cerium or magnesium was to reduce that sulphur down to something of the order of 0·01 per cent. What happened after that was in doubt.

On the question of reliability of the magnesium process, if one were working on a known source of pig iron the results were likely to be completely satisfactory in all cases, but if some unknown factors were introduced in the pig iron poor results might be forthcoming. The knowledge in this field had improved very much in the last year, and it was now generally possible to say why there had been a particular failure. He agreed that it was by no means impossible to have a combination of cerium and magnesium, and investigations were actively in progress along that line at the moment.

On corrosion fatigue he had no data whatever, but in judg-

* Amer.Soc.Mech.E. 1951. Preprint 51—F-5.

ing the relative merits of ductile cast iron and of propeller bronze it was reasonable to suppose that ductile cast iron under ordinary fatigue conditions was probably superior, but under conditions where corrosion played the predominant part propeller bronze would be the better.

The value of the cast iron skin was questionable. In certain cases a grey cast iron might give a somewhat better corrosion resistance on the skin than on the machined surface, but he felt that it was unsafe to rely on a fortuitous factor like the casting skin. In the case of spheroidal graphite cast iron he would not like to say that the casting skin was beneficial, and he believed it was generally better to have a machined surface.

On the question of quenching and tempering he had no fears at all. He did not think the material would distort in quenching any more than would high carbon steel.

With regard to cavitation resistance and its relation to tensile strength, he had tried to be very careful in his remarks. Beeching's* results had suggested that in a series of similar alloys there was a rough relationship between tensile strength and resistance to cavitation erosion. Considering the two materials, grey cast iron and spheroidal graphite cast iron, it was merely suggested that in view of the higher tensile strength of the latter, it would be worth testing. The conclusion had been borne out to some extent by laboratory experiment, but not yet finally proved.

Mr. Evans had referred to crankshafts and general engine structures. The crankshaft design had to be considered carefully and one had to recognize that a design suitable for a heat-treated steel with a tensile strength of 60 tons per sq. in. might not necessarily be suitable for spheroidal graphite iron with 40 tons per sq. in. tensile strength. He would say, answering the question in general terms, that spheroidal graphite cast iron would certainly find a big place in the field of general engine structures, including crankshafts.

General Davidson had raised an interesting point on machining properties. Most of the papers which had been published on this subject came from America; he thought they were quite reliable. The higher tensile strength of the material meant that more power was required to cut at a given speed, but the wear on tools, and the rate of cutting on the "as cast" material were unaffected. With annealed material more power was still needed, but the cutting speed and tool wear were considerably better than when machining ordinary cast iron.

The author was grateful to Mr. Mathias for his remarks and agreed that there was no really satisfactory short title for the new iron. The term "spheroidal cast iron" was inaccurate since, of course, it was the graphite in the iron which was spheroidal, and not the iron itself. One reasonably convenient abbreviation was to refer to the new material as "S.G. cast iron", "S.G." indicating spheroidal graphite.

In the author's experience the shape of the spheroids did not alter very much in castings ranging from ½ inch to 4 inch in thickness but there was a steady increase in the size of the spheroids over that range.

It was certainly possible to make use of the ductility of the annealed material and pipe alignment should be perfectly practicable. One case could be quoted of some thick walled pipe of rather small outside diameter (about 1 inch) and narrow bore, which required to be bent around a slight angle. It was difficult to cast this in the required curve and the solution was to cast solid rod which was then bored out in a straight line and bent hot to the final shape. No trouble was experienced.

The importance of graphite quantity had been referred to in the reply to Dr. Everest. The only point remaining to be proved was whether the greater areas of metal relatively remote from the graphite in spheroidal graphite iron could be lubricated by the graphite as effectively as the metal areas in a flake graphite iron, which were generally much closer to the graphite, even though the exposed area of graphite was the same in the two irons under comparison. There was no doubt that the greater hardness of the new material was beneficial in promoting wear resistance.

Some reference to cost had been made in the reply to Mr. Archer. As already stated, it was necessary to balance the raw material costs against the ease of founding. The author would prefer not to comment on the thickness of pipe walls until he had had more experience in this particular field. He believed that Mr. Mathias was referring to minimum thickness rather than to maximum. This would depend to some extent on the length of the pipe, but he did not hold out much hope of casting appreciable lengths in thicknesses of much less than ⅜ inch.

The contribution of Professor Pope was welcomed. His views on the relationship between stress concentrations at the end of graphite flakes and the occurrence of necking in the ductile material were most interesting and suggestive. More information on the specialized properties of nodular cast iron were given in the paper by Majors referred to in the reply to Mr. Archer. This worker suggested that the damping capacity of nodular cast iron was even less than that of annealed mild steel. Other workers from the British Cast Iron Research Association had tended to place nodular cast iron between cast iron and steel. It was very satisfactory to hear of the large programme of work proceeding at Nottingham University and the author looked forward to co-operation with Professor Pope in that direction.

In reply to Mr. Smibert, the author was very glad to have the latest information on the promising performance of the nodular iron piston. All marine engineers would follow this experiment with great interest. It was felt that there should be no difficulty in using nodular iron rings with a nodular iron piston, and no doubt experiments with nodular cylinder liners as well would have to be undertaken eventually.

* Trans.I.E.S. in S. 1942. Vol. 85, p. 210.

INSTITUTE ACTIVITIES

Minutes of Proceedings of the Ordinary Meeting held at the Institute on Tuesday, 11th December 1951

An ordinary meeting was held at the Institute on Tuesday, 11th December 1951, at 5.30 p.m. Mr. J. Turnbull, O.B.E. (Chairman of Council), was in the Chair. A paper by Mr. M. M. Hallett, M.Sc., F.I.M. (Member), entitled "Ductile Cast Iron", was read and discussed. Thirty-seven members and visitors were present and five speakers took part in the discussion.

A vote of thanks to the author was proposed by Mr. C. P. Harrison (Member of Council) and enthusiastically accorded. The meeting ended at 7.10 p.m.

Award of Honorary Membership to Mr. B. C. Curling

By a Council decision taken at their meeting on 12th November 1951, Mr. B. C. Curling has been elected to Honorary Membership of the Institute. By adding Mr. Curling's name to the short list of those who have been selected in the past to receive this honour, the Council wish to establish, on his retirement, their special recognition of his outstanding services to the Institute during the last thirty years and particularly since he succeeded to the Secretaryship in 1930.

The certificate of Honorary Membership will be presented to Mr. Curling by the President at the Annual Dinner to be held at Grosvenor House on Friday, 14th March 1952.

Local Sections

Cardiff

A junior lecture entitled "Marine Diesel Engines" was given at the Cardiff Technical College on Thursday, 24th January 1952. The author, Mr. C. C. Pounder (Member), was unable to be present and his paper was ably read by Mr. J. E. Church (Member of Council). Dr. A. Harvey, principal of the college, presided at the meeting, which was attended by 140 members and visitors.

Swansea

A lecture, "Petroleum Refining", was given by Dr. E. J. Boorman at the Central Library, Swansea, on Wednesday, 12th December 1951, to an appreciative audience of fifty-two members and friends of the Swansea District and Local Section of the Institute. Mr. A. R. Edmiston (Member) was in the Chair.

Briefly summarized, Dr. Boorman's lecture was as follows: "Crude petroleum was useless as it came from the ground and the group of processes which were used to convert it into motor spirit, kerosene, fuel oils, lubricants, asphalt, synthetic chemicals, etc., was called 'refining'. The numerous hydrocarbon molecules in oil were first separated into groups corresponding to the final products by distillation through the fractionating tower of a pipe still. This repeated intermingling of vapours and condensed liquid resulted in the production of the necessary fractions, which were afterwards given a final purification before being pumped to storage.

As the demand for motor spirit exceeded the supply from that naturally present in crude oil, the less volatile fractions were converted into more and better motor spirit by high temperature treatment called cracking. The most modern fluid catalytic cracking processes now produced a large proportion of today's petrol.

Still heavier fractions were treated, purified and blended to produce the large range of modern and specialized lubricating oils which industry required. Additional products like grease, paraffin wax and bitumen were also derived from oil. By-product gases were converted into chemicals, synthetic rubber, plastics, fibres and numerous other materials. The continued development of all these products was maintained by extensive research".

Each step of the lecture was well illustrated by a film strip and the audience was given an insight into the complicated processes and plant used in the refining of crude petroleum. Afterwards, Dr. Boorman showed a film entitled "Fawley", which depicted the construction of the large oil refinery near Southampton and which conveyed to the audience the magnitude of such an undertaking.

Question time brought forth a variety of enquiries ranging from types of fuels used in jet engines to the possibility of producing non-inflammable lubricating oils.

Having expressed his personal appreciation of Dr. Boorman's lecture, the Chairman called upon Mr. R. Shaw (Member) to propose a vote of thanks to the author, which was ably seconded by Mr. R. E. Knowles (Member) and heartily endorsed by all present.

Junior Section

85, The Minories, London, E.C.3

On Thursday, 3rd January 1952, at 7 p.m., the Junior Section held a meeting at the Institute to discuss "The Education and Training of the Marine Engineer Apprentice". Mr. F. D. Clark (Associate Member of Council) was in the Chair and forty-two members and visitors were present.

A panel had been formed, representing various marine engineering interests, and consisting of Messrs. C. M. Brain, J. Calderwood, M.Sc. (Vice-President), F. S. Gander, S. Hogg (Member of Council) and A. Logan. Mr. Logan opened the discussion with a stimulating address and was followed by fourteen speakers from the floor, whose questions and comments were answered, in a lively interchange of ideas, by the members of the panel. The meeting ended at 9 p.m. Mr. Logan's opening remarks and the first instalment of a report of the discussion appear on pages 2 to 4 of the Supplement to this issue.

College of Technology, Liverpool

A meeting was held at the College of Technology, Liverpool, on Thursday, 17th January 1952, when Com'r(E) J. I. T. Green, R.N. (Member) read his paper on the development of "Modern Naval Boilers". Dr. R. H. Grundy, head of the mechanical engineering department of the college, was in the Chair and was supported on the platform by Mr. L. Baker, D.S.C. (Member of Council).

About thirty-three student members and visitors were present and their appreciation of Commander Green's lecture became evident in the very lively discussion which followed and in which a considerable number took part.

Sunderland Technical College

A lecture was delivered on Thursday, 24th January 1952,

The late Sir Amos Lowrey Ayre, K.B.E., D.Sc.

SIR AMOS LOWREY AYRE, K.B.E., D.Sc.

An appreciation by Dr. S. F. Dorey, C.B.E., F.R.S. (President).

With the sudden death of Sir Amos Ayre, our British shipbuilding industry has undoubtedly lost an outstanding figure. Unfortunately also, his loss comes at a time when the industry is called upon to contribute so much to the life of the nation and can ill spare one of its leaders.

Sir Amos had a notable career and made his mark right from the days of his apprenticeship. To his high technical ability he brought unusual enterprise and the quality of courage. The success and reputation today of the Burntisland Shipbuilding Company, which he founded with his brother in 1918, are in no small way due to his exceptional qualities.

We, who are connected with shipbuilding and engineering, will gratefully remember his splendid record of public service, in which he never spared himself.

As a young man he first came to notice in the 1914/18 war, when he became Admiralty District Director of Shipbuilding in Scotland. Between the wars he rapidly rose to the fore, and among the important posts he filled were President of the Shipbuilding Employers' Federation, in the difficult days of the depression in trade, and the first Chairman of the Shipbuilding Conference when it was formed in 1936.

His brilliant work during the last war readily comes to mind. On the outbreak he was appointed Director of Merchant Shipbuilding and Repairs in the Ministry of Shipping and later, when the Admiralty took control, became successively Director of Merchant Shipbuilding and Deputy Controller of Merchant Shipbuilding and Repairs. There is no doubt that he made an outstanding contribution to the magnificent part played in the war effort by British shipbuilding.

After the war he resumed his work with the Shipbuilding Conference and again used his great ability and drive for the improvement of the industry.

Sir Amos did much for the technical societies and we in the Institute of Marine Engineers are proud to record that he was our President for two years, 1946 and 1947, a fact which, in itself, testifies to the great respect we had for him.

We recall the very able address which he gave to us at each election; his masterly survey of the history of marine engineering; his broad, confident outlook on the future of marine propulsion, and his stimulating advice to all our members.

Our Institute will also always be grateful to him for his efforts in connexion with our National War Memorial Building Fund.

Sir Amos was undoubtedly a great leader and yet, with all his ability and talents, he kept the common touch. He was a very human personality and we, who knew him well, will always remember him with affection.

S. F. D.

at the Sunderland Technical College by Mr. R. R. Strachan (Member), the subject being "Refrigeration at Sea". A crowded audience was presided over by Mr. D. A. Wrangham, M.Sc., the Principal of the College, and the Institute was represented by Mr. W. H. Fraser, the Local Vice-President.

The lecturer dealt with the growth of the carriage of frozen cargoes from the earliest stages until the present time and, with numerous lantern slides, illustrated the modern layout of the larger installations. Afterwards, members of the interested audience put many questions to Mr. Strachan, showing the critical manner in which they had followed the lecture.

A vote of thanks to the lecturer was proposed by Mr. W. L. Bryde, head of the mechanical and civil engineering department.

Membership Elections

Elected 11th January 1952

MEMBERS

William Henry Arnold, Com'r(E), R.N.
James Barford
Marcel Charles Jourdain
Archibald Conrad Fyfe Porteous
Pero v. Sakic
Edwin Francis Stopford
John Douglas Whineray
Robert Douglas Yuill

ASSOCIATE MEMBERS

John William Allen
Hugh Clare Gibson

ASSOCIATES

David Ashley Anderson
Sydney Duthie Anderson
Benedict Patrick Bulley
David Wilson Chalmers
James Gallagher
Arthur Kingsley Guest
George Michael Gywnn Jones
Peter James Nickels
Robert Harvey Scott
Ian Henderson Stewart
Harry Arthur Triggs
John Alan Watt
William Arnold Winter

STUDENTS

Cornelious Elliot
Henry Lyth

TRANSFER FROM ASSOCIATE MEMBER TO MEMBER

John Duncan

TRANSFER FROM ASSOCIATE TO MEMBER

Robert Joseph Brooks Keig, M.A.
Henry Carmichael McCormick
George Arthur Maddick
James Colston Robey

OBITUARY

JAMES ALEXANDER CAVELL (Member 9731) served an apprenticeship from 1931-36 with R. H. White and Company, Wellington, New Zealand; from 1936 he served at sea with various companies as junior to chief engineer and obtained a First Class M.o.T. Certificate with motor endorsement. He gained experience in refrigeration work with J. and E. Hall, Ltd., at Dartford, and was engaged for a time with Foster Wheeler, Ltd. In 1946 he returned to New Zealand as building services inspector to the Ministry of Works at Christchurch; early in 1951 he resigned from the department to take an appointment with the Palmerston North Hospital Board but died shortly afterwards, on 27th February. Mr. Cavell was elected an Associate of the Institute in 1943 and transferred to full Membership in 1948.

JAMES HENRY HARGREAVES (Member) was apprenticed to Dunlop, Bell and Company, Liverpool, from 1914-20. From 1920-28 he served as 8th to 2nd engineer with the Blue Funnel Line and obtained a First Class M.o.T. Certificate in 1925. From 1928-32 he was 2nd engineer with the British and Continental Steamship Company. Then he left the sea and was engaged as assistant engineer with the Majestic Spinning Company, Oldham, from 1932-37. From 1937-39 he was engineer with the Westwood Park Institution, Oldham, and in 1939 he was appointed resident engineer at the County Hospital, Farnborough, where he remained until his death. Mr. Hargreaves was killed in a road accident on 22nd January 1952. He had been a Member of the Institute since 1946.

JAMES MACDONALD (Member 1932) was apprenticed to James and George Thomson of Clydebank; he joined the British India Steam Navigation Company in 1889 as 4th engineer, obtained a First Class B.o.T. Certificate, and was promoted chief engineer in 1899. In 1912 he was appointed to the s.s. *Mombassa* and was still serving in her as chief engineer when she was torpedoed in October 1916. Mr. MacDonald left the sea at this time and lived in retirement in London until his death on 11th November 1951. He was elected a Member of the Institute in 1907.

JOHN HENRY MARTIN (Associate Member 4919) was educated at Daniel Stewart's College, Edinburgh, and served the first few months of his apprenticeship there with Brown Brothers and Co., Ltd., and then four years with John Lewis and Sons in Aberdeen. He finished his initial training at a very bad period during the slump in the 'twenties and could neither obtain employment at sea nor in the shipbuilding yards in Aberdeen. He therefore started his own business as an electrical and radio engineer in a very small way until he was able to go to sea in 1928; from that time onwards he was seagoing, serving with various companies. He obtained a First Class B.o.T. Certificate in 1938. In 1944 he was chief engineer of the s.s. *Empire Bunting,* one of the ships chosen to be partly submerged off the coast of Normandy to assist in the erection of mulberry harbours for the D-day landings. Mr. Martin left home on the 15th October 1951, apparently in the best of health, to join the s.s. *Flyingdale,* owned by Headlam and Sons, as chief engineer; he died suddenly on 26th October on the way to Buenos Aires. He was elected a Student Graduate of the Institute in 1923 and was transferred to Associate Membership in 1933.

REAR ADMIRAL(E) THOMAS HAROLD SIMPSON (Member) was born in 1896. He attended the Royal Naval Engineering College, Keyham, from 1919-20 and the Royal Naval College, Greenwich, from 1920-22. From 1922-24 he was senior engineer in H.M.S. *Southampton* and then until 1928 he served on the staff of the Engineer-in-Chief at the Admiralty. He was senior engineer in H.M.S. *Rodney* until 1929 and then, for two years, lecturer on applied mechanics and machine design at the R.N. College, Greenwich. In 1931-32, 1934-37 and 1941-44, he served further periods at the Admiralty and as Commander(E) in H.M.S. *Sussex* from 1932-34 and 1937-39. He was officer in charge of the Admiralty Fuel Experimental Station from 1939-41 and engineer officer of the British Pacific Fleet from 1944-46. In 1948, after serving for two years as Rear Admiral(E) in Scotland and Northern Ireland, he retired from the Royal Navy. From 1948, until his death on 5th January 1952 in a road accident, Admiral Simpson was engaged as the senior combustion engineer for the Anglo-Iranian Oil Co., Ltd. He was elected a Member of the Institute in 1949 and was also a Member of the Institution of Mechanical Engineers.

JOHN YOUNGER (Member 2492) served an apprenticeship with A. Reid and Company, Dunfermline, from 1893-98 and worked from then until August 1900 with the Fairfield Shipbuilding and Engineering Co., Ltd., Glasgow. In 1901 he joined the British India Steam Navigation Company as a junior engineer and, except for two brief intervals (with John Brown and Co., Ltd., Glasgow, from 1907-08 and with Alexander Stephen and Sons, Ltd., from 1908-09) he remained in the company until his retirement. He was promoted chief engineer in 1916 and acting superintendent engineer in the same year; in 1926 he was sent to Bombay as assistant superintendent engineer and was promoted superintendent engineer in 1932. He retired from the company on pension in 1939 but for the whole period of the last war he served as an inspecting officer of the Ministry of Fuel and Power and in 1942 he was appointed a member of the London Regional Fuel Efficiency Committee. Mr. Younger gave valuable service to the Institute as Vice-President for Bombay from 1930-37; he was elected a Member in 1911.