Corrosion-Resistant Materials

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The authors discuss the various forms of corrosion to which metallic materials are subjected, and give a brief survey of the main corrosives which are encountered as well as the effect of other influences such as chemical composition, surface condition and physical properties. They also deal with the general corrosive behaviour at both room and elevated temperatures of both non-ferrous and ferrous materials and brief details are given of the principal physical properties of these metals and alloys. Opportunity is also taken in this latter section of the paper of drawing attention to special properties of these materials with a view to aiding the marine engineer in selecting the most appropriate material for some of the particular service problems he encounters.

I—INTRODUCTION

Corrosion, the destruction of metals by chemical or electro-chemical agencies, and erosion, destruction by mechanical agencies, remain the principal causes of maintenance costs in marine engineering installations. Consequently much work has been done and information published concerning individual problems such as arise in steam valves, condensers and other equipment particularly subject to the adverse effects of these agencies. However, some considerable time has elapsed since an attempt was made to collect useful information on the application of corrosion-resisting materials in marine engineering and present it in a compact form which will be of use to builders and users of marine engineering equipment. It is hoped that this purpose will be served by the present paper.

The paper is divided into three main sections. The first section is a brief introduction to the theoretical aspects of corrosion; the second describes the corrosive media normally encountered in marine engineering; the third, the general corrosion-resisting properties of the metals and alloys commonly used in these applications. A bibliography has also been prepared which it is hoped will prove useful to any person interested in obtaining more detailed information on any particular aspect than can be included in the body of a general paper of this type.

II—THEORETICAL ASPECTS OF CORROSION[1, 2]

A. Forms of Corrosion

There are two principal forms of corrosive attack:—

    (i) direct chemical attack
    (ii) electro-chemical attack

and all particular corrosion phenomena such as pitting, dezincification, high temperature oxidation, sulphidation, etc., are the result of either or both of these forms. Practically all "wet" corrosion and in many cases even "dry" corrosion are electro-chemical in character.

(i) *Direct Chemical Attack.* Although the dissolution of a metal by an acid is sometimes considered to be a form of direct chemical attack, it is really an example of electro-chemical action. Typical examples of chemical attack are oxidation and sulphidation in dry gases and the character of the resulting corrosion products has an important bearing on the subsequent corrosion. If these products form a protective film, the rate of corrosion will fall and may, as in the case of the heat resistant alloys, become extremely small.

(ii) *Electro-chemical Attack.* The usual form of corrosion in aqueous media, or under damp conditions, is electro-chemical, and results from the formation of an electrolytic cell in which the corroding metal constitutes the anode. The insoluble products of corrosion are usually formed indirectly by interaction of the anodic and cathodic products, and are not necessarily formed on the metal. An electric current flows through the metal and the solution, generated by the difference in the tendency for solution of different parts of the metallic surface or of oxide and other scales thereon.

Such cells are formed in various ways. The corroding metal may be anodic to:—

    (a) another metal with which it is in electrical contact;
    (b) corrosion products or protective films on its own surface;
    (c) chemical or physical inhomogeneities at the surface.

The extent of corrosion also depends on the reaction at the cathodes, which is greatly affected by the oxidizing character (for example, air-content) of the medium, and the extent of electrical insulation afforded by oxide, paint or other protective films.

(a) Indicates the well-known danger of using different metals in contact with each other in an aqueous corrosive media. Table 1 shows the galvanic series of metals and indicates the tendencies of metals and alloys to set up galvanic or electrolytic cells. In Table 1 metals that are grouped together have

TABLE 1. GALVANIC SERIES OF METALS AND ALLOYS

Corroded end (anodic, or least noble)

Magnesium
Magnesium alloys

Zinc

Aluminium

Cadmium

Steel or iron
Cast iron

Chromium-iron (active)

18/8 Chromium-nickel-iron (active)
18/8/3 Chromium-nickel-molybdenum iron (active)

Lead-tin solders
Lead
Tin

Nickel (active)
Inconel (active)

Brasses
Copper
Bronzes
Copper-nickel alloys
Monel

Silver solder

Nickel (passive)
Inconel (passive)

Chromium-iron (passive)

18/8 Chromium-nickel-iron (passive)
18/8/3 Chromium-nickel-molybdenum iron (passive)

Silver

Graphite
Gold
Platinum

Protected end (cathodic, or most noble)

no strong tendency to produce galvanic corrosion on each other, and from the practical standpoint are relatively safe to use in contact with each other. The coupling of two metals from different groups and distant from each other in the list will result in galvanic or accelerated corrosion of the one higher in the list. The further apart the metals stand the greater will be the tendency.

(b) The effect of scale, corrosion product or protective film is illustrated in Fig. 1. For this type of electrolytic cell to be initiated the corrosive media must be in contact with both the metal and the scale or other non-metallic coating, i.e., the latter must be discontinuous as a result of, say, scratching of the coating.

(c) Variation of the concentration of the corroding media over the surface of the metal will occur wherever conditions are stagnant, as in crevices, cracks, pits, etc., and such locations are always likely to induce corrosion.

It has been shown that different portions of a metal surface which are subject to different stress conditions show vary-
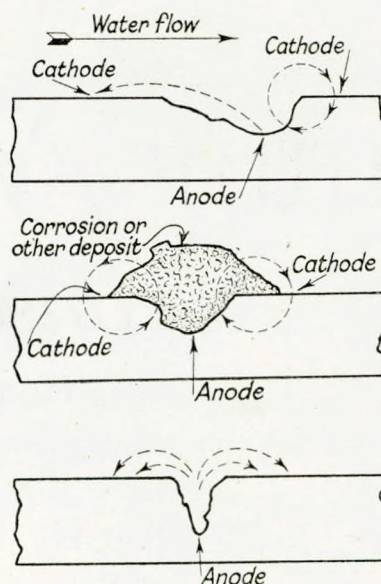

(a) *Impingement attack.* Water flow removes corrosion products from anode and the cathodic areas are depolarized and kept active by moving aerated water.

(b) *Deposit attack.* As a result of diffusion effects the concentration of oxygen decreases towards the anode and a concentration cell is set up. The cathodic areas are kept depolarized and active by the dissolved oxygen outside the deposit.

(c) *Pitting.* Once a pit is initiated the attack proceeds due to the formation of a concentration cell as described above.

FIG. 1—*Examples of electrolytic corrosion cells*

ing potentials when in contact with an electrolyte. These varying potentials will cause localized corrosion as electrolytic cells will be set up.

Chemical inhomogeneity of the metal will act in a similar manner to (a) as, in effect, two different metals will be coupled in contact with an electrolyte. If the inhomogeneity is a non-metallic inclusion the effect may be similar to that described in (b) above.

B. Particular Corrosion Phenomena[1, 2]

All corrosion phenomena result from either or both of the forms of corrosion described above or a combination of one or more of these with an erosive or similar mechanical agency, but a brief description of the more important phenomena may be helpful.

(*i*) *Pitting.* Corrosion may frequently be localized and where an area of corrosion is comparatively small as compared with the remaining area of the metal it is referred to as a pit (Fig. 1). A corrosion pit may have a wall which approaches normal to the metal surface or be more gradual in its formation. The total loss of metal by corrosion may be small but the actual damage severe. An exaggerated example of this is shown in Fig. 1. Pitting may be the result of several mechanisms; a break in a protective scale or film on the surface of a metal may cause local corrosion, deposits of foreign matter or loose corrosion product on the surface of the metal cause differential aeration with consequent pitting attack; inhomogeneity in the metal, most likely due to non-metallic inclusions, will result in pitting either by simple solution of the inhomogeneity or the formation of a very localized electrolytic cell; localized stressing of the metal is another cause.

It is extremely difficult to assess damage by pitting which, unlike general corrosion, cannot be measured by average thickness or weight loss.

(*ii*) *Dezincification.* Dezincification, or copper re-deposition, is a corrosion phenomenon normally limited to brass. The higher the zinc content of the brass the more likely it is to occur. In dezincification the brass is corroded and the products of corrosion go into solution. For various reasons a concentration cell is formed and, as a result of this, copper from the corrosion products is re-deposited almost at the same position where it was first taken into solution. Thus copper deposits are formed which give the effect of the removal of zinc.

The most dangerous form of dezincification is the plug type in which very localized attack is observed and deep pits, leading to perforation of the metal, are formed. This local

attack may be the result of deposits of one type or another which have resulted in the setting up of a concentration cell in the manner previously indicated.

If the dezincification should be of the layer type, then the attack is general over the metal surface and is not so serious.

For the description of the phenomena of intergranular attack, stress corrosion and corrosion fatigue it would be difficult to impove on a recent description of these given by Whitwham and Evans.[3]

(iii) Intergranular Attack. If a material, containing an intergranular network more susceptible to corrosion than the substance composing the grains, is placed in a liquid just sufficiently aggressive to attack the network but to leave the rest untouched, intergranular attack may be expected. Usually, the network will provide the anodes of the corrosion cell, and the rest of the grains will provide the cathodes, so that the latter may receive additional protection, making sharper the distinction between attacked and unattacked portions. However, intergranular attack can be expected only if the chemical or electrochemical contrast between the grain interiors and grain edges is sufficiently pronounced, and if the liquid is one which can act selectively; a liquid so strongly corrosive as to produce general attack will fail to start intergranular penetration.

(iv) Stress Corrosion. Although for a given amount of metal destroyed, intergranular corrosion must produce more weakening than general corrosion, its effect on mechanical properties becomes far more pronounced if a tensile stress is applied during the attack, since the destructive effect is then concentrated on a *limited* number of grain boundaries, notably some of those running at right-angles to the stress direction. Under such conditions, the intergranular grooving produced by the corrosion may at certain points lead to a stress concentration sufficient to start cracks, which propagate themselves inwards by conjoint mechanical-chemical action. Probably the chemical attack helps the mechanical cracking by destroying any mechanically strong bridges which would otherwise hold up the advance of a crack, whilst the mechanical stress aids the chemical action proceeding at the tips of suitably orientated cracks, by rupturing chemically resistant bridges, breaking up protective films, and possibly shifting the potential in a direction favourable to anodic corrosion as a result of plastic deformation.

Stress corrosion can cause cracking to extend along any paths of low chemical and mechanical resistance which run in the right direction. As already stated, these are often intergranular in character, but sometimes, as in magnesium-base alloys, they may be transgranular. Since, however, cracking is only likely if the material has been so treated as to produce paths definitely more susceptible to attack than the main part of the material, and if the liquid is one which will act preferentially on the material of the paths, leaving the rest untouched, it follows that the stress corrosion produced by simple tensile stressing is not a very common phenomenon.

(v) Corrosion Fatigue. In the case of corrosion cracking produced by alternating stress, almost any corrosive liquid can produce failure on almost any material, irrespective of its previous heat-treatment. This is probably because the deformation itself produces disorganized and chemically sensitive material. Even though the stress range applied is below the fatigue limit, there may be notches, cavities, or other defects which allow local plastic deformation to take place in the opening stages, as a result of stress intensification. In the absence of a corrosive substance, however, the disorganization of the material along any temporary slip bands brings about a rise in the elastic limit (work-hardening), and in due course the whole specimen subjected to alternating stress is able to undergo elastic, as opposed to plastic, deformation. If, however, a corrosive agent is present, the disarrayed material formed locally along small slip bands may be very susceptible to attack, and usually the contrast between the disarrayed and undis-arrayed material will be so pronounced that the latter remains quite unattacked. Very fine cracks therefore advance inwards, by conjoint chemical-mechanical action, until the specimen breaks. It would seem that, whereas *stress corrosion* due to simple *tensile* stress requires *pre-existing* paths of chemically weak matter produced by previous heat-treatment or otherwise, *corrosion fatigue,* set up by *alternating* stresses, manufactures its disorganized sensitive matter as the crack advances. Thus the cracks follow, on the whole, the directions along which incipient or temporary gliding would be likely to produce disorganized matter.

(vi) Impingement Attack. This form of attack, which may also be described as "corrosion erosion", occurs in pipelines and other components handling moving sea-water. The water impinging on the protective film on a metal surface erodes it and, if the rate of erosion exceeds the rate of repair—i.e., a critical water speed is exceeded—the film will be ruptured and the water then corrodes the exposed anodic area of metal surface. The severity of the attack will increase with higher water speeds and the amount of entangled air and is, of course, radically modified by any factors which affect the rate of formation of the protective film.

Consideration of the foregoing various types of corrosion should emphasize the point which should be borne in mind throughout—that the use of a material labelled "corrosion-resisting" does not, of necessity, imply that its use will overcome a particular corrosion problem. There are many other factors to be borne in mind before a satisfactory answer to a problem can be found. The description will also serve to define terms which will be used later in this paper.

III—CORROSIVE MEDIA ENCOUNTERED IN MARINE ENGINEERING

The principal corrosive media encountered in marine engineering are:—

(a) Fuels and products of their combustion.
(b) Boiler water and steam.
(c) Sea-water.
(d) The atmosphere.

These media must be considered in conjunction with the other factors which will affect the nature and rate of their corrosive action; such factors include the presence of erosive effects or high temperature. It will be useful to consider these media briefly to enable a more definite picture to be gained of the conditions of service under which a given material may be expected to operate.

(a) Fuels and Products of Their Combustion

The three major types of fuel in use today are coal, fuel oil and Diesel oil. None of these gives rise to any severe corrosion problem in handling them in their raw state, but their products of combustion can create serious problems for, under certain conditions, components of them may be highly corrosive.

Thus coal may contain from 0·5-5·0 per cent sulphur which forms sulphur dioxide on combustion. This component of the flue gases is harmless provided the temperature of the gases remains above the dew point. If, however, the temperature should fall below that value then condensation of water will occur and the sulphur dioxide dissolving in this will form the highly corrosive sulphurous acid. Such conditions may well occur in air heaters and economizers when raising steam, or in the exhaust circuit of Diesel engines and, though suitable redesign of the equipment or of the operating cycle of the equipment can frequently overcome such difficulties, the use of special materials may be necessary.

Fuel oil may usually have a sulphur content of below 2 per cent but may, despite this, give rise to difficulties similar to that described above. In addition, however, the burning of fuel oils can give rise to severe corrosion problems resulting from the nature of the ash following their combustion. Typical analyses of the ashes from fuel oils derived from various oilfields are given in Table 2.[4] It can be seen how the composition varies with the source. Experience has shown that if the ash from certain sources, where a high vanadium pentoxide content is normal, is in contact with metals which are normally oxidation resisting, at a temperature at which components

Source	California	Wyoming	Mid-Continental	Texas	Pennsylvania	Kansas	Oklahoma	Iranian (a)	(b)	(c)
SiO_2	38·8	40·3	31·7	1·6	0·8	10·0		52·8	18·1	12·1
Fe_2O_3, Al_2O_3 and TiO_2	17·3	51·4	31·8	8·9	97·5	19·1		13·1	37·1	18·1
CaO	8·7	3·5	12·6	5·3	0·7	4·8		6·1	8·1	12·7
MgO	1·8	1·2	4·2	2·5	0·2	1·3		9·1	3·8	0·2
MnO	0·3	0·2	0·4	0·3	0·2	trace		trace	trace	trace
V_2O_5	5·1	trace	trace	1·4		0·4	22·1	14·0	24·9	38·5
NiO	4·4	0·3	0·5	1·5		0·6	5·9	1·4	5·3	10·7
Na_2O	9·5	2·6	6·9	30·8	0·1	23·6				
K_2O					1·0	0·9				
SO_3	15·0	1·4	10·8	42·1	0·9	36·4		2·6	1·0	7·0
P_2O_5		0·1								
Cl				4·6		0·1		also traces of other elements		

*"The Science of Petroleum", Vol. II, p. 1053, published by The Oxford University Press.

of the ash are liquid then the oxidation-resisting property of the metal may be destroyed and corrosion of the metal occur at a very high rate. The exact mechanism of this phenomenon is still subject to investigation as is also the modifying effect of the other constituents of the ash.

Diesel fuels, being distillate fuels, are comparatively pure and, though if they contain a high sulphur content difficulties may occur, in general they give rise to few corrosion problems.

(b) *Boiler Water and Steam*

If high purity water were always available for boilers, feed corrosion problems would be practically non-existent as the initial corrosion of the iron or steel in the boiler would quickly be reduced to a negligible value by the formation of the fairly protective oxide film. Such pure water is, however, rarely available and contaminants are normally present which can cause severe corrosion in boilers. The main contaminants which may be present in boiler water and which can cause trouble are:—

(i) Oxygen.
(ii) Acids.
(iii) Alkalis (i.e., caustic soda).
(iv) Calcium or magnesium salts.

(*i*) *Oxygen.* Oxygen is the most general and possibly the most serious cause of corrosion present in boiler waters as its action may be severe and localized. For low and medium pressure plant it is reported that the oxygen concentration should not exceed 0·1 ml. per litre, and for high pressure plant 0·02 ml. per litre. Pitting and severe local deterioration of water tubes is normally accountable to a high oxygen content. The oxygen concentration is usually controlled by de-aerators which reduce the content to 0·01-0·05 ml. per litre and then by the addition to the feed-water to the boiler of sodium sulphite, ferrous hydroxide or organic reagents such as tannin.

(*ii*) *Acids.* When make-up water is distilled from water from certain locations, including sea-water, it is often appreciably acid and, if used without further treatment, would lead to a gradual wasting of the boiler components. It is, therefore, the practice to neutralize the acid and, in fact, keep the boiler water slightly alkaline.

(*iii*) *Alkalis.* In Fig. 2 is reproduced a curve giving the relative attack on steel by acid and alkali solutions of varying *p*H values. It will be noted from this that it is desirable to keep the *p*H value at a figure lying between 11 and 12. This is frequently attained by the addition of caustic soda, but the presence of the free hydroxyl ion in substantial concentration can itself give rise to other problems such as excessive corrosion due to the high caustic concentration formed locally during steam bubble formation at a heated metal surface, or embrittlement arising from a high concentration of caustic. The control of these effects is normally carried out by suitable additions of tri-sodium phosphate which, whilst maintaining a suitable *p*H value, limits the free hydroxyl ion available.

(*iv*) *Calcium or Magnesium Salts.* The hardness or scale-forming properties of water are the result of its content of calcium and magnesium salts. In modern installations difficulty due to this cause is not generally experienced as make-up feed water is normally obtained by distillation and the salts of calcium and magnesium only enter the boiler by accident. If they are present they may form a scale and cause localized regions of high temperature in boiler tubes due to the poor thermal conductivity at the scale and result in excessive corrosion and scaling.

Apart from the corrosion in the form of oxidation occurring when steam at high temperature is in contact with metals and alloys, steam may contain small but measurable quantities
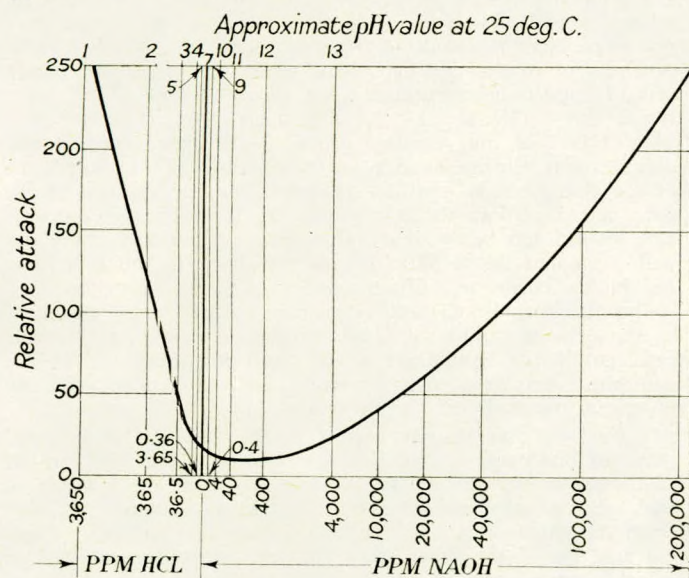

FIG. 2—*Attack on steel at 310 deg. C. (590 deg. F.) by water of varying degrees of acidity and alkalinity. (Curve by Partridge and Hall, based on data of Berl and Van Taack)*

of oxygen, carbon dioxide, sulphur dioxide, sulphuretted hydrogen and ammonia, all of which may directly and indirectly cause corrosion. The efficient removal of these gases or their neutralization by additions of suitable chemical reagents is, therefore, of importance.

It will be apparent from the above that the corrosion effects likely to be encountered with boiler water and steam are not simple.

(c) Sea-Water

With the exception of that polluted or contaminated in some way, sea-waters in various widely separated localities have been shown by extensive corrosion tests to have only small

TABLE 3. CHEMICAL ANALYSES OF TYPICAL SAMPLES OF SEA-WATER AT TWO LOCALITIES

Constituent	Concentration, in parts per million	
	Locality	
	Kure beach, N.C.	Annapolis, Md.
Sodium as Na	10,590	3,250
Chlorine as Cl	19,200	5,770
Magnesium as Mg	1,292	397
Calcium as Ca	404	137
Potassium as K	403	—
Sulphate as SO_4	2,664	833
Bromine as Br	67	—
Iron as Fe	Negligible	Trace
Carbonate as CO_3	Negligible	0·01
pH	7·7	8·1

differences as regards their corrosion of common metals and alloys. This is despite wide variations in salinity, temperature, etc., which variables appear to change in such a way as to negative any tendency for there to be a radical increase or decrease in corrosiveness. In the case of polluted or otherwise contaminated water the corrosion rates experienced with normal sea-water will not apply. There is likely, therefore, to be a difference in behaviour between marine engineering components in contact with sea-water in estuaries or ports for long periods and those normally in contact with sea-water from the open sea. The possible variation in analysis from location to location, is well illustrated in Table 3.

Thus the difference in the corrosive nature of uncontaminated sea-water at various locations only becomes of importance when investigating the comparative resistance of various materials to such corrosion in the laboratory when the differences in the behaviour of the various alloys under test may themselves be small, but the difference in the corrosive effect between contaminated and clean sea water must always be borne in mind.

(d) The Atmosphere

Marine atmospheres may vary from actual sea spray which noticeably wets surfaces to suspensions of sea-water so fine that they would pass unnoticed except for their corrosion effects. The variation in the corrosion effects of marine atmospheres,

TABLE 4*. TOTAL CORROSION OF SIXTEEN FERROUS MATERIALS IN MARINE ATMOSPHERE AT VARIOUS LOCALITIES

Station	Approximate mean air temperature	Rainfall, inch per annum	Position	Total loss in weight in 10 years (grms.)
Halifax	50	54	Normal	2,108
Auckland	64	44	Normal	5,025
Plymouth	50	45	Very subject to spray	13,153
Columbo	80	90	to spray	29,583

*"Deterioration of Structures of Timber, Metal and Concrete Exposed to the Action of Sea Water." The Fifteenth Report of the Committee of the Insituttion of Civil Engineers, 1935, p.61.

as opposed to that of sea-water, can vary considerably and is well illustrated in Table 4,[5] in which the total loss in weight of some sixteen materials exposed to marine atmospheres at various locations is given. It will be noticed that the nature of the atmosphere, as quoted under "Position", the temperature and the rainfall all affect the corrosion rate to be expected.

IV—CORROSION BEHAVIOUR AND PHYSICAL PROPERTIES OF VARIOUS METALLIC MATERIALS

A. Non-Ferrous Alloys

Metals and alloys to be considered in this main group can be conveniently sub-divided into six classes:—

    (i) Copper.
    (ii) Copper-zinc alloys.
    (iii) Copper-tin and copper-aluminium alloys.
    (iv) Copper-base alloys (for heat exchanger and other tubing).
    (v) Nickel-base alloys.
    (vi) Aluminium alloys.

(i) *Copper.* The corrosion-resisting properties of copper are so well known that it is only necessary to point out those cases where the service conditions, applying in modern equipment, have proved too severe for copper to be used and rendered necessary the development of new alloys. Table 5 compares the corrosion resistance of sea-water of the various copper alloys under various conditions of service: the mechanical properties of these alloys are given in Table 6. The various types of pure copper commercially available may be regarded as equivalent so far as corrosion resistance is concerned.

In clear sea-water which is not moving at any great speed copper is protected by a complex film which forms. If the film remains intact a corrosion rate in the region of 0·002 inch per year[2] is to be expected. If, however, any condition is present which will tend to prevent the formation of, or remove this film then the corrosion rate will increase considerably. Thus, contaminated water may remove or prevent the formation of a protective film and erosion by solid particles or fast-moving water may erode the film. As both these factors which prevent the full benefit of the corrosion resistance of copper being made available have become more prevalent it has been necessary to develop new alloys to overcome the difficulties which have been encountered. These new alloys are described later, but attention is drawn to the recent paper by Slater, Kenworthy and May[17] which discusses this problem with particular reference to H.M. ships.

The corrosion resistance of copper to boiler water and steam is of importance primarily because of the deleterious effect of copper salts in solution in boiler water on water tubes and drums.[6, 7] The cause of the corrosion of copper situated in the boiler feed or steam circuit will be the presence of contaminants such as ammonia, chlorine ion, oxygen, and such corrosion will be increased if erosion is also present. Any copper salts which are formed by this corrosion and pass into solution in the boiler water will be carried through to the boiler drums and tubes and may be deposited as metallic copper. The exact mechanism of re-deposition is not known, but where such deposits occur electrolytic attack of the steel of the drums and tubes is to be expected. This type of corrosion can be particularly severe in high-pressure high-temperature installations, and it has become necessary both in land and marine equipment to avoid the use of copper or any alloy which is copper-bearing and liable to corrode at an appreciable rate. This again implies the development of more corrosion-resisting alloys.

It is only in certain modern equipment where conditions of service have become more severe that the traditional use of copper has led to failure. In ships where the service for which the ship is intended does not require optimum designs of machinery copper remains a satisfactory material for many items. However, the effect of the increasing competition by Diesel equipment for the propulsion units in larger ships, hitherto the province of steam units, will undoubtedly lead to a call for materials to resist conditions of service in more efficient steam plant than is at present in use.

	Resistance to dezincification or analogous corrosion	Ability to maintain corrosion resistance with increase in temperature in absence of impingement effects	Resistance to corrosion and impingement attack in absence of entrained air at velocities, ft. per sec.*				Resistance to corrosion and impingement attack in presence of entrained air at velocities, ft. per sec.*				Freedom from fouling under severe fouling conditions at low velocity
			Under 3	4 to 7	8 to 15	Over 15	Under 3	4 to 7	8 to 15	Over 15	
Copper	Immune	Good	Fair	Poor	Bad	Bad	Fair	Bad	Bad	Bad	Good[1]
Si bronze	Immune	Good	Fair	Poor	Bad	Bad	Fair	Bad	Bad	Bad	Good[1]
Phosphor-bronze[9] (8 per cent Sn)	Immune	Good	Excellent	Good to excellent	Good	Fair	Excellent	Good to excellent	Good	Fair	Fair[2]
Admiralty brass	Fair	Fair	Good[5]	Fair to good[5]	Fair to poor	Poor to bad	Good[5]	Fair to poor	Poor to bad	Bad	Fair[2] to good[1]
Inhibited Admiralty brass	Excellent	Fair to good	Good	Fair to good	Fair to poor	Poor to bad	Good	Fair to poor	Poor to bad	Bad	Fair[2] to good[1]
Aluminium brass	Poor	Poor	Excellent[5]	Excellent[5]	Good[5]	Fair	Excellent[5]	Excellent[5]	Fair to good[5]	Poor	Poor[3]
Inhibited Al brass	Excellent	Fair to good	Excellent	Excellent	Good	Fair	Excellent	Excellent	Fair to good	Poor	Poor[3]
Red brass	Good	Fair to good	Good	Pocr	Bad	Bad	Fair	Poor	Bad	Bad	Good[1]
Muntz metal	Bad	Bad	Good[5]	Good[5]	Good[5]	Fair[5]	Good[5]	Good[5]	Fair[5]	—	Fair[2] to poor[3]
Naval rolled brass	Fair to poor	Poor to bad	Good[5]	Good[5]	Good[5]	Fair[5]	Good[5]	Good[5]	Fair[5]	—	Fair[2] to poor[3]
70/30 Cu-Ni alloy with Fe under 0·15%	Immune	Good	Excellent	Fair to good	Fair to poor	Poor to bad	Excellent	Fair to good	Poor	Bad	Fair[2] to good[1]
70/30 Cu-Ni alloy with Fe over 0·15%	Immune	Good	Excellent	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Good	Poor[3]
Cu-Ni alloys containing over 10% Ni and 1% Fe	Immune	Good	Fair[6]	Good to excellent[6]	Excellent	Excellent	Fair[6]	Good to excellent[6]	Excellent	Excellent	Poor[3] to bad[4]
Tin (solder) coated Cu[7]	Immune	Fair	Excellent	Excellent	Good to excellent	Fair to good	Excellent	Excellent	Good to excellent	Fair to good	Bad[4]
90/10 Cu-Ni alloy with 2% Fe	Immune	Good	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent	Good	Poor
Cast tin bronze containing over 5% Sn	Immune	Good	Excellent	Good to excellent	Fair to good	Fair	Excellent	Good to excellent	Fair to good	Fair	Fair[2]
Cast tin bronze containing under 5% Sn	Immune	Good	Good	Fair to good	Poor	Poor	Good	Fair	Poor	Poor	Good[1]
Cast silicon bronze	Immune	Good	Good	Fair to poor	Bad	Bad	Fair	Poor to bad	Bad	Bad	Good[1]
Cast Mn bronze	Poor to bad	Poor to bad	Good[5-10]	Good[5-10]	Good[5-10]	Good[5-10]	Good[5-10]	Good[5-10]	Good[5-10]	Fair[5-10]	Fair[2] to poor[3]
Cast Al bronze	Good[8]	Fair to good	Good	Good	Good	Good	Good	Good	Good	Good	Bad[4]

* Ratings take into account the probability of aggravated attack in regions of excessive disturbance of stream line flow or turbulence.

[1] Good. Generally free from fouling.

[2] Fair. Occasionally subject to fouling.

[3] Poor. Occasionally free from fouling.

[4] Bad. Generally subject to fouling.

[5] Alloys subject to dezincification will suffer such damage if exposed to sea water at low or no velocity. Consequently, their relatively good resistance to impingement attack cannot be used to advantage where conditions favouring dezincification may be encountered also.

[6] Given less than excellent rating because of possibility of local attack under deposits or organisms that may remain attached at low velocity. Excellent rating even at low velocity would apply to 70 per cent Ni–30 per cent Cu alloy (Monel) in all applications involving contact with less noble materials, such as iron and bronze, as in valves and pumps.

[7] Such tin (solder) coatings should be applied in substantial thickness, e.g., ⅛ inch by wiping. Thin coatings, such as may be applied by dipping, are unreliable, and may cause serious acceleration of corrosion of copper exposed at bare spots.

[8] Not rated as immune because of occasional susceptibility to a dezincification type of attack.

[9] Data do not refer to use as pipe or tubing, but for such purposes as staybolts.

[10] Data refer particularly to use as propellers where good performance is aided by galvanic protection from steel hulls.

Multiply ft. per sec. by 0·305 to obtain metres per sec.

Corrosion-Resistant Materials

TABLE 6 PHYSICAL PROPERTIES OF VARIOUS NON-FERROUS ALLOYS

Alloy	Cu	Ni	Zu	Sn	Al	Si	Mn	Pb	Fe	P	As	Limit of proportionality	0.1 per cent proof	Ultimate tensile strength	Elongation in $4\sqrt{A}$	D.P.H.	Linear coefficient of thermal expansion per deg. C.	Thermal conductivity, CGS units at 20 deg.C	British Standard Specifications
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	t.s.i.	t.s.i.	t.s.i.					
Copper	99·9											1a–12h	4a–21h	14a–24h	4h–55a	50a–110h	16·6×10⁻⁶ (20–100°C)	0·92	444, 518, 1110, 659, 24 Part V., 61
Silicon bronze	96			3	1							4a–20h	6a–40h	23a–50h	5h–65a	70a–210h	17·1×10⁻⁶ (20–100°C)	0·07	
Phosphor bronze	91·5			8·25						0·25		15–25 h	25–35 h	30–40 h	20–40 h	120–140 h			
Cast tin bronze (Sand cast)	87·5			12									8	11–19	4–15	80–100			
Cast tin bronze (Chill cast)													10	15–20	2–5	100–130			
Admiralty gunmetal	88		2	10									7	18–22	20	70–100			382, 383
Gunmetal	86		5	7				2					7	14–18	15	60–70			1023, 1024
Gunmetal	85		5	5				5					6	12–16	15	60–70	18·4×10⁻⁶ (20–100°C)		897, 898
Typical admiralty propeller bronze	56	2	41	1·0	0·3				1·0		0·3		18	35	27	B.H.N. 156			
Cast high tensile brass or manganese bronze	54·1	2·4	39·1										22	39	19				} 1400
	57·1	0·3	39·2	1·3	0·6		0·7	0·2	0·6					31	14		20·0×10⁻⁶ (20–100°C)	0·24	
Nickel bronze A	Bal.	50						0·01 max.						23–30	10–20	100–120			
B	Bal.	50	1·0 max.	4–5		6–12	2·0 max.	nil	1·0 max.					25–40	nil–1·0	B.H.N. 150–400			
Low nickel bronze	Bal.	3–5	4–6	6·5–7·5	0·1 max.		5–6						9	18	in 2″ 22	B.H.N. 70–80			
Aluminium bronze	88				9				3			10		32	in 2″ 30	BHN 100		0·19	
	81	1			13·5	0·5			4			16		40	3	BHN 300		0·15	
	80	5			10				5			12		48	10	BHN 170	18×10⁻⁶ (20–250°C)	0·18	
Admiralty brass	70		29	1								4a–15h	5a–28h	22a–38h	10h–70a	65a–175h	20·2×10⁶ (20–300°C)	0·19	378, 885, 886
Aluminium brass	76		22		2							4a–16h	7a–30h	24a–40h	8h–70a	65a–175h	19·6×10⁻⁶ (20–300°C)	0·24	
Red brass	85		15									25a–12h	45a–24h	19a–32h	10h–60a	60a–150h	17·6×10⁻⁶ (20–100°C)	0·38	
Muntz metal	60		40									4	7	24	40	75	19·5×10⁻⁶ (20–100°C)	0·30	
Naval brass	62		37	1								5	8	25	40	80	20·0×10⁻⁶ (20–100°C)	0·28	
70/30 cupro-nickel	70	30												27a–42h	8h–45a	85a–160h	16·2×10⁻⁶ (20–300°C)	0·06	374
10% nickel, copper-nickel-iron alloy	88	10							2					20a–37h	10h–45a	90a–180h	16·0×10⁻⁶	0·11	
5% nickel, copper-nickel-iron alloy	93·5	5							1·5			5a–12h	7a–18h	19a–27h	in 2″ 12h–47a			0·14	
Nickel	99·5												(0·2%) 8a–35h	33a–55h	15h–45a	110a–190h	13·3×10⁻⁶ (25–100°C)	0·145	
Monel (wrought)	Bal.	67				0·1	1·0		1·4				(0·2%) 12a–42h	34a–48h	12h–45a	135a–230h	15×10⁻⁶ (25–300°C)	0·062	
Monel (cast)	Bal.	63				0·5–1·2	0·5–1·5		3·0 max.				(0·2%) 11	27	25	125			
		68																	

a — annealed   h — after a typical degree of cold work

(ii) Copper-Zinc Alloys. Brasses vary very considerably in composition from alloys containing 50 per cent of zinc to alloys which are almost pure copper. They may also be modified by additions of a wide range of elements which may amount to as little as 0·01 per cent or to as much as 30 per cent. However, the alloys which are now acceptable for marine engineering applications are limited and each has usually been developed to meet a definite application in this field. Reference should again be made to Table 5 for a comparison of the corrosion resistance to sea-water of various typical brasses with other alloys, and to Table 6 for general physical properties.

As with copper, the corrosion of a simple brass depends on the conditions of service to a very marked degree, and it is unusual to find a simple copper-zinc alloy in service. It has previously been mentioned that one of the principal mechanisms of corrosion of these alloys is dezincification. This type of failure occurs with alloys of high zinc content but rarely with those of lower zinc content or with special additions to prevent dezincification. Thus, in general, alloys with more than 85 per cent of copper or alloys containing additions of tin, say 1 per cent, antimony, say 0·25 per cent, or arsenic, say 0·02-0·05 per cent, are more resistant to this form of attack, though under severe conditions dezincification may still occur. Naval brass, containing 60 per cent copper, 39 per cent zinc, 1 per cent tin, is widely used for condenser tube plates, weed grids and similar items. Compared with other suitable alloys it is more readily rolled to large plates, and in conjunction with correctly fitted iron protector blocks rarely gives trouble.

If dezincification of the layer type should occur a corrosion rate of only 0·003 inch per year may be experienced.

Season cracking, another type of failure to which these brasses are subject, is a form of stress corrosion cracking described earlier in this paper. It rarely occurs with alloys containing less than 15 per cent zinc and can be avoided by suitable stress relief annealing of the material.

The principal uses of the various brasses in marine engineering are for condenser and other heat-exchanger tubing, pump components and propellers. As a discussion of materials for heat-exchangers involves a direct comparison of brass and other materials, including copper-nickel alloys, this subject will be covered separately.

Pump components and marine propellers are not only liable to be highly stressed and require special attention from that aspect, but also because they are, by nature of their service, in contact with water moving at high speed, they are subject to corrosion-erosion conditions and, in addition, are liable to a form of attack known as cavitation-erosion.[10, 11, 12, 13, 14] This phenomenon has been the subject of considerable investigation both to determine, firstly, the mechanism of attack and, secondly, the relative resistance of the various alloys to this attack. Beeching[10, 11] has described the mechanism as being "primarily of a mechanical nature, the surface being disrupted by high localized stresses resulting from the impacts caused by the collapse of vapour pockets".

Standard copper-zinc alloys do not show any great degree of corrosion-erosion or cavitation-erosion resistance, and are not suitable for use where such conditions exist.

Modification of the simple alloy by additions of manganese, iron, nickel, tin and aluminium radically changes the properties, as can be seen by a comparison of alloys in Table 5, and makes available both higher degrees of mechanical strength and corrosion resistance. These alloys have been known for a number of years as manganese bronzes or high tensile brasses, but more recently the development of the aluminium bronze alloys has improved on the properties available to the shipbuilder and enabled even more severe operating conditions than those acceptable with the high tensile brasses or managese bronzes to be overcome.

Beeching arrived at a comparison of the resistance of various alloys to cavitation-erosion as measured by his experimental equipment, and this is summarized in Fig. 2. The very considerable improvement of the nickel aluminium bronze is well

brought out and this alloy is, in fact, adopted for propellers and impellers where cavitation-erosion is likely to occur.

It is, however, only for the most severe conditions of service, such as exist with propellers transmitting great power, or in high speed propellers or impellers that the nickel aluminium bronze becomes essential, and a very large number of units are made using high tensile brass compositions.

It will be realized that in the majority of applications where brasses are used in marine engineering there is usually present a service condition, such as normal erosion or cavitation-erosion, which has a much greater effect on the performance of the alloy than simple corrosion. The various brasses do, however, show differing degrees of corrosion resistance, this being mainly apparent between alloys of different constitution. Wholly *a* alloys (i.e., alloys usually containing not less than 63 per cent copper) being the most resistant, alloys with an $a + \beta$ constitution (usually containing 58-60 per cent copper) corrode more rapidly and more unevenly than a alloys, and β alloys (containing approximately 50 per cent each of copper and zinc) are thought to corrode at a slightly lower rate than the $a + \beta$ type but are subject to inter-crystalline cracking if stressed in contact with sea-water; they are therefore not used to any great extent in marine applications. The coupling of brasses to other copper alloys does not lead to an appreciable increase in corrosion of either, but the coupling of brasses to less noble materials such as iron, steel, aluminium, magnesium, may lead to considerable trouble and should be avoided.

(iii) Copper-Tin and Copper-Aluminium Alloys. With the possible exception of the alloys used for the tubing of the various types of marine heat-exchanger, the materials grouped under the title "bronzes" are used to a greater extent in marine engineering than any other non-ferrous alloy. In marine applications they are almost exclusively used in the cast form and it is the alloys suitable for this purpose that will be considered here.

The general corrosion resistance of typical bronzes is indicated in Table 5 and mechanical properties in Table 6, and it will be noted that they show a uniformly good resistance to corrosion by sea-water under most typical conditions. In addition, modifications of the basic bronze compositions are in common use for resisting erosion and corrosion by high temperature steam.

As in the case of brass a very wide variety of bronze compositions have been developed but the number actually adopted for marine applications is limited and may be grouped into four main classes:—

       (*a*) Phosphor bronzes.
       (*b*) Gunmetals.
       (*c*) Nickel bronzes.
       (*d*) Aluminium bronzes.

The first three groups may be regarded as copper-tin alloys modified by addition of other elements for various purposes. The last group does not contain tin but, as the alloy is complementary to the tin bronzes and has been given the generic title of a bronze, it is convenient to consider it here.

(a) The Phosphor Bronzes, i.e., alloys of copper and tin, containing usually 8 to 14 per cent of tin, which have been modified by addition of other elements for various purposes, been used in marine applications for a very long time. The addition of this small percentage of phosphorus to the basic copper-tin alloy renders the molten metal more fluid with little, if any, loss of corrosion resistance. The basic composition is also hardened by the addition of phosphorus due to the formation of copper phosphide. The development of the gunmetals with their advantages with regard to casting production has led to the overlooking of the phosphor bronzes as regards their use for corrosion resisting purposes, though they remain an important series of alloys as a result of their bearing qualities. In view of this little more need be said concerning them.

(b) Gunmetals. The production of satisfactory pressure-tight castings in either straight tin or phosphor bronzes is a difficult matter, and the high cost of tin has led to a search for
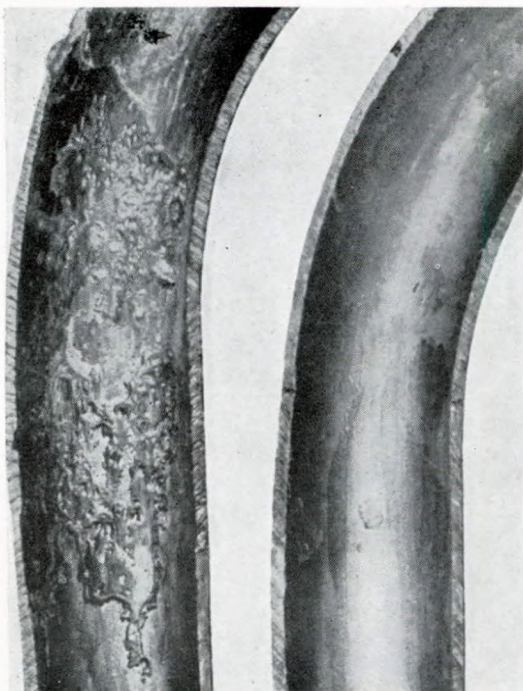
Gunmetal
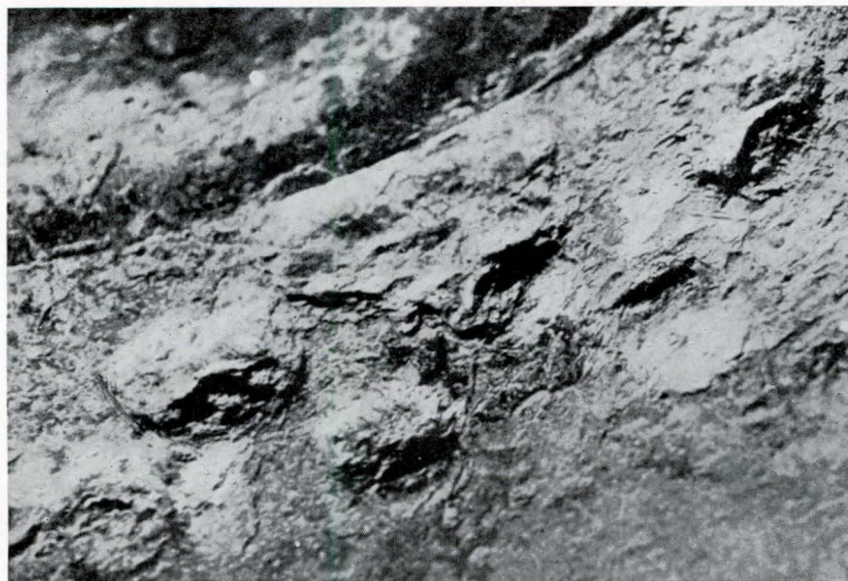
Steel   × ½

FIG. 4[17]—*Steel main inlet trunking (shipbuilders' tube), adjacent to gunmetal valve housing, showing severe wastage to rivet heads*
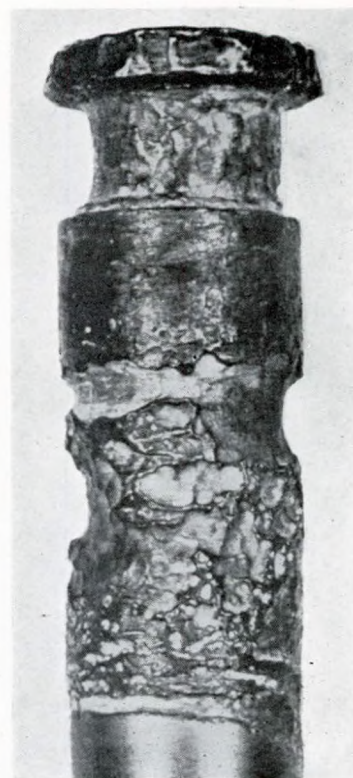*By courtesy of the Institute of Metals*
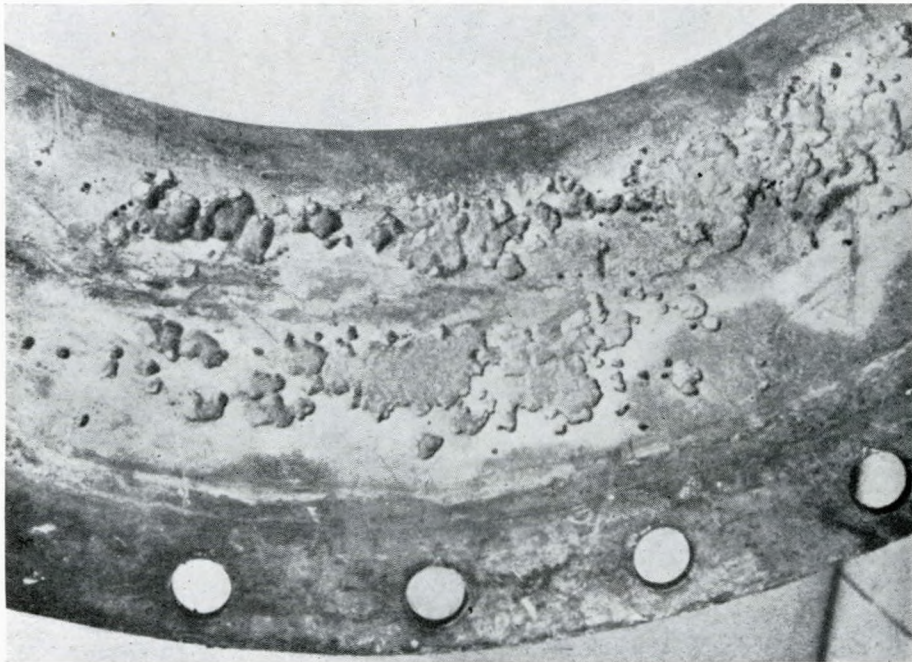
Copper   B.N.F. 5% Ni 1·5% Fe Cu-Ni-Fe alloy

× 1

FIG. 5[17]—*Sectional pipes, showing condition after carrying sea-water at 16ft. per sec. with 2 per cent entangled air for 3 months in experimental apparatus*
By courtesy of the Institute of Metals

× 1

FIG. 6[17]—*Naval brass valve spindle from fire main system, showing impingement attack*
By courtesy of the Institute of Metals

Plate 2

$\times \frac{1}{4}$

FIG. 17[17]—*Portion of copper bellows piece severely affected by impingement attack at radius of leading face*
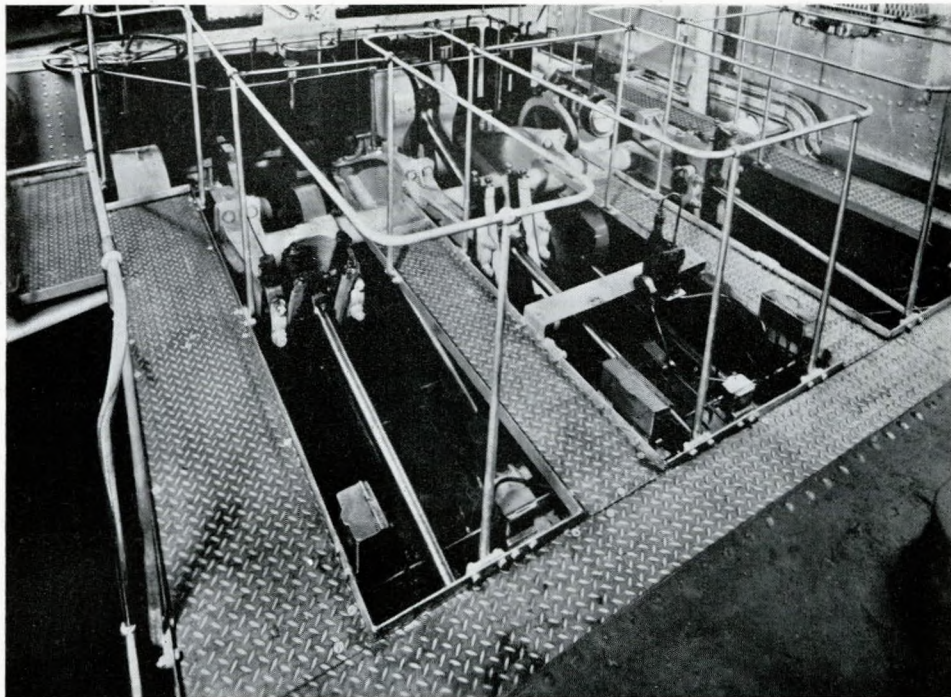
By courtesy of the Institute of Metals

FIG. 8—*Positive grip pattern treadplate in the engine-room of S.S. Sarayu built for service on the Ganges by Messrs. Yarrow and Co., Ltd. The material is 1 per cent silicon, 0·7 per cent magnesium aluminium alloy BA 25*

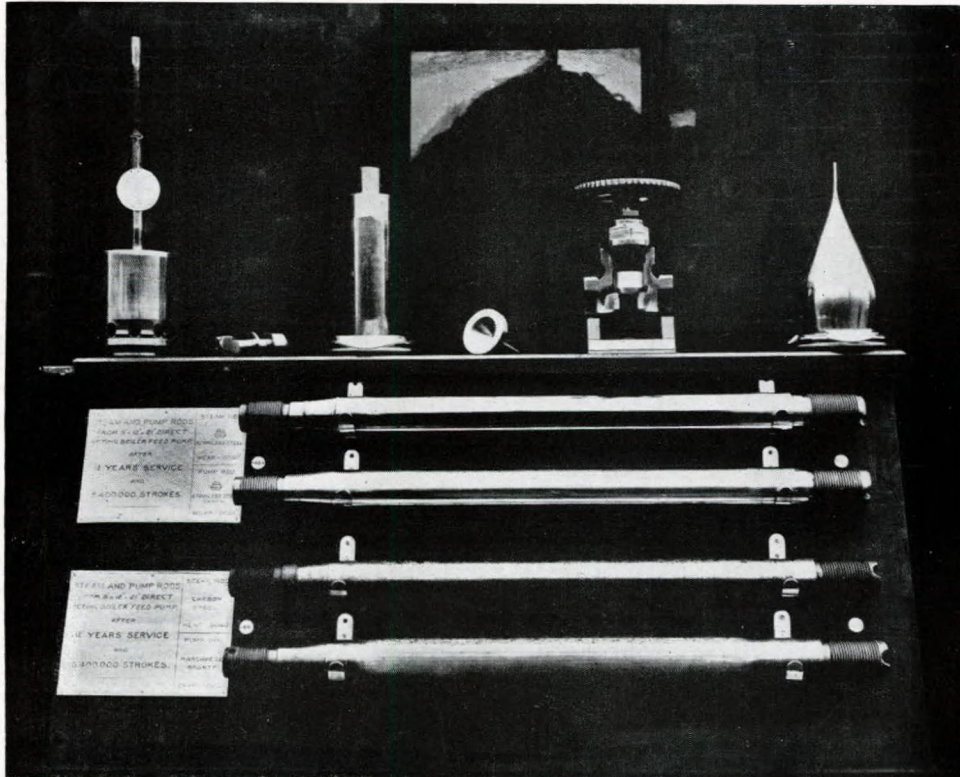*By courtesy of The British Aluminium Co., Ltd.*

FIG. 9—*Showing comparative corrosion on the one hand of steam and pump rods made of 13 per cent chromium steel and 18/8 steel respectively and, on the other, made from carbon steel and manganese bronze*

The respective wear after $1\frac{3}{4}$ years' service ($5\cdot4 \times 10^6$ strokes) are:

Steam rod			Pump rod		
13% Cr steel ...	...	0·0005 inch	18/8 steel ...	...	0·0035 inch
Carbon steel ...	...	0·0040 inch	Manganese bronze ...	0·0210 inch

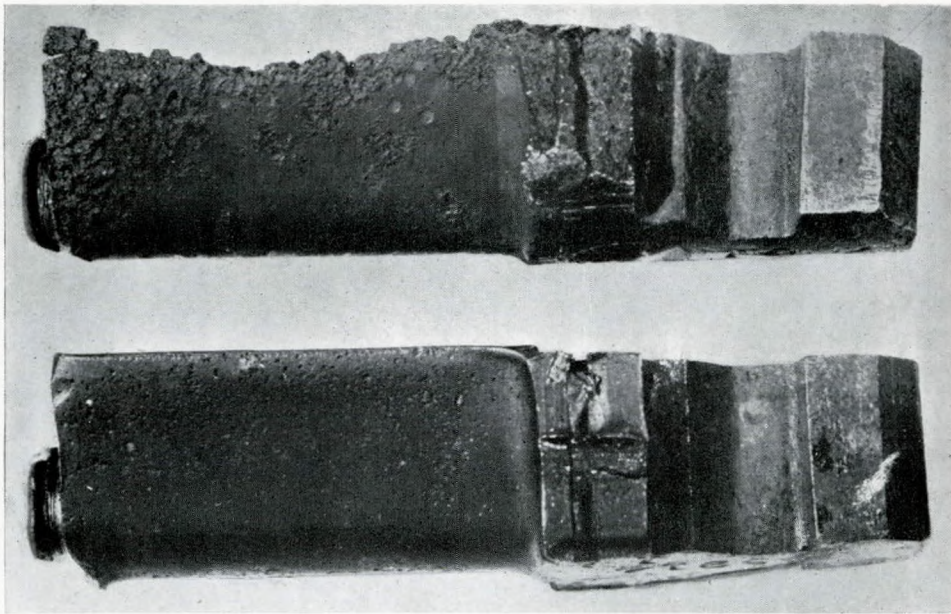*By courtesy of Messrs. Brown Bayley's Steelworks, Ltd.*

FIG. 10—*Showing erosion-corrosion caused by saline-contaminated steam on turbine blades which had operated in the same marine steam turbine for two years. The upper blade showing very marked attack was a 13½ per cent chromium steel blade and the other was the 36/12 nickel-chromium type of steel*

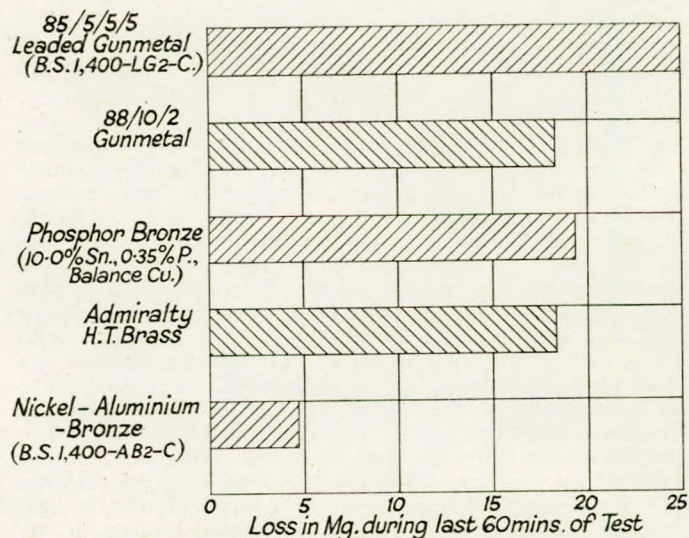*By courtesy of Messrs. Hadfields, Ltd.*

FIG. 3—*Weight lost by various alloys during sixty minutes erosion in sea-water*

The bar chart shows, with labels on the vertical axis:
- 85/5/5/5 Leaded Gunmetal (B.S.1,400-LG2-C.)
- 88/10/2 Gunmetal
- Phosphor Bronze (10·0% Sn., 0·35% P., Balance Cu.)
- Admiralty H.T. Brass
- Nickel-Aluminium -Bronze (B.S.1,400-AB2-C)

Horizontal axis: Loss in Mg. during last 60mins. of Test, scaled 0, 5, 10, 15, 20, 25.

a technique for reducing the tin content required for a given purpose. Considerable advance was made in solving these problems when it was found that the addition of small percentages of zinc—i.e., 2 per cent—to a basic tin bronze composition not only rendered the molten metal more fluid but also enabled the tin content to be reduced slightly as the zinc provided, to a limited degree, the beneficial effects of the tin. The 88 per cent copper, 10 per cent tin, 2 per cent zinc alloy known as Admiralty gunmetal was developed over a period of years and provided a valuable material for the construction of pump and valve bodies and components, and where onerous service conditions are met remains the standard alloy.

The addition of around 5 per cent of lead assists in the production of castings which are required to resist pressure. Where the working conditions do not require the use of the full Admiralty gunmetal composition advantage can be taken of the benefits given by further additions of lead and zinc as regards both reduction of cost and improvement of castability and machining properties of the alloys. Two typical compositions are the 86 per cent copper, 7 per cent tin, 5 per cent zinc, 2 per cent lead, and 85 per cent copper, 5 per cent tin, 5 per cent zinc, 5 per cent lead alloys which are now very extensively used. There is some lowering of both corrosion resisting and mechanical properties with these alloys, as can be seen from Table 6, but for many purposes such as pumps or valve components they are satisfactory. Small additions of nickel are sometimes made to obtain some recovery both of mechanical properties and corrosion resistance, whilst retaining the improved casting and machining properties, and these additions also appear to assist in the prevention of segregation of the lead in the castings.

The leaded gunmetals provide a material, resistant to impingement attack and other forms of corrosion likely to occur in water circuits, which can readily be cast into pressure-tight castings for water boxes, pump and valve bodies, etc., and which, used in conjunction with Monel, aluminium-bronze or gunmetal pump impellers, guide vanes and valve trim, enable pumps and valves which will give a long trouble-free life to be manufactured. It must be noted, however, that under certain conditions gunmetal may become highly cathodic and stimulate attack on adjacent more anodic components (Fig. 3). The corrosion of tin-bearing alloys with the consequent availability of tin salts in solution in the water is believed to increase the corrosion of other copper alloys such as cupro-nickels, aluminium brass, and the use of bronze ferrules in a condenser has been thought to be the cause of early failure of the tubes.

(c) *Nickel Bronzes.* The effect of small nickel additions

on the tin bronzes was briefly mentioned above, but probably the greatest interest in such additions arises when they are increased to 20-50 per cent when the alloys develop properties which are of particular interest for the designer of steam valves. In valves controlling steam at high temperatures and pressures the moving and mating components such as lids, seats, and valve faces in slide valves must retain their hardness and strength at the steam temperatures, have a coefficient of thermal expansion comparable with that of the valve body to prevent undue thermal stressing, non-galling characteristics when sliding against adjacent components, and corrosion and erosion resistance. By increasing the nickel content of a gunmetal containing from 6-8 per cent tin and 1-2 per cent zinc, 20-50 per cent copper a series of alloys is available which provides the properties required for components to operate under increasing steam temperatures—the higher the steam temperature the higher the percentage of nickel required. Two typical alloy compositions for the higher range of temperatures are:—

Ni 50 per cent : Zn 1·8 per cent : Sn 4-5 per cent
Ni 50 per cent : Zn 1·0 per cent : Sn + Si 6-12 per cent

The first of these is suitable for the manufacture of unsupported steam valve lids; the alloy is stable at steam temperatures. The second alloy, whilst retaining its hardness at steam temperatures, ages during service and in time loses some ductility so that, though its general properties are superior to those of the first alloy, it should not be used unsupported. This particular series of bronzes has, therefore, a limited but very essential application in marine engineering.

(d) *Aluminium Bronzes.*[15] Though the presence of aluminium in even small percentages is detrimental to the tin-bearing bronzes, the alloys of copper with up to 14 per cent aluminium, known as aluminium bronzes, have become of increasing importance during recent years. The alloys are not amenable to the foundry and fabrication practices developed for other copper alloys and, though their useful properties have been known for some time, it is only during the last thirty years that suitable techniques have been developed for handling them. Now the alloys cover a very wide range of compositions including modification of basic aluminium-copper alloys by additions of iron, manganese, nickel and other elements. Again, in marine engineering the major application has been for castings in which the basic composition is 9-10 per cent A1 with addition of other elements if thought necessary. Their corrosion, erosion and wear resistance are excellent and, in addition, they retain their mechanical properties at elevated temperatures rather better than such alloys as the manganese bronzes, and are oxidation resistant up to even 800 deg. C., though their mechanical strength at such temperatures is negligible.

The difficulties in founding these alloys has deterred designers from very extensive use of them, but they are coming into increasing service for water-pump impellers, valves and similar applications where their corrosion and erosion resisting properties show to advantage. Of particular note is their development for propellers and impellers, and the work by Beeching quoted above, and Kerr, shows the advantage to be obtained by their use.

The effects of addition of other elements to cast aluminium bronzes are still being determined and are principally confined to improvement of the mechanical properties, as indicated in Table 6. Lead is also added up to 2 per cent to improve machinability, and silicon improves the casting properties of the alloys. An interesting point is that a nickel aluminium bronze[16] has been shown to be less anodic to mild steel than a gunmetal and is, therefore, less likely to promote electrolytic corrosion when in contact with mild steel, as can occur with sea-cocks, discharge valves, etc. This is undoubtedly the result of the polarizing effect of the protective film which forms over the surface of aluminium bronze.

(iv) *Copper-Base Alloys (for Heat Exchanger and other Tubing).*[17, 18, 19, 20, 22, 23, 24, 25, 26] Tubular type heat exchangers, whether condensers, drain coolers, oil or water coolers, are some of the most critical units in marine engineering installations

of all types. The majority of heat exchangers use sea water as the cooling medium in the tubing with a comparatively innocuous medium such as steam, fresh water or oil round the tubing. It is, therefore, on the sea-water side that the most severe service conditions exist. The inevitable desire to increase the efficiency and reduce the size of each component of propelling machinery has resulted in a requirement for materials to resist the attack of sea-water moving at the higher speeds by use of which the efficiency of a heat exchanger can be increased. At the water speeds in the region of 7 ft. per sec. common in earlier installations little trouble was experienced with such materials as Admiralty brass, but as water speeds were increased impingement attack with existing alloys became serious, whilst deposit attack and dezincification remained and it, therefore, became essential that materials resistant to these more severe conditions should be developed. Considerable work has, in fact, been carried out to this end and recently a general summary of it was published in the *Transactions*.[26] The major part of the work has been carried out by, firstly, a Committee of The Institute of Metals and subsequently by The British Non-Ferrous Metals Research Association. Various papers describing this work have been published, but of great importance in this respect is a paper which has been prepared by G. L. Bailey, Director of the above-named Research Association shortly to be published in the Journal of The Institute of Metals. This paper describes the later stages of the investigation in detail and, taken together with the paper referred to earlier by Slater, Kenworthy and May,[17] covers the subject so well that it is inappropriate for it to be dealt with in detail here.

TABLE 7. COMPARISON OF RESISTANCE OF DIFFERENT ALLOYS TO IMPINGEMENT ATTACK AS ASSESSED IN JET TESTS CARRIED OUT BY THE BRITISH NON-FERROUS METALS RESEARCH ASSOCIATION AT 15 FEET PER SECOND (1·5–5 PER CENT AIR BY VOLUME ADDED)

Material	Range of depths of attack, mils.	Average depth, mils.	No. of runs (2 specimens in each)
Arsenical copper	4–25	14	5
Admiralty brass* (70/29/1)	5–20	14	8
Aluminium brass (76/22/2)	0–26†	2	8
70/30 cupro-nickel (0·04 per cent iron)	0–13	4	8
70/30 cupro-nickel (0·2 per cent iron)	0–5	1	8
5 per cent nickel, 1·5 per cent iron‡	0–4	1	8
5 per cent nickel, 1·5 per cent iron reheated 600 deg. C. for 30 minutes	1–12	6	5
10 per cent nickel, 2 per cent iron‡	0	0	8

*Admiralty brass was tested in a different series of runs from the other materials in this table.
†One specimen 26 mils. No other greater than 1 mil.
‡Commercial tubes.

Table 7, which is abstracted by kind permission of the Institute of Metals from the forthcoming paper by Bailey, when considered with the comments made in the paper by Gilbert and May,[26] summarizes the position at the present time. The inferiority of arsenical copper and Admiralty brass is clearly indicated, as also is the superiority of the 70/30 copper-nickel alloy of high iron content and aluminium brass. The latter alloy shows a liability to occasional deep attack when conditions are severe.

Worthy of particular note are the two low nickel content copper-nickel-iron alloys listed in Table 7. Both these alloys have been developed by The British Non-Ferrous Metals Research Association and will be described by Bailey. Both the alloys have been shown by the work of the association to have a corrosion resistance of the same order as that of the 70/30 cupro-nickel alloy of high iron content. The alloy of composition 5 per cent nickel, 1·5 per cent iron is a copper-smithing alloy which has already been shown by service experience[17] to be satisfactory to those locations in sea-water trunk lines where copper has failed as a result of impingement attack.

The alloy of composition 10 per cent nickel 2 per cent iron is not a coppersmithing alloy but is suitable for condenser tubes and, though it has not yet been used in this country, has been proved by quite extensive service in the United States.[27]

All these alloys used for condenser tubes depend for their success on the formation of a protective film on the metal surface. It is the properties of this film which decides the adequacy of the resistance of the alloy to attack. A weak film, such as is formed on Admiralty brass, is easily broken by even mild impingement attack and the film on a pure cupro-nickel alloy is only a little more effective. However, the addition of a small percentage of iron to the cupro-nickel or aluminium to the brass results in the formation of a strong adherent film which resists impingement. If the film should be weakened or not formed properly, as in the case of aluminium brass in contact with contaminated estuarine waters, then the performance of the alloy is correspondingly reduced; if the film fractures the effect may be disastrous due to the formation of pits by the electrolytic action between the cathodic film and the anodic basis metal.

There are, therefore, alloys available for the manufacture of condenser tubes and other sea-water pipelines which are resistant to the range of service conditions which may be encountered. The selection of the most appropriate material is dependent on the economic factors involved and the degree of reliability in service which is required.

The use of Naval brass for tube plates has been referred to earlier and, unless conditions are particularly severe, rarely show serious deterioration. Ferrules may be made from Admiralty brass and if these fail in service, both cupro-nickel and aluminium brass ferrules have been found successful.

No section on this subject would be complete without a note on the use of protector blocks. In protector blocks deliberate use is made of the phenomenon of electrolytic corrosion by placing in electrical contact with the metal which is to be protected a piece of another metal less noble, as indicated in Table 1, so that the metal to be protected becomes cathodic and is not corroded whereas the "protector block" is gradually wasted away. Thus the corrosion of steel or iron can be reduced by suitably placed zinc protector blocks, but the combination of greatest interest is the use of steel protector blocks for reducing the corrosion of the non-ferrous alloys in condensers. These steel blocks are bolted securely to the tube plates and not only protect these tube plates from corrosion but also the ferrules and tubes. It is, however, interesting to note that it has been suggested the use of such protector blocks slows down the formation of the protective film on condenser tubes and may, in fact, under certain conditions result in increased attack on the tubes.

(v) Nickel-Base Alloys.[28] There are certain components in marine engineering equipment for which the specific properties of individual nickel base alloys have proved of value.

Pure nickel is a soft ductile material which is resistant to attack by high temperature steam and is frequently used for gaskets in turbine assemblies or steam pipelines.

The alloy of nickel and copper containing 70 per cent nickel and 30 per cent copper with minor additions of manganese and iron, known as Monel, is used in a wide variety of applications in marine engineering. It is resistant to attack by sea and fresh water and steam and this, combined with the good mechanical properties which can be obtained both from wrought and cast Monel products, has led to its adoption for such items as pump impellers and diffusers, for blading in the wet stages of turbines where erosion by water droplets on the rear of the blades is experienced, and steam nozzles in air ejectors.

The possibility of using gas turbines as prime movers in marine engineering is currently being closely examined and has awakened the interest of designers of marine equipment in the

TABLE 8. DETAILS OF ALUMINIUM ALLOYS FOR MARINE PURPOSES

Type of alloy	Specifications		Condition		Minimum tensile properties		
	B.S. General	Similar B.S./STA7			0·1 per cent P.S. tons per sq. in.	M.S. tons per sq. in.	E per cent on 2 inch
1¼ per cent manganese	1470–NS3	AW3C	Sheet	Soft	—	6	30
			Sheet	½ H	—	9	7
2¼ per cent magnesium	1470–NS4	AW4C	Sheet	Soft	—	11	18
			Sheet	⅛H	12	15	5
	1476–NE4	AW4A	Bar	As manufactured	—	11	18
3½ per cent magnesium	1470–NS5	AW5C	Sheet	Soft	6	14	18
			Sheet	¼H	11	17	8
	1476–NE5	AW5A	Bar*	As manufactured	6	14	18
5 per cent magnesium	1470–NS6	AW6C	Sheet	Soft	8	17	18
			Sheet	¼H	14	19	8
	1476–NE6	AW6A	Bar*	As manufactured	8	16	18
0·7 per cent magnesium	1470–HS10W	AW10D	Sheet	Solution heat-treated	7	13	15
1·0 per cent silicon	1470–HS10WP	AW10E	Sheet	Fully heat-treated	15	19	8
	1476–HE10W	AW10A	Bar†	Solution heat-treated	7	12	18
	1476–HE10WP	AW10B	Bar†	Fully heat-treated	15	18	10
5 per cent magnesium	1490–LM5M	AC5	As cast	Sand cast	—	9	3
				Chill cast	—	11	5
12 per cent silicon	1490–LM6M	AC6	As cast	Sand cast	—	10·5	5
				Chill cast	—	12	7

*Up to 2 inch diameter.
†Up to 6 inch diameter.
N.B.   Sheet refers to both sheets and strip.   Bar refers to bars, rods and sections.

materials which have been developed during recent years to resist scaling and creep at high temperatures. It is not possible to give any detailed description of these alloys in this paper but references are quoted which cover the subject very completely, and attention is drawn to the symposium shortly to be held on this subject by The Iron and Steel Institute and which is of great interest to anyone considering these alloys.

(*vi*) *Aluminium Alloys.* Aluminium and its alloys form a continuous and tenacious oxide film which is self-sealing and which possesses a greater inherent resistance to sea-water than do the ferrous metals with the exception of the corrosion-resisting steels.[29] Moreover, this film can be thickened by an electrolytic process of anodic oxidation, thereby still further improving the corrosion resistance. Alloys particularly suitable for marine conditions are mainly of three types:

(a) . Those containing up to a maximum of 5·5 per cent of magnesium, and which are not susceptible to heat treatment. (Although higher contents of magnesium provide good resistance it is not advisable to exceed 5·5 per cent as such compositions are apt to be subject to stress corrosion.)

(b) Those containing small amounts of magnesium and silicon which can be given enhanced tensile properties by appropriate heat treatment.

(c) Alloys containing 10 to 12 per cent of silicon.

Type (a) is used in both the wrought and cast forms, (b) in the wrought and (c) in the cast forms.

Table 8 gives details of some typical aluminium alloys in the above three groups. The coefficient of expansion of the 3½ per cent magnesium alloy, for example, is of the order of 0·000023 per deg. C. for the range 20-100 deg. C. and the thermal conductivity 0·33 c.g.s. units.

As the application of aluminium alloys to marine engineering has already been fully dealt with in the Proceedings[30] it is not considered necessary to give any further details here.

B. Ferrous Materials
(*i*) *Corrosion-Resisting Steels*

Since their introduction some thirty-six years ago stainless steels, or more preferably corrosion-resisting steels, have developed into a wide variety of types which can, however, be conveniently classified into three main groups, according to the

TABLE 9. CLASSIFICATION OF CORROSION-RESISTING STEELS

Group	Type	Normal chemical composition, per cent			Micro-structure	Tensile range available	Official specification
		C	Ni	Cr			
Ferritic (a)	15/18 chromium iron	0·05–0·15	—	15·0–20·0	Ferrite	25–35	—
(b)	25 per cent chromium iron	0·10–0·30	—	23·0–28·0	Ferrite	30–40	—
(c)	25/5 chromium-nickel-iron	0·10–0·30	1·0–5·0	23·0–28·0	Ferrite+ austenite	40–50	—
Martensitic (a)	13 per cent chromium steel	0·06–0·40	1·0 max.	11·5–14·0	Tempered martensite	35–100	En.56, S.61, S.62
(b)	18/2 chromium-nickel steel	0·10–0·25	1·0–3·0	15·5–20·0	Ferrite+ tempered martensite	55–90	En.57, S.80
Austenitic (a)	18/8	0·20 max.	8·0–12·0	16·0–20·0	Austenite	35 min.	En.58A
(b)	18/8 modified	0·20 max. with additions of Ti, Nb, Si, Cu, Mo &c.	8·0–12·0	16·0–20·0	Austenite+ ferrite	35 min.	En.58, En.58B

predominating micro-structure, i.e. ferritic, martensitic and austenitic, and examples of these are shown in Table 9.

(a) *Martensitic Steels.* Dealing with the martensitic 11·5-14 per cent chromium steels first as these include the type of steel originally invented by H. Brearley and used for cutlery, it will be found that they have a similar response to heat treatment to that of medium carbon and alloy steels. Thus the maximum Brinell hardness on quenching will vary from about 400 to 600 according as the carbon content increased from 0·10 to 0·35 per cent. This type of steel has satisfactory resistance to mildly corroding conditions such as water, steam and some chemicals and is employed for steam valve parts, steam turbine blading and has also been used abroad for ships' propellers. Some improvement can be effected by hardening and by polishing. Tempering in the range 400-600 deg. C. should be avoided however. By increasing the chromium content to about 18 per cent, considerably better general corrosion-resistance is obtained as well as improved resistance to scaling. This steel becomes ferritic and does not respond to heat-treatment and consequently has relatively poor mechanical properties from the engineering standpoint. It can, however, be modified by the addition of 1 to 3 per cent of nickel which enables hardening to be achieved by the normal heat treatment methods and provides a useful range of mechanical properties. Apart from use as control spindles, etc., in steam valves, it also has good resistance to sliding contact with carbon and is used for garter springs for carbon rings in turbines.

(b) *Ferritic Steels.* The low carbon 25/30 chromium type of steel is ferritic but because of its coarse grain is rather brittle especially at 25 per cent chromium. This can be largely overcome by the addition of nitrogen and nickel[32] which produces a ferrite + austenite structure with a small grain size. The hardness of the 25/5 chromium-nickel steel can be considerably increased by a precipitation hardening treatment at about 730 deg. C., values of about 500 D.P.N. being obtained, but this is accompanied by a very low Izod impact value. Such

susceptible to attack in the form of pitting by chloride ions. The main contribution of chromium to corrosion resistance is for oxidizing conditions and usually 17 to 19 per cent of chromium is adequate for most industrial applications. Nickel exerts a marked influence on both the constitution and structure, in particular in ensuring the austenitic condition, and also it extends the corrosion-resistance to applications involving lower oxidizing conditions as well as supplying improved resistance to neutral chloride solutions. The optimum resistance to corrosion of this group of steels is obtained in the soft annealed and descaled or polished state.

Although this group is often referred to as the 18/8 chromium-nickel type, it really consists of a wide range of compositions due to the addition of various elements for specific purposes and as a result the structure may not always be wholly austenite as is the case with the original 18/8 steel.

The main types of austenitic corrosion-resisting steels are the straight 18/8, a low carbon 18/8 type which is used for deep drawing and spinning, the 12/12 type which is used for a similar purpose but has not such good corrosion-resistance due to its lower chromium content, the 18/8 type stabilized with either titanium or niobium (columbium), and the molybdenum bearing type which usually contains 2 to 4 per cent molybdenum. This addition has the effect of inhibiting a tendency to pitting in such media as chlorides, sodium and calcium brines, etc.

The austenitic steels are more difficult to machine than ordinary low or medium alloy steels but the addition of such elements as sulphur, molybdenum, zirconium, selenium and phosphorus effects considerable improvement at the sacrifice of some corrosion resistance, although in this respect selenium is preferable to sulphur. The addition of these "free-machining" aids also improves the resistance to galling in sliding contact.

Table 10 gives details of the physical properties of typical corrosion-resisting steels.

TABLE 10. TYPICAL PHYSICAL PROPERTIES OF CORROSION-RESISTING STEELS

Steel specification No.	Type	Chemical composition, per cent				Heat treatment, deg. C.	Tensile properties			Izod impact, ft. lb.	Coefficient of thermal expansion $\times 10^6$ at 20 deg. C.	Thermal conductivity at 20 deg. C. c.g.s. units
		C	Ni	Cr	—		Y.P. tons per sq. in.	M.S. tons per sq. in.	E per cent			
	13 per cent chromium iron	0·11	0·55	12·4	—	OQ 950; T 730	33	41	29	92	11	0·059
	13 per cent chromium steel	0·27	0·28	13·2	—	OQ 970; T 700	39	48	27	91	11	·058
	{ Ball bearing quality	0·40	—	11·5	—	OQ or AH 1000	BH No. about 560				11	0·056
	{ High carbon stainless	0·80	—	17·0	Mo 0·5	OQ or AH 1050	BH No. about 600				11	0·056
	15/18 chromium iron	0·10	0·3	17·9	—	AH 950; T 600	22	29	37	5	10	0·052
	18/2 Cr-Ni steel {	0·09	2·1	17·8	—	AH 950; T 600	34	43	28	85	10	0·045
		0·15	2·50	16·9	—	OQ 1000; T 620	52	59	21	53		
	25 per cent Cr iron	0·11	1·12	25·2	*	WQ 1150	31	43	46	97		
	25/5 Cr-Ni iron	0·12	4·5	26·0	—	WQ 950	30	42	32	40	11·3	0·05
	18/8	0·12	8·6	18·0	—	WQ 1050	14	38	50	100	17	0·036
	18/8 stabilized	0·12	8·0	18·0	Ti 0·60	WQ 1050	18	42	45	80	16	0·038
	18/8 stabilized	0·12	10·0	18·0	Nb 1·2	WQ 1050	17	41	58	80	17	0·038
	18/8 low carbon	0·05	10·0	19·0	—	WQ 1050	15	40	60	80	16	0·038
	12/12 Cr-Ni	0·10	12·5	12·5	—	WQ 1000	15	37	50	100	18	0·037
	18/8Mo stabilized	0·07	8·0	18·0	{ Mo 3·25 Ti 0·30	WQ 1050	18	40	50	80	16	0·039
	18/8Mo	0·07	9·5	18·0	Mo 1·25	WQ 1050	17	40	50	80	17	0·040

*0·24 per cent nitrogen also present.

treatment can be used for pump parts where normally seizure is liable to be encountered and where resistance to shock is not required.[33] Steels of this 25/30 chromium type possess very good resistance to scaling and are dealt with more fully in the section dealing with heat-resisting steels.

(c) *Austenitic Steels.* The third group of austenitic steels is of considerable importance in the corrosion field because of the resistance to a wide variety of media, the lack of which is a drawback to the straight chromium type which is rather

(ii) *Heat Resisting Steels*

As resistance to scaling, etc., at elevated temperatures is closely related to corrosion-resistance, it is convenient to discuss the heat-resisting steels at this stage. These can be divided into three main groups:—

(a) 3 to 10 per cent chromium.
(b) 11 to 30 per cent chromium.
(c.1) Austenitic chromium-nickel—
13 to 30 per cent chromium

TABLE 11. HEAT-RESISTING STEELS

Type	Typical chemical composition, per cent					Heat treatment, deg. C.	Tensile properties		Maximum service temperature, deg. C.*	Coefficient of thermal expansion per deg. C. at 20–100 deg. C. ×10⁶	Thermal conductivity, c.g.s. units at 20 deg. C.
	C	Si	Ni	Cr			Y.P., tons per sq. in.	M.S., tons per sq. in.			
2–3 per cent Cr-Mo	0·2	0·3		2·0/3·0	Mo 0·5/1·0	A.850	18	30	600	13·0†	0·08
4–6 per cent Cr-Mo	0·15	0·3		4·0/6·0	Mo 0·5/1·0	A.850	13	31	650	12·5†	0·065
7–9 per cent Cr-Mo	0·15	0·3		7·0/9·0	Mo 0·5/1·0	A.850		36	700	12·0†	0·055
8 per cent Cr-Si	0·45	3·5		8·25		{ OQ.1000 / T.675	42	56	800	13·0	0·055
13 per cent Cr	0·35	0·4		13·0		{ OQ.975 / T.700	35	50	750	10·0	0·055
16–18 per cent Cr	0·12	0·3		17·0		A.C.780	21	32	850	10·4	0·07
20–22 per cent Cr	0·10	0·3		21·0		AC or WQ 750	26	35	1000	10·0	0·05
25 Cr	0·2	0·5		25·0		AC.780	21	32	1100	10·4	0·05
26/4 Cr-Ni	0·10		4·5	26·0		WQ.950	30	42	1100	11·0	0·05
30 Cr	0·20	0·7		30·0		{ OQ.1050 / T.700	22	34	1150	10·0	0·03
30/2 Cr-Ni	0·10	1·0	2·0	30·0		WQ.780	23	35	1150	10·0	0·04
13/13/3 Cr-Ni-W	0·45	1·0/2·5	13·0	13·0	W 3·0	A.950/1020	34	60	800	17·0	0·033
18/8 (stabilized)	0·12	0·75	8·5	18·0	Ti 0·6	A.950/1150	16	42	800	16·0	0·038
20/7/3 Cr-Ni-W	0·3	1·25	7·5	20·0	W 3·5	A.950/1020	30	55	1000	16·0	0·033
24/12/3 Cr-Ni-W	0·2	1·5	12·0	23·5	W 3·0	AC.1050	26	46	1050	15·0	0·03
25/20 Cr-Ni	0·20	1·75	21·0	25·0		AC.1050	20	41	1150	15·0	0·03
17/37 Cr-Ni	0·20	2·0	17·0	37·0		AC.1050	25	45	1100	13·0	0·03

*Under oxidizing conditions.
†Temperature range 20–450 deg. C.

7 to 25 per cent nickel.

(c.2) Austenitic nickel-chromium—

    25 to 36 per cent nickel

    12 to 20 per cent chromium.

All the above types may also have present small amounts of silicon, aluminium, tungsten and molybdenum. Table 11 gives suggested maximum range of temperature in which these various grades of heat-resisting steels can operate together with some physical property data.

(a) *3 to 10 per cent Chromium Steel.* The 3 to 10 per cent chromium group comprise a series of chromium-molybdenum steels varying from 3 up to 10 per cent chromium and containing about 0·5 to 1·0 per cent molybdenum which have been primarily developed for the oil industry for applications involving creep strength at intermediate temperatures up to about 700 deg. C. coupled with corrosion resistance to crude oils and sulphur compounds.

Also in this group will be found the well-known Silchrome valve steel (En.52) which for many years was the standard material for motor car exhaust valves. The general adoption of motor fuel treated with tetra-ethyl lead has created the need for a steel having better corrosion resistance and this has been met by the development of Silchrome XB steel (En.59) which is now being increasingly adopted. The 13/13/3 nickel-chromium-tungsten valve steel (En.54 or D.T.D. 49B) is employed for exhaust valves when more arduous conditions arise such as for aero-engines and marine Diesel engines. In cases where still better corrosion-resistance is required, it is the practice to coat the head and seat of the valves with "Brightray" an 80/20 nickel-chromium alloy.

(b) *10 to 30 per cent Chromium Steels.* The straight 25-30 per cent chromium type of steel possesses very good resistance to scaling at high temperatures especially in sulphurous atmospheres. Owing to their rather brittle nature and low elevated temperature strength they should not be employed in applications involving shock loading and severe stresses. Heating at 900-1,000 deg. C. leads to grain growth accompanied by embrittlement which cannot be removed. The addition of up to 5 per cent nickel inhibits this grain growth in the region of 1,000 deg. C. and also has the advantage of making it somewhat easier to obtain satisfactory welds.

(c) *Austenitic Steels.* In order to obtain increased strength at elevated temperatures it is essential that the steel shall be in the austenitic condition with the added advantage that a good degree of toughness is also provided. There is a wide variety of steels in this range to suit most conditions of service as will be seen from Table 11. It might be advisable at this stage to refer to the effect of sulphur. The severity of the attack due to sulphur depends on the atmosphere, i.e. it is not very harmful if oxidizing conditions prevail and a high percentage of chromium is present. It is much more dangerous however under reducing conditions since sulphide corrosion products are less protective than oxides. High nickel content steels are subject to attack in a sulphur atmosphere but for those applications in an oxidizing atmosphere where toughness is essential, which means the employment of an austenitic steel, then it is preferable to choose a steel with a high chromium content, say 25 per cent, and low nickel, say 7-12 per cent.

An important application of corrosion or heat-resisting steels is for blading in steam turbines and this particular aspect has already been covered in an excellent paper by J. H. G. Monypenny.[36] It may, however, be of interest to refer to Fig. 10, Plate 4, which demonstrates, as has been stated earlier, the superiority to the effect of saline contamination in steam

TABLE 12. SPECIAL CAST IRONS

Cast iron	Main use	Chemical composition, per cent					Tensile strength tons per sq. in.	B.H. No.
		Total C	Si	Mn	Ni	Cr		
"Ni-Resist"	Resistance to corrosion and heat	3·0	1·5	1·0	14·0*	2·0	12	180
"Nicrosilal"	Resistance to heat	1·7	4·5	0·8	18·0	2·0†	12	180
Low-Expansion	Low thermal expansion	2·2	1·5	0·8	34·0	2·0	12	180

* The normal "Ni-Resist" also contains 7·0 per cent of copper. If copper-free metal is desired the nickel should be increased to 22·0 per cent.
† For hard grades the chromium may be increased to 5·0 per cent.

of the austenitic steels to the straight chromium type. In this particular case erosion also played a part. The 25/12 chromium-nickel steel in the form of castings is often favoured for superheater spacers.

(iii) Cast Iron

Various types of cast iron have been developed to resist corrosive conditions. These include the high-silicon irons containing up to 18 per cent silicon which resist many acids (with the exception of hydrofluoric acid and hot concentrated hydrochloric acid), also conditions involving "wet" chlorine and solutions containing copper salts. They are, however, very weak and brittle and are very hard and unmachinable which factors limit their application. High chromium irons containing 24 to 35 per cent chromium provide good resistance to rusting and scaling as well as nitric acid and strong caustics.

The most commonly employed corrosion-resisting iron is that known as Ni-Resist, particulars of which are given in Table 12. Such iron is relatively tough, soft and readily machinable. Its rate of rusting is much lower than that of ordinary cast iron or steel and in addition it resists scaling at elevated temperatures without growth. Ni-Resist shows a high degree of resistance to sulphuric acid, various organic acids such as acetic, oleic, etc., and to alkalis and caustics. Mention may also be made of a 34 per cent nickel cast iron, which was primarily developed for low thermal expansion purposes, and Nicrosilal which has specially good heat resistance, both of which possess a good degree of resistance to corrosion. Ni-Resist and Nicrosilal are both incidentally non-magnetic.

The new magnesium process for increasing the strength of cast iron by developing the spheroidal form of graphite is also being applied to the corrosion-resisting cast irons with marked success.

C. Metallic Coatings

(i) *Electro-deposited Coatings.* Cases may arise when it is not expedient to employ a corrosion-resisting metal for a

TABLE 13. HARDNESS OF ELECTRO-DEPOSITED METALS COMPARED WITH THE ANNEALED OR CAST OR WORKED STATE

Metal	D.P.N. hardness		
	As electro-deposited		As annealed, cast or worked
	Normal practice	Maximum range known	
Chromium	750–950	400 to >1050	65 to >120
Platinum	600–640		45 to >110
Rhodium	590–640		100 to >150
Nickel	230–450	120–550	65–300
Palladium	180–430		45–110
Cobalt	200–380	160 to >400	80 to >300
Iron	180–300	140 to >370	65–150
Copper	65–120	50–300	30–100
Silver	60–130		25– 65
Cadmium	15– 30	15– 50	17– 35
Zinc	35– 50	35– 50	30– 50
Tin	8– 25	8– 25	8– 22
Lead	8– 25	8– 25	8– 22

component because it either has not the desired engineering properties or because economic considerations rule it out. In such an event the employment of an electro-deposited coating will often solve the problem.

Many metals can be electro-deposited, such as zinc, cadmium, copper, tin, nickel, chromium, etc., as well as alloys such as copper-tin, nickel-tin, nickel-cobalt, etc., and details of the hardness range of several metals are given in Table 13.[41]

In many quarters electro-deposition is looked upon as a means of providing decorative results only and it is not always generally appreciated that quite thick deposits of a metal can be produced and, moreover, that these deposits can be laid down on to the basis metal with a high degree of adhesion provided that the necessary precautions are taken in the pre-

liminary cleaning and etching operations prior to the actual electro-deposition. Typical examples of the degrees of adhesion as determined by the Ollard adhesion test which can be obtained are shown in Table 14.[41] For many years nickel has

TABLE 14. TYPICAL ADHESION VALUES OF ELECTRO-DEPOSITED NICKEL TO VARIOUS METALS.

Underlying or basis metal	Adhesion, tons per sq. in.	Location of fracture
Mild steel rolled bar	28	In steel
3 per cent nickel steel, forged	32	In steel
Ni-Cr steel, hardened and tempered	21	In steel, near interface
Case-hardened steel	21	In steel, near interface
Cast iron (pearlitic)	7	Near interface
Nickel-coated mild steel	28	In nickel
Copper, extruded rod	18·5	In copper
70/30 brass	23·5	In brass
60/40 brass	19·2	In brass
Phosphor-bronze	15	In phosphor-bronze
Aluminium	3·5	In aluminium
Hot dipped tin coating on mild steel	1·8	In tin coating
Electro-deposited lead on mild steel	1·0	In lead coating

been the main metal used for building up worn parts or correcting over-machined parts having superseded iron during the 1914-18 war. In more recent years chromium has also been employed especially where high hardness or improved resistance to wear is desired. In those cases where it is necessary to apply heavy deposits it has been found more satisfactory first to deposit nickel and then to finish off with chromium which, because of its hardness, is better able to resist galling, etc. Such metals provide an easy means of combating corrosion fatigue and nickel is extensively used for protecting turbine blading when made from carbon steel or 5 per cent nickel steel. Corrosion fatigue tests carried out by the N.P.L.[40] give some indication of the beneficial effect. Mild steel having a tensile strength of 32 tons per sq. in. was coated with nickel by the Fescol process and corrosion fatigue tests carried out in a fine spray of 3 per cent common salt solution gave values of + 12·2 and + 7·3 tons per sq. in. for the protected and unprotected steel respectively, i.e. an improvement of 67 per cent.

It should be pointed out that when some metals such as chromium, cobalt, iron, nickel, etc., are electro-deposited on to, say, steel there may be some reduction in the actual fatigue strength in air owing to the fact that a tensile stress is present in the deposited metal. It is not always possible to choose plating conditions which avoid this but in the case of nickel considerable improvement can be effected by the application of cold work such as shot peening.

(ii) *Other Metallic Coatings.* Besides the use of electro-deposition, metallic coatings can be applied in various ways, of which the following are examples:—

(a) Sherardizing. This is a process by which the surfaces of steel articles are actually impregnated with zinc in the form of zinc-iron alloys by heating in an atmosphere of zinc dust. Whilst not producing corrosion resistance quite as good as that obtained by galvanizing or electro-deposition, nevertheless this process does give satisfactory results.

(b) Calorizing. In which the surface of the metal is impregnated with aluminium which provides a surface having a certain amount of corrosion-resistance but more especially resistance to scaling.

(c) Chromizing. In this process there is an actual replacement of iron atoms by chromium atoms, so that a chromium rich case forms on the surface.

(d) Metal spraying. In many cases where it is difficult to produce hot-dip coatings on to a component it may be suffi-

cient to spray the metal by one of the well-known metal spraying processes.

(e) *Cladding.* A protective coating on steel can be produced by hot rolling a composite slab, the final product having a thin coating of nickel or 18/8 steel as the case may be and which not only forms a continuous non-porous coating but also adheres strongly to the steel.

In the case of high tensile aluminium alloys such as the duralumin or super-duralumin type, which are affected by sea-water corrosion, corrosion protection is provided by cladding sheet or plate with a layer of pure aluminium or an alloy of the magnesium-silicide type, the cladding usually having a thickness about 5 per cent of the whole. The cladding acts in the same sacrificial manner as does zinc in the case of steel.

CONCLUSION

Corrosion problems met in marine engineering vary considerably from installation to installation, but it can safely be said that there are available to marine engineers materials resistant to practically all conditions of service. This does not mean to imply that the use of a resistant material is the answer to all problems for in many cases a change to such a material would not be an economic proposition. It is, however, frequently possible by careful examination of a corrosion or erosion problem to arrange for a compromise by which, by small redesign of equipment and the adoption of an alloy slightly more resistant to the service conditions than that previously used, an economical answer can be obtained.

This question of design has been adequately stressed by Slater, Kenworthy and May but it is re-emphasized as, in the authors' opinion, it remains one of the principal factors in overcoming corrosion and erosion problems. Good mechanical design must, however, always be accompanied by the correct selection of materials of construction, and if this paper has in any way assisted by indicating the general principles of corrosion and the general properties of corrosion-resisting metals used in marine engineering, its purpose will have been served.

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Discussion

DR. J. E. GARSIDE said he was glad that the authors had stressed the point of electrolytic corrosion, a point often overlooked by marine engineers but which was quite vital. Such corrosion depended, of course, upon the individual electrode potentials of metals and alloys.

One did not always realize the seriousness of differential oxygenation in causing corrosion, a subject which was touched upon in the paper. Mr. Johnson had mentioned it when he spoke of a crack, and the way in which the different oxygen concentration at different parts of the electrolyte enveloping the metal could give rise to an anode at one point and a cathode at the other. That was all very true but it was also true that one had to consider objects and structures immersed to a large degree in various liquids. In such connexions the problem of waterline corrosion was a very serious one indeed; it was one which they had all encountered and it was not easy to see how one could combat it without using highly corrosion resistant materials and usually very costly materials. The number of points given in the paper were indeed valuable because they indicated how one could overcome this defect by using different types of materials.

Pitting was important, he stressed. One point which had possibly been overlooked was that pitting usually arose because of coring which was present, which was very common in cast objects. One came across that to quite a pronounced extent in some cases. A little more thought might be given by engineers to that aspect of corrosion.

A point which he thought was very much related to stress corrosion was the problem of caustic embrittlement; by which he meant the embrittlement of boiler steel by caustic soda. It was true that one could combat this by use of tri-sodium phosphate but this was somewhat costly. If the boiler pressure was not very high, that is to say not above 250lb. per sq. in., it could be combatted more cheaply by the use of sodium carbonate. That was a point he considered worth mentioning and he wanted the authors' opinions on it.

Mention had been made of season cracking sometimes occurring in brasses. He had read fairly recently about a process called the "Soro" process and he understood that brasses produced by that process were not susceptible to season cracking, or, at the worst, only very slightly. He would be grateful to the authors for comment on that point because if one was able to produce brasses not susceptible to season cracking it would be of great assistance. He had not heard of the process being used in this country, but it had been used in Germany and Switzerland: that was as far as his knowledge went.

He was a little surprised not to see more mention of aluminium and its alloys. He thought that they deserved quite an important place in marine engineering papers because, as they all knew, they were now having funnels, cowlings and superstructures made of aluminium alloys; they had been used for a long time for ships' lifeboats and they had a quite excellent corrosion resistance. They were worthy of a greater consideration than perhaps might have been thought. He wondered whether the authors could tell of any application in marine engineering to which these particular alloys had been applied.

With regard to austenitic stainless steels, they were diffi-cult to machine in the ordinary way unless one made an addition of sulphur or selenium and then the corrosion resistance suffered. In the paper the authors made no mention of lead, and he would be glad to have the authors' opinions on its usefulness in this connexion.

The authors quite rightly thought it was necessary to draw to one's attention cast iron. Indeed, from a marine engineering point of view cast iron was quite important, one could think of many applications to which it could be put, crankshafts for Diesel engines and the like. He wondered what was the corrosion resistance of cast irons, say of the innoculated type, compared with cast irons of the nodular type.

Metallic coating came into the discussion when one was talking about corrosion resistant materials. He thought that some of the fairly recent introductions in alloy deposition might have quite important applications in marine engineering. He was thinking of some electro-deposits such as speculum which might even have application for instrument cases and so on. This particular branch of technology was worthy of consideration, and one should keep one's eyes on it with regard to the use of those alloys on engineering.

Metal spraying was a very important process of metal coating. He thought that it ought to be pointed out that when one was spraying zinc on steel it did not matter very much if there was a certain amount of what might be called "granularity" because of the voltaic cell effect, to which the authors had already made reference. That this sacrificial corrosion of zinc is a very real process is borne out by the fact that the Menai Bridge had been sprayed at the commencement of the recent war and it was still in very excellent fettle. That perhaps augered well for the way in which zinc on steel could stand up to corrosion conditions of a marine type. He thought that possibly a good deal of equipment on deck might with advantage be metal sprayed with zinc *in situ*.

Talking about spraying one very naturally found one's mind moving not to the spraying of metal, but the spraying of plastics; the flame spraying of plastics was a fairly new field but it was of considerable importance already in many directions. That process ought to be kept in view, because there were some parts of marine structures which might well be sprayed with plastics and so given an enhanced resistance to corrosion.

The authors had mentioned nickel being "clad" on alloy steels, carbon steel or aluminium alloys, but there was the "Soro" process to which he had made reference. He understood that one could produce a bi-metallic strip by that process and, if that was so, there was an excellent method of producing a very firmly adhering metal coating of one composition on top of another of different composition; and he felt that the process might have the advantage over the ordinary type of "cladding" process.

Reference had been made to zinc protector plates. He was not very sure about their continued use and would like to leave a question with the authors. He was under the impression that the Admiralty had suggested that the practice of zinc protector plates be put in abeyance for the time being, but he was not sure of that. He would also be glad if the authors would say whether the good that was done by zinc protector

MR. H. F. SHERBORNE, M.C., M.A. (Associate) said that most of those persons who had the misfortune to be engaged in the non-ferrous metal industry had been busily occupied during the last two or three months trying to get some of the metals to do many of those things described in the paper and it would be nice when they could get the zinc with which to do the spraying to which Dr. Garside had referred.

The only part of the paper on which he considered himself really competent to comment in any detail was the part of it which referred to tubes, and in particular tubes for heat exchangers, of which the principal manifestation to the marine engineer was the condenser tube and also pipes for conveying salt water.

One thing he thought was particularly excellent was the bibliography, which was very comprehensive, and possibly it was not inappropriate to make just two quotations from a previously published paper although not included in the bibliography.

The authors said in their opening paragraph that some considerable time had elapsed since an attempt was made to collect useful information on the application of corrosion resisting materials in marine engineering and present it in a compact form which would be of use to builders and users of marine engineering equipment. It seemed to him that having regard to all that was going on and appeared likely to go on in shipbuilding and therefore marine engineering, the paper was well and appropriately timed. The authors said in their concluding paragraph it could safely be said that there were available to marine engineers materials resistant to practically all conditions of service.

To get this in proper perspective it was necessary as usual to look back a little. It was less than twenty-five years ago that no less a person than Sir Charles Parsons had said in a paper which he presented to the Institution of Naval Architects entitled "Some Investigations into the Cause of Erosion of the Tubes of Surface Condensers" published in the Transactions of the Institution of Naval Architects, 1927, Vol. LXIX

"The problem of the failure of the tubes of surface condensers is so well known that it seems only necessary here to allude to a few of the salient facts bearing upon the question. Whilst no adequate explanation has as yet been assigned for such failure, many attempts have been made to overcome it. On the theory that it is caused by electrolytic corrosion, counter-electromotive force has been applied to neutralize the action, on the theory that it arises from chemical action, such means as coating the inside of the tubes with a bituminous paint or with a protective scale of oxide have been tried. None of these measures have proved to be more than palliative in their effects, and sometimes not even that".

It seemed that a very remarkable piece of progress had been made over a relatively short period. In the discussion on Sir Charles Parsons' paper, Mr. Sterry B. Freeman was reported as having said:

"Some months ago, on a visit to his works at Wallsend I ventured to tell Sir Charles that in my judgment he ought to direct his wonderful gifts to fathoming the causes and prevention of condenser tube troubles because that was the greatest stumbling block in the path of extending the use of turbines for marine propulsion".

He hoped that this little historical reference would be thought to be worth while.

There were five points about which he had made a note and he wanted to speak about them not only in the interrogative but particularly with a view to getting the thing cleared up a little.

The first of them was on p. 68 of the paper:

"All these alloys used for condenser tubes depend for their success on the formation of a protective film which decide the adequacy of the resistance of the alloy to attack. A weak film, such as is formed on Admiralty Brass, is easily broken by even mild impingement attack and the film on a pure cupro-nickel alloy is only a little more effective".

That was the first time, he thought, that he had seen that statement in print and it was high time it was said. Copper nickel without the iron and without manganese was no more use than brass, and brass was no use at all.

The next point in connexion with this particular aspect of the subject, namely the vital importance of minor constituents, was dealt with on p. 66 of the paper under the subheading "Copper-Zinc Alloys" in the second paragraph.

"It has been previously mentioned that one of the principal mechanisms of corrosion of these alloys is dezincification. This type of failure occurs with alloys of high zinc content but rarely with those of lower zinc content or with special additions to prevent dezincification. Thus, in general, alloys with more than 85 per cent of copper or alloys containing additions of tin, say 1 per cent, antimony, say 0·25 per cent, or arsenic, say 0·25 per cent, are more resistant to this form of attack, though under severe conditions dezincification may still occur".

There was obviously something wrong there with the figuring because the proper amount of arsenic in aluminium brass or brass (not that anyone would put brass in a ship but there were a quantity of land power stations still using brass where the circulating water was reasonably clean) was 0·02 to 0·05 per cent, not 0·25 per cent. It might be there was some confusion with the arsenical content of copper for main and general engineering purposes which was 0·3 to 0·5 per cent.

In the Table on p. 64 there were distinctions drawn between degree of resistance in the first column headed "Resistance to dezincification or analogous corrosion". The highest grading was "immune". Obviously if the alloy had no zinc it could not dezincify.

As regards inhibited aluminium brass, however, by which he understood arsenical aluminium brass containing 0·02-0·05 per cent arsenic, he would like to say that in his experience there had never yet occurred a case of dezincification. He had never been able to hear of a case in anyone else's experience either. If anything different was known he would like to be informed specifically.

There was another point referred to also by the previous speaker which he wished to touch on, and that was on p. 68, where mention was made of "steel blocks".

"These steel blocks are bolted securely to the tube plates and not only protect these tube plates from corrosion but also the ferrules and tubes. It is, however, interesting to note that it has been suggested the use of such protector blocks slows down the formation of the protective film on condenser tubes and may, in fact, under certain conditions result in increased attack on the tubes".

That statement came as somewhat of a surprise and he wondered for a moment if it was possible that there was some confusion between steel or iron blocks and zinc blocks. Zinc blocks should be kept away from the tubes of condensers in all circumstances. He believed it was right to say that in some parts of the hull certain types of brass fittings were still used and zinc blocks were useful but certainly not in the condensers. If one was talking of steel blocks he did not see what harm they could do.

The fourth point was one which if there turned out to be anything in it might conceivably be of very considerable importance. It related to the suggested greater efficiency as regards vacuum of the aluminium brass tube over cupro-nickel. It was accepted that the thermal conductivity of aluminium brass was many times better than that of cupro-nickel but that had not be regarded as of any great practical importance because what really determined the heat transference of a condenser

tube was not the thermal conductivity of the metal wall of the tube but rather the nature of the films that formed on the inside and outside of the tube. A good deal had been made of this point recently in connexion with land power station design and based only in that case on the relative thermal conductivities of the two alloys. As regards marine experience, however, there had been a most interesting reference by Com'r(E) W. B. S. Milln, R.N., in his contribution to the paper before the Institute of Metals "Corrosion and related Problems in Sea-Water Cooling and Pipe Systems in H.M. Ships" by Kenworthy, May and Slater. The only report of it appeared to be in *Metal Industry* for 17th November 1950: — •

"Mentioning one point on the Paper by Kenworthy, May and Slater which had only just come to their notice, Com'r Milln of the Admiralty said that on page 318 the authors said: —

'Aluminium brass possesses better thermal conductivity properties than cupro-nickel, but the significance of this difference in a condenser is still being investigated'.

The significance of that difference had just hit them violently between the eyes, because they had fitted cupro-nickel tubes in destroyers in condensers which were basically designed for the original Admiralty brass. During the war, as Churchill remarked, they had no 'condenseritis', and they could not understand it. They still had no 'condenseritis', but what they had got was fouling of the condenser tubes to a degree which knocked the full power vacuum, particularly in the Mediterranean and tropical waters, back to about 22in. which had an effect not only on the speed but also on the range of ships. They had been faced with the problem of getting a high vacuum back. There were only three methods which they had thought of: one was to re-tube, which was expensive and not convenient; another was to try and clean it out mechanically, which had not been successful in experiments which had been tried; and so they had had to fall back on the third, and rather boldly, in one or two selected ships, they had tried cleaning it out with acids inhibited against metallic attack. That had had the desired result, in that they had had a report from the Mediterranean the other day saying that a ship which had had the condenser cleaned in that way achieved 27in. of vacuum in that one, as against 22in. in the uncleaned one, in a sea-water temperature of 80 deg. F. He asked the authors what was going to happen now? Had they by introducing a dilute acid—only 3½ per cent sulphuric acid—started another cycle of corrosion, and possibly 'condenseritis'? If they had, then they would be a bit foxed. Experiments were going on at the moment to see whether the degree of dezincification of tube plates was severe, but there seemed to be no method of protecting the tube plate. They had taken advice from various people who had tried this chemical descaling, and at the moment they were not sure whether this acid cleaning was a success or whether they would have to fall back on re-tubing in aluminium brass or some other material which had a higher conductivity. Cupro-nickel also fouled to some extent, but took rather longer. If they were going to stick to cupro-nickel, it looked as though a method of cleaning the condensers without a great deal of taking them to pieces would have to be found".

The author in his reply dismissed it very scantily and said:

"The solution of the point raised by Commander Milln was simple. If he would keep the water moving in his condenser tubes with a speed of 2ft. (sic) a second, fouling organisms would never settle, and when the condensers were not in use they should be emptied".

Members would appreciate that that had nothing to do with the point raised by Commander Milln at all. It did, however, raise a practical point of great importance. If any of those concerned with the practical running of marine engines had any experience bearing on this point it would be of very great interest.

Finally, on the subject of pipes and the question of copper-nickel-iron, or aluminium brass, he was a little puzzled to justify the 30 per cent extra cost of the former over the latter. One still had to think a little in terms of the cost of those things. The question of copper-nickel-iron *versus* aluminium brass for salt water constantly arose. Copper for this purpose was finished: therefore it would have to be one or the other of those two. He thought that Mr. Bailey might have something to say on that subject, but someone ought to get a clear line on it for the benefit of the marine engineer who had to decide what to put in his ship. He had had some figures worked out for a range of typical copper-smithing sizes and copper-nickel-iron proved to be 30 per cent more expensive than aluminium brass. In a paper before the Institute in 1947,[*] Mr. John Lamb in reply to some questions he (Mr. Sherborne) had asked him, had then referred to the fact that he had had completely satisfactory service from aluminium brass.

"In many of their ships they had experienced serious trouble with wastage of copper pipes of salt water systems, especially in recently built ships. Some of the pipes lasted only six or seven months. For the sea water services of ships built in the years immediately before the last war, they specified tungum for some and aluminium brass for others, and in both cases the results had been very satisfactory. No wastage of any account had been reported in pipes made of these materials".

Why then was it necessary to look any further for pipes carrying sea-water? He appreciated that stagnant as opposed to moving sea water opened up another chapter.

MR. J. WILKINSON said that there was one point on which he would like to say a few words, and that was the question of the influence of iron on the corrosion resistance of the cupro-nickel alloys.

He thought he might make his point more clearly if he went through very briefly the development of cupro-nickel alloys for condenser tubes, which was the only thing of which he had had experience. In the early 'twenties when they first made cupro-nickel alloy tubes, they started off with the 15 per cent nickel alloy and later made the 20 per cent nickel alloy. Attempts to keep the alloys pure were not always successful and in many of the casts there was some iron. Later the 70/30 cupro-nickel alloys were produced and at that time the Admiralty specification had demanded a pure copper-nickel. After tubes had been in service for some time it was found that the tubes which had failed and been returned for examination were 85/15 cupro-nickel or 80/20 cupro-nickel with very low iron and manganese contents, and the failures had been due to pitting and not always impingement attack. They knew that they had supplied a large quantity of cupro-nickel tubes with iron in the alloy and were inclined to the view that iron was beneficial rather than harmful, and they gradually built up the iron content of these alloys until it came to the point when the British Admiralty had said "these tubes will not do, there is too much iron in them" and they had to take them back. Some very valuable work on the cupro-nickel alloys was done by the British Non-Ferrous Metals Research Association in the year 1928 and onwards and it had been found eventually that iron was a very desirable constituent of cupro-nickel and a specification was produced which allowed a small amount of iron, something in the region of 0·5 per cent. Later on, because of the results of further research, the British Admiralty specification demanded a minimum iron content of 0·4 per cent and allowed up to 1·0 per cent. It was quite obvious that it was a most important constituent.

* Lamb, J. 1947. Trans.I.Mar.E., Vol. 60, p. 1. "The Burning of Boiler Fuels in Marine Diesel Engines". (See Discussion p. 36.)

In the paper the authors had stated that cupro-nickel which was pure was little better than a brass but they had not amplified the statement "high iron content". It was, he thought, reasonable to say that an iron content of less than 0·4 per cent as was now specified by the Admiralty was not high and 0·4 to 1·0 per cent was a reasonable quantity. One was rather inclined to look upon a high iron content as something in the region of 1·75 to 2·25 per cent. This conclusion had been reached because in the early 'thirties there had been cases where the ordinary cupro-nickel with a moderate iron content had not stood up to impingement attack by sea water with solids in suspension. They had made trials with tubes of an alloy containing 1·5 per cent of iron and these were obviously so much better that they had made later trials with a 30 per cent nickel alloy containing 2 per cent iron; they had, incidentally, used 2 per cent manganese so that the alloy had been almost Monel with the copper and nickel contents reversed. If one could accept that a high iron content was something in the region of 1 per cent or more, he would like to ask the authors to reconsider the statement made on page 68 where they said that the last two alloys mentioned in Table 7, i.e. the 5 per cent nickel with 1·5 per cent iron, and the 10 per cent nickel with 2 per cent iron, were as resistant to corrosion as the 70 per cent alloys with high iron content. He was quite certain that the 5 per cent nickel alloy was nothing like so good in its resistance to either impingement attack or to pitting attack as 70/30 cupro-nickel with more than 1·0 per cent iron.

There was also a point in Table 5 on page 64, and he wondered if this was a misprint because there was a reference to cupro-nickel alloys containing over 10 per cent nickel and they were shown as being extremely good, almost the best in the Table. He wondered whether the nickel content referred to was correct or whether there was some other constituent which was not specified.

MR. G. L. BAILEY said he was glad to accept an invitation to take part in the discussion because he had a great respect for people who could put together so much information in so concise and useful a way. It was inevitable, however, that in so wide a paper there would be a number of points with which everybody did not exactly agree and there were one or two points on which he desired to touch. If he picked out the points with which he did not agree and they appeared to be relatively insignificant, that only showed how much he liked the paper as a whole.

He referred to the passage on page 68 which had also been referred to by Mr. Wilkinson, which dealt with copper-nickel-iron alloys of low nickel content. In the first place, Table 7, which had been quoted from an advance copy of a paper by himself summarizing the work of his colleagues on those alloys, referred to material normally used today in making tubes; even from that point of view he was conscious that the 70/30 cupro-nickel did not contain enough iron.

The conclusion drawn at the bottom of page 68 to the effect that the low nickel alloys "have a corrosion resistance of the same order as that of the 70/30 of high iron content" was true if the iron content of the 70/30 alloys was of the order of 0·3 to 0·5 per cent and the words "of the same order as" were not interpreted to mean necessarily "as good as". The 10 per cent nickel 2 per cent iron alloy might well be fully as good as the 70/30 alloy in many conditions but the 5 per cent nickel alloys, although in the properly heat-treated condition possessing a corrosion resistance approaching that of the 70/30 alloy, were not likely to be quite so good as the higher nickel material.

Mr. Sherborne had queried the necessity for the introduction of those low nickel alloys. His Association was impressed in the early days of the War by the Admiralty's urgent need for a material for sea water pipes such as fire-mains, in which the water was stagnant most of the time but went through at a high velocity at other times. The Admiralty wanted something which could be more easily coppersmithed than aluminium brass. The Association took that statement at its face value: they knew that the Admiralty had been im-

pressed with the value of aluminium brass for a long time and felt that they must have some good reason for asking for something which was more easily worked by the coppersmith for that particular purpose. Following, therefore, work on the iron content of the 70/30 alloys, where they had convinced themselves and the Admiralty of the soundness of Mr. Wilkinson's observations, they tried adding iron to lower nickel alloys and those materials were the result. The reference in the second column on page 68 to the American use of an alloy 10 per cent nickel and 2 per cent iron (which was a bit hard for easy working by the coppersmith) for condenser tubes, was not, he thought, quite right, because the Americans believed that 0·7 per cent iron was sufficient with 10 per cent nickel; although a second American company claimed a good result for a condenser tube containing 10 per cent nickel and 1·5 per cent iron. He would be glad if the authors could confirm American usage of the alloy containing 10 per cent nickel and 2 per cent iron.

One other point was the reference to aluminium brass in Table 6. He did not much like the distinction which the authors had drawn between aluminium brass and inhibited aluminium brass. He thought that was probably based on American terminology and American practice. He also thought that he was right in saying that any aluminium brass tube that anybody bought from a reputable British manufacturer was inevitably and always inhibited and that the description of aluminium brass and its poor behaviour as regards dezincification, in Table 5, would not apply to what is normally called aluminium brass by a British tube manufacturer, because that would be inhibited with 0·02 to 0·05 per cent of arsenic. He wanted to support Mr. Sherborne on that point. Some of his American friends had tried to persuade him that the addition of arsenic in those amounts was not really a proper guard against dezincification and it was better if one put antimony in. He had never succeeded in finding a tube containing that amount of arsenic showing any signs of dezincification whatever.

It was important here to make clear the distinction in dezincification behaviour between the copper-rich alpha brasses, the structure of which was a single solid solution, and the lower copper duplex alloys which contained the beta phase. The alpha alloys were the ones always used for tubes in condensers because they were readily cold-worked whereas the alpha beta alloys of higher strength were used for castings and hot rolled plates such as Muntz metal and Naval brass.

What he had said about the beneficial effect of arsenic in preventing dezincification of brass tubes was true because the tubes were of alpha structure. He had to admit that arsenic was of little value in preventing the much more rapid and serious dezincification of the beta phase in duplex alloys. The same was true, as far as he knew, of other inhibitors and there was no really satisfactory method of inhibiting dezincification of brasses of duplex structure.

MR. S. C. HOLLOWS said that the only other point he thought he could add to the discussion was that in Table 5 there was not included the 5 per cent nickel content copper-nickel-iron which merited equal inclusion with the others.

DR. S. A. MAIN said that the paper was limited in the main to what could be done for one's problems by choice of materials but there were of course other means, either by the treatment applied to the waters or the conditions under which the materials had to work, to enable one to suffer less from this difficult corrosion problem. That was rather outside the scope of the paper, although there were certain points, in particular the one about the anodic protection, with regard to which he was very much impressed by the progress which had been made in recent years, especially in America but now on this side. Large amounts of money were being spent, perhaps not quite in this particular field of marine engineering, although that would come, but more particularly in connexion with harbour structures. Quite large anodes of magnesium were being

used, and thousands of pounds were being spent on particular structures in that way. It was a method which must be applied very carefully and under good advice from the people who knew all about it .

On the subject of the protective methods that could be applied he recommended a publication which many still did not know about. That was Special Report No. 41 prepared by the Waters Corrosion Committee of the British Iron and Steel Research Association and published by the Iron and Steel Institute. This, he said, although not specifically directed to marine engineers offered recommendations of general interest, and did deal with some of the particular problems concerned.

Members had heard only in this discussion from metallurgists, of which he was yet another, but he felt that metallurgists could never hear too much of the problems of marine engineers. He would therefore like to hear some of the marine engineers speaking about their problems and troubles so that he and his steel and non-ferrous colleagues could apply themselves to those problems. In particular he wanted to know how far the question of salty steam was a trouble to them. He understood this to be a rather debatable question, sometimes people said that it was nothing and caused no trouble at all; in other cases, as could be seen in Plate 4, one got very serious corrosion from the fact that the steam was salty. Were there any methods of keeping the steam free from salt, or reasonably free from salt; if so, metallurgists would like to know about them. If there were not, then the important thing for the turbine was not to use ordinary stainless steels but a rather special type such as that indicated in Plate 4. That steel was an excellent one; it had the advantage also that although the steam temperatures in the marine engineering field did not follow very closely those for land use or in the Admiralty (although they would eventually) temperatures were bound to go up; in that case one would have a steel which would withstand the very high temperatures and leave some of the others behind.

Authors' Reply

MR. BRADBURY, replying to the discussion and dealing first with Dr. Garside's contribution said he felt that an explanation was due to him on the title of the paper inasmuch as the authors were requested to limit its scope to corrosion-resistant materials in the actual propelling and ancillary equipment and the paper was written with that in mind.

One point in which Dr. Garside might be interested, however, was water line corrosion, which was a very severe problem not only in marine engineering. In one case in the oil fields in Venezuela where the derricks were mounted in sea water they were overcoming the water-line corrosion by sheathing the structures with corrosion-resisting materials. One of them, in actual fact, was Monel, but they were trying quite a number of materials. The sheathing covered between the high and low water mark levels and the rest of the structure was left unprotected.

Dr. Garside had mentioned the "Soro" process as producing a brass which was not subject to season-cracking. The Soro process was a method of centrifugally casting brass by which a ring was produced and the ring could, if conditions were correct, be clear of flaws, and if cut and straightened and drawn through dies, did give material of very good quality. In fact he knew of its use only for cartridge cases. He did not think he would trust that process to produce a brass not subject to season-cracking without the use of a suitable stress-relieving treatment.

Dr. Garside had also mentioned the Soro process for use in the production of bi-metallic strip. It was possible to use it for this purpose but he did not think it would be any more satisfactory than producing clad material by the more usual process such as was used for Sheffield plate where copper strip or sheet was merely bonded by rolling on to silver. The bond was quite as satisfactory as anything one would ever produce in the Soro process.

Dr. Garside had also mentioned the difference between the corrosion resistance of inoculated and nodular cast iron. It was perhaps rather too early in the life of the nodular cast irons, which had only been introduced for about a year, to compare their corrosion resistance; in fact, he was not sure whether there was any data at all on that subject.

Others of Dr. Garside's queries would be dealt with later by Mr. Johnson.

Mr. Sherborne had raised several queries on the subject of tubes. He thought there should be an explanation here that in writing the paper, Mr. Johnson and he had had a very difficult task in condensing a vast amount of information. A particular case in point was the section in which they dealt with materials used for heat exchangers. He wished to impress on everyone interested in this subject that they should read the paper written by Mr. G. L. Bailey referred to in the text and which would be published shortly by The Institute of Metals. When reading this paper the size and extent of the work which was carried out and the difficulty of condensing it would be appreciated.

With regard to the arsenic content, it had been a little difficult to differentiate between cast and wrought materials. The arsenic content in cast material was normally at a higher level than in wrought material and he confirmed Mr. Sherborne's point that 0·02 and 0·05 was the arsenic content of wrought material; in fact, it was only in rare cases that these figures were exceeded in cast material. But he did not entirely agree with Mr. Sherborne or Mr. Bailey that in cast brasses which had been arsenic inhibited one could not get dezincification. It was well known that inhibited cast brass could quite definitely fail by dezincification.

He thanked both Mr. Bailey and Mr. Sherborne for emphasizing the points regarding the straight or pure copper-nickel alloy and felt that they could not be stressed too strongly. Regarding the statement he made when comparing the low copper nickel alloys with the 70/30 he used the phrase "the same order". That phrase "the same order" was meant to be read in a general sense and he would confirm that the 5 per cent nickel and 1·5 per cent iron was not in the same class as the 10 per cent nickel and 2 per cent iron, or the 70/30 with high iron content.

Turning aside then to Mr. Bailey's comment, he also con-

firmed his point that the alloy composition of 10 per cent nickel and 2 per cent iron had not yet been used in the United States. That was meant to be a general comment but he pointed out that the alloy which was being used in the United States had shown a very great deal of success and that the alloy produced in this country was likely to be even better.

Mr. Wilkinson had made the point that in Table 5 on page 64 there was mention made of copper nickel alloys containing 10 per cent of nickel. Mr. Sherborne was quite right, the iron addition should have been stated in that Table. The Table was compiled by one of his colleagues in America and was a little "Americanized", although it had been modified where thought fit. Reading along that line it was quite obvious that no straight copper-nickel would give the performance that was given there and an iron content must be implied.

Regarding Mr. Hollows' point on the 5 per cent alloy and its absence from Table 5, he admitted that they could find too little information to go right along that Table and rather than leave blank spaces they had omitted the alloy.

MR. JOHNSON, who also replied to the discussion, said that his colleague and co-author Mr. Bradbury had dealt with most of the points raised but there were one or two left over. Firstly, Dr. Garside had said that he would have liked to see more mention of applications of aluminium and its alloys. As Mr. Bradbury had just said, the paper had been kept purely to marine engineering applications because they did not wish to trespass on the Institution of Naval Architects' ground. Dr. Garside had mentioned the funnel and as he, Mr. Johnson, was not quite certain where the funnel came in, whether it was within the province of the marine engineer or the naval architect, he had purposely omitted that topic.

Another question raised by Dr. Garside was that of the use of lead in improving the machinability of stainless steel. There was practically no use of lead,* the preferred practice being to add selenium or sulphur with or without molybdenum, or zirconium to effect improvement. These elements did impair the corrosion resistance slightly but they also had a very impor-

tant property from the anti-galling point of view. Austenitic stainless steel was somewhat apt to gall and if an addition of selenium or sulphur was added it improved the resistance to galling.

Dr. Garside had also referred to speculum plating. This was a copper-tin alloy, and had been developed by the Tin Research Institute. It had good corrosion-resistant properties, being mainly used for indoor uses, was hard and as was the case with hard electro-deposits, of relatively low ductility. They were also developing another electro-deposited alloy of tin and nickel which was also of the same category, i.e., was tarnish- and corrosion-resisting and was also hard. This alloy had interesting possibilities for outdoor use and was going to be the subject of a paper which the Tin Research Institute was presenting at the Electro-depositors' Technical Society Conference in a month or two's time.

In connexion with metal spraying he understood Dr. Garside to say if one used zinc it did not matter very much if there were pores present in the case of steel because the zinc would act in a sacrificial manner. On the other hand, it was important to realise that if one was spraying zinc on to copper it was necessary to ensure that pores were absent.

The same applied in electro-deposition, i.e., very thin deposits were porous and it was only by having adequate thickness that absence of porosity could be ensured. In the case of nickel, for example, this aspect was covered by a British Standard Specification, i.e., 1224.

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* Written communication—H. Thielsch in the *Welding Journal*, August 1950, p. 378-S in a paper "Alloying Elements in Chromium-Nickel Stainless Steels", referred to U.S. Patent 2,215,734 (British Patent No. 523,251) covering the use of 0·3 to 1·0 per cent of lead for improving the machinability. He pointed out, however, that because of the extremely low solubility of lead in these steels, lead inclusions below 0·005 per cent lead would form in the primary grain boundaries and would be detrimental to hot working operations. He also referred to the health hazard aspect when welding although presumably this could be countered by adequate exhausting methods.

INSTITUTE ACTIVITIES

MINUTES OF PROCEEDINGS OF THE ORDINARY MEETING HELD AT THE INSTITUTE ON TUESDAY 13TH FEBRUARY, 1951

An ordinary meeting was held at the Institute on Tuesday, 13th February 1951, at 5.30 p.m. Mr. G. Ormiston (Chairman of Council) was in the Chair. A paper entitled "Corrosion-Resistant Materials" by Mr. L. W. Johnson and Mr. E. J. Bradbury was read and discussed. Seventy-five members and visitors were present and six speakers took part in the discussion.

Mr. J. Turnbull, O.B.E. (Vice-Chairman of Council) proposed a vote of thanks to the authors which was accorded with acclamation.

The meeting terminated at 7.10 p.m.

BARROW MEETING

The second of the series of meetings under the auspices of the Institute was held at Barrow-in-Furness Technical College on Friday, 2nd March, when Mr. G. H. Jackson read his paper on "Some Notes on the Hardening and Heat Treatment of Steel". The Chair was occupied by Com'r(E) J. N. F. Haigh, R.N. A spirited discussion took place at the conclusion of the lecture, six members of the audience taking part and all questions being very satisfactorily dealt with by the lecturer. A vote of thanks was accorded to Mr. Jackson on the proposition of Mr. Horn, seconded by Mr. C. H. Verity (Member). Dr. G. H. Forsyth, M.B.E. (Local Vice-President) voiced the thanks of the Institute to Com'r Haigh for taking the Chair, and to Mr. Sandham, Principal of the College, for his kind co-operation.

LOCAL SECTIONS

Sydney

The Annual General Meeting of the Sydney Local Section was held on Friday, 16th March 1951, at 7.45 p.m. at Science House, Sydney. Mr. H. A. Garnett (Local Vice-President) was in the Chair and seventy members and guests were present. The Minutes of the preceding General Meeting held on 17th October 1950 were read and confirmed.

The Committee presented the Annual Report and Balance Sheet for the year 1950. Their adoption was proposed by the Chairman and seconded by Mr. F. W. Harper and carried unanimously.

The Chairman announced the names of the office bearers for 1951:—

    Chairman: H. A. Garnett
    Honorary Secretary: Eng'r Capt. G. I. D. Hutcheson, R.A.N.(ret)
    Honorary Treasurer: N. A. Grieves.
    Committee: W. G. C. Butcher, D. N. Findlay, F. D. Gillan, G. T. Marriner, C. McLachlan, H. P. Weymouth.

A vote of thanks to the retiring committee was proposed by Mr. N. W. Lees and seconded by Mr. C. McLachlan and carried with acclamation.

A lecture was then delivered by Mr. B. P. Fielden on "Lloyd's Register of Shipping". This proved of great interest to the members and a keen discussion followed in which several members took part.

A vote of thanks to Mr. Fielden was proposed by Mr.

H. P. Weymouth and seconded by Mr. G. T. Marriner and carried by acclamation.

Supper was served at the conclusion of the meeting and an opportunity afforded to members and their guests for informal discussion.

Members of the Sydney Local Section were very fortunate in February in being able to arrange a visit to R.M.S. *Caronia* while she was in Sydney on a world cruise. On account of the fact that the passengers were living on board, the ship was not open generally for visitors and as a special recognition to the Local Section the representatives of the Cunard Co. in Sydney communicated with the Captain and it was possible to arrange for a visit by members.

About forty attended and were very kindly received by the Chief Engineer, Mr. J. G. Wilson, and a number of his officers and were made most welcome and given a most instructive and enjoyable inspection of this important ship.

The members greatly appreciated the courtesy of the ship's officers and the privilege of being able to see this beautiful ship under such excellent conditions.

JUNIOR SECTION

Lecture at Sheerness

On Tuesday, 6th March 1951, a lecture was given at Sheerness Technical Institute by Mr. J. W. Coulthard, D.S.C. (Member) on the subject of "Welding in Ship Repair Work". The lecture was attended by sixty students and representatives of local industry. The speaker was introduced by Mr. P. F. Harrop, B.Sc.(Eng.), the Principal of the College, who took the Chair at this meeting.

Lecture at Borough Polytechnic, S.E.1

On Thursday, 8th March, Mr. R. R. Strachan (Member) gave a lecture on the subject of "Refrigeration at Sea" to a large audience at the Borough Polytechnic, including a number of students from the National College of Refrigeration.

Some good slides were shown to illustrate the lecture, which was followed by a lively discussion opened by Mr. C. W. Tonkin (Associate Member). The Chair was taken by Mr. G. L. H. Bird and the vote of thanks to the lecturer was proposed by Mr. J. H. Brier of the Institute of Refrigeration.

MEMBERSHIP ELECTIONS
Elected 9th April 1951

MEMBERS

    George Noble Bell
    William Russell Trench Blackwood
    George McGeorge Dalling
    Jack Darryl Watson Ebeling
    Walter Richard Evans
    Donald Bertram Hall
    Robert Kenneth Henderson
    Percy Job
    Denis Mark Venning Parkinson
    John Lewis Evan Rowlands
    Richard Shaw
    Harold Arthur Stanley Swailes, Lt.-Com'r(E), R.N.

Obituary

Jan Stepien
Robert Turner, Lieut.(E), R.N.
Heinrich Valdemar
David Wallace
George Wilson

ASSOCIATE MEMBER
Donald Nothard Bingham

ASSOCIATES
Walter James William Arnell
Malcolm Stephen Arratoon
Roy William Charles Black
Derek Sydney James Brown
Bernard William Bruning
Ian Ross Campbell
Charles Inkerman Campion
Albert Frenkel
William Henry Frost
Davide M. Garre
Charles George Edward Gudge
Robert Talbot Hess
Robert Mitchell Hills
Helmy Ahmed Hilmy
Thomas Ian Kirk
Alan Roy Lipscombe
Harold Douglas Makinson
Robert Nicol
Percival George Partington
Alastair Stewart Robb
Alexander Rolland
Ronald Scotwick

James Denzil Screech
Peter Nathaniel Short
Leslie Ernest Smith
Andrew Arthur Stewart
Francis George Tothill
Harry Robert Triggs

TRANSFER FROM ASSOCIATE TO MEMBER
Peter Luen Gaches
George William Lascelles
Stuart Hay Nelson
John Clive Thomason
William Fornear Welch

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER
Samy Aly El Rashidy, Lieut.(E), R.E.N.
Derek John Lochhead
George Newbegin Wallace

TRANSFER FROM GRADUATE TO MEMBER
Ronald Charles Brown

TRANSFER FROM GRADUATE TO ASSOCIATE MEMBER
Omar Mostafa Amin, Lieut.(E), R.E.N.
Mohamed Salah El-din Rida, Lieut.(E), R.E.N.

TRANSFER FROM STUDENT TO ASSOCIATE MEMBER
Peter Emerson Melly, Lieut.(E), R.N.

TRANSFER FROM STUDENT TO GRADUATE
George Hassan, B.Sc.
Peter Meyrick Threlfall

OBITUARY

DAVID B. CARSWELL (Member 6938) was born in 1884 and was trained in the Paisley works of Thos. Reid and Son. He went to the United States just before the outbreak of the first World War and became superintendent of the Detroit Shipbuilding Co., and then manager of the Duluth Shipbuilding Co. In 1919 he went to Canada and in 1921 was appointed superintendent engineer of Canadian National Steamships, Ltd. From 1928 to 1933 he was managing director of Canadian Vickers, Ltd., and when the second World War broke out he was appointed director-general of shipbuilding in Canada. From 1941 to 1944 he was controller of ship-repairs and ship salvage; then for a year he was in joint control of shipbuilding, ship-repairing and salvage, and in 1945-46 he was president of Wartime Shipbuilding, Ltd. He was awarded the O.B.E. in 1943 in recognition of his services. After the war Mr. Carswell set up in practice as a consultant being retained in 1947 by Ming Sung Industrial Co. in a consultative capacity. He was elected a Member in 1931 and was elected Vice-President for Montreal in 1939, being re-elected in that capacity in 1942, 1945 and 1948. He was also a member of the Society of Naval Architects and Marine Engineers, New York.

ALASTAIR DORNIE MCRAE FRASER (Member 12736) was born in 1900 and educated at Falkirk High School. He commenced his apprenticeship at the Carron Ironworks, Grangemouth Dockyard, in 1917. He joined the R.N.A.S., which subsequently merged into the R.A.F., in the same year, being demobilized in 1919. After demobilization he completed his apprenticeship and then joined Harland and Wolff, Ltd., on the Diesel engine construction side; after gaining experience in the test shop, he joined the Royal Mail Steam Packet Co. as a junior engineer in 1924. After serving some two years with that company he transferred to Andrew Weir and Co., obtaining his First Class Certificate. He joined the Anglo-Saxon Petroleum Co., Ltd., as third engineer in 1927. Mr. Fraser was transferred from that company to the Asiatic Petroleum Co. (North China) Ltd., and promoted to Chief Engineer in

1930, serving in that capacity until 1938 when he was attached to the Asiatic Petroleum Co., Marine Department, as Acting Assistant Superintendent Engineer. In 1941 he joined the Royal Naval Reserve, being appointed Lieutenant(E) in November 1941 and serving until May 1942 when he returned to the Anglo-Saxon Petroleum Co., Ltd., serving as Chief Engineer of the m.v. *Daphnella* until he was appointed to the Ministry of War Transport Tanker Division in South Africa in November 1942. He was recalled by the M.O.W.T. to the United Kingdom in 1944 and appointed to France in the early days of the invasion and subsequently proceeded East with the Anglo-Saxon Petroleum Co. (Eastern) Ltd., to Colombo for duties with Ministry tankers for the re-occupation of Singapore. At the conclusion of the war he was appointed Superintending Engineer, Anglo-Saxon Petroleum Co., Ltd., serving in Hong Kong and Singapore until May 1947 when he was appointed Resident Superintending Engineer at Suez, which appointment he held until his death which occurred on 27th February 1951. He was elected a Member in 1950.

NORMAN HART (Member 9212) was born at Blackburn in 1886. He was educated at Giggleswick School and Manchester University. He was on the staff of Mirlees, Bickerton and Day during the first World War and afterwards transferred to Cox and King for a short time, setting up on his own account as a naval architect in 1928 and specializing in the design of yachts. He will be remembered by yachtsmen as the designer of such yachts as *Campeador, Ecila, Wilna* and *Leprechaun*. At the beginning of the 1939-45 war Mr. Hart joined the Fairmile Organization and designed the "A" and "C" class M.L. On resigning his appointment in 1942 he devoted himself to continuing his original research into methods of constructing resilient curved structures with particular reference to waterborne hulls and was the holder of several patents in this connexion. He was elected a Member in 1941. He was also an Associate Member of the Institution of Naval Architects. He died in January 1951.