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THE INSTITUTE OF MARINE ENGINEERS

THE CORROSION OF CARGO SHIPS AND ITS PREVENTION

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Read in London at the Spring Meeting of The Institution of Naval Architects on March 22, 1956, Sir Stanley Goodall, K.C.B., O.B.E. (Honorary Vice-President), in the Chair, supported by Mr. H. N. Pemberton (Member of Council I.Mar.E.).

1. General Discussion of the Problem

(*a*) *Introduction*

Sea-water, which contains about 3 per cent of common salt and has a high electrical conductivity, is one of the most corrosive natural agencies. Under many conditions its corrosiveness is imparted to marine atmospheres in which considerable amounts of sea salts may be present in the form of a fine spray. It is not surprising, therefore, that the use of metals in ships and more particularly of steel, which plays a preponderating part in their construction, is accompanied by a number of corrosion problems that have to be solved if ships are to operate safely and efficiently. The purpose of this paper is to focus attention on the subject and to promote its discussion, by setting out briefly what has been learnt about the corrosion of iron and steel in ships and its prevention, through practical experience and as a result of research. No reference will be made, however, to the corrosion of oil tankers, which is a highly specialized subject.

The problem of corrosion is not, of course, a new one, and has long been recognized in the Rules of Lloyd's Register of Shipping, which are summarized in Appendix I. It is interesting to note that even in their first form, 1888, they fully recognized the importance of the two major measures for preventing corrosion of the outer bottom: the removal of millscale before painting and the desirability of dry-docking new ships for repainting within a short time after launching.

(*b*) *Occurrence of Corrosion in Ships*

It is impracticable to suggest a mean rate of corrosion for steel in ships, since this depends on so many factors, such as abrasion, which produce conditions more conducive to corrosion in some cases than in others. Analysis of plate renewals throws this point into perspective for these show that colliers require approximately three times as many shell renewals as do deep sea vessels. The difference is obviously due to the much more frequent ranging of the colliers against quays and other ships and their grounding at loading berths, which removes the paint besides scouring the steel.

This brings out the point that the removal of paint is one of the commonest reasons for corrosion, particularly where other conditions occur to accelerate it. Internally and above the waterline the removal of paint accompanied by damp or wet conditions is a serious matter. For example, the use of grabs for handling cargo causes abrasion and removes paint, so that with dampness from cargoes corrosive conditions are produced. Below the waterline the removal of paint by mechanical damage may lead to local attack or pitting of the plate at a truly alarming rate; in some cases grazes caused when a ship struck some floating wreckage have been opened up to grooves over $\frac{1}{8}$ in. deep in the course of a single voyage. Such local attack is considerably accelerated by turbulence, which tends to denude the steel of paint and greatly increases the supply of oxygen available for corrosion. Reports on surveys of ships clearly indicate the truth of this, since corrosion is most prevalent under the bottom forward and around the bilge and near the waterline, all places where turbulence is pronounced. In these regions corrosion of rivet points standing slightly out from the shell is often severe. It would be incorrect, however, to suggest that turbulence of this type occurs only in riveted ships, although welding is generally considered to give a relatively smoother surface.

Before passing on to consider the occurrence of corrosion in the three main parts of a ship—the underwater plates, the superstructure and the internal spaces—it may be profitable to discuss three general factors that bear upon the problem: steel quality, design, and methods of protection.

(*c*) *Effect of Steel Quality*

One of the first questions that springs to mind when considering the corrosion of steel in ships is whether and, if so, to what extent, the corrosion could be decreased by alterations in the composition of the steel. Very broadly the answer to the first half of this question is "No." Consequently, for practical purposes it is better to pay attention to the efficiency of the protective measures adopted, which will be discussed later.

The facts of the matter are these.

The steels available to the shipbuilder can be classed in three groups, as regards corrosion resistance: ordinary steels, slow-rusting steels and rust-resisting steels. Apart from special cases, as, for example, when steel is in contact with a loose cargo, the corrosive media encountered in a ship are sea-water or an outdoor marine atmosphere, or an internal atmosphere, which is often very humid. The results of researches in several countries, notably Great Britain, France, and the United States, on the resistance of steels to these various media, agree in showing that:

(i) When bare steels are submerged in sea-water there is no great difference in their resistance to corrosion unless a fairly high percentage of chromium is added to the steel. The addition of 3 per cent of chromium roughly halves the corrosion rate.

The use of rust-resisting ("stainless") steels, which contain much higher percentages of chromium and other elements as well, e.g. 18 per cent of chromium and 8 per cent of nickel, fails to solve the corrosion problem under these conditions. Although the general corrosion rate of these steels is much less than that of ordinary steel, this reduction is achieved at the expense of greater vulnerability to pitting. In some circumstances the pitting of rust-resisting steels in sea-water can proceed so rapidly that a $\frac{1}{8}$ in. thick plate is perforated within a year. Moreover, the use of rust-resisting steels for general shipbuilding would be uneconomical, and, indeed, the available supply of these materials would not permit this.

(ii) When freely exposed to sea air in the bare condition, steels containing small percentages of certain alloying elements, notably chromium, copper, and nickel, rust considerably more slowly than ordinary unalloyed mild steel. The performance of these steels in a marine atmosphere may

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be illustrated by a result obtained by the American investigator, C. P. Larrabee,* in a test at Kure Beach over 7½ years. Here a well-known proprietary steel, Cor-Ten, containing 0·15 per cent of phosphorus, 0·8 per cent of silicon, 0·4 per cent of copper and 1·1 per cent of chromium, suffered only about one-fifth of the reduction in thickness of an ordinary mild steel exposed beside it. The use of "slow-rusting" steels of this and similar types for the superstructure would, therefore, tend to reduce corrosion. As, however, corrosion is seldom serious in this part of the ship, because it is usually painted at frequent intervals for appearance's sake, it is doubtful whether such steels should be chosen on the grounds of their better corrosion resistance alone; in this connection it should be noted that many of them are of the high tensile type and that their improved mechanical properties were the primary reason for their industrial development.

Rust-resisting steels of suitable composition are little affected by exposure to marine atmospheres but here again it is doubtful whether their use would be economically justified.

(iii) Under conditions of exposure to enclosed atmospheres, rust-resisting steels are practically unattacked and their use for certain purposes, such as ornamental fittings, might be worth while. There is, however, no marked difference in the corrosion rates of ordinary and of low-alloy steels under these conditions.

(iv) There is no evidence that the corrosion rate of steel of ship plate quality is appreciably affected by differences in the process by which it is manufactured, e.g. the open hearth process as compared with the Bessemer process. For example, after reviewing extensive tests made in the United States, Larrabee† concluded that "Under similar conditions of exposure at one location, the atmospheric corrosion rates depend mainly upon composition of the steel and not upon method of manufacture." Without going into detail, it may be taken that what Larrabee said of atmospheric exposure also relates to immersion in sea-water, as, indeed, has been demonstrated by experiment.

In general the influence of the steelmaking process as such on the corrosion resistance of the product can only operate in so far as the composition and purity of the steel is affected. Probably the most important factor is the location and quantity of non-metallic inclusions. This is the reason why, for example, rivets made from bars of rimming steel proved particularly liable to corrosion, since the segregated sulphide inclusions were exposed when the bar was sectioned to produce the blank. The use of this type of rivet has, however, been banned for a long time. Under modern conditions of production careful watch is kept on the purity of the steel and no such exposure of segregates should take place on the surface of well made ship plate.

TABLE I

WASTAGE OF "OLD" AND "NEW" SHIPS AT THEIR 24-YEARS SURVEY

Position of drilled plates	Average wastage, in.			
	Old ships (built 1899–1914)		New ships (built 1926–1930)	
	Port	Starboard	Port	Starboard
Midships	0·0851	0·0853	0·0860	0·0980
Forward	0·0433	0·0484	0·0449	0·0411
Aft..	0·0587	0·0549	0·0396	0·0360
Overall average ..	0·0626		0·0576	

* LARRABEE, C. P.: "Corrosion Resistance of High-Strength Low-Alloy Steels as Influenced by Composition and Environment," *Corrosion*, 1953, **9**, August, 259–271.

† LARRABEE, C. P.: "Effect of Composition and Environment on Corrosion of Iron and Steel." In *Corrosion of Metals*, American Society for Metals, Cleveland, Ohio, 1946, p. 37.

Before leaving this subject, brief reference may be made to the view, still expressed sometimes, that modern steel is less resistant to corrosion than that produced one or two generations ago. To provide evidence on this point the plate drillings made at the 24-years survey, as recorded in the files of Lloyd's Register, for 45 ships built during the period 1899–1914 have been compared with those for 45 ships built between 1926 and 1930. The average wastages of the plates are given in Table I, for positions situated midships, forward and aft, and in Fig. 1, where all the 270 figures available

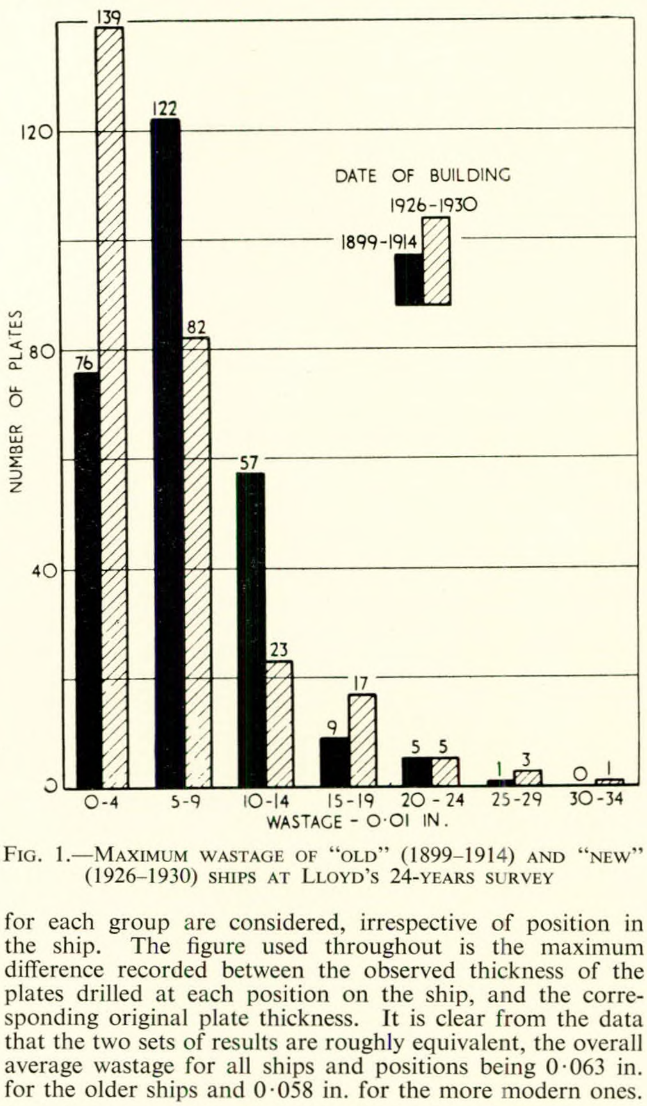


FIG. 1.—MAXIMUM WASTAGE OF "OLD" (1899–1914) AND "NEW" (1926–1930) SHIPS AT LLOYD'S 24-YEARS SURVEY

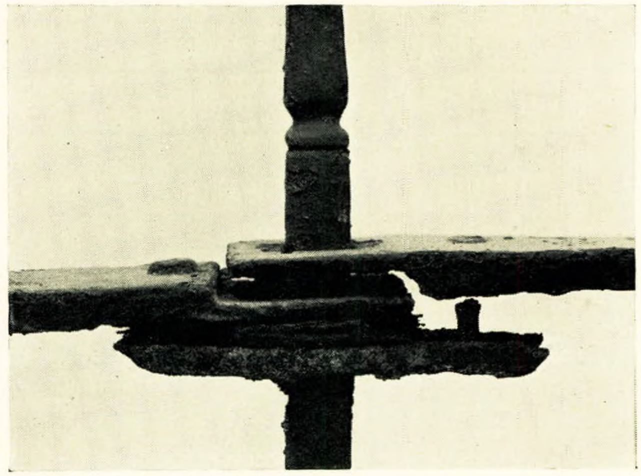
for each group are considered, irrespective of position in the ship. The figure used throughout is the maximum difference recorded between the observed thickness of the plates drilled at each position on the ship, and the corresponding original plate thickness. It is clear from the data that the two sets of results are roughly equivalent, the overall average wastage for all ships and positions being 0·063 in. for the older ships and 0·058 in. for the more modern ones.

(*d*) *Effect of Design on Corrosion*

Careful attention to design is of great importance in minimizing the severity of corrosion and in making it easier to apply adequate protective measures. Since the most damaging forms of corrosion are generally associated with the presence of water, the first major guiding principle is to design an assembly in such a way that water drains readily from it and cannot be trapped on ledges or in crevices. The second important principle is that everything practicable should be done at the design stage to make it easy to apply and renew, as and when necessary, the protective coating, which will generally be paint. A few illustrations of these principles are shown in Fig. 2. The case of the inaccessible

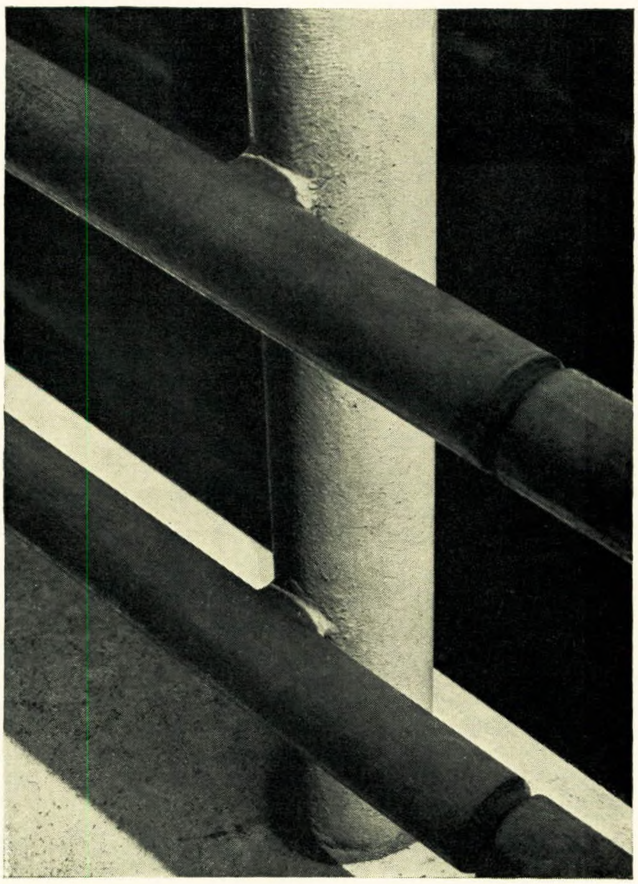
(*a*) Parapet of footbridge at St. James's Park, London

The upturned members at the bottom have formed a trap for water, dirt, and rust, and the iron has corroded through there.



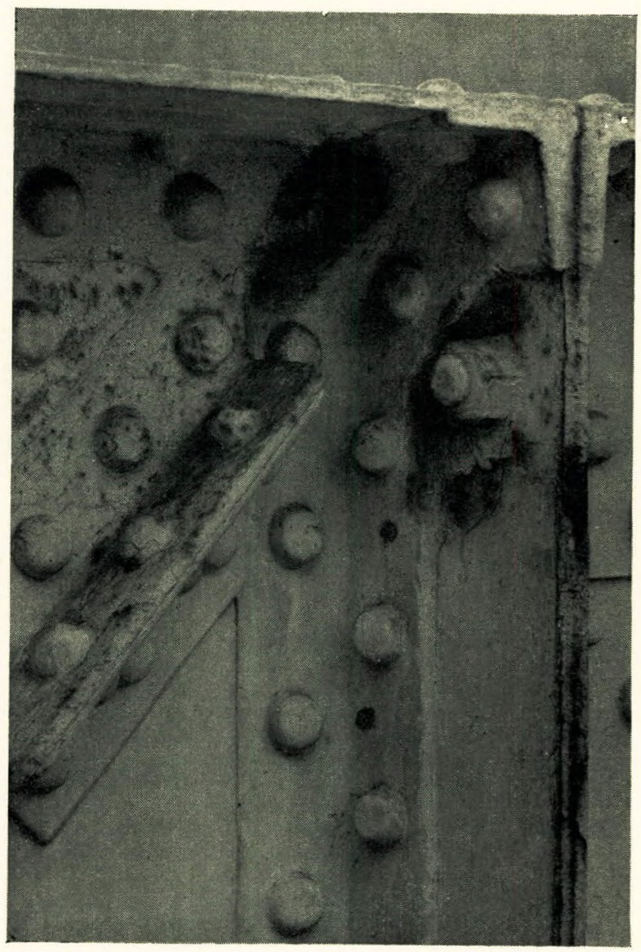
(*b*) Detail of old railings round Westminster Abbey

A good example of the dangers of rusting at laps and crevices; the expansion due to the rust has snapped the bolt.



(*c*) Detail of modern railings on Waterloo Bridge, London

The welded construction used is simple and readily accessible for painting; the danger of corrosion at the joints is considerably reduced thereby.



(*d*) Detail of parapet of tollbridge at Caernarvon

Complicated assemblies such as this are difficult to paint effectively.

Fig. 2.—Effect of design details on corrosion

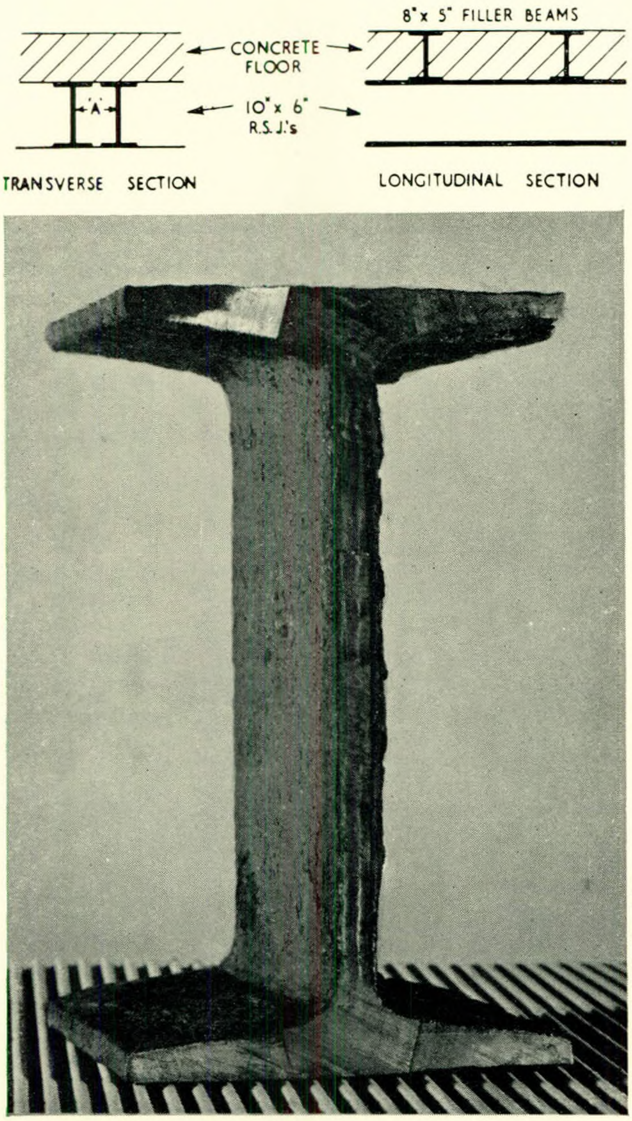


FIG. 2.—EFFECT OF DESIGN DETAILS ON CORROSION—*contd.*

(*e*) CORRODED ROLLED STEEL JOIST FROM A COLD STORAGE BUILDING

Rolled steel joists carrying the concrete floor of a cold store had been twinned and placed so closely together as to render it impossible to paint their inner surfaces. Consequently, they had to be renewed after 23 years, because of the severe corrosion of these surfaces caused by condensation. In the new structure the distance "A" was increased to 18 in., so as to give all round access for painting.

twin girders seems too ludicrous to be true, but experience has shown that it is by no means an isolated example of such lack of foresight.

There is no need to labour these points, which will commend themselves at once to designers and stimulate them to look for and avoid similar features in the future, but it may be of interest to give a few practical examples of the interrelation of design and corrosion in ships.

(i) The horizontal plates over the tank top at the bottom of the hold in a cargo ship were found to have corroded more immediately beneath the hatch than elsewhere. This was obviously because rain had fallen down the hatch when the covers were off. It seemed probable, however, that corrosion had been increased by the fact that the plates had been joggled and thus formed a natural tray about $\frac{1}{2}$ in. deep from which the rain water would drain with difficulty.

(ii) Externally on the hull but above the waterline the places where corrosion is most frequently found are below discharges and in positions where abrasion removes the paint coating. Corrosion also occurs around shell openings, i.e. round the edges of water inlet or outlet openings.

(iii) Cases of heavy corrosion of stern frames and rudders, particularly of the streamlined type, are not uncommon (see Fig. 3). These arise from a variety of causes, some of which are still imperfectly understood, but there is no doubt that in some instances inadequate clearance between the corroded parts and the propeller, which leads to excessive turbulence, is a contributory factor.

(iv) Direct contact of steel with non-metallic materials is often dangerous. Plating below wood sheathings and tiling appears to be particularly vulnerable, since penetration of moisture is easy if the caulking of the wood deck fails or if the tiles begin to lift. Compositions are effective in protecting plating under these circumstances, provided they are sufficiently flexible to avoid fracture. Modern methods of laying wood deck with welded bolts are preferable in some respects to the use of through bolts, since water cannot pass from one side to the other.

(v) Construction of the steel cargo ship has altered considerably in detail in the last 20 years due to the introduction of welding. Whether this has increased or decreased the liability of a steel ship to suffer corrosion is a matter of opinion, which will be discussed in the next section, (*e*). Meanwhile it may be noted that, as regards design, riveted vessels contain certain details that encourage corrosion and wastage. Seams and butts are overlapped; rivet heads stand out, rivet points are frequently fairly full and bars are attached to the plating by means of flanges. These items collect dirt and moisture, paint application is less uniform and they are subject to abrasion. The abrasion and the non-uniform application of paint assist the removal of the latter, producing bare or partially bare patches and conditions very conducive to corrosion.

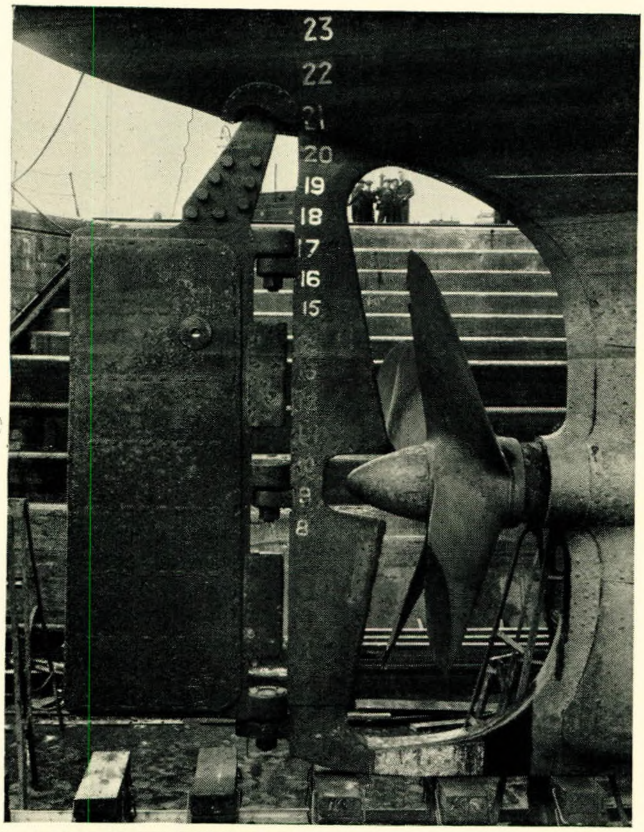
(vi) Contact between dissimilar metals should be avoided whenever possible, particularly on the submerged parts of the outer hull or internally where severe condensation is to be expected. Helpful guidance on this point is given in a statement drawn up recently by U. R. Evans and (Mrs.) V. E. Rance, for the Corrosion and Electrodeposition Committee of the Inter-Services Metallurgical Research Council, Ministry of Supply.*

(*e*) *Does Welding Affect Liability to Corrosion?*

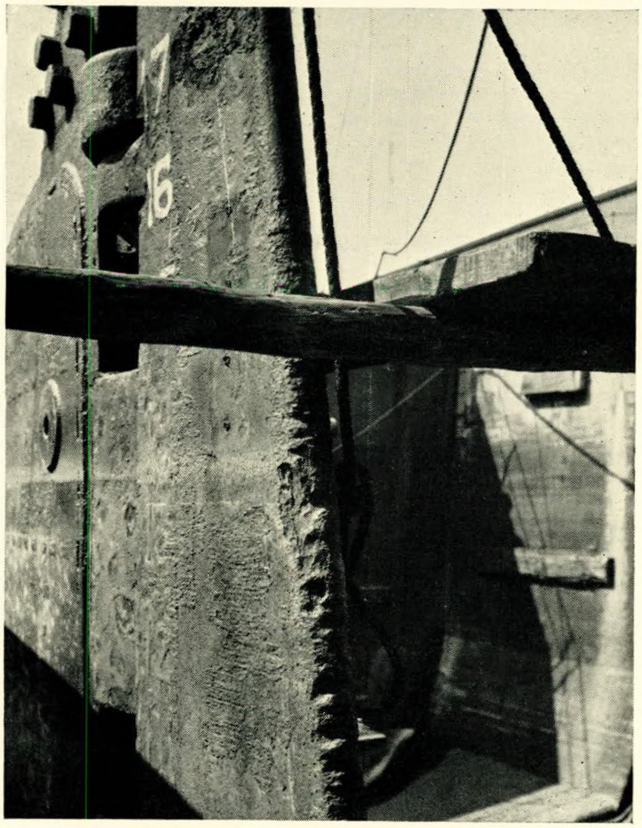
So far as the corrosion hazard is concerned, welding might be expected to be a better method of assembly than riveting, because it affords a means of providing a smooth surface free from crevices. The possible difference between the two processes in this respect is well illustrated by the photographs of the two different types of railing shown in Fig. 2. Much depends, of course, on the method by which the welding is carried out and it is perhaps unfortunate that a certain amount of the welding in the underwater portion of a ship is of necessity of a type that is far from smooth. It is well known that butt joint welding of plates varies considerably according as to how the work is done. Hand welding done down-hand is frequently smooth and almost flush with the surrounding plating. Machine welding, which is invariably down-hand, shows these properties to an even greater degree. Vertical welding can be reasonably smooth if well done but does not always attain this condition. Overhead welding is the most troublesome. It is usually applied as a sealing run, the back of the seam having been chipped or burnt out to clean metal. The overhead weld is invariably proud of the plating, may be uneven and in the worst cases will have the well-known appearance of drops of weld metal.

From the foregoing it is clear that even application of paint

* EVANS, U. R., and RANCE, V. E.: *Corrosion and its Prevention at Bimetallic Contacts.* To be published by H.M. Stationery Office in 1956.



(a)



(b)

FIG. 3.—CORRODED STERN FRAME AND RUDDER
(*a*) General view.
(*b*) Details of upper part of stern frame.
Vessel built: August 1950.
Photographs: September 1954.

is most likely to be achieved over machine welds or hand welds carried out down-hand.

Development of welded construction has led to the fabrication of ships in panels. The panels themselves are frequently welded into large sections in the shops and then brought to the berth for assembly. In modern practice shop welds are usually machine done on both sides of the plating, giving an excellent surface. The welds on the berth will be either machine or hand welded on the upper surface, depending on their position, but the under surface is invariably hand welded. These hand welded seams, particularly in the bottom where done overhead, are relatively uneven and consequently subject to corrosion, because of the difficulty of covering them adequately with paint. Ships' inspections indicate clearly that, where corrosion appears on the bottom shell, it is hand welding that is most severely attacked. (See Appendix II. Case B.)

For the connections of stiffeners to plating fillet welding is required. Whereas in riveted ships the faying surface of the plate and stiffener are both coated with red lead before erection, this is not done with welded stiffeners. Where continuous welding is used no harm may ensue but, although as yet the evidence is inconclusive, it would appear that with intermittent welding there must be some danger of corrosion between stiffener and plate. A popular construction is to scallop stiffeners where welded to plating, and the material at the radius of the scallop corrodes and may eventually crack. This may be due to the punch of the scallops removing the millscale in this region.

It is perhaps as well to mention that when connecting thick members it may be necessary to provide more weld material than is required for strength, since because of corrosion, the welded connection might otherwise disappear long before the members were sufficiently reduced in thickness to justify renewal.

Reference will be made in Section 2 and Appendix II to some cases in which the corrosion of outer bottom plates was associated with welding and also in Section 2(*g*) to some sea-immersion tests by the British Iron and Steel Research Association on specimens of welded plate. The main result of these tests was to indicate that the use of welding introduces no appreciable corrosion hazard, provided that care is paid to the surface preparation of the plates.

2. Corrosion of Underwater Plates

(*a*) *Practical Experience*

Some typical examples of survey reports by Lloyd's Register of Shipping, taken at random from those indicating corrosion, are given in Appendix II. Examination of a number of these has established certain general factors. For example, the majority of references to corrosion relate to the outside of the underwater plating. This is to be expected since, with a few notable exceptions, maintenance is comparatively easy in other parts of the ship, and consequently corrosion is much less severe there.

In view of its importance, the docking schedule was first studied. It was found that for a sample of 170 new ships examined, 85 had their first service dry-docking six months or less after delivery, 136 were dry-docked not more than 9 months after delivery and 153 dry-docked within a year. Some of the dry-dockings were no doubt involuntary, due to damage but the figures probably give a fairly true picture of current practice. Detailed examination of reports indicates that an early dry-docking after delivery is an insurance against severe corrosion. The treatment of the plating in the first year or two of the ship's life governs its subsequent condition to a large extent and almost invariably where severe corrosion occurs, other things being equal, it can be linked with long periods between dockings in the early stages.

The chief locations where corrosion is reported are on the bottom forward, where turbulence occurs, and on the side in way of the wind and water strakes and in the region of the bilge. A more localized position is around the rudder. The corrosion generally stands out as affecting rivet points, plating and welding, particularly hand welding, in the form of localized or general pitting. Occasionally sharp lines of corrosion are found across the plates. Typical extracts from reports are as follows:

(i) "Several areas of corrosion on under water side shell and bilge and plates bare of paint."

(ii) "Under water shell bare of paint in places. Three plates pitted in region of welding of tank margin" and, two years later,
"Two plates deeply corroded in way of margin plate weld."

(iii) "Extensive corrosion in bottom plating and rivet points, 12 plates renewed."
(This was at delivery dry-docking.)

(iv) "Rudder plating Port and Starboard deeply pitted in way of propeller stream."

(v) "Bottom shell plating found bare of paint and somewhat pitted, especially in way of bilge strake."

(vi) "Extensive pitting found on the bottom and side shell welded butts and seams. Keel plates affected in small areas by deep corrosive pitting."

(vii) "The hand electric welded seams and butts from the bilge strake to the waterline and in way of the forward shoulder plating up to the waterline slightly pitted."

(viii) "Scattered patches of corrosion in bilge and side shell plating, also in bottom shell plating, mainly in way of joggling of shell plate seams and around rivet holes. In a few cases pitting occurs in line with welding of internal structure."

(ix) "Scattered areas of corrosion up to a maximum depth of $\frac{3}{8}$ in. especially in way of plate corresponding with launching cradle."

(x) "A considerable amount of severe pitting and corrosion of plates, rivets and butts extending over the forward quarter length."

These typical cases follow the general pattern. Of 70 ships examined in some detail corroded rivets were mentioned in 25 cases, corroded welding in 18, pitting of plating 35, and corrosion of rudder and stern frame in 21 ships.

The corrosion observed is mainly electrolytic in character and is generally attributable to the following factors.

Pitting of plating is usually due to partial removal of millscale, the places where it is removed being anodic to the surrounding millscale. The relative areas of bare steel and millscale are important and if the bare parts are small compared with the area of the millscale, deep pitting will result. Corrosion of plating around rivets is due to similar reasons, the punching of the hole, the local heating, and the hammering up of the rivet tending to remove the scale. Removal of millscale also takes place on the opposite side of plating that has a welded attachment, e.g. on the outside shell in way of welded margin plate. Pitting may occur here. Sometimes working of plating is another cause of millscale removal.

(b) Mechanism of Corrosion by Sea-water

The rusting of iron is essentially an oxidation process and reflects the natural tendency of the metal to revert to the ore whence it is derived. In atmospheric rusting the primary reaction is the formation of ferrous hydroxide:

$$Fe + 2H_2O \longrightarrow Fe(OH)_2 + H_2$$

If the reaction is to proceed vigorously, the hydrogen has to be removed, either by diffusion or by combination with oxygen. Assuming that the conditions permit of this removal, a further complicated series of reactions follows between ferrous hydroxide, water and oxygen, leading to the formation of various higher oxides and hydroxides of iron, including magnetite, Fe_3O_4, and ferric oxide, Fe_2O_3. The final product, the familiar brown rust, consists largely of hydrated ferric oxides, such as gothite, Fe_2O_3, H_2O, which occurs naturally as a mineral.

The corrosion process for iron in sea-water is substantially the same but it should be emphasized that, although, for the sake of simplicity, rusting has been presented above as a sequence of straightforward chemical reactions, in practice direct chemical combination seldom occurs. For example, the direct decomposition of water by iron can only be made to take place under carefully chosen conditions in the laboratory. In fact, corrosion by sea-water is an electrochemical process, in which the surface of the metal is split up into a number of electrolytic cells; as a result, some areas, the "anodes," are attacked, whilst others, the "cathodes," are protected. A simple illustration of this mechanism is given by a classical experiment of U. R. Evans (Fig. 4). When a drop of salt water is placed on polished steel, the centre of the area covered by the drop becomes anodic and iron is dissolved there as ferrous chloride, whereas near the edges of the drop the steel becomes cathodic and the electrochemical reaction results in the formation of sodium hydroxide, with no attack on the steel. The sodium hydroxide diffuses inwards and the ferrous chloride from the central area outwards; where they meet a precipitate of ferrous hydroxide forms, which is gradually oxidized to rust. The final result is that the steel is corroded away at the centre of the drop and remains bright round its edges, which are separated from the centre by a ring of brown rust.

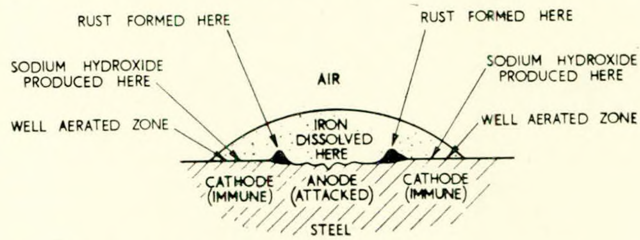


FIG. 4.—CORROSION OF STEEL BY A DROP OF SALT WATER (AFTER U. R. EVANS)

In this example the formation of anodic and cathodic areas is the result of potential differences caused by local variations in the rate of oxygen supply, the periphery of the drop being better aerated than the centre, to which oxygen has less easy access. In practice, on the hull of a ship there are numerous possible causes of potential differences between one part and another,* so that the conditions for the initiation of electrochemical corrosion are always present. The three major causes of these potential differences are: (i) the presence of millscale on the plates, (ii) holidays in the bottom painting scheme and (iii) the juxtaposition of dissimilar metals.

(i) Millscale is dangerous, because it has a potential about 0·3 volt nobler than that of bare steel, so that millscale and bare steel side by side form an electrolytic cell in which the corrosion of the bare steel is stimulated.

(ii) Holidays in the paint are injurious, because they form a cell with the painted area in which the corrosion is concentrated at the relatively small holiday. When, in an experiment, a holiday of $\frac{1}{4}$ sq. in. was left on a painted steel immersed in sea-water, penetration at the bare area occurred at the rate of 0·07 in. per year. Even higher rates of penetration have been observed on ships in service where the paint on the plates has been damaged, because corrosion is

* K. N. Barnard has reported an interesting survey of the potential differences on the underwater hull of a ship belonging to the Royal Canadian Navy. "Corrosion of a Steel Ship in Sea Water," *Canadian Journal of Research*, 1948, F, 26, September, 374–418.

accelerated by the increased oxygen supply resulting from the motion of the ship.

(iii) There is an appreciable potential difference between many non-ferrous metals and steel, to the detriment of the steel, so that suitable precautions should be taken when non-ferrous metals are let into the bottom plating at outlets and elsewhere.

In the absence of oxygen the corrosion of steel by sea-water tends to come to a standstill, because, unless the hydrogen is removed by oxidation, the accumulation of hydrogen at the cathodes stifles the corrosion cells. Normally, however, there is sufficient oxygen in the sea-water to allow the corrosion of bottom plates to proceed at or near the maximum rate, if there are unprotected areas on them. This is particularly so when the ship is in motion and the water is nearly saturated with oxygen because of the turbulence.

If the amount of dissolved oxygen present is reduced, the rate of corrosion falls. In laboratory experiments, for example, the corrosion of steel by distilled water is roughly proportional to the oxygen content of the water up to the limit corresponding to the maximum solubility of air in water. Corrosion does not necessarily cease when the oxygen content of sea-water is reduced to zero, because a different corrosion mechanism may then come into play. This mechanism, known as "sulphate reduction," is associated with certain bacteria, which can flourish only under anaerobic conditions, i.e. when their habitat is free from oxygen, and make use of sulphates as part of their life cycle. The sulphate-reducing bacteria concerned "reduce" sulphates to sulphides, thereby making the oxygen of the sulphates available for the corrosion of iron or steel near the bacteria.

The microbiological reactions involved are complicated but the following is a simplified explanation of what happens:

(i) The sulphate, e.g. calcium sulphate, is reduced to sulphide, thus:

$$CaSO_4 \longrightarrow CaS + 4O$$

(ii) The 4 atoms of oxygen resulting from this reaction will oxidize 4 molecules of hydrogen, which in turn correspond to the corrosion of 4 atoms of iron, as below:

$$4Fe + 8H_2O \longrightarrow 4Fe(OH)_2 + 4H_2$$

$$4H_2 + 4O \longrightarrow 4H_2O$$

(iii) Double decomposition occurs between one molecule of ferrous hydroxide and the molecule of calcium sulphide, yielding calcium hydroxide and ferrous sulphide:

$$CaS + Fe(OH)_2 \longrightarrow Ca(OH)_2 + FeS$$

(iv) The final result, obtained by adding the corresponding sides of all these equations, is as follows:

$$4Fe + 4H_2O + CaSO_4 \longrightarrow 3Fe(OH)_2 + FeS + Ca(OH)_2$$

It will be noticed that iron sulphide occurs in the corrosion product, so that attack by sulphate-reducing bacteria, e.g. on pipes buried in a waterlogged soil, is recognized in practice by the black appearance of the corroded layer immediately in contact with the metal and the evolution of sulphuretted hydrogen when this crust is wetted with hydrochloric acid.

Corrosion due to sulphate-reducing bacteria is most prevalent in the case of ferrous metals buried in impermeable clay soils but it may also affect ships, since sulphates are present in sea-water. Corrosion of the bottom plates through bacterial action can occur if for any reason a ship sinks on to a mud bottom, as in an interesting case described by W. S. Patterson.* Anaerobic conditions may also develop locally if a small area of the bottom becomes covered with mud or if a continuous layer of precipitated rust seals off the outer surface of a blister. Under such circumstances attack by sulphate-reducing bacteria may take place. So far as is known at present, the danger resulting from this bacterial corrosion does not lie so much in the rate of general attack, which seems to be no greater than that caused by normal access of oxygen, as in the fact that through its very nature, corrosion by sulphate-reducing bacteria is often concentrated on a restricted area. Thus although in the case reported by Patterson, the rivet points were pitted and the plates were grooved and scored, localized attack of equal severity is frequently observed on the side plating under conditions of complete aeration. (Compare, for instance, some of the cases described in section 2(*a*).)

* Patterson, W. S.: "External Ship Corrosion due to Bacterial Action," *Transactions of the North East Coast Institution of Engineers and Shipbuilders*, 1951, **68**, 92–106.

(*c*) *Remedial Measures*

As stated in section 1(*c*), the corrosion of ship plate when immersed in sea-water is not materially affected by the composition of the steel. Consequently, corrosion under these conditions cannot be prevented by alterations in the steel itself, so that resort must be had to protective measures. Here there are two possibilities:

(i) To alter the fundamental electrochemical corrosion cell (see section 2(*b*)) in such a way that the bottom plates can no longer corrode. This process is known as "cathodic protection" and will be discussed later in section 2(*h*).

(ii) To provide adequate protective coatings. Here main reliance has been and will continue to be placed upon painting but the use of metallic coatings, particularly of zinc or aluminium, in conjunction with paint may prove advantageous under certain circumstances.

(*d*) *Protective Painting*

Success in the protection of ships' bottoms by painting depends on careful attention to three factors: good surface preparation of the plates to receive the paint, the use of an efficient painting scheme of adequate thickness and good painting conditions.

To deal with the last point first: It is obvious that the practical conditions under which ships operate may render it imperative on occasion to rush the painting of a bottom, and cases are not unknown in which this has been begun immediately after dry-docking before the plates were dry. It should be made quite clear, however, that this is bad practice and should not be encouraged. To obtain the best results painting should be carried out in good weather conditions; where there is any latitude of choice, in Great Britain the period between April and October inclusive is likely to prove the most propitious.

Further discussion of the subject may usefully be grouped under four headings: (i) Current practice for new ships. (ii) Maintenance painting. (iii) Methods of applying paint. (iv) Recent research on anti-corrosive bottom compositions.

(i) *Current Practice for New Ships*

About 20 years ago, Dr. J. Montgomerie, then Chief Ship Surveyor to Lloyd's Register of Shipping, expressed the opinion that:

"Provided the surface of the steel is clean and provided the paint adheres to the steel there is no problem of corrosion such as we know it today."

This statement undoubtedly contains the gist of the matter, which is that efficient plate preparation followed by the provision of an adequate paint coating at the very start is the real solution of the problem. Since some of the paint is inevitably removed in service, the second essential is regular dry-docking, for there is no doubt that vessels that spend long periods in service without dry-docking in their early life invariably become corroded.

The first point to be considered is the treatment of the plating before coating. Weathering and subsequent wire brushing is the most common practice, and is fairly effective, providing the weathering period is not too short. Wet or dry sandblasting has been employed at dry-dockings after service but has not been resorted to frequently for new construction. Pickling, which is the standard protection for warships, is rare for merchant ships.

It is a matter for regret that, despite increasing recognition of the vital importance of good surface condition, far too often coatings are still applied without adequate plate preparation. Normal practice is to apply two coats of paint to the underwater shell before launching and two coats on delivery dry-docking, the latter consisting of one coat of anti-corrosive and one coat of anti-fouling composition. The coats before launching may be one coat of primer and one coat of anti-corrosive or two coats of anti-corrosive without a primer. Proprietary preparations are sold for coating welds before applying the priming coat to the hull: there is not sufficient evidence yet to suggest that they are necessary or effective. The weather conditions under which coatings are applied vary considerably and, due to late tank testing, it is frequently impossible to delay coating when the weather is bad. If late riveting or welding takes place and the paint is applied soon afterwards, it is unlikely that the adhesion of the paint will be good and experience amply confirms this.

(ii) *Maintenance Painting*

It must unfortunately be admitted that considerable corrosion sometimes occurs while fitting-out and cases have been known in which as many as twelve plates required to be renewed. It is always difficult to determine the exact cause of the corrosion. For example, in one case considerable attention was focused on a vessel where corrosion by sulphate-reducing bacteria was suspected as the cause of the trouble. Other reports made by Lloyd's surveyors have cited the presence of a sewer outfall near the fitting-out berth as a possible factor in the corrosion of three vessels. Of these three ships, vessel X received four coats of paint prior to launching and at the first dry-docking, less than a month after delivery, considerable corrosion was found. Vessel Y received two coats prior to launching and no corrosion was reported at the first dry-docking, five months after delivery. The plates of vessel Z had been pickled and two coats applied before launching; at the delivery dry-docking her bottom was found to have lost most of its paint and to be slightly pitted. The lack of conclusiveness of these last three examples is typical of the apparently fortuitous manner in which corrosion occurs in practice. Some more definite cases, in which fairly detailed investigations were made, are described in Appendix II.

The efficiency of protection by paint is a function of the coating thickness, so that the normal practice at dockings of coating on top of the old paint eventually results in plate protection. This is one reason why a good start and correct early treatment are essential, for it seems certain that if the original painting is good and the paint is maintained intact, no corrosion will occur. The chief aim of shipowners should be to prevent the inception of corrosion. In this connection it is noteworthy that although, when corrosion is found in the early stages of a vessel's life, eventual success in arresting the corrosion is almost invariably independent of the detailed measures taken, which depend to some extent on the individual tastes of the superintendent, these measures always include adequate surface preparation. In other words everything is done, such as sandblasting, that should have been done, but was omitted, when the ship was new.

Wasted rivets are sometimes welded up, which is not really satisfactory, since welding up will produce difficulties at subsequent repairs, or they may be renewed. Where rivets are slightly corroded, wirebrushing before recoating is usually resorted to. Provided recoating is satisfactorily carried out, any of these measures is usually effective in arresting corrosion.

Corroded welds should on no account be welded up without first chipping out; if this is done and the area carefully recoated, the corrosion will usually be arrested. Welds are sometimes chipped to give a smooth surface. Some owners and builders object to this but, if the resultant surface is smooth and homogeneous, the coating will adhere satisfactorily and corrosion will then be less likely than with unchipped welds. With the present trend towards large prefabricated units the amount of hand welding that will require chipping will not be excessive.

Minor cases of pitted plating are usually wire brushed and recoated; if the pits are deep, they are sometimes welded up, in which case it is advisable to level off the weld surface, while in a few cases sand-blasting has been resorted to. Efficient coating after these measures should prove satisfactory. Special paint treatments noted are the local coating of wire-brushed pitted areas with gold size, and in another case the application of hot white lead paint. As the corrosion is usually checked after one or two dry-dockings, it is impossible to decide whether any one treatment is more effective than the others.

Finally, in connection with maintenance painting, it should again be emphasized that, as a general principle, it is inadvisable to leave too long a period between the early dry-dockings of a new ship. During the first year or so of her life, until a body of intact paint has been built up on her bottom, it will generally repay the trouble taken to dock and repaint at about six-monthly intervals.

(iii) *Methods of Applying Paint*

Until quite recently all paint was applied to the hulls of ships by brush. This was, of course, at one time the sole method of applying paint for any purpose. In other fields the use of spray painting has become popular and more recently roller painting has been introduced. As was to be expected, the use of spray and roller has spread to ships in dry-dock and on the stocks.

One continental district has almost exclusively turned over to spray or roller painting. It is understood that the general opinion there is that, if well done, brush painting is best, but that spraying and rolling are satisfactory, the latter being the better of the two.

In this country brushing seems to have been partly replaced by rolling but spraying is less popular. On new construction one procedure is to brush on the first coat and then use the roller. This appears a reasonable compromise, since it permits of the first coat being well worked in. Brushing is essential at riveted seams and bilge keels; one firm uses a brush for these parts and a roller for the rest, including the welds. The roller is said to give a 15 per cent reduction in paint used. It is not so advantageous, where staging is available and the use of the long handle can be avoided.

While some time must elapse before a complete assessment of the different methods of application can be made, it is a fact that the efficiency of a paint film in combating corrosion depends very largely upon its watertightness. There must be some doubt of this tightness with roller application on a surface not completely smooth and still more doubt with spraying, particularly under windy conditions.

The coverage of paint per gallon depends upon various factors, such as the state of the surface and the atmospheric conditions, but the allowance made by shipyards for brush-applied paint varies from 30 to 60 sq. yd. per gallon. These figures correspond to average wet paint film thicknesses of from 0·007 to 0·0035 in. The thickness of the dry paint film will vary with the formulation of the composition but may be roughly assessed as falling within the range 0·004 to 0·0015 in. In a test application on the deckhouse of a ship 92 sq. yd. was covered by 1 gallon of paint.

(iv) *Recent Research on Anti-Corrosive Bottom Compositions*

The problem of protecting the submerged parts of a steel hull differs materially from that of protecting an atmospheric structure, such as a railway bridge. Perhaps the major difference is that, whereas steel exposed to the atmosphere is only occasionally wetted by rain and condensation, a ship's bottom is continuously immersed in a good electrolyte, sea-water, for long periods. As soon as any rusting of the steel plates occurs under the latter conditions, caustic soda (sodium hydroxide) is formed at the cathodes of the corrosion cells. (See Fig. 2.) Like other alkalis, caustic soda has the property of destroying paint media consisting of ordinary drying oils, by a process known as saponification, in which the oils are split up into their constituents, glycerol and fatty acids. For this reason the choice of a suitable medium with a high resistance to saponification is probably the most important single factor in determining the successful performance of an anti-corrosive composition. In this respect, the incorporation of bitumen in the paint medium may offer certain advantages but the following discussion will be limited to paints based on drying oil media, which are in more common use.

Linseed oil itself is easily saponified, with the result that an ordinary red oxide in linseed oil paint is far from suitable as a priming coat for a new ship or indeed for the maintenance painting of a ship in service. A mixed red lead and white lead in linseed oil paint, similar to that specified in B.S. 2523: 1954,* would give better results if ample time, say a week, could be allowed for it to dry on the stocks before over-painting with ships' compositions, because reactions between the pigments and the oil strengthen the dry paint film and increase its resistance to saponification. Even so, the use of straightforward linseed oil paints, however pigmented, is not to be recommended for ships' bottoms.

Fortunately, within the last twenty years or so, the development of synthetic resins that can be incorporated in drying oil media or used by themselves as simple solutions has made available to the paint industry a wide variety of media with extremely good resistance to saponification and, therefore, to water permeability, which often is closely linked with this. As examples may be cited the phenolic resins, the chlorinated rubbers, the polystyrenes and the vinyl resins. Theoretically, it would seem that, failing the development of a perfectly impermeable and non-saponifiable paint, which would exclude the sea-water entirely, success in the production of an anti-corrosive composition may depend upon its having a definite but not excessive permeability. This is because any inhibitor pigments, such as red lead or zinc chromate, contained in the paint must pass into solution, to however slight a degree, before they become effective and some slight degree of diffusion of water through the paint film is needed to ensure this. In other words the optimum practical anti-corrosive composition may prove to have a medium with a permeability approaching but not quite equal to zero.

Be this as it may, the fact is that excellent anti-corrosive compositions are now available. Individual manufacturers have solved the problem of producing them in different ways; for example, at the moment in the United States great faith is placed in paints with vinyl resin media. In Great Britain extensive researches in this field have been conducted by the Protective Coatings (Corrosion) Sub-Committee† of the British Iron and Steel Research Association and it may be of interest to give a brief outline of their findings.

After trials of numerous pigment combinations and media, formulations were evolved in which the medium was a modified phenolformaldehyde stand oil varnish and the main constituent of the pigment was basic lead sulphate. One anti-corrosive composition of this series, No. 173, with the formulation given in Table II, was adopted by the Admiralty in the early '40s for use on all naval construction and, with slight modifications, has been satisfactorily used for this purpose ever since. The general formulations of two other anti-corrosive compositions of the same type, No. 185 and No. 655, are also given in Table II. They differ from No. 173 in that their main secondary pigment is metallic aluminium instead of white lead. Moreover, the medium for No. 655 contains an admixture of tung oil. On the whole, as has been established by full scale service trials made with the kind collaboration of the owners on the *Pretoria Castle* and other vessels of the Union Castle fleet, No. 185 is slightly better than No. 173 and No. 655 than No. 185.

Further evidence of the performance of No. 185 has been made available through the courtesy of the Cunard Steamship Company Ltd. This composition has been in continuous use on the two "Queens" since 1949, except that on the *Queen Mary* a proprietary composition of substantially the same formulation was substituted for it from 1952 onwards. The procedure is to apply two coats of the composition over the old paint when the liners are dry-docked for their annual overhaul in December and January; a final coat of anti-fouling composition is applied over the anti-corrosive paint on the sides but is omitted on the flats of the bottom, where negligible fouling is experienced on this route. Because of the good condition of the old paint, little surface preparation is needed other than cleaning down with water and brushes but a number of plates are "sliced" annually in rotation so as to break the head of any small blisters that may have formed. At the annual inspections the paint has been found to be perfectly intact and the amount of rusting insignificant, except over small local areas where mechanical damage, e.g. chafing, has occurred. Indeed, the performance of the paint has been such that it has proved possible to omit the summer application of anti-corrosive paint, which used to be customary, i.e. the protective painting in the winter now lasts for the full twelve months.

The Cunard Company is perfectly satisfied with the protective properties of a/c composition No. 185, which has been in constant use as stated above for six years. At the end of this time, however, appreciable surface roughness has developed on the *Queen Elizabeth*, mainly through the local flaking of one or two coats of old paint. This problem is probably common to all bottom painting schemes and it is difficult to preserve a perfectly smooth surface on a ship's hull over a period of years during which a dozen or more coats of paint may have been applied to it. It would seem that the only way of ensuring such surface smoothness would be to strip the paint to the bare metal and to begin to build it up again. In practice this would mean that the shipowner would have to balance the cost of this relatively expensive treatment against the increase in fuel consumption for equal speed, caused by the roughness of the old paint.

It would be presumptuous to claim that the anti-corrosive compositions developed by the British Iron and Steel Research Association are the only ones capable of giving satisfactory performance on a ship's bottom. Alternative formulations and proprietary materials, some of which make use of the media mentioned earlier in this section, are available. In the long run all of them must be judged on their practical merits, particularly cost, ease of application, and lack of sensitivity to adverse conditions at the time of painting. Perhaps one particular merit of the B.I.S.R.A. paints is that they set a good and reasonable standard by which others may be judged, as is demonstrated by the photograph of a laboratory test specimen shown in Fig. 5.

Paints such as a/c No. 185 require a fair drying time, e.g. they should at least be left to dry overnight before being overcoated. This can normally be arranged without difficulty for new ships on the stocks but there is obviously an advantage in having a quick-drying paint when time is limited in dry-dock. The most recent investigations of the Protective Coatings (Corrosion) Sub-Committee have been directed towards developing a/c compositions of the latter type for use for maintenance purposes. Service trials on one of the most

* British Standard Specification B.S. 2523: 1954. "Lead-Based Priming Paints for Iron and Steel (Types A, B, and C)."

† Fancutt, F., and Hudson, J. C.: "The Protection of Ships' Bottoms and the Formulation of Anti-Corrosive Compositions," *Journal of the Oil and Colour Chemists' Association*, 1947, **30**, May, 135–162. For a description of later work, see reference (4) of the Bibliography.

TABLE II

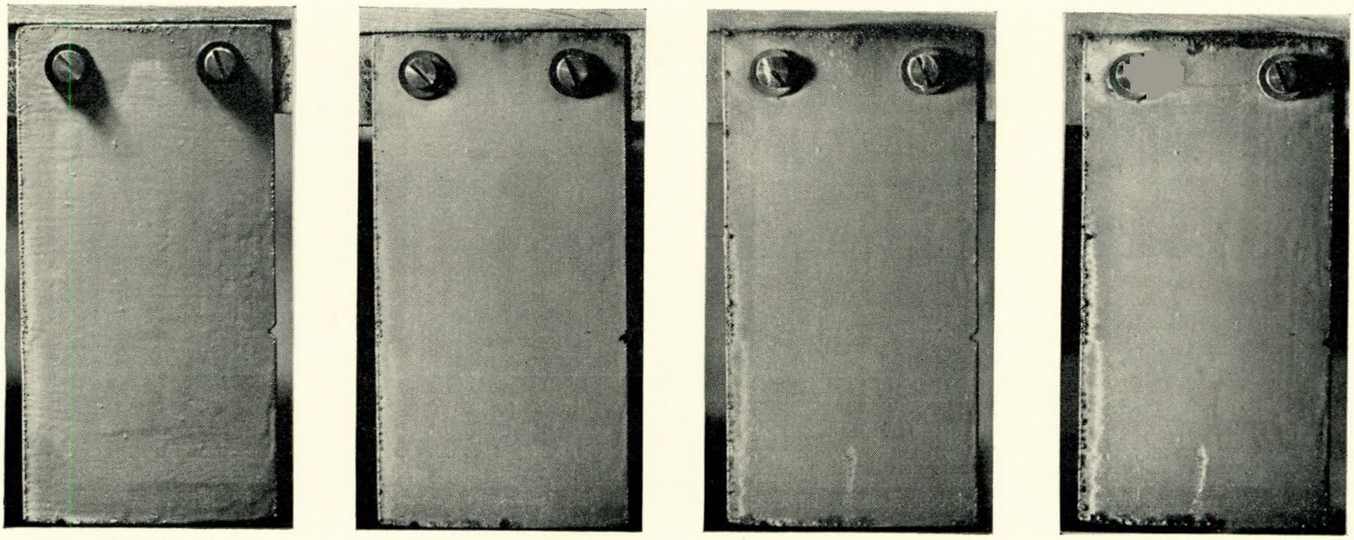
FORMULATIONS OF ANTI-CORROSIVE COMPOSITIONS* (B.I.S.R.A.)

	No. 173	No. 185	No. 655
Composition of pigment (per cent by weight)	Basic lead sulphate .. .. .. 40 White lead .. .. 20 Burntisland red† .. .. .. 20 Barytes 20	Basic lead sulphate .. .. .. 40 Aluminium powder .. .. .. 20 Burntisland red† .. .. .. 20 Barytes 20	As for No. 185
Composition of medium (per cent by weight)	Modified phenol-formaldehyde resin‡ .. .. 19·76 Stand oil (60 poise) .. .. 39·52 White spirit .. .. .. 36·46 Lead naphthenate (Pb 24%) .. 3·41 Manganese naphthenate (Mn 8%) 0·85	As for No. 173	Modified phenol-formaldehyde resin‡ .. .. 22·33 Stand oil (60 poise) .. .. 22·33 Tung oil .. .. 22·33 White Spirit .. .. .. 32·08 Lead naphthenate (Pb 24%) .. 0·74 Manganese naphthenate (Mn 8%) 0·18
Method of manufacture of medium	Heat the stand oil to 220° C. and add the resin. When solution is complete, raise the temperature to 240° C., hold for a clear bead, cool to 150° C., thin and add driers.	As for No. 173	Heat the stand oil with half the resin to 280° C. in ¾ hour and hold to a long string. Add the remainder of the resin and dissolve this at 210° C. Add the tung oil and hold the temperature at 240° C. to a long string (approx. ½ hour). Cool to 180° C., thin and add driers.
Method of manufacture of paint	The method of manufacture used for experimental batches (½ gallon lots) was to mix the pigment and medium thoroughly together and pass the mixture through a cone mill once. After having stood for about a week at room temperature, the paints were adjusted to a suitable brushing consistency by the addition of naphtha.		
Composition of the paint (parts by weight)	Pigment .. .. 100 Medium .. .. 45 Thinners 11	Pigment .. .. 100 Medium .. .. 86 Thinners 21	Pigment .. .. 100 Medium .. .. 71 Thinners 30
Pigment/non-volatile vehicle ratio (by weight)	3·95 : 1	2·03 : 1	2·08 : 1
Weight per gallon (lb.)	19·5	14·0	14·2
Efflux time (sec). (First 50 c.c. from a full No. 4 Ford cup at 70° F.)	25	26	24

* It will be appreciated that the detailed composition of a paint is affected by variations in the properties of the raw materials from one batch to another. Minor adjustments from the figures given might, therefore, prove desirable at the manufacturer's discretion in bulk production.

† Burntisland red is prepared from the residue left after the extraction of aluminium from bauxite; a red iron oxide pigment such as an Indian red, can be used instead if desired.

‡ The resin used had a viscosity of 32 poises when tested at 20°C. as a 65 per cent solution in toluene; its acid value was 14·2 mg. KOH per g. of resin.



8 weeks | 13 weeks | 27 weeks | 35 weeks

FIG. 5.—EFFECTIVENESS OF MODERN ANTI-CORROSIVE COMPOSITIONS

These photographs are intended to demonstrate the good performance of well-formulated modern anti-corrosive compositions. The steel specimen concerned, after pickling and painting, had been tested under severe conditions of movement and turbulence by immersion in synthetic sea-water in the B.I.S.R.A. Rotor Apparatus for the periods stated. The painting scheme consisted of a single coat of pretreatment primer [see section 2(*d*)(iv)] about 0·0002 in. thick, followed by a single coat of a/c composition No. 173 (see Table II), 0·0014 in. thick. Despite the thinness of the paint film—a total initial thickness of about 0·007 in. is desirable for a new ship entering service—the body of the paint was in good condition after 35 weeks, breakdown being confined to the edges and to a slight graze.

promising of these maintenance compositions are now being made by the Admiralty in collaboration with Joint Technical Panel N/P2 of the Sub-Committee.

Good performance of the anti-corrosive composition can be achieved only when it is applied to a properly prepared surface and the question naturally arises—What is the best method of preparing the outer bottom of a ship for painting? A complete answer to this question cannot yet be given but it has already been established beyond doubt that all millscale should be removed from the plates.

The presence of millscale on the steel is injurious to the paint in two ways:

Firstly—if the millscale is loose or becomes loose as a result of being undermined by rust, it flakes off and carries away the paint film with it.

Secondly—Millscale is cathodic to bare steel, the potential of millscale in sea-water being roughly 0·3 volt nobler than that of bare mild steel. This means that the conditions on a ship plate partly covered with millscale are favourable to the development of electrolytic corrosion cells and to all the evils that this entails. Such a surface condition is most dangerous when the millscale is almost perfectly intact, i.e. there are a few breaks in it only, for then the whole of the corrosion, which is broadly determined by the amount of oxygen reaching the plate, is concentrated at the bare areas, where severe pitting may result. Contrariwise, if the steel has shed most of its millscale, say to the extent of 90 per cent, electrolytic corrosion due to the millscale will be much less intense and less dangerous.

There are three practical methods of removing millscale from ship plate: pickling, gritblasting and weathering. Of these, the first two are greatly to be preferred, because descaling by exposure to the weather, in the shipyard and on the stocks, is a chancy business. It is doubtful whether the complete removal of the millscale from the entire bottom of a ship could generally be ensured in this way, because periods of a year or more are needed to remove some millscales even when steel is freely exposed in the open.

Pickling, using a cold solution of hydrochloric acid, has long been used by the Admiralty for the surface preparation of ship plate; the method seems to be a convenient one for the general run of shipbuilding, because the capital cost of the necessary plant is not excessive and the plates can be handled in small batches as occasion arises. Recent developments in gritblasting machinery may render this process competitive with pickling and there are indications that gritblasting may be preferable to pickling for descaling high-tensile plates, as distinct from plates of ordinary ship plate quality.

When painting steel exposed to corrosion in air, as distinct from water, it is important to apply the priming coat of paint immediately after the millscale has been removed, whether by pickling or gritblasting, before any rust has formed on its surface. This is not so for ships' bottoms. In this case the presence of slight, but not excessive, rusting on the plates is often advantageous, because for some reason, not yet properly understood, many, though not all, anti-corrosive compositions do not adhere well to a perfectly blank steel surface obtained by pickling or gritblasting. The presence of rust seems to provide a necessary key. The same result can be achieved by the use of chemical surface treatments with solutions based on phosphoric acid or better still of pretreatment primers. The latter, developed by the Bakelite Corporation in the United States during the Second World War, consist essentially of an alcoholic solution of phosphoric acid, a synthetic resin and a chromate pigment. A commonly used formulation* is given below:

A. *Pigment Base*	*Per Cent by Weight*
Polyvinylbutyral resin	9·0
Basic zinc chromate	8·6
Magnesium silicate	1·3
Lamp black	0·1
Butyl alcohol, normal	20·0
Ethyl alcohol	61·0
	100·0

* Steel Structures Painting Council, 4400, Fifth Avenue, Pittsburgh 13, Pa., U.S.A. Pretreatment Specification PT3–53T. "Basic Zinc Chromate—Vinyl Butyral Washcoat," March 1953.

Aircraft Material Specification of the Ministry of Supply, D.T.D.868, "Etching Primer," November 1953, is an equivalent British specification.

B. *Acid Diluent*

Phosphoric acid (85 per cent)	18·0
Ethyl alcohol	65·9
Water (maximum)	16·1
	100·0

The pigment base and acid diluent are kept separately and are mixed together in the proportion of four to one by volume immediately before the pretreatment primer is needed for use. The primer is applied by brushing or by spraying at a spreading rate of about 350 sq. ft. per gallon. It should be emphasized that, owing to the high proportion of volatile matter present, the thickness of the dry film obtained is much less than that of a normal coat of paint, so that a pretreatment primer is to be regarded essentially as a surface preparation and no reduction should be made in the number of coats of ordinary paint that would normally be used.

It will be gathered from these remarks that certain aspects of the preparation of ships' hulls for painting still need some clarification. Research, in which the Admiralty Corrosion Committee are collaborating with the British Iron and Steel Research Association, is in hand with this object in view.

(*e*) *Metallic Coatings*

Although it is improbable that extensive use will be made of protective metallic coatings for the hulls of merchant ships, passing reference may be made to the fact that these are a valuable additional defence against corrosion. The two metals warranting practical consideration for the purpose are zinc and aluminium. Both are anodic to steel, i.e. they are the corroded member of the cell: zinc or aluminium/sea-water/mild steel, so that they protect the steel at any place when this is laid bare by a scratch or similar damage to the protective coating. According to the electrochemical series aluminium is considerably more anodic to steel than zinc, but when measured under practical conditions the E.M.F.s of the cells formed by one or other of the metals with steel are practically the same and about 0·3 to 0·5 volt.

Conflicting views are held regarding the respective merits of zinc and aluminium coatings for the underwater protection of steel. In some immersion tests in sea-water made by the British Iron and Steel Research Association, a zinc coating weighing 3 oz. per sq. ft. of surface, or about 0·005 in. thick, protected steel satisfactorily for 6 years. Similar specimens coated with sprayed aluminium of approximately the same thickness were removed after two years' immersion, as the coatings were then thought to be on the point of failure, but it would probably be unfair to generalize from this single observation and further experimental evidence is needed to settle the point.

The Admiralty normally hot-galvanize ship plate of ¼ in. thickness or less and this would seem to be a wise precaution, for small vessels with light plates. When hot-galvanized plates are assembled by welding, it may be necessary to omit or remove the coating from the plates within an inch or so of the joint; in any case the coating within this area would be largely destroyed by the heat. This is not a vital factor as regards efficiency of protection, because the coating elsewhere will tend to protect the bare steel areas cathodically; moreover, these can be made good by the application of a stripe-coat of protective composition, e.g. of "zinc-rich" paint in which the content of metallic zinc pigment in the dry paint film is so high as to ensure electrical contact between the zinc particles and the steel.

(*f*) *Anti-Fouling Compositions*

Although this paper is primarily concerned with corrosion, a brief reference is desirable to anti-fouling compositions, because the efficiency of a protective bottom painting scheme may be impaired unless it is covered with an effective anti-fouling composition. Fouling tends to disrupt a paint film physically and may conceivably have a damaging chemical effect on it too.

The best practical treatise on fouling published so far has been drawn up by the Woods Hole Oceanographic Institution.* In principle the solution of the problem of preventing fouling is simple: the finishing coat of anti-fouling composition applied to the hull must emit toxic agents into the sea-water in its immediate vicinity at a rate above a certain minimum and must continue to do so steadily so long as the ship is at sea. The two most potent toxins are copper and mercury; arsenic by itself is not very effective but some progress has been made in making use of organic poisons for the purpose. British and American investigators have both demonstrated that, in the case of copper, the "critical leaching rate" for immunity to fouling is 10 microgrammes per sq. cm. per day. This means that, for fouling to be prevented, copper must pass continuously from the paint to the sea-water at that rate, which is equivalent to 0·01 oz. of copper per sq. ft. per month.

In practice, however, the manufacture of an efficient anti-fouling composition calls for considerable skill and experience. It is not enough to ensure that the composition has an adequate leaching rate initially. This rate must be maintained for a long period, i.e. in popular terms, the "pores" of the paint film must not become clogged up with time. On the other hand, the critical rate must never be greatly exceeded, for then uneconomical use would be made of expensive toxic material. It would be inappropriate to discuss the subject in detail here but one final remark may be helpful. On the basis of the figures given above, not less than 0·06 oz. of copper is needed per sq. ft. of hull coated with anti-fouling composition to ensure freedom from fouling for a period of 6 months. It follows that there must be a minimum toxin content, related to the thickness of the paint film as applied under practical conditions, below which the efficiency of an anti-fouling composition cannot be guaranteed.† It also follows, in fairness to the paint manufacturer, that there is a certain minimum price below which he cannot be expected to supply a first-class anti-fouling composition. These are matters regarding which a shipowner can make the necessary calculations for himself in view of all the circumstances and the market conditions at the time.

(*g*) *Rivets and Welds*

The corrosion of rivets is one of the most aggravating manifestations of corrosion on the underwater plates of a ship and cases in which hundreds or even thousands of rivets have had to be renewed, particularly in new ships, are by no means rare. Reference has already been made in section 1(*d*) to the fact that riveted assembly by its very nature entails design features that may prove conducive to corrosion. The fact is that rivet corrosion is mainly due to electrochemical differences between the rivet material and the surrounding plates and that the conditions obtaining on a ship's hull will more often than not tend to ensure that it is the rivet that is the anode of the corrosion cell, rivet/sea-water/surrounding plate. For example, severe rivet corrosion has been observed on certain trawlers that were built very rapidly, so that, when they were launched, up to 90 per cent of the millscale was still adhering to the bottom plates. It is true that an oxide scale may also have formed on the rivet points during hot-riveting but it is doubtful whether this would be as uniform as that on the plates. If there were any small areas on the rivets free from scale, these would suffer intense corrosion when immersed, as a result of their contact with the large cathodic areas of plate covered with millscale. Moreover, the very fact that the rivet points protrude may tend to cause the paint

* *Marine Fouling and its Prevention.* The United States Naval Institute, Annapolis, Maryland. 1952.

† Satisfactory performance may, of course, be obtained from a relatively poor anti-fouling composition if the ship is not exposed to serious fouling on her route, as is sometimes the case.

to be abraded from them. If so, the conditions would again be propitious for severe anodic attack.

Some years ago several cases of rivet corrosion were definitely associated with the use of rimming steel for the manufacture of rivet bars. In this type of steel the sulphide inclusions, which are unavoidably present to some degree in all industrial steels, are concentrated at some depth below the surface instead of being more uniformly distributed throughout the steel. This segregation is immaterial when the steel is used in plate or sheet form, since the inclusions are buried beneath an adequately thick surface layer of purer metal but it may have serious consequences when the cross-section of the steel is exposed, as happens when it is fabricated into rivets. The use of rimming steel for rivet production has, therefore, been prohibited. In consequence, it is rare nowadays to trace a connection between corrosion and the rivet material; so far as is known, in all recent cases when sample rivets have been tested following reports of corrosion, the steel has been found satisfactory with no sign of sulphur segregation.

It is clear that, as Dr. S. Livingston Smith* has said, the danger of rivet corrosion would be materially reduced if the millscale were removed from the bottom plates, e.g. by pickling, and careful attention were paid to painting before launching and thereafter, particularly during the first year of service of the ship.

Another obvious remedy, in theory at least, is to make the rivet material of a different type of steel that would be cathodic to the steel plating. Certain low-alloy steels are known to have electrode potentials that are a few tenths of a volt "nobler" than steel of ship plate quality but how far it would be practicable to use them for riveting and how effective the remedy would prove under practical conditions are not yet known.

On the whole, welding will yield a smoother bottom than riveting, particularly if the welds are dressed flush with the surface, where practicable. There will, therefore, be less tendency in welded construction for corrosion cells to be set up because of differences in oxygen concentration, which, as has been demonstrated experimentally, give rise to differences in potential, the parts in contact with sea-water rich in oxygen being cathodic to those in contact with less well oxygenated sea-water. Moreover, there is less chance of local removal of the paint film, which often leads to pitting, from a smooth hull. On the other hand, in the conditions of flowing water round a ship's hull, it is conceivable that the bottoms of the cavities of unsmooth welds, being less well aerated, might function as anodes and suffer aggravated corrosion. Corrosion at or near welds may also be hastened by the removal of millscale from the plates due to the heat of the welding process; clearly this could be avoided by using plates that had been descaled by pickling or some other means.

The question also arises whether potential differences may occur between the weld metal and the surrounding plating, which would occasion corrosion. As an interim reply to this, it may be stated that in some experiments conducted by the British Iron and Steel Research Association in collaboration with the British Shipbuilding Research Association, the results of which are as yet unpublished, welding was not found to have any serious effect on corrosion. In these tests relatively small pieces of ship plate were assembled at a shipyard by a number of welding processes in current use. The assemblies were then painted and immersed in the sea from a raft at Caernarvon for a year. At the end of this time there was no evidence of undue local corrosion at or near the welds. This evidence, so far as it goes, is reassuring but it is obvious that a small piece of stationary plate cannot be fully representative of thousands of tons of steel moving at speed through sea-water, so that experience must be the final criterion.

* SMITH, S. L.: *Note on the Corrosion of Rivet Points.* Prepared for the Waters (Corrosion) Sub-Committee of B.I.S.R.A., November 1950.

(*h*) *Cathodic Protection*

In the previous discussion constant reference has been made to the electrochemical character of the corrosion of steel by sea-water. Corrosion cells are set up in which one set of poles, the anodes, are corroded and the other set, the cathodes, are not. The principle of cathodic protection is simple and may be expressed thus: "Let us make one large corrosion cell of our own in which the metal or structure in which we are interested (in the present case the bottom plates of a ship) is the cathode and, therefore, remains uncorroded." This in fact is the reason behind the common practice of fitting protective "zincs" at places where bi-metallic contacts occur on the hull. Unfortunately, the practical effectiveness of this method, as applied, is often doubtful and in some cases its use amounts to little more than a gesture.

Scientific knowledge of cathodic protection dates back for over a century, for its inception was due to Sir Humphry Davy, but it is only within the last generation or so that the method has been widely applied, first of all to buried pipelines and, more recently, to harbour installations and to ships. One of the earliest marine applications known to the authors was made by an Italian engineer, C. Manzitti, who, after investigating local corrosion of the propeller shafts of the liners *Rex*, *Savoia* and *Victoria*, round about 1933, suggested the use of an applied potential to prevent this and investigated the possibilities of the method during a round trip of one of these ships from Genoa to New York and back.*

In practice the cathodic protection cell can be set up in two ways. The first consists in coupling the steel to a less noble metal, such as magnesium. The two metals and the electrolyte then form a corrosion cell of the right type by themselves and no external source of electric power is needed. In the second way, the corroded members of the cell are of cast-iron, steel or some other material, e.g. graphite, which do not engender the appropriate electromotive force when coupled to the steel. In this case the necessary electromotive force has to be imposed from without by some suitable means. No generalization can be made as to which method is the more economical. This depends entirely on the local circumstances and in any particular case it is wise to seek advice from an expert. It is certain, however, that either method is completely effective in stopping corrosion when it is correctly applied under appropriate conditions.

When applying cathodic protection to ships' hulls, two complicating factors should be borne in mind.

(i) The whole of the submerged hull is the cathode of the corrosion cell. Consequently, the conditions in the immediate vicinity of the plates become alkaline and, as explained in section 2(*d*)(iv), alkali tends to break down paint by saponifying the medium. If it were applied in a haphazard manner, cathodic protection might, therefore, have a damaging effect on the bottom painting scheme. Fortunately, good anti-corrosive compositions are, by their very nature, resistant to saponification and trouble from this cause can be prevented, where necessary, by painting the parts of the hull nearest to the sacrificial anodes with compositions having exceptionally high resistance to saponification; for example, vinyl paints are used for this purpose in the United States and Canada.

(ii) The development of alkalinity at the cathodes also reduces the solubility of the calcium and magnesium salts present in sea-water, with the result that they are thrown out of solution. Sometimes they are precipitated, mainly in the form of calcium carbonate and magnesium hydroxide, as an adherent deposit on the hull itself, i.e. on top of any anti-fouling composition that may be present. It is clear that the formation of this surface deposit may interfere with the delicate mechanism on which the efficacy of an anti-fouling composition depends [see section 2(*f*)]. Little seems to be known about this aspect of cathodic protection so far, but it certainly should not be overlooked.

* MANZITTI, C.: "Sugli equilibri elettrici dovuti al movimento con referimento al fenomeno di corrosione per cavitazione," *La Marina Mercantile*, 1951, **4**, February.

For detailed discussion of practical methods of applying cathodic protection to ships, reference will best be made to papers by members of the scientific staff of the Admiralty and of the Royal Canadian Navy,* who have had experience of its use for this purpose. This experience has firmly established that cathodic protection is of great value for ships laid up or out of commission, to which it can be easily applied. Although there is no insuperable difficulty in using the method for active ships at sea, in this case its practical advantages are not so obvious, as they have to be weighed against the complications caused by the provision of apparatus that might impair the efficient working of the ship. It will be clear that, as the presence of an electrolyte is essential, cathodic protection can only be used for the submerged parts of the ship and is not applicable to the superstructure and internal spaces generally, with the possible exception of ballast tanks.

3. Corrosion of the Superstructure

(*a*) *General Observations*

Serious corrosion of the superstructure is rare for the simple reason that all accessible parts are usually repainted at frequent intervals for appearance's sake. This is particularly true for liners and, as an example, it may be noted that when the old *Mauretania* was broken up after twenty-eight years' service, the hard white enamel on the deckhouses was found to be about 1/16th in. thick, which represents something like 30 coats of paint.

Corrosion sometimes occurs on deck plating that is fully exposed to the weather, particularly when this is covered with planking. The remedy is to use a good bitumen bedding composition and to apply this generously, both to ensure adequate protection of the steel and to avoid spaces remaining between the wood and the deck. This is particularly necessary on modern welded deckhouse tops, which, due to the combination of welding and thin plating, often have an undulating surface.

Funnels are sometimes corroded internally, although on the *Mauretania* mentioned above the general wastage of the inner surfaces of the funnel plates was only about 1/32 in. In some cases too, because of the heat, protection of the outsides of funnels by paint presents difficulties; this problem will be considered later in section (*c*).

Although the corrosion of the superstructure may not cause much trouble, it is obviously desirable to reduce it to a minimum, so as to facilitate and cheapen the necessary maintenance. Perhaps the single feature that would help most in this respect is careful attention to design. The superstructure of a ship is a place *par excellence* where condensation and entrapment of salt-laden moisture is liable to occur, and there is ample scope for the application of the simple principles discussed in section 1(*d*). In particular, care should be taken to provide adequate drainage arrangements for all horizontal surfaces and enclosed spaces, e.g. the extensions of superstructure decks which may be bordered by vertical plating, so as to form a pocket. Discoloration of paint through rust or through water draining from scuppers is a fairly frequent eyesore and may necessitate repainting before this is really needed through failure of the protective properties of the paint itself. Clearly in any practical ship there must be scuppers but it might be found possible to reduce the disfiguration caused by them by suitable alterations in design.

A few comments on steel quality, protective painting and metallic coatings in relation to the protection of the superstructure may be of interest.

(*b*) *Effect of Steel Quality*

As discussed in section 1(*c*)(ii), the use of "slow-rusting" low-alloy steels would reduce the corrosion of the superstructure appreciably if this were left unpainted or if maintenance painting were imperfect. As it is, at least with the standard maintained by most shipping companies, it is doubtful whether the use of such steels would be of much practical benefit from the corrosion standpoint, although there might be marked advantages in making use of their superior mechanical properties to save weight. If this were done, the greater corrosion risk to the thinner sections, should maintenance in fact prove imperfect, would be counteracted by the greater intrinsic corrosion resistance of the slow-rusting steels.

(*c*) *Protective Painting*

The principles governing the successful protection of a ship's superstructure by paint are essentially the same as for a land structure, e.g. a steel bridge. In brief these are as follows:

(i) Correct surface preparation.

(ii) The application of one or preferably two coats of a suitable priming paint containing inhibitive pigments.

(iii) Building up the painting scheme by means of suitable undercoats and finishing coats to a dry film thickness of about 0·005 in. In practice this entails the application of at least three, and more generally four, coats of paint, including the priming paint.

(iv) The careful conduct of all cleaning and painting operations under the best working conditions that circumstances will allow.

A few salient features relating to these principles, to maintenance painting and to heat-resisting paints will be discussed below; more detailed expositions of the whole subject will be found in some of the publications cited in the Bibliography (section 5).

Surface Preparation.—Maximum paint durability is secured by putting the first coat of paint on to a clean steel surface, perfectly free from millscale and rust. The best practical way of securing such a surface is by pickling or by gritblasting. This treatment may increase the life of a painting scheme to four or five times that observed on a weathered and wire-brushed surface. For example, in one exposure test a two-coat painting scheme had a life of 8·1 years when applied to pickled wrought iron but of only 1·8 years when the iron was prepared for painting by weathering.

Priming Paint.—The best priming paints for steel are those containing an "inhibitive" pigment, which tends to passivate the steel and stifle corrosion at birth. For general all round use on structural steel exposed to the atmosphere a mixed red lead and white lead in linseed oil paint in accordance with B.S. 2523: 1954 is as good as any, although there are a number of alternatives both as regards pigmentation and medium. Paints in a linseed oil medium, such as that mentioned, have the advantages of being less sensitive to the adverse effects of poor surface preparation, i.e. they will perform relatively well on weathered steel, and of yielding thicker dry films per coat than most of the more modern paints in synthetic resin media. The latter only become fully effective when they are applied to well prepared steel surfaces, descaled by pickling or gritblasting; when this condition obtains, they in their turn have the advantages of drying more quickly—an important consideration when the freshly applied wet paint has to be left exposed to an atmosphere polluted with smoke and grime—and of yielding a harder film.

Undercoats and Finishing Paints.—If the foundations for successful protection have been properly laid by correct surface preparation of the steel and the use of the right type of priming paint, the choice of the undercoats and finishing coats to complete the painting scheme for the superstructure is not critical and can be made with due regard to such external considerations as the colours adopted by the line concerned and the desirability of retaining gloss and of avoiding fading. Care should naturally be taken to choose paints of good quality that are compatible with each other and, in the case of undercoats, also with the priming paint.

* See, for example, the papers by J. T. Crennell and K. N. Barnard in the *Symposium on Cathodic Protection.* Reference (7) of the Bibliography. Also the paper by L. T. Carter and J. T. Crennell. Reference (8).

Until fairly recently the best weather-resisting paints for use as finishing coats were made with media of the stand oil type, but synthetic resin media are favoured in modern practice. Alkyd media, for example, are particularly useful for the purpose and there is a growing list of others. The range of available pigments has been usefully extended, notably by the development of inert titanium pigments, which are particularly valuable, because they are white and can easily be tinted by admixture. Leafing pigments, such as graphite, aluminium, and micaceous iron ore, are also commonly used in underwater and finishing coats, because it is believed, probably correctly, that they increase the resistance of the paint film to penetration by water; micaceous iron ore is particularly valuable when the painted structure is exposed to abrasion by wind-borne grit or dust.

Painting Conditions.—Common sense suggests that painting is best carried out in good weather, when the air is warm and its relative humidity low. Although the practical conditions under which ships operate render it difficult to conform invariably to this ideal, it should be followed as closely as possible. The best months of the year for painting land structures in Great Britain are those from April to September, inclusive, and this statement applies equally well to ships.

Maintenance Painting.—The maintenance painting of a ship's superstructure should present no serious problem, because a repainting interval of four or five years is perfectly practicable for land structures, provided they have been properly painted initially, and, as already remarked, ships are commonly painted at much shorter intervals than this for aesthetic reasons. Two general observations may be helpful, however. First, some thought should be given to the painting scheme as a whole, as it will be constituted over a period of years. A suitable choice of the original finishing coat may facilitate the application and effectiveness of the paint subsequently applied for maintenance. Secondly, a thorough cleaning down before repainting will probably more than repay the additional expense involved. The presence of sea salts below the paint film may prove just as damaging as that of soot and grime beneath paint on steel exposed to an industrial atmosphere. In both cases, washing down with water, preferably hot and containing a little detergent, will generally prove beneficial.

Heat-Resisting Paints.—Most paints contain a high proportion of organic material, which tends to decompose on heating, so that there is an upper temperature limit to their usefulness. For example, the durability of many paints in ordinary linseed oil media is considerably curtailed at temperatures above 100–150° C. if they are exposed to the weather at the same time. There is a limited field of application for heat-resisting paint in ships, such as for example the protection of funnels, mentioned in section 3(*a*). There is evidence that some modern heat-resisting paints will protect steel satisfactorily at temperatures of 250–300° C. Indeed, in laboratory tests by the Houston Paint and Varnish Production Club a paint in a silicone resin medium and pigmented with a mixture of zinc dust, zinc oxide, silica, and graphite, was found to give excellent results at 500° C.* Research on heat-resisting paints is proceeding in several quarters and interesting practical developments in this field may be expected.

(*d*) *Metallic Coatings*

Metallic coatings, notably of zinc or aluminium, on steel add considerably to the effectiveness and durability of paint applied over them. There is a growing tendency, therefore, to make use of metallic coatings in conjunction with paints for the protection of structures exposed to atmospheric corrosion, such as steel bridges and important industrial buildings. Experience alone could decide how far this procedure would prove economically advantageous for a ship's superstructure but it would certainly diminish discoloration of the paint by staining and might, therefore, reduce considerably the amount of repainting that was necessary throughout the life of the ship.

* A short account of the results of this work will be found in reference (5) of the Bibliography (Discussion).

4. Internal Corrosion

(*a*) *Occurrence of Internal Corrosion*

Internally the places most liable to corrosion are generally well known but may perhaps be mentioned again here. These are, under boilers as the result of attack by water, heat, and cinders, although the latter effect is partly abrasive; in the structure where boilers approach close to the steel; in bilges due to moisture, dirt, and water; and in deep tanks, double bottom tanks (particularly water ballast tanks), tanks under boilers, peak tanks, chain lockers, and coal bunkers. These are all positions where moisture is present to a greater or less degree. It should perhaps be emphasized that corrosion will occur in any place where access for maintenance is difficult or impossible. It is necessary that spaces above tanks, cofferdams, and similar spaces should be large enough to provide reasonable access. Ship owners and designers are well advised to ensure that this requirement is a priority, as surveys invariably indicate lack of upkeep and severe corrosion where access is difficult.

In addition to the parts previously mentioned, which may generally be called working parts of the vessel, there are certain places where, in the nature of things, inspection is impossible. Such parts are steel deck below wood sheathing, composition or cement, and steel below scuttles in lined cabins and behind insulation. In lined cabins some owners provide portable hatches below scuttles to allow inspection and maintenance. This is excellent practice. Reference has already been made in section 3(*a*) to the desirability of separating wood sheathing from steel plates by the application of a generous layer of bitumen bedding composition. Other places where corrosion is likely to be found are behind steam pipes, behind soil pipes and at the lower portion of deckhouse sides and ends.

Weathering is the usual method employed to remove millscale before the material is erected. Frequently, however, the period is of insufficient length, as may be vividly indicated when sections are coated in way of a riveted faying flange; if the flanges have been left for some time before attaching the plating, the paint flakes off with the millscale. The removal of millscale by working is also responsible for the increased tendency to corrosion in flanges and near the edges of stiffeners in bulkheads where some working of the plating no doubt occurs. With toe welded stiffeners it is not unusual in tankers to find the plating split alongside the edge of the weld after some years of service.

One case of internal corrosion for which considerable detail is available relates to a ballast tank in a vessel 16 years of age. This phenomenon is quite usual but the case is quoted as an example. The deep tank was extremely wasted and it should be noted that the after bulkhead of the deep tank was the forward machinery space bulkhead, the machinery being diesel.

The following renewals were carried out and can be taken to indicate that the weardown was of the order of 35 per cent or more of the original thickness.

Deck stringer plates port and starboard over deep tank.

Forward deep tank bulkhead.
All stiffeners and top and bottom brackets.
Plating of horizontal girder and tripping brackets and lugs of girder.

After deep tank bulkhead.
Stiffener brackets to tank top. One plate of horizontal girder.

Centreline bulkhead.

Top strake of plating of fore and aft. Forward vertical strake and adjacent strake and forward part of horizontal girder.

All frames and beam knees. Shell stringer plating, tripping brackets and lugs.

Beams, web of all beams doubled.

Two points of interest arise. First, the renewals on the forward bulkheads were much greater than on the after bulkhead; this was probably due to the fact that the heat from the engine room dried off the after bulkhead more quickly, thus removing the film of moisture, which would form an electrolyte for electrolytic corrosion. Secondly, there was excessive wastage on the material attacked on both sides, stiffeners, frames, etc.; in these cases the weardown was of the order of 50 per cent and was most prevalent in the webs. Channel stiffeners are rolled with heavy flanges but varying web thicknesses. In view of these observations it seems desirable that in a position, such as a deep tank, where corrosion is to be expected, channels with unduly thin webs should not be fitted, as the corrosion of web weakens them relatively quickly and they become ineffective.

On the old *Mauretania* the plating of some ventilator shafts, originally about ¼ in. thick, was found to be perforated at the end of her life, where the shafts passed through a smoking room. This plating had been padded with wool and then panelled with wood. It seemed clear that the rusting was due to the condensation of moisture caused by the difference in the temperature of the air passing through the shafts and the warm air of the room. This illustrates the point that the primary cause of internal corrosion is condensation, for at other places in the *Mauretania's* saloons no rusting whatever had occurred beneath the wooden panelling and the original paint and chalk marks were still clearly visible on the steel plates.

Condensation is often a source of trouble in holds and, if coupled with a corrosive cargo, serious damage may result. For example, ammonium sulphate has been known to be carried loose in a ship and, not surprisingly, the plates of the hold were found to be badly corroded.

(*b*) *Air Conditioning*

Valuable data about the variations in the atmospheric humidity and temperature inside the holds of merchant ships during voyages from British to Australian ports have recently been obtained and published by E. A. Shipley,* who was interested in the damage to motor cars caused by the growth of fungi on fabrics and by the corrosion of metal components in the course of shipment overseas. The observations showed that there was a steady rise in the relative humidity of the air from about 60–70 per cent in Great Britain to 80–90 per cent during the voyage or in Australia. Moreover, at times the temperature inside the cars themselves was as much as 30° F. below the temperature of the hold and well below the dew-point of the outside air at deck temperature.

Clearly, therefore, for valuable cargoes it may be worth while to consider the provision of dehumidified holds for, as Shipley remarks, "haphazard ventilation is by no means a good thing." The fact is that serious rusting of iron and steel in air occurs only when the moistness of the atmosphere exceeds a certain critical level, which W. H. J. Vernon† has shown to lie roughly at 70 per cent relative humidity. Air that is drier than this, with a relative humidity below, say, 60 per cent, has little effect on steel. Consequently, there is now a tendency to provide air conditioning for part of the storage space on ships. The additional expense has, of course, to be passed on to the customer but there is a growing recognition on his part of the fact that he gets good value for his money, because of the elimination of the corrosion hazard whilst his goods are on board ship. Although these remarks apply primarily to the ship's cargo, it is obvious that air conditioning, where adopted, will have an important effect in decreasing the corrosion of the steel of the ship itself.

* Shipley, E. A.: "Deterioration of Motor Cars during Shipment Overseas," *Transactions North East Coast Institution of Engineers and Shipbuilders*, 1955, February, 237–245.

† Vernon, W. H. J.: "A Laboratory Study of the Atmospheric Corrosion of Metals," *Transactions of the Faraday Society* 1935, **31**, 1668–1750.

(*c*) *Protective Measures*

The protective measures to be adopted for preventing corrosion inside a ship vary somewhat according to the nature and function of the parts to be protected but, in general, they are similar to those used to protect the superstructure, discussed in section 3. It should be noted, however, that, as stated in section 1(*c*), there would be no advantage, so far as rusting was concerned, in using slow-rusting steels for internal construction because, when exposed to enclosed atmospheres as distinct from outdoor ones, these slow-rusting steels rust at substantially the same rate as ordinary mild steel.

So far as painting is concerned, the same guiding principles apply as for the superstructure. The surface preparation must be good, the priming paint inhibitive in character and the painting done under good conditions. In a recent case inspected, the paint on the hold of a new ship was literally peeling off by the square yard within little more than a year after she entered service. The cause appeared to be that the paint had been put on over a rusty surface, presumably under humid conditions, but more particularly that an aluminium paint had been applied directly to the rusty steel. As mentioned in section 3(*c*) aluminium powder is a valuable constituent of finishing paints but paints pigmented solely with aluminium and containing no inhibitive pigment are not good for priming steel, particularly when it is prepared by weathering and wirebrushing. As already explained, an inhibitive paint should be used for this purpose, such as the mixed red lead and white lead paint mentioned in section 3(*c*).

Cement washes, concrete coatings and bitumen are valuable means of internal protection and their use in appropriate positions is called for in Lloyd's Rules (See Appendix I). As in other cases, it is important that these coatings should be applied at adequate thicknesses. On land a depth of cover of about 2 in. is generally recognized as being desirable to ensure immunity from rusting to steel embedded in concrete, and bitumen coatings at least ⅛ in. thick and preferably thicker are needed for pipes buried in corrosive soils. Presumably, however, practical considerations may make it difficult to adhere to these standards inside a ship; for example, the movement of the ship might cause thick concrete coatings to crack.

Coatings consisting essentially of zinc dust in sodium silicate (waterglass), which are "cured" after application by heating or by chemical treatment, are said to be useful for protecting steel plates that are liable to be grazed by cargo. A. J. Liebman* has recorded that coatings of this type have remained effective for nine years.

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* Personal communication. See also U.S. Patents Nos. 2,440,969 (1938) and 2,462,763 (1949). Executors of V. C. J. Nightingall.

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The Authors wish to express their thanks to the Committee of Lloyd's Register of Shipping and to the British Iron and Steel Research Association, respectively, for permission to publish this paper.

APPENDIX I

Extracts from the Rules of Lloyd's Register of Shipping relating to Corrosion

The problem of corrosion is not new and in this connection it may be of interest briefly to trace the changes over the years in the Rules of Lloyd's Register of Shipping relating to it.

In 1885 the Committee required that millscale should be completely removed from the surfaces previous to painting, which should be delayed as long as possible.

The first complete Rules for steel ships, issued in 1888, included the following:

1. The workmanship to be well executed and submitted to the closest inspection and amended where necessary before coating or painting; it is not, however, intended to prevent the coating of the plates inside in way of the frames.
2. The black oxide or "millscale" should be removed from the surfaces before coating and/or painting, which should be delayed as long as possible.
3. Experience has also shown that, as regards durability, it is highly desirable to place steel vessels in dry-dock within a reasonably short time after being launched for the purpose of cleaning and recoating the bottom.

As a result of experience, the following letter was sent to Owners in 1889:

"With reference to the question of the liability of vessels built of steel to deterioration from corrosion, I am directed to acquaint you that the Committee of this Society, who have had this subject under their notice, think it right to place the results of their experience in regard thereto before owners of this description of property."

"It is found that, in cases where the surfaces of vessels built of steel have not been properly scaled in the first instance and then protected with paint of good quality, the material is liable to great deterioration from corrosion, particularly in that portion exposed to the action of salt water. The Committee have no doubt that, with this information in your possession, you will see the desirability of taking the precaution of having new steel vessels belonging to you placed in dry-dock and examined, within six months from the date of launching, so that, if symptoms of corrosion are found, the bottom may be properly scaled and coated."

"I am also directed to point out the importance of having the inside and outside surfaces of steel vessels kept free from scale, and properly painted."

In the following years only minor amendments took place. The word "should" in paragraph 2 of the extract from the first Rules was replaced by "must" in italics; then in 1908, the wording was again altered to read "It is recommended that black oxide or millscale be removed. . . ." This remained until it was slightly reworded in the Rules published in 1922, thus: "It is recommended that cementing or painting be delayed as long as possible so that the removal of black oxide or millscale may be facilitated."

A special section was inserted in 1922 on cementing and painting, from which the following extract is taken:

"All steel and iron work, not covered with cement, should receive at least two coats of paint of suitable composition. Previous to the painting, the surface of the steel and iron is to be thoroughly cleaned and the painting of the external steelwork should be delayed as long as possible."

In the revised rules of 1950, this was amplified somewhat and then read as follows:—

Cementing

"3001 In single bottom ships the shell plating and framing to the upper part of the bilges are to be effectively covered with Portland or other approved cement, mixed with sand to form a suitable composition. Free edges of cement are to be proper thickness. Clear watercourses are to be maintained throughout."

"3002 In double bottoms under the boiler room the frames and shell plating are to be efficiently cemented unless the tanks are used solely for oil fuel; elsewhere inside the double bottom the cement may be dispensed with. The bilges are to be cemented or coated with a suitable composition; if cement is used it should not extend above the upper edge of the inboard flange of the margin angle."

"3003 When it is desired to apply asphalt or a similar composition its use is to be sanctioned by the Owners and approved by the Committee."

Painting

"3004 All steelwork not protected as required by 3001 to 3003 is to receive at least two coats of paint of suitable composition, except inside tanks intended for oil; tanks not intended for oil may be coated with cement wash."

General

"3005 Care is to be taken that all surfaces are thoroughly cleaned and in a suitable condition to receive the coating to be applied.

All practical steps should be taken to ensure that the millscale has been removed or weathered off before painting and with this in view the coating of external steelwork should be delayed as long as possible."

"3006 Experience has shown that it is highly desirable to dry-dock ships reasonably soon after launching in order to clean and recoat the bottom."

The latest amendment, which took place in 1954, reads as follows:—

"3006 Experience has shown that when several months elapse between the dates of launching and commissioning it is highly desirable to dry-dock ships immediately before going into service, in order to clean, examine and recoat the bottom. Experience has also shown the desirability of dry-docking for the same purpose when a ship has been about six months in service."

This bears a striking similarity to the notice of 1889 and indicates that the problem, which was with us then, still exists.

APPENDIX II

Some Cases of Corrosion reported by Lloyd's Surveyors

Case A: Tanker. All-welded

Launched: December 20, 1951.

First Dry-docking (Delivery): February 1952.

First Service Dry-docking: July 1953, i.e. 17 months after previous dry-docking.

Construction Data

Original Welding

Flat of bottom machine welded from inside with overhead hand sealing runs on outside bottom, remainder of plating hand welded. Machine joints, Y preparation. Hand joints, 50 deg. Vee. Plate edges prepared by oxygen burning machine. Back of joint flame burned to clean metal for application of overhead sealing run. Each run of welding hammered, wire brushed and blown out.

Preparation of Plating

No special steps taken to descale plating and welds other than welding, wirebrushing, and cleaning before painting. No chemical cleaners employed.

Painting

No special protective coating on welds.

Before launch: 1 coat paint primer, 1 coat anticorrosive.

At delivery dry-docking: 2 coats anticorrosive, 1 coat antifouling.

Service

Persian Gulf to Philadelphia.

Report at First Service Dry-docking: July 1953

Keel plates Nos. 1, 2, and 3 from forward pitted. Plating pitted in way of upper electric welded butts. Electric welded seam also affected. Shell plating pitted from forward to aft in way of E, F, and G strakes port and starboard at position of Light Load Draught. Depth of pitting 1/16 to 1/8 in. Bottom plating and plating above G strake not affected. No evidence of millscale or of scale or slag in way of electric welded seams. Welding appears well fused to plating.

Action taken

Wirebrushed, welding chipped out, cleaned and welded up. 3 coats anticorrosive, 1 coat antifouling applied.

Report at Second Service Dry-docking: May 1954

Shell plating in good condition.

Case B: Dry Cargo Vessel. All-welded

Launched: April 11, 1949

First Dry-docking (Delivery): June 7, 1949

Construction Data

Welding carried out by fully qualified welders using approved electrodes. Normal preparation and painting were special out before launch and at delivery dry-docking but a carried preparation was applied to the welded butts and seams.

Report at First Service Dry-docking: December 1949

Welding of seams of shell plating port and starboard and forward and aft showing signs of deterioration and has dropped out in places.

(It is of interest to note that the welding showing the most severe corrosion at this inspection was stated to be that carried out during the last stages on the berth. Moreover, the preparation used for coating the welds had been used on other vessels on which no excessive corrosion had been noted.)

Action taken

Worst cases veed out and welded. Bottom recoated.

Report at Second Service Dry-docking: May 1950

The manual electric welded shell seams and butts, particularly at ends of vessel were more or less eroded. In some cases the full length of the butt weld was affected, the remaining weld metal having an almost smooth trough like appearance, as if the metal had been "washed out." (Fig. 6.) Where

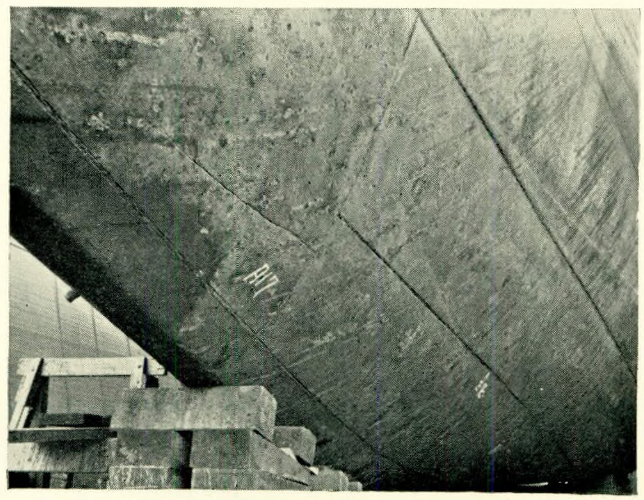

FIG. 6.—HEAVY CORROSION OF HAND-WELDED SEAMS (SEE APPENDIX II, CASE B)

Unionmelt or similar machine welds had been used, the surface of the weld metal was smooth and virtually unaffected by corrosion.

Seam welding of "D" strake forward, rewelded at dry-docking in December 1949 also showed slight signs of deterioration.

The outside surface of the shell plating below the LWL, for practically the full length of the vessel, showed minor corrosion, which had left the bottom roughened with small pits or shallow eroded areas.

On the flat of bottom the erosion was more dense and definite in way of the line of floors. In addition, the bottom was sparsely marked with eroded spots generally below 0·10 in. deep but in isolated instances, particularly in way of the echo sounding device and tank drain plugs, the measured depths were well up to 0·2 in.

Action taken

All defective welds of shell seams and butts (about 750 ft. run) cleaned out and electrically welded. The worst pits and scores in shell plating built up by electric welding. Underwater surface sandblasted and carefully recoated.

Report at Third Service Dry-docking: October 1950

Most of paint adhering but isolated lengths had lost paint and were rusting.

Action taken

Rusted parts wirebrushed. Surface recoated.

Subsequent Dry-dockings: March 1951; *August* 1951; *June* 1952; *December* 1952; *June* 1953; *December* 1953

No further reports of corrosion.

Considerable investigation of this case took place and the gist of reports and comments made by two independent authorities is given below.

The first authority reported that when the vessel was dry-docked in December 1949 severe pitting corrosion was noticed on much of the welding. About 150 ft. run of welding at the top edge of the D strake forward, port, and starboard, was built up at that time. At the next inspection in May 1950 the characteristic whitish deposits, which are typical of corrosion stimulated by millscale, were observed on much of the shell plating.

The presence of millscale on the plates was confirmed by scraping down to bare metal and hammering them with the flat head of a hammer, when the millscale "popped off." This led the authority to conclude that corrosion stemmed from the presence of millscale, the conclusion being confirmed in his mind by the fact that some of the December 1949 welding was beginning to show signs of attack; he expressed the view that any repair welding would deteriorate so long as the mill-scale was left on the vessel. He pointed out that corrosion of the welding was worse where turbulent conditions would be encountered, i.e. away from the middle body of the ship, and that, in general, the cleanest welds were the least attacked. In his opinion vertical welding was always likely to trap more slag and the vertical welds on the ship appeared to be significantly worse, whereas Unionmelt welding, which was invariably smooth and free from trapped slag, seemed significantly free from corrosion. He concluded with the following recommendations:—

"(1) Much of the original millscale is still on the plate and constitutes a continual threat. Unless this millscale is removed further corrosion of this vessel must be expected. This corrosion is just as likely to occur on the new welding as on the old. Therefore, I recommend that the vessel be sandblasted at this docking."

"(2) It is not necessary to do a perfect job of sandblasting just as long as most of the millscale is removed. I do not recommend, therefore, that the vessel be fleeted to catch the areas under the keel blocks, etc. However, easily removed blocks, such as bilge blocks, should be removed for sandblasting."

"(3) Due to the active nature of sandblasted steel it is essential that a washcoat primer* be used as the first coat. This should be applied by spray and should not be applied thicker than approximately 0·0005 in. One hour drying time is ample before applying the next coat of paint."

The second authority, after studying the report of the first, stated that the corrosion of the outer hull appeared to be of three main types:

(*a*) small pitting and shallow areas of erosion;

(*b*) more dense and definite erosion on the bottom in way of the line of floors: also sporadic eroded spots with depths up to 0·20 in.;

(*c*) severe erosion of the manual electrically welded seams and butts, particularly at the ends of the ship.

He commented that in the first report all three types of corrosion seemed to be attributed to galvanic action between residual millscale and adjoining areas of bare steel. He considered this opinion to be correct in respect of types (*a*) and (*b*) and supported the recommendation that as much as possible of the millscale be removed by sandblasting, as the presence of disintegrated millscale beneath paint was detrimental to its protective properties. He also endorsed recommendation (3) regarding the use of a washcoat primer, because freshly sand-blasted steel tended to absorb moisture in humid atmospheres, which impaired the efficiency of the priming paint unless this was quickly applied.

In a further discussion of the causes of the corrosion, this authority pointed out that it had been frequently observed that the heat transferred through the plating, when welding frames to the shell, was sufficient to break up the millscale on the immediately opposite outer surface. This could give rise to the corrosion, type (*b*) noticed in way of the line of floors.

He considered that the severity of the attack observed in the corrosion of type (*c*) was more intense than could have arisen from galvanic action alone, for the effect produced was more akin to the deep grooving observed in fast moving ships wherever the paint is removed by scratching. The rate of corrosion of bare mild steel could be increased from five to ten times the rate in still water, if it was exposed to a rapidly moving stream of aerated sea-water; such action resulted in the corrosion of plating at after butts, at the bottom seams of outside strakes, in short, at any place where turbulence could arise. If the exposed surface was restricted, as in a scratch or score, the rate could be still further increased, as the rapidly moving stream of water prevented the accumulation of corrosion products on the surface, which, in still water, would "stifle" the corrosive action.

To attain such conditions in this ship, it was necessary that the welded seams and butts should be denuded of paint. It was common knowledge, in the case of riveted ships, that it was extremely difficult to obtain good adhesion of paint to the points of newly driven rivets, which are covered with an extremely thin polished layer of scale, whereas, with rivet points from which this scale had been removed by weathering no such difficulty arose.

The outer surface of an electric weld was similarly covered by a thin scale, which, if present when the paint coating was superimposed would also impair the adhesion of the paint to the metal. In the case of this ship the Unionmelt welds made during prefabrication would be exposed to weathering conditions for a much longer period than the manual welds that had corroded, which were said to be almost the last welded into the shell. Thus the probability that the scale had been removed and that good adhesion had been obtained between paint and metal would be greater for the machine welds.

These assumptions would account for the severe corrosive effects observed on this ship, as, once the manual welds had lost their paint, the rapidity of the localized corrosive action would be increased by the turbulent motion of the sea-water. They would also explain why the seams, rewelded in December 1949, showed signs of deterioration when examined again in May 1950. The fact that such deterioration had affected welds made under different conditions from the welds already in the vessel tended to nullify any contention that the severe corrosion was due to the welding technique originally employed.

Case C: Dry Cargo Ship. Bottom shell welded; Floors riveted

Launched: August 9, 1951
First Dry-docking (Delivery): October 9, 1951
First Service Dry-docking: April 1952
Report at First Service Dry-docking: April 1952

A considerable amount of severe pitting and corrosion of plates, rivets, and welded butts extending over forward quarter length, port, and starboard.

Practically no original paint remained on the shell below the 13 ft. draught mark and there was abundance of millscale on the plating.

The underwater shell plating was generally pitted especially where launching poppet brackets had been removed.

* "Washcoat primer" is another name for the pretreatment primer described in section 2(*d*)(iv).

35 per cent of rivet points corroded at centres and in a few cases edge of countersink exposed.

Welded plate butts slightly corroded in scattered locations.

Action taken

Routine cleaning and painting.

Report at Second Service Dry-docking: September 1952

Wasted rivet points were brushed, cleaned, and painted.

Subsequent Dry-dockings: April 1953; *September* 1953

No corrosion. Bottom cleaned and recoated.

Case D: Tanker. All-welded

Launched: August 15, 1952
First Dry-docking (Delivery): November 10, 1952
First Service Dry-docking: May 1953

Construction Data

Welds carried out according to usual practice, i.e. about 50 deg. V angle preparation and back of weld flame cut to clean metal and welded. X-ray films were taken of some of the welds subsequently found affected, these were found to be good. No special steps taken to descale the plating other than normal weathering, wirebrushing, and cleaning before painting. No special preparation on welds.

Painting Scheme

2 coats a/c composition before launch.

1 coat a/c composition, a/f composition at delivery dry-docking.

Report at Delivery Dry-docking: November 10, 1952

On nearly all plates there were yellowish-white deposits ¾–1¼ in. diameter, which, after drying, had a barnacle-like appearance.

On certain plates the deposits were concentrated in large groups, on other plates they were spread out. Under the deposit was bare plate, clear corrosive attack.

Where the paint was not damaged it was of relatively good quality. Apart from a few places on the starboard side aft, the welds were fairly good.

Action taken

The surface was wirebrushed, cleaned, and coated.

Report at First Service Dry-docking: May 1953

Extensive corrosion reported port and starboard in welded shell butts and seams in A, B, C, D, and E strakes. In all about 1,200 ft. run of welding was affected. There was also pitting in the keel strake.

(1) The bottom and side plating was generally in poor condition and the paint could be easily removed showing evidence of black oxidation underneath. There was no evidence of excessive millscale.
(2) The corrosion was discontinuous.
(3) Machine welds were in good condition except for a few isolated deep pits.
(4) The presence of scale or slag in the weld was not apparent and penetration was good without undercut.

Action taken

About 800 ft. run of weld chipped out and rewelded. Remainder of affected welding cleaned out, scraped, and wire-brushed. Weld metal painted with two coats of gold size and anticorrosive and antifouling paint applied.

Corrosive pitting of keel plates similarly treated, viz. scraped, wirebrushed, and coated with gold size before application of a/c and a/f paint.

Report at Second Service Dry-docking: December 1953

Deep corrosion in several seams and butts of the shell plating mainly located in the fore ship but also under midships and forward bottom plating and in various locations in the bilge and side plating.

Several transverse butts of panels of bottom plating were found attacked by corrosion in the back welds outside. Depths of corrosion of ⅜ in. were found.

The machine welds were found to be lightly or not attacked by corrosion but these are located where there is less turbulence. However, manual back welds in same region showed corrosion.

The process of breaking up of the millscale layer was evident in its various stages on the plain surfaces of the shell plating in different locations.

Approximately 50 per cent of the bilge keel was found to be pitted.

Action taken

Bottom and side shell plating dry sandblasted. Affected welds chipped or burnt to clean metal and welding renewed and ground. Completed weld surfaces sandblasted and wire-brushed. About 3,300 ft. run dealt with. As work proceeded welds painted immediately with special composition (proprietary). Pitted rivets welded up. Boot top painted one coat wash primer,* 3 coats plate primer, 2 coats boot topping. Bottom coated with 3 coats plate primer and one coat antifouling.

Subsequent Dry-dockings

Plating in good condition.

DISCUSSION

Dr. S. Livingston Smith, C.B.E., D.Sc., F.C.G.I. (*Member of Council, I.N.A., Member I.Mar.E.*): I think this is a most interesting and valuable paper, in so far as it puts before us the present stage of knowledge and the present state of the art of corrosion prevention.

The first point I want to emphasize has been made by the authors, namely, that paint removal is one of the commonest reasons for corrosion, and in this connection the turbulence of the water doubtless plays an important part. Perhaps the most important position in the ship for this to occur is at the stern post and rudder in single-screw ships; these are directly in the screw race and are subject to the scouring action of the water.

The authors show in Fig. 3 a badly corroded rudder post, and we in the B.S.R.A. can confirm from our own experience that this sort of thing happens frequently. Indeed we have come across several instances which are very much worse than that shown in Fig. 3. The probable explanation is that soon after entering into service the "hydraulic blast," as it were, from the screw tears off the protective coating of paint and galvanic action is set up between the bronze propeller and the bare steel, and the steel corrodes. Then the scouring action of the screw race washes away the corrosion products and supplies more oxygen, and the net result is a most efficient corrosion mechanism, the effects of which can be quite alarming in the course of time.

The problem appears to be very largely one of finding a protective coating which will withstand the scouring action of the water from the screw race. It seems that paints as we know them cannot very well stand up to this, and I should like to ask whether the authors can suggest any other protective coatings which would be more adherent? For example, would a sprayed metal coating be better and, if so, what metal would they suggest? Alternatively, would cathodic protection provide the answer?

It would appear that the incidence of corrosion on stern frames and rudders of single-screw ships is greater now than it used to be. We think that this is probably due to two causes: firstly, the present-day tendency to put more power into a single-screw shaft than hitherto, thus producing more "hydraulic blast," and secondly the tendency for shaft *rpm* to increase, especially with the change from steam to diesel propulsion. Both tendencies will increase the intensity of the impact of the water on the stern frame and rudder of single-screw ships and it will be difficult to maintain an effective protective coating. From

* Yet another name for pretreatment primer [section 2(*d*)(iv)].

cases brought to our notice, it appears to be a pressing problem; I should like the authors' views on the problem in general and on how it could be overcome.

I am interested in the point made in the paper that inadequate clearance between the corroded parts and the propeller is probably a contributory factor. Close fitting fins were doubtless introduced because of certain claims for a small propulsive advantage. From recent work, however, it seems rather doubtful whether there is anything in this and it would appear, therefore, that this question of providing adequate clearance should receive close attention in design. Another consideration is that small screw clearances often give rise to the excitation of vibration.

This question of the prevention of corrosion in ships is most important.

Mr. J. Barrington Stiles (*M.I.Mar.E.*): A most praiseworthy aspect of their paper is its unusual combination of practical experience and scientific research.

I was disappointed to find that the corrosion of oil tankers was excluded; because this particular problem is one of the worst and most urgent. It is hoped that an equally instructive paper on that subject may be forthcoming in the not too distant future.

Under the sub-heading of "Surface Preparation" of superstructure it is rightly said that maximum paint durability is secured by putting the first coat of paint on to a clean steel surface free from millscale and rust and that the best practical way of securing this is by pickling or gritblasting. Taken in its context of protective painting I have no quarrel with this. But I would like to qualify the statement by saying that it applies only to protective systems which are exclusively paint. I am sure the authors will agree that where it is economically practical a system involving gritblasting and metal spraying provides a base which will substantially improve the durability of a subsequent appropriate paint treatment. Quite apart from the virtues of zinc and aluminium in protecting steel, both mechanically and sacrificially, these metals, when sprayed, provide an ideal base for the paint. Their surfaces are matt and have an order of roughness comparable with a gritblasted surface, but in addition the pores in the sprayed metal absorb a certain amount of a suitable priming coat, so that the paint is really mechanically locked to the surface.

The authors say that, while they must refer to the fact that metallic coatings are a valuable additional defence against corrosion, it is improbable that extensive use will be made of protective metallic coatings for the hulls of merchant ships. I should like to ask them on what they base this opinion. The history of metallized hulls shows that it has been practically confined to barges, fishing vessels and yachts. The steady increase in volume of such work, while no doubt being due mainly to increased consciousness of corrosion losses, must also be some indication of customer acceptance, and I am expecting to see larger vessels tackled in the very near future. The biggest marine metallizing job being carried out at the present time is a contract for 38 new barges, 160 ft. long by 29 ft beam and 7 ft. 6 in. depth, being zinc sprayed during building. These barges are destined for Burma, where corrosion conditions are abnormal, and it is believed that the initial extra cost will be saved in comparatively few years. At the other end of the scale the protection of steel hull yachts throws emphasis on the appearance factor, in which the substantially lowered cost of maintaining a spotless condition can offset the initial extra. The position of cargo vessels generally falls somewhere between these two, but it should involve a degree of both these economies.

It should not be overlooked that the time taken to metallize a steel hull is proportional to its size; so that it is easier to convince the owner of a small craft being built that an extra day or two on the stocks is worth while than to persuade Cunard that the "Queens" should take a holiday for metallizing. However, metallizing is being speeded up (using 3/16 in. diameter zinc wire, a coating of 10/1,000 in. thick can be applied to a hull at upwards of 1,000 sq. ft. per 9-hour day with a METCO type 5E metallizing gun. Thus four men can metallize 20,000 sq. ft. in a five-day week with a zinc coating thick enough for any service. Thinner coatings take proportionately less time).

What does this mean in terms of cost? If the authors' recommendations regarding gritblasting are accepted as a preparation for painting, then the additional cost of metallizing with zinc is really only the cost of the zinc wire plus about 20 per cent for labour and material used to apply it.

In Appendix II, sub-paragraph (3), I cannot make sense of the reference to "the active nature of sandblasting steel." The authors appear to be so much in favour of brush painting that they have scarcely been fair to spray painting. Experience seems to indicate that at least for the matt condition of gritblasted or metal sprayed surfaces it is best to spray the paint, and although brushing is satisfactory, rolling is an extremely doubtful method.

Abrasion has been referred to in the paper. There is no doubt that wear and tear on plates is often referred to as abrasion of the steel when it is in fact a cycle of formation, removal and reformation of corrosion products. May I quote from my 1948 paper to the Institute of Marine Engineers on "Metallizing in Relation to Marine Engineering" (Vol. LX, No. 12, p. 253):—

"One pre-war example of sprayed zinc on a vessel impressed the author very favourably. A dredger had part of its deck metal sprayed where the action of salt water plus abrasion by ballast falling on the decks during unloading had very much thinned the deck plates until there was definite danger of failure. The vessel discharged ballast nightly, polishing part of the deck in so doing. The following day, on putting to sea to refill with ballast, the deck rapidly rusted, so that the cycle of rusting and polishing was in operation daily. It was considered at the time that zinc might not sufficiently well resist abrasion, but the comparison was not between zinc and steel, but between zinc and rust. The zinc spray was regarded as highly experimental, but it performed better than had been hoped and is still giving good service."

Finally, this morning's issue of the *Financial Times* reports, under the heading "Stopping Corrosion," brief details of a new discovery, as follows:—

"A new chemical which stops metals from corroding under extremely adverse conditions, and which is derived from a fungus found in the soil, has been identified and is undergoing further tests at the Chemical Research Laboratory, Teddington.

"This chemical, which was found as a result of the excavation of metal objects at Chew Stoke, near Bristol, by the Ministry of Works, is expected to prove of considerable economic importance. It is estimated that £200 million of damage is caused by corrosion in the U.K. each year."

I can only add that, although I have enjoyed seeing pots of geraniums in wheelhouses and ward rooms, I trust we are not looking forward to an era in which chief engineers have to cultivate fungi on the fo'c'sle!

Mr. J. M. Murray, M.B.E., B.Sc. (*Member of Council, I.N.A.*): Corrosion in ships occurs in cycles, and this has been the case since the introduction of steel. What seems to happen is that there is a sporadic outbreak of corrosion, remedies are introduced, corrosion ceases, in the course of time precautions are relaxed and then there is another outbreak of corrosion. At the present time we seem to have passed a period when there were many examples of corrosion and are in that part of the cycle when precautions are being taken. It is to be hoped that these precautions will not be relaxed in the future, as has so often happened before.

The evidence put forward on the wastage of old and new ships is extremely interesting, but unfortunately it is doubtful whether it is relevant to ships being built at the present time.

During the 30 years covered by the investigation there were few changes in the methods of steel production; it is subsequent to 1930 that the modern fast rolling mill was introduced, and with it a different type of millscale. It does not follow, therefore, that because there was no difference in the wastage of ships built between 1899 and 1914 and those built between 1926 and 1930 the same situation exists to-day. We shall need to wait for another 20 years before we know the answer, and by that time technique of steel-making may have altered again, so that there does not appear to be any means of answering this question definitely.

I am pleased to see that the authors attach so much importance to the removal of millscale from the plates. My experience has been that a very great majority of corrosion of outer shell plating can be attributed to imperfect removal of millscale, although other causes are sometimes suggested. Here, I am pleased to see that the authors have not even mentioned an explanation which is often put forward and which has entirely no foundation, that of stray electric currents from the ship's generators.

A few years ago I was able to inspect the *Queen Mary* when she was in dry-dock, and I was very much impressed with the underwater surface. The state of preservation of the steel was excellent, the edges of the seams and butts being unusually sharp for a ship of her age. No doubt the very complete weathering process to which the ship was subjected during construction was in some degree responsible for the excellent condition of the bottom.

On the question of brushing versus rolling or spraying as a method of applying paint, I was under the impression that the main advantages of brushing was that any small beads of moisture on the surface of the steel were worked through the composition to the surface by brushing, where they evaporated, whereas when rolling or spraying was used the moisture was entrapped under the surface of the paint. I would like the author's comments on that suggestion.

Finally, it is interesting to see from Appendix I that Lloyd's Register in 1889 had much the same trouble as we have at the present day, both with regard to corrosion and with finding a synonym for the word "ship." The phrase "owners of this description of property" instead of plain "shipowners" does not seem to have been a particularly happy choice.

Mr. S. J. Jones, B.Sc. (*Assoc. I.N.A., Associate, I.Mar.E.*): Perhaps I may be permitted to add to the portion of the paper dealing with air conditioning (in Part 4).

You will note that the term "relative humidity" appears to be used as a basis concerned with the possibility of rusting. As the name implies, "relative humidity" must be related to something, and it is, in fact, defined as the ratio of the actual vapour pressure of the air to the vapour pressure of saturated air at the same temperature. In other words, "relative humidity" really means little until it is related to the air temperature.

One might assume, from the reference in the authors' text attributed to Dr. W. H. J. Vernon, that if the surrounding air is at a relative humidity below 60 per cent, little or no damage can result to steel; but there are many cases in ships' voyages where such conditions could occur and where damage to cargoes and ships' structures could result, even though the surrounding air relative humidity was below 60 per cent.

In the same way, one must not assume that the relative humidity in United Kingdom areas is always in the region of 60–70 per cent, and in Australia 80–90 per cent, as might perhaps be supposed from the voyage report attributed to E. A. Shipley.

I am sure the authors do not wish to convey this in their text, but I did think it advisable that this point should be amplified.

As I see it, corrosion internally, where not necessarily associated with salt spray or corrosive cargoes, is caused by condensation on the surface of the steel in the presence of oxygen in the air, and if at any time, therefore, the cargo or structure of the ship is at a temperature below the dewpoint of the surrounding air, condensation results and corrosion can take place.

Take, for example, a cargo of rails loaded in Montreal in winter. The ship then travels south and as the outside air temperature rises a stage could be reached where air at a suitable temperature and a relative humidity of less than 60 per cent, if passed into the hold, would in fact cause condensation on the rails, simply because the dewpoint of the air being circulated was higher than the temperature of the rails; and, vice versa, a vessel travelling from a warmer climate into Rotterdam in winter, if the hold were sealed, could contain air of higher dewpoint than the temperature of the ship's structure, and the result would be condensation on the ship's structure. The possibility of condensation in this latter case could in fact be cured by introducing a vigorous circulation of outside air which is cold, but may be at 90 per cent relative humidity.

It therefore brings us to the conclusion that it is the question of the surrounding air dewpoint compared with the temperature of the cargo or ship's structure which determines whether condensation and consequently corrosion of this kind can occur.

There is, in fact, a rule which can be applied to ships' holds; it is that when the outside air dewpoint is below the inside air dewpoint, maximum ventilation should apply, and where the inside dewpoint is less than the outside air dewpoint, air recirculation or closure should be applied. If de-humidifying plant is fitted, it enables the dewpoint of the air inside the hold to be kept down.

Changes in atmospheric conditions either way, and even with de-humidifying plant fitted, must be anticipated as far as is possible and the appropriate action taken, so that the air in the cargo spaces is at the lowest possible dewpoint.

There is another source of condensation which can cause trouble, even though the above precautions are taken; I refer to that which occurs in holds, due to the proximity of refrigerated spaces. Consider the case of a bulkhead, dividing refrigerated spaces, which butts on to a hatchway.

The dividing bulkhead or deck between the cold rooms will eventually get to a temperature near the mean between the two refrigerated compartments. Where it butts on to the hatch, cold will leak to the hatch bulkhead and deck around the hatch. Thus we have areas of cold on the bulkhead and deck where the temperature of the steel will almost invariably be below the dewpoint of the surrounding air and condensation will, therefore, take place.

This trouble has been overcome successfully on a number of ships recently by the use of "thermal injection," which is the application of low voltage electric heating at the butt joint, as indicated. This can be an economical and sure way of defeating this source of trouble, instead of the previous idea of insulation at these points which, of course, tended only to spread the area of cold to another point further away and to cause condensation there. The quantity of cold coming out from this source can be estimated quite accurately, and by arranging the balance of heat at these points to give a surface temperature of (say) 80° F., the chances of condensation at any time with any air can be completely eliminated.

A paper to the Institution of Refrigeration Engineers at the Paris Convention recently by W. H. Glass, O.B.E., deals with this matter in detail.

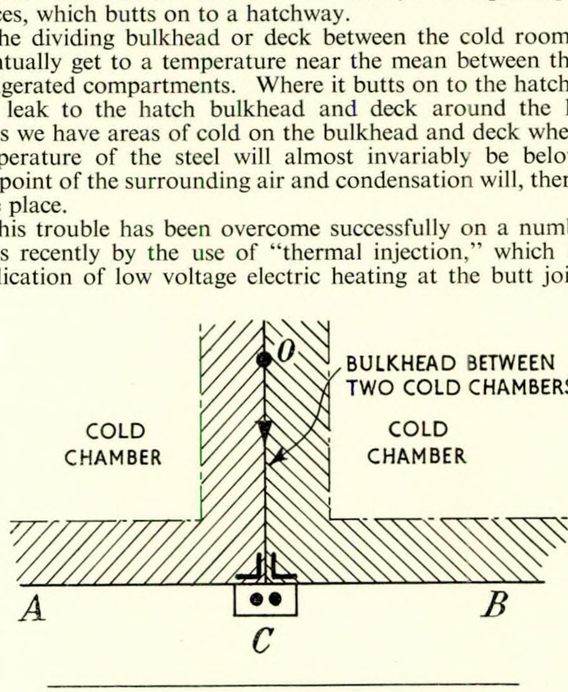

FIG. 7.—FLOW OF COLD OUTWARDS FROM BULKHEAD SURFACE O AFFECTS SURFACE AB EXPOSED TO NORMAL AIR. CONDENSATION TAKES PLACE OVER LARGE SURFACE AB. APPLICATION OF LOW VOLTAGE ELECTRIC CABLES SPECIALLY DESIGNED AND PROTECTED CLIPPED TO BULKHEAD AT C BALANCES COLD LEAKAGE AND KEEPS SURFACE OF STEEL AT TEMPERATURE ABOVE NORMAL AIR DEWPOINT

Mr. G. A. Bassett, C.B., R.C.N.C. (*M.I.N.A.*): I am particularly glad that the authors emphasize the importance of surface preparation. There is no doubt that this is an all-important factor in this problem. If you have a clean, dry surface you are on a good wicket; if you coat over a rusty, dirty, or wet surface you ask for trouble. When the last paper on this sort of subject was presented to The Institution we had quite a discussion on sandblasting. Since then quite a bit of work has been done to improve the plant to make it practicable for use in shipyards in the United Kingdom, there is no doubt that better resistance to corrosion of ship's hulls could be assured.

There is some difference of opinion as to whether, when you have sandblasted the bottom of a ship, you should put the inhibitor coating on straight away or wait a month. The authors make reference to a change of coatings to the *Queen Mary* and the *Queen Elizabeth*. It is very interesting to note that when the change was made the ships were descaled up to the waterline involving 15,000-odd square yards on each ship. An inhibitor coating was applied at once and the descaled area was never left uncovered overnight. Undoubtedly, the results on the "Queens" were the better for this pretreatment. The Cunard Company carry out a continuous programme of descaling as opportunity offers. I am confident that the Cunard Company would bear me out that this has proved very well worth while.

I was very interested in the remarks by Mr. Barrington Stiles on metallizing. Some years ago the Admiralty tried to introduce it on deck plating of all destroyers. There was quite a lot of trouble in the shipyards. It was said that the sand was flying about everywhere, including places where it should not go. There were complaints from engineers about the machinery and the bearings, complaints from the sandblasting operators that the job was very unpleasant and they demanded extra pay, etc. But we have made considerable progress lately.

As a matter of interest, metallizing has been used for a purpose not indicated in the paper. On the first or the second occasion when the *Queen Mary* was docked, I had to look at her from the Admiralty's point of view, and some extraordinary pitting had occurred on an inner strake plate on one shaft swell. It was decided to sandblast the area and fill it up with zinc; but the metallizing process was done and, so far as I know, the result is still satisfactory. At the same time on the *Alcantara* a plate at fore foot was similarly treated and, here again, so far as I am aware, no further trouble occurred.

One has to bear in mind the question of access, and I feel that not enough attention has been paid to that in the past. I refer to this question with feeling because, as a young man, I had to look after the building of H.M. submarines and had to get into some very difficult places. I have seen a warship from abroad in which those responsible had extraordinary ideas of what they should do with the various spaces. For example, the space under the boilers was used as a dump. They had coal bunkers, but used them for another purpose. Very extensive replacement of structure had to be made arising from the excessive corrosion. This example shows what can happen if proper precautions are not taken to examine and coat compartments.

It is essential to keep watch on the structure and to keep compartments as clear as possible. An important factor in this is accessibility.

Mr. J. A. Shepherd: I would like to bring to the attention of the meeting the remarkable case of the *Beta III*.

The development of the protection of hulls by zinc spraying has been retarded only by the one-time difficulties associated with shotblasting, and the high cost of zinc over the war years, plus a certain amount of reluctance on the part of shipowners to "experiment" with a process not already established.

Sufficient evidence is now, however, available, to show that the application of a layer of zinc on to the suitably prepared hull of a vessel, subject to either fresh or salt water, will provide a protection out of all proportion to its initial cost.

The *Beta III* gives a striking example of a vessel subjected to the worst conceivable corrosive conditions the waters of Britain can offer, yet receiving the minimum of maintenance and showing virtually no corrosion over the last twelve years.

In 1944 this vessel was a firefloat, belonging to the L.C.C. Fire Brigade, permanently moored in the Thames near Westminster Bridge. That year she was metallized by the METCO process inside and out, with 0·005 in. of pure zinc. The frames were also treated.

Two years later she changed hands and became a waterbus, plying from Westminster pier—in *fresh water*.

Each year she has been moored at Leigh-on-Sea, where she now lies in and out of every tide—in *salt water* (and salt sea air).

During the last nine years, the hull has been painted once only, above waterline, and in the fore and aft holds. Her bottom has received a few coats of bitumastic paint.

Yet there is no sign of corrosion, or even of lifting of the paint film on the whole of the vessel. The frames are still in perfect condition and the rivet points show no sign of pitting.

It may be interesting to know that the conventional zinc slabs are still to be seen near the stern end, and have dutifully been covered with bitumastic each time her bottom was painted.

The subsequent record of most vessels treated by this process has been difficult to follow; for example, the Crown Agents for the Colonies regularly specify zinc spraying for resistance to corrosion in tropical waters; any means of checking their progress, however, without actually visiting Lake Takaradi or some other corner of the Commonwealth seems to be impossible. But in *Beta III*, and a few other comparatively local examples, such as Thames barges, R.A.F. air/sea rescue launches, and one or two privately owned yachts, we can establish and in fact have established, that zinc spraying gives the most permanent protection, coupled with a strong degree of anti-fouling, that it is possible to give.

Mr. L. G. Stevens, R.C.N.C. (*M.I.N.A.*): Generally I think it may be said that Admiralty practice conforms to the procedures recommended in this paper. I would refer to the first paragraph of Section 2(*a*), where the authors suggest that, with a few notable exceptions, maintenance is comparatively easy in parts of a ship other than the outer surface of the underwater plating. I realize that the paper deals with the corrosion of cargo ships; but there are very many places necessarily difficult of access in warships which present us with a major problem of maintenance. I would underline the emphasis made several times for careful surface preparation and the application of the paint in good weather conditions. A great deal of effort has been and is still being devoted to the improvement of paints, but I feel that much of that effort will be wasted if this counsel is not heeded. However, the problem of surface preparation and satisfactory application of paint presents difficult practical problems, and anything that can be done in the way of developing paints which are not quite so difficult in this respect will pay considerable dividends.

The authors refer to anti-corrosion composition No. 173, which is in common use for the Admiralty, and to two other compositions which they say are slightly better. We have treated some ships' hulls with one of them, No. 655, and it has shown to some advantage in the static conditions between launch and completion. It is now intended to try out that composition under sea-going conditions.

The statement that the Admiralty normally hot-galvanize ship plate of ¼ in. thickness or less is not strictly correct; we regard it as the right thing to do, but very reluctantly that procedure has been restricted to some extent. The fabrication of structures in galvanized plating presents a number of difficult problems. Can we weld on the galvanizing or must it be removed in the vicinity of the weld first is one of the problems. Further, the areas where protection is most needed are just the areas where the zinc no longer exists after welding. The authors point out, quite rightly, that so far as the outside of the ship is concerned, the coating elsewhere will tend to protect the bare steel areas cathodically, where the galvanizing is burned off. But much of the corrosion occurs inside what are called "dry" compartments—not so dry as to prevent corrosion, but dry enough to avoid contact between the unprotected areas and those galvanized and therefore any cathodic protection from the zinc. Would the authors prefer to treat such areas with zinc-rich paint, or would they recommend metallizing?

Mr. C. V. Manley (*Assoc. I.N.A.*): The problem of corrosion is an age-long one; it existed in iron ships, though not to the same extent, and I was interested to note that it was discussed in a paper presented to this Institution by Mr. Robert Mallet in 1872. The opening sentence of that paper, couched in the stately language of those far-off days, is worthy of note. It reads:—

"Next to a suitable choice of material and just disposition of parts in reference to stress and strain (not wholly disregarding even aesthetic effect), it will not be contested that the constructor, if his work be not avowedly ephemeral, is called upon to take into account the elements of its decay; that is to say, of the more or less gradual alteration or destruction of the materials employed, owing to their taking new molecular forms, or forming new chemical combinations with surrounding bodies."

One of the remedial measures advocated in those days was the copper sheathing of iron hulls, but it was not apparently proceeded with as it presented strong defects regarding the method of attachment of the copper.

They experimented with protective coatings, and one which was apparently found effective was that of long-boiled coal tar, laid on when the iron was hot.

It is striking that, by way of practical suggestion, the present authors repeat the advice given by Lloyd's Register in 1888 when steel ships first began to be built.

The problem, therefore, seems to be insoluble, and, after all, has anyone paused to think what would happen if they did produce a solution. The steelmakers would roll less steel, the shipbuilders would build fewer ships and the shipowner would find his ships lasting so long that they would be out of date before he could bring himself to scrap and replace them.

There is one question which I should like to ask the authors. When the *Queen Mary* was built, she lay on the stocks, with work suspended for some years. It was said at that time that this would prove extremely beneficial from the point of view of corrosion, as it would result in a complete descaling of the structure by prolonged weathering. The authors in the paper give some comparative results of annual inspections of the shell plating of the *Queen Mary* and *Queen Elizabeth* since 1949. Have they any similar information prior to 1949 which would show whether, as a result of the unusually long period of weathering mentioned, the plating of the *Queen Mary* did, in fact, show a greater resistance to corrosion in service?

Professor E. V. Telfer, D.Sc., Ph.D. (*Vice-President I.N.A., Member I.Mar.E.*): I would like to raise three points of semantic interest arising out of the paper. Dr. Hudson invites us to explain what is meant by the word fleeting. This is a very old nautical word. When a ship is fleeted she is merely being moved, generally by a small amount by way of an adjustment to a new position either longside a quay or in coming into dry-dock. The word appears to be closely related to the Norwegian *flytte*, to move or to shift; and we have the same word and meaning when we move house and do a flit.

There is another word which presumably Dr. Hudson uses in the paper which always annoys me. I refer to the use of the expression "holidays" in paint; and whilst I am a lover of the picturesque in language I have always regarded a paint holiday as somewhat stupid terminology, most probably fairly recent in origin and introduced by paint technologists. I was thus greatly surprised on looking up the use of the word last night in the *Shorter Oxford Dictionary* to find that it is of nautical origin and dates back to 1785. A "holiday" is there defined as a "small gap in the tarred surface of a ship, generally not exceeding a quarter of an inch." In those bad old days when workers worked there was nothing so rare as a holiday; and an untarred spot on a ship's surface was thus then described with some nostalgic force and accuracy as a holiday. However true this may have been in the eighteenth century, nowadays we have so many holidays that the paint significance of the word is completely lost on us. Holidays in paint have given way to holidays with pay in the language of the worker and we must therefore all fleet with the times. What is wrong with unpainted, bare-spot, gap, and so on? Perhaps they are too simple or too obvious.

My final terminological quarrel is probably with Mr. Adams, and it concerns his use of the word turbulence. I am afraid that his very popular use of the word will not be admitted by the modern student of fluid flow and ship resistance. Turbulence as now understood is a micro-agitation of the fluid. The flow round a moving ship is always turbulent, but this turbulence certainly does not produce corrosion or erosion. What the authors have obviously in mind is eddying or vortex flow. When this flow impinges on a ship structure excessive corrosion can undoubtedly occur. This is particularly the case in the vicinity of the stern-frame and rudder of ships. The tip and boss vortices in the propeller slipstream impinge on the fin or rudder and induce erosion. In the old single-plate rudder the boss vortex action was generally the most severe. When a fin is arranged too close to the blade trailing edge in an attempt to trap the flow rotation and so improve propeller efficiency, the fin flow stalls and heavy erosion may result on its suction side. Such action is generally much more pronounced when the propeller is deficient in area since this intensifies the boss and tip vortex action. Cutting the fin back in this case will not cure further erosion. The only cure lies in increased blade area on the propeller. Streamline rudder erosion is really an excellent indicator of good and bad design in the propeller-rudder-aperture combination. Moderate the flow angles on to the rudder by good clearance between propeller blade area and correct pitch distribution particularly at the boss, correctly design the fin or rudder nose and there will then be no erosion or corrosion of the rudder. The problem is thus one of pure hydrodynamic design, it is neither metallurgical nor chemical. So long as Lloyd's Register do not choose to interfere in the hydrodynamic design of rudders, propellers, and apertures they must expect their outport surveyors to continue blaming everything but the right cause for the excessive corrosion found in this vicinity. Dr. Smith has just ascribed this corrosion to the "scouring" action of the water. Normally there is no such action. If this were so our faster ships would corrode away quicker than our slower. In this connection I am glad that the authors repeat Dr. Montgomerie's advice which I heard him give many times to our Corrosion Committee. He was quite impatient with those who said that they did not understand the mysteries of corrosion. He said there was no mystery. The simple explanation was that owners did not paint their ships sufficiently or properly. Presumably he meant that their fleeting turbulent life was too often one long holiday!

Captain J. P. Thomson, O.B.E. (*Associate Member of Council I.N.A., Associate I.Mar.E.*): I want to make it clear that the merchant navy officer, from his first day at sea, lives very close to this problem of corrosion; he witnesses it under all conditions, and I confirm the authors' views that salt water in spray is a most destructive element from the corrosion point of view. Most deep water ships in these days spend most of their time in the tropics; as ships become faster there is more spray from the bows, and the superstructures get more of it.

I do not wish to fall out with the paint manufacturers, but I find that not one paint made to-day will stand up to the nine to twelve months' service looked for on tankers. Of course, some paints are better than others, and some companies to-day have a preference for and use acid-free tar; which has been mentioned here to-day. It can be produced quite cheaply and is in good supply, and from the corrosion point of view it is certainly above the average of these substances.

In this paper the authors indicate the extent of wastage of plates of cargo ships in 24 years. We would get very much more wastage on a tanker; if we could examine a tanker after 24 years and find that she has suffered no more wastage than is shown in this paper we would think we had done remarkably well.

In the case of cargo tanks in tankers corrosion takes place and is most serious in those carrying clean oil, when the ships' strength members are literally pumped away overboard in the form of a rusty liquid. The outside underwater portion will not suffer serious deterioration so long as the paint film remains unbroken, which applies to any kind of paint.

With regard to the internal compartments—and I suppose this must apply to any ship—if you can prevent the occurrence of sweating and keep the compartments well ventilated you will be going a good distance towards preventing corrosion there.

Coming to metal spraying, I know the case of a small ship in which the bilge strakes had reached the point at which Lloyd's Surveyor was considering condemning them; after discussion with the Superintendent, however, it was decided to re-metal and to apply a good composition after the re-metalling. I saw the ship ten years afterwards and the plates were then as good as they were before.

On the question of paint "holidays," I do agree with what has been said about the weather conditions under which these paints are applied. If you try to cover a wet surface you cannot expect anything other than "holidays"; the surfaces should be dry.

Finally, on the question of the underwater plating, my company had a ship for 15 years and sold her to a whaling company; she is now 42 years old. She goes to the Antarctic every year as a whale factory ship and has carried whale oil, lubricating oil and fuel oil for the most of her life. The wastage of shell plating has been very small indeed.

Mr. J. H. K. Tait: I wish to put forward a few facts which tend to support the authors' views on cathodic protection. They say quite categorically that it will prevent the corrosion of ships' hulls. I have been concerned with the protection during the fitting-out period of about a score of ships in this country and the Commonwealth, and I do not think that any ship examined so far which has been protected cathodically during the fitting-out stage has shown any pitting or other corrosion of the steel when docked and examined.

With regard to the cathodic protection of ships in service at sea, in the discussion of the paper by Carter and Crennel last year I mentioned two such cathodically protected ships. One of them has now been at sea for 29 months and the other for 21 months. Both have been cathodically protected since launch and have been dry-docked and inspected within the past two or three months. Not the slightest trace of corrosion below the waterline was found on either. Both have been engaged in service in the course of which corrosion may normally be expected to occur. Many ships have been equipped during the past year or so, but I mention these two particularly as they have now been in service for a significant period.

There is mentioned in the paper a suggestion that the provision of cathodic protection apparatus might impair the efficient working of a ship. I do not think that the master or chief engineer of any cathodically protected ship would know from observation of the performance of the ship that the special equipment was fitted. It has no significant effect on fuel consumption or anything like that; there must be some effect, but it cannot be significant for otherwise I am sure that we would have received complaints by now.

Two or three speakers have mentioned the protection of oil tanker cargo/ballast compartments. It may well be thought that this is now a problem of decreasing urgency as about 130 tankers have been fitted with cathodic protection in or from this country to date and others are being equipped at an increasing rate. I think the time will come when the corrosion of oil tankers will be largely of academic interest; I hope so, anyhow!

Mr. H. T. Shirley: There is one matter on which I would raise a minor dissentient voice. On the first page the authors have slipped in a remark which rather seems to dismiss summarily the stainless steels from the marine sphere, and in one or two cases it has already produced a certain amount of uncertainty. Quite obviously, none of us would ever think of producing a whole hull of stainless steel; neither its availability, nor its cost now or in the near future, would permit that. But in connection with depth-sounding equipment, propeller shafts, propellers, and so on, these materials, if properly designed, have behaved very satisfactorily, and I hope they will continue to do so.

I do not wish to cut short any enjoyment on the part of the whales in the Antarctic, but stainless steel in propellers whistles less than do non-ferrous propellers!

Mr. W. A. D. Forbes, R.C.N.C. (*M.I.N.A.*): I would like to refer to one aspect of corrosion which is not dealt with in the paper, and that is corrosion fatigue. In the course of the last few years the Admiralty Corrosion Committee has had to consider a number of instances of corrosion fatigue of outer bottom plating, and I am of the opinion that this form of corrosion is more prevalent than is generally recognized. It can be very dangerous.

In general, corrosion fatigue in outer bottom plating starts in the characteristic form of a multiplicity of hairline cracks which, once set up, rapidly deepen and weaken the plating. I recall one instance where a piece of plating subjected to panting actually fell out during a voyage and led to extensive flooding. Panting is one of the most likely causes of corrosion fatigue. It is probable that the plating of merchant ships is less liable to this type of failure than that of warships, since the outer bottom plating of merchant ships is generally thicker than that of warships of corresponding size, and the frame spacing is smaller. But merchant ships are more liable to this trouble with the propelling machinery, the shafts, and rudders. It must be borne in mind that merchant ships spend a far greater portion of their lives under full power than do warships, and in consequence the liability of such items in merchant ships to corrosion fatigue is correspondingly greater than in warships. If serious trouble, such as fracture, does arise with such items the possibility that the trouble might have been caused through corrosion fatigue should not be overlooked, observing that in such circumstances fracture could occur at stresses well below the normally safe working stress.

Mr. H. N. Pemberton (*Member of Council I.Mar.E.*): As the representative of the Council of the Institute of Marine Engineers it is my pleasure to say how much we have enjoyed this joint meeting, and to thank not only the authors of the paper, but all who have taken part in the discussion.

Written Contributions to the Discussion

Mr. K. A. Slade (*A.M.I.N.A.*): I was hoping that some mention would be made of flame cleaning as applied to ships' structures. We are told that flame cleaning removes millscale, dirt, oil and rust, and drives out moisture, giving a good surface for paint application, providing better adhesive qualities if the paint is applied while the surface is still warm.

I know very little about flame cleaning and should not be surprised if it had its limitations, i.e. danger of fire to interior surface of plates coated or lined with combustible materials, or is the heat dissipated quickly? Perhaps the authors could throw some light on the matter.

The paper does bear out the absolute necessity of removing millscale. Being brought up in a Royal Dockyard, I was surprised to learn some years ago that the commercial yards do not "pickle" their plates to the degree that the dockyards do. When one reads of the damage done by the electrolytic action due to the presence of millscale, one cannot understand why the millscale is not removed by the builders for the good of the job.

I was alarmed to read in case "B" that some of the seam welding had fallen out, just as though it were putty. Surely this might be due to original defective workmanship such as lack of penetration, undercutting, incorrect jointing, etc., but to fall out completely is puzzling.

In case "D" we read of pitted rivets being welded up; is not this a bad practice and one to be discouraged?

The fitting of zincs as sacrificial protection is evidently not successful; what protection then is substituted for the zincs?

A proprietary brand of zinc-rich paint, painted on the hull in the vicinity of non-ferrous fittings, is suggested by the makers to be better than fitting zincs. Is this so, or can the electrolytic action between the non-ferrous fittings and the hull be completely prevented by good outer bottom anti-corrosive paints?

Lastly, we read that if the outer bottom composition is intact it is coated over; admitted it is best not to disturb a good coating, but does this added weight at each docking affect the vessel's performance?

Mr. J. A. H. Lees, B.Sc. (*M.I.N.A.*): Pickling is fashionable: it sounds easy to do, and provided the plates are properly washed afterwards it perhaps does not matter how it is done. The processes and opinions regarding this matter, however, appear to be varied and diverse. It would be helpful if the authors would add a note for the guidance of those responsible for specifying such a process and seeing that it is properly carried out; i.e. relative merits of hydrochloric, sulphuric, and phosphoric acids, and corresponding temperatures and immersion periods; defects which may show up in the plate during pickling and subsequently indirectly as the result of pickling.

Corrosion fatigue, although troublesome, may not be of major importance in steel cargo ships; it seems to be quite evident, however, that corrosion rate is related to stress and, if this is so, the function of the protective coating may need to be re-examined. Perhaps the authors will comment with special reference to aluminium structures.

Mr. Harry Benford, B.S. (*A.M.I.N.A.*): The authors' recommendations relative to the importance of design details in the fight against corrosion are well worth noting and the naval architect can partially assuage the owner's troubles by devoting proper attention to the design principles outlined in the paper.

Mention is made of the superiority of welding as against riveting in the provision of easily maintained joints. One of the best examples is the use of the flush tank top, made possible by welding. The older knuckled-margin type produced isolated pockets which were not only snug harbours for rats but dependable sources of corrosion as well.

Inverted angle stiffeners, particularly in the smaller sizes, present a difficulty owing to the relative inaccessibility of one face of the flange for cleaning and painting. The steel mills could oblige the shipping industry by making available bulb plates as one answer to this problem.

The low profile funnels, which were popular for a time, led to an interesting corrosion problem not touched on by the authors. In one instance, the ship in question had two funnels, the after one being a dummy. The forward funnel was not only too low but poorly shaped to suit. The resulting cascade of combustion products on the forward half of the dummy funnel caused the latter to waste completely away at the base twice in fifteen years.

In another case known to the writer, the mate of a rather ancient freighter essayed to fill the number one double bottom by attaching a hose to an overflow pipe. A couple of hours after starting this operation the tank was found to be empty. Investigation showed that the overflow pipe had rusted completely through, allowing the water to run down on to the second deck whence it ran aft to the engine-room bulkhead, there being no intermediate bulkhead in the 'tween decks. At this point the deck was rusted through so the water intended for number one tank ended up in the bottom of number two hold. Fortunately, the holds were empty of cargo at the time.

The authors' statements relative to the difficulty of painting rivet heads has also been borne out by personal experience. As a student, the writer spent one or two summers on shipboard. Among other duties, painting the deck head over the engine-room was well remembered for this very point. The minimum coverage per gallon cited in the paper was by no means approached unless the painters' clothing could be included. It was on one of these same ships that it was not considered poor practice to paint the engine-room tank top under a good inch of water.

The subject of fouling is dealt with very succinctly in the paper. Reference is here made to Mr. Paul Ffield's paper "Some Aspects of Ship Bottom Corrosion" (*Trans. S.N.A.M.E.*, Vol. 58, 1950), in which a rather curious case of a copper-sheathed steel hull is cited. What has been said about electrolytic reaction was borne out all too well in that instance.

Mr. C. R. Perrin (*Assoc. I.N.A.*): It was pleasing to see the mention of the unfortunate impracticability of painting only under good atmospheric conditions, and that one of the reasons for the generally good protection given by priming paints based on oil media, is their ability to provide a good job when neither the steel preparation nor the atmospheric conditions are ideal.

There is, however, one statement in the paper which is liable to misinterpretation. The authors, when speaking of maintenance painting in the second paragraph of Section 2(*d*)(ii), say: "the efficiency of protection by paint is a function of the coating thickness." Applied to any one particular paint this is quite true, the thicker the film the less likely is water to reach the steel substrate, a necessary condition of active corrosion, and thus the better the protection. However, this does not strictly apply to appreciably different paints. In priming paints, for example, there are factors of greater importance than film thickness. The nature of the inhibitive constituents can be a dominant influence.

This is particularly well illustrated by a practical trial carried out on the topside of a ship. Three different priming paints were used, namely genuine red lead one coat, metallic lead one coat, zinc chromate two coats. The whole area was then painted over with normal topside paint. The difference in film thickness of the priming coats was very considerable, the metallic lead paint being approximately only half that of the two coats of zinc chromate and two-thirds that of the red lead paint. Yet in service in the North Atlantic the thinnest film, the metallic lead, gave the best performance.

Whilst there is great need for caution in assessing the practical true worth of anti-corrosive priming paints, there can be no doubt that, compared with traditional primers, certain newer paints show both increased protection against corrosion and direct economic saving. The authors illustrate this in their reference to the excellent results being obtained with the comparatively new basic lead sulphate/aluminium primer on ships' bottoms. Consideration of accessibility has, I believe, led the authors to suggest that corrosion elsewhere on ships is less severe. But in two major places, deep tanks and at the boot-topping, corrosion is certainly a continuous and costly problem. Again, in these two places metallic lead-based paints appear to be an improvement on other anti-corrosive paints.

Mr. William Waters, B.Sc. (*A.M.I.N.A.*): Steel shortages and modern prefabrication methods rule out any possibility of the shell plating being properly weathered before painting and the millscale must be removed by some extra process. Of the various methods now available pickling has the advantage of removing the scale from both sides of the plate. The authors point out the dangers of the partial removal of millscale during the welding of shell connections and this condition could be every bit as troublesome in the cargo holds and double bottom tanks as on the outside shell.

The writer agrees wholeheartedly with the authors' statement that a good start for the paintwork is essential. The period prior to the launch of the vessel is probably unique in the life of the ship for there are few other occasions when all parts of the shell plating are so easily accessible, and with more time at his disposal the painter can take advantage of any good weather and avoid the very bad conditions. In dry-dock rollers and spray guns will produce results as good, if not better, than long-handled brushes, but it is false economy to miss this opportunity to apply the first coats of paint by hand.

The "all-welded" double bottom is a perfect illustration of the way in which the structure can be designed to minimize corrosion. The elimination of riveted seams and shell bars results in a tank bottom completely free of traps for water, and those areas which although exposed to corrosion can never be properly coated, such as exist at each joggle in a riveted bar, are entirely eliminated. With a little attention to detail the internal structure of a tank can be completely sealed against corrosion.

In the main structure of the vessel continuous fillet welds are commonplace and the "completely sealed" condition can be achieved with little extra cost, but in the superstructure circumstances are different. The light plating does not lend itself to welded construction and there is a natural reluctance to apply continuous welds where intermittent welding provides more than ample strength. However, there are obvious places such as galleys and washplaces where the life of the structure would be greatly increased by the elimination of riveted overlaps and intermittent welding. In such spaces pressed "swedge" stiffeners and toe-welded flat-bar stiffeners are far superior to riveted angle bars.

The three chlorinated rubber paints included in the B.I.S.R.A. investigations* all appeared in the list of eight "very good" compositions and this seemed to foretell a tremendous future for this type of paint. Has this early promise been confirmed by later experiments or practical applications and have the early difficulties now been overcome?

Mr. L. T. Carter, B.Sc., R.C.N.C. (*M.I.N.A.*): Admiralty practice and experience in the field of corrosion and protective measures are broadly in line with those described in this paper. In particular, the prime importance of adequate surface preparation prior to painting is strongly endorsed. A good paint applied to a poorly-prepared surface may well give an inferior performance to a poor paint applied to a well-prepared surface.

B.I.S.R.A. anti-corrosive composition No. 173 in the form of Admar has been successfully used by the Admiralty for outer bottoms for many years. It may be of interest to note that it has also frequently been employed with some success as a weatherdeck paint in cases where non-slip properties are not required.

Referring to the authors' remarks about corrosion in the stern area which may be accentuated by turbulence, it has been found that the use of Neoprene-based paints on the shaft brackets and rudders is effective in overcoming such corrosion. This type of paint is also being used for coating inlets and discharge tubes where corrosion due to this cause was prevalent.

As regards the considerable corrosion which may occur during the fitting-out period of a ship during building, it is felt that sufficient evidence is now available to show that if cathodic protection is applied at this stage in addition to the normal painting of the ship's outer bottom, these corrosion problems can be overcome.

If, due to failure of the protective coating, heavy rust scale is formed on the ship's bottom, it is essential for the success of subsequent re-painting that such scale be completely removed by meticulous mechanical scaling, or preferably wet sandblasting. Electrolytic descaling, a process which has been successfully employed for certain floodable interior compartments, such as ballast tanks, is being explored by the Admiralty as a means of cleaning ships' outer bottoms.

Weatherdecks are particularly prone to corrosion, due largely to the incessant lodgement of water and the difficulty of adequate maintenance during the ship's life. It seldom seems possible to clean or chip thoroughly or keep decks free of traffic long enough to ensure complete hardening of the paint which is applied. There is a need for a quick-drying weatherdeck paint which will take hard wear and a quick-drying primer.

Regarding paint for the ship's side and superstructure, the Navy has now for some time adopted alkyd-based paints because oil-based paints formerly used, although giving good adhesion and protection against corrosion, were very liable to chalking. Experience is showing that the principal drawbacks of the alkyd based paints for external use are that they do not lend themselves to satisfactory application by unskilled hands and there is a certain lack of coat-to-coat adhesion under water-soaked conditions. Although correct surface preparation is always the aim, under Service conditions of maintenance it is not always possible to obtain perfect application with the use of undercoats and the correct drying time. For maintenance purposes, i.e. "touching up," efforts are being made to obtain a modified paint formulation which will tolerate less meticulous preparation of the surface and which will be suitable for application directly in one coat over old paintwork. Another important requirement for topside paintwork in the Navy is colour fastness, so that the touching-up can be effected without a patchwork appearance being obtained. The use of a medium of tobacco-seed oil instead of linseed oil has been found to give successful properties of colour fastness.

Regarding interior corrosion, Admiralty experience is that among the most difficult areas to deal with are the machinery bilges. This problem is mainly due to difficulties of access and the difficulty of cleaning and degreasing the steel surfaces prior to painting. The paint which is applied has to withstand severe conditions of contamination by oil and moisture.

The interior paint which is used in the living spaces of warships is required to be fire retardant, and this quality appears to be largely incompatible with the requirement for a pleasing gloss surface which is not dirt retentive but readily cleanable. A certain success has been obtained by the use of Gum Damar-based paints.

One of the burning questions in the field of warship habitability is the treatment of bathrooms, particularly in tropical stations. These spaces call for a disproportionate maintenance effort. High humidity and temperature conditions make adhesion of coatings difficult; top coats soften and are thrown off and corrosion goes on below. Mould growths are frequent. There is little doubt that the use of galvanized plating or of shotblasting and zinc spraying prior to the application of a protective paint system would yield the best results. The use of a complete chlorinated rubber-based paint system is also being considered.

Captain A. D. Duckworth, R.N. (*Secretary I.N.A.*): Would the authors' remark on the effect of the *weight* of paint considered in relation to a ship's performance. The cumulative effect of applying coat after coat of paint to all parts of a ship, year after year, must surely result in having to carry much unnecessary weight up and down the high seas. One recalls the chipping of paint from the turrets and upperworks of H.M. ships in days past, where heavy flakes of paint, sometimes more than ⅛ in. thick, strewed the decks (disclosing by the different coloured layers the stations on which she had been serving). Since it is scarcely a practicable proposition to chip or burn off old paint throughout the ship on every occasion—on goes a new coat of paint over the old. Considering the enormous areas of metal to be coated inside and outside any ship, may not all this additional weight of paint sooner or later appreciably affect a vessel's displacement, speed, or even stability? The writer believes that this question had some practical significance in the first fitting out of H.M.S. *Kent* at Chatham in 1926, and possibly with other H.M. ships completing after the Washington Treaty of 1922, when every idea for saving tonnage weight was being explored.

Authors' Reply

We are glad to have Dr. Livingston Smith's confirmation of the seriousness of corrosion of the type that we show in our paper round the stern post and rudder. Although Professor Telfer has objected to the use of the word "turbulence," perhaps we may be permitted to use it here and to say that we agree entirely with Dr. Livingston Smith that it is the turbulence of the water round this part of the ship that removes the paint and enables corrosion to occur. We also agree with him regarding the probable causes of the trouble, which may well have been aggravated by the tendency in recent years to close up the aperture between the stern post and the propeller in an attempt to improve propulsion efficiency.

It may be of interest however to add that in the experience of one of us (H. J. A.) it was decided that, in a ship of a similar type to the one illustrated in the paper, the gap between the propeller and the stern post was too small. The stern post was, therefore, cut down to reduce the breadth of the fin and repainted;

* First Report of Joint Technical Panel N/P2, published January 1950. "The Formulation of Anti-corrosive Compositions for Ships' Bottoms and Underwater Service on Steel."

despite this action, it most regrettably began to corrode again after six or eight months.

It should be possible to obtain protective coatings that will withstand these severe conditions. "Zinc rich" paint is used for the purpose by at least one shipping company. Certain plastics, such as neoprene, have good resistance to scouring by water but, apart from questions of cost, their use under the circumstances in question would involve difficulties associated with application and adhesion. Another possibility is the application of hot-applied bitumen mastic, although we do not know whether this has ever been tried in the region round the propeller and the stern frame. It is expensive but has been found in survey work to give remarkably good results in internal parts of ships that normally corrode very heavily.

Perhaps the best solution of the problem of stern frame corrosion would be some form of cathodic protection but it must be remembered that the efficiency of cathodic protection in sea water is considerably enhanced by the precipitation of a natural deposit of calcium and magnesium carbonates on the protected cathodic surface. Presumably this deposit would form less readily and be washed away by the rapidly moving water. If so, a greater current density would be needed to ensure protection and this would involve greater cost. Sprayed metal coatings, particularly of zinc, would be helpful as an alternative to cathodic protection but they themselves would be abraded and corroded away in time; how long they would last under the given conditions can only be a matter of conjecture.

Mr. Barrington Stiles and Mr. Shepheard have made a plea for metal spraying. Our experience of its use on ships' hulls is not wide but, from that experience, it appears to be satisfactory. There is no doubt that, if metal spraying shows itself to be efficient and economic, it will not be long before shipowners start to use it and that its use will then advance rapidly. We must, however, stress the word "economic." For small craft such as barges, the hulls of which are extremely liable to suffer damage, yachts, where an immaculate appearance is desired, or naval vessels with light plating, ¼ in. or less thick, where there is little margin of safety for the effects of corrosion, the use of metal coating—we should prefer zinc—needs no justification. The zinc coating provides additional resistance to mechanical damage and exerts cathodic protection over parts of the hull that have suffered such damage. The problem of protecting the hull of a larger ship is somewhat different. As the experience on the Queens mentioned in the paper has shown, fully satisfactory results can be obtained by the conventional methods of surface preparation coupled with the use of good bottom compositions. If, after being metal sprayed, a liner could be sent to sea and remain in service for several years without her bottom's requiring any further attention, the case for metal spraying large ships might be indisputable. In practice, however, on many sea routes ships' bottoms need repainting at intervals certainly not exceeding twelve months and often less, because of fouling. As explained in the paper, the mechanism by which anti-fouling compositions function is a delicate one. It is easily upset if the composition is applied over an unsuitable substrate, so that good practice involves the previous application of at least one coat of a comparable anti-corrosive composition over the hull, whether the ship be a new one on the stocks or an old one in dry-dock for maintenance painting. In other words, it is doubtful whether any anti-fouling composition yet devised is capable of functioning efficiently when applied directly over bare steel or over a bare sprayed metal coating. Other complications would ensue from such a step, into which we need not enter here, but it is pertinent to remark that, although metallic zinc has a toxic effect on marine organisms, this effect is slight and of a much smaller order of magnitude than that of a well made anti-fouling composition. It follows, therefore, that until new types of anti-fouling composition are devised, with much longer effective lives, the possible advantages of using sprayed metal coatings on large ocean-going ships will not be fully realized. Whether or not these coatings are sufficiently advantageous as matters stand, is a question for individual shipowners to decide.

We think it would be generally agreed that, where straightforward painting under good warm and dry atmospheric conditions is concerned, spray painting and brush painting are equally effective. Indeed, on a rough and readily absorbent surface, like that of a sprayed metal coating, spray painting might be found to have some practical advantage. Spraying, however, is much more sensitive than hand painting to adverse weather conditions, such as are frequently encountered in shipyards and dry-docks, and it is certain that for the general run of structural steelwork, including ships, the priming coat at least is best applied by brush. The vigorous working of the brush does, as Mr. Murray suggests, tend to drive moisture to the surface of the paint film and it is a fact that, given careful workmanship of this kind, wet steel can be hand-painted with passable results.

We agree with Mr. Barrington Stiles that the effects of abrasion are the composite result of several processes involving the removal of paint, which provides the necessary conditions for corrosion, the periodic formation and removal of corrosion products, and, on occasion, actual abrasion of the steel itself. Which factor is predominant, it is often difficult to say.

Mr. Murray is right, of course, in his suggestion that the figures given in Table I for the wastage of new and old ships might be interpreted in other ways. This is true of all statistics. As regards his general point, the difficulty of deciding whether modern steel is any worse or any better than steel of 30 years ago, we will merely hazard the guess that the marine superintendents of that generation were bemoaning the fact that steel was not so good as the steel of 30 years before their time. In fact, this complaint seems to have persisted throughout the ages for a similar implication to the same effect appears in a passage in Pliny's *Natural History* (*c.* A.D. 70). He wrote that "an iron chain still exists, at the town of Zeugma on the Euphrates, which was used by Alexander the Great in bridging the river there. Those links which have been renewed are a prey to rust, from which the original links are quite free."* However, being merely a historian with no financial interest in the chain, Pliny contents himself with stating the facts without attempting to apportion responsibility.

We are glad to have Mr. Murray's personal impression of the excellent condition of the bottom of the *Queen Mary*, which confirms our own. This is a good example of the results that can be obtained by regular and careful treatment. Unfortunately, to anticipate part of our reply to Mr. Manley, we have no information about the Queens prior to 1949, so we can express no opinion as to the effects of the long period of weathering spent on the stocks by the *Queen Mary*.

Mr. Jones's comments on air conditioning and on condensation adjacent to refrigerated spaces are of considerable practical interest. There is no doubt that condensation is the most frequent cause of corrosion in these internal spaces, because it is always on ledges where the moisture running down can collect that corrosion is found.

We welcome Mr. Jones's theoretical observations and agree with him that in the practical working of ships the diurnal variation in temperature† and dewpoints of the outside and inside airs are important factors in determining corrosion. On the other hand, it seems to us that his statement that maximum ventilation should apply when the outside air dewpoint is below the inside air dewpoint may be misinterpreted and needs qualification. It is not sufficient to ensure that no condensation occurs on the steel, because, as Dr. Vernon showed, rusting can take place at relative humidities ranging from saturation down to 70 per cent. On the assumption, which we shall discuss later, that the critical relative humidity for rusting, roughly 70 per cent in Vernon's experiments, is independent of temperature, our interpretation of his results is that the admission of outside air would be dangerous to unprotected steel cargo if the vapour pressure of the moisture in this air exceeded 70 per cent of the

* K. C. Bailey: *The Elder Pliny's Chapters on Chemical Subjects* (London. Edward Arnold & Co., 1932), p. 150.

† Details of the diurnal variation in the atmospheric humidity in Great Britain will be found in *Protective Painting of Structural Steel*, by F. Fancutt and J. C. Hudson (London, Chapman & Hall Ltd.) (to be published shortly).

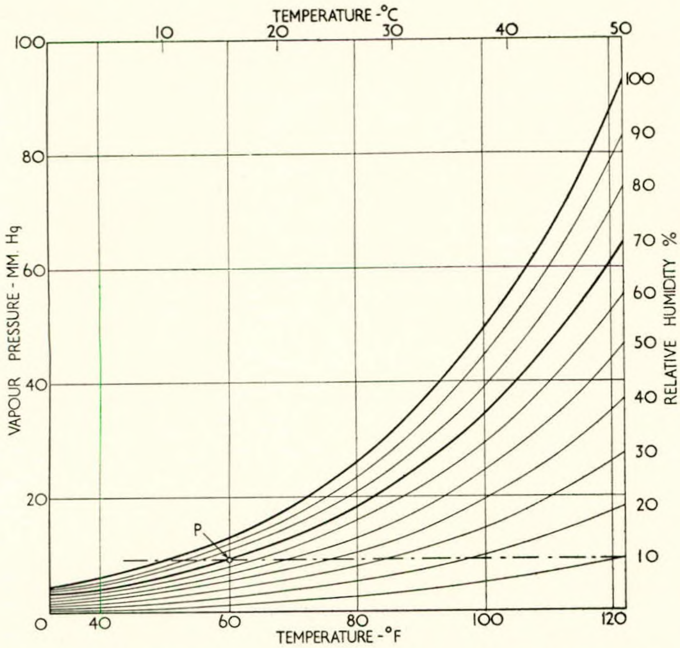

FIG. 8.—VAPOUR PRESSURE OF WATER IN AIR OF DIFFERENT RELATIVE HUMIDITIES AT 0° C—50° C. (32° F.—122° F.)

vapour pressure of water at the temperature of the steel. Reference to *Fig.* 8 may help to make this point clear. Here the vapour pressure of water is plotted against temperature and similar curves have been added for various relative humidities from 10 per cent upwards in steps of 10 per cent. Steel at a temperature of 60° F., for example, will be liable to corrode when the water vapour pressure in the air reaches 9·2 mm. If a horizontal line is drawn through this point in the graph, it becomes evident that this condition will obtain when the outside air admitted to the hold has the following temperatures and minimum relative humidities:—

Temperature of outside air, ° F.	80	100	120
Relative humidity per cent	35	18	11

Alternatively, it can be deduced that the highest permissible dewpoints of the outside air for given temperatures of the steel in the hold are as follows:

Steel temperature, ° F.	40	60	80	100
Maximum dewpoint of outside air, ° F.	32	50	69	88

It should be made clear that Vernon worked at a constant temperature of 25° C. (77° F.) and that in his experiments the temperature of the steel was the same as that of the surrounding air, i.e. the air in immediate contact with the metal surface. We think it necessary to draw attention to this important point because the third paragraph of Mr. Jones's contribution is rather confusing. We presume that by "surrounding air" he means air that is outside the cargo spaces and which may be admitted to them. Otherwise his statement that "there are many cases . . . where damage to cargoes . . . could result, even though the surrounding air humidity was below 60 per cent." is untenable. We may add that, to the best of our knowledge, no one has extended Vernon's fundamental work on atmospheric corrosion to other temperatures. In view of the wide range of temperature encountered in different parts of the world, it is highly desirable that this should be done. For the moment we can only assume that the critical relative humidity for rusting does not vary greatly with the atmospheric temperature and assume that it has a constant value of 70 per cent.

We are glad to learn of Mr. Bassett's practical experience of the condition of the bottoms of the Queens and of other matters, which supports the conclusions drawn in the paper. His remarks on the advantages of gritblasting are pertinent. There can be no doubt of the beneficial effects of this process on the efficiency of protection achieved. Economics will eventually decide how far the extra expense involved in this and in alternative procedures such as flame-cleaning is justified. The practice of descaling a certain number of plates in rotation carried out by the Cunard Company is an excellent idea. After a number of coats of paint have been applied to the hull over a period of years, a certain roughness of the outer paint surface is almost inevitable. This is undesirable so far as propulsion is concerned. Moreover, although the protection of the steel will be efficient, it is arguable that this result is achieved at the expense of carrying far more weight of paint than is necessary. Captain Duckworth raised the same point later in the discussion and it seems appropriate to deal with it here. A distinction will be made between the bottom and the parts of the superstructure that are fully exposed to the weather; in practice the internal painting of the ship would also have to be considered.

(i) A minimum thickness of 7 mils. (0·007 in.) of paint is generally regarded as desirable for the efficient protection of a ship's bottom and the ideal is to build this up as quickly as possible on a new ship, for example, by applying two anti-corrosive coats on the stocks and two further anti-corrosive coats plus a final coat of anti-fouling composition when the ship is dry-docked before entering service. If anti-corrosive compositions of the type described in the paper were used, the total weight of the dry paint in a film of this thickness would be 1·2 lb. or less per sq. yd. when the application was done on a small scale in the laboratory. In practice, however, considerably more paint is used and the total paint applied to a small tug in a recent service trial in which the Admiralty Corrosion Committee collaborated with the British Iron and Steel Research Association, was 2·1 lb. of dry paint per sq. yd. Maintenance repainting, if consisting of one full coat each of anti-corrosive and anti-fouling compositions would add about 0·9 lb. per sq. yd. on each occasion. There is, however, quite an appreciable loss of paint from the hull of a ship in service amounting to perhaps half the coat of anti-fouling composition between consecutive dry-dockings. In addition, there is a fairly appreciable correction for the buoyancy of the paint when immersed in sea-water; for a film 7 mils. thick this would be roughly 0·3 lb. per sq. yd.

(ii) A thickness of about 5 mils. of paint would be desirable on the exposed parts of the superstructure. This would involve the application of three or four coats of paint. The weight of dry paint in a four coat system, using a mixed red lead and white lead priming paint, would be of the order of 0·7 lb. per sq. yd. and each additional finishing coat, such as might be used for maintenance painting, would amount to roughly 0·15 lb. per sq. yd.

It follows that in the case of a 12,000 ton ship with a bottom area of about 3,000 sq. yd. the dead weight due to the bottom paint ranges from about 1·6–2·8 tons upwards, less a correction for additional buoyancy of about 0·4 ton. This is about the minimum weight of paint consistent with adequate protection and the figure would increase by not more than 1·2 tons, less the buoyancy correction, on each occasion that the ship was repainted. After five such repaintings, therefore, the total amount of paint would be up to 8·8 tons. Similar calculations could be made for the amount of paint on the superstructure of a ship. In the aggregate, therefore, the added weight due to the paint on a ship of this size may amount to something up to 20 tons. No doubt this is sufficient to affect performance but the relative cost of the slightly increased resistance may be set against the possibility of losing the value of the sealing of the shell against corrosion by the existing paint coat, if the bottom is completely scaled.

We are glad to have Mr. Bassett's support of our advocacy for greater ease of access, when practicable, to internal parts. As another example of this observed during survey, there was a case where a small dry counter tank aft was fitted with a small boiler for heating accommodation. It was impossible to protect the tank properly because of difficulty of access and, as a result, the steel floor literally disappeared in places through corrosion.

In reply to Mr. Stevens, we fully appreciate that the difficulties of protecting parts of a ship because of inaccessibility are particularly acute in a man-of-war. The most satisfactory solution in some cases may be to put on a particularly good and more expensive coating at the time the ship is built and to allow, so far as considerations of weight permit, a greater tolerance than usual for the effect of corrosion on plate thickness. We entirely concur with Mr. Stevens's suggestion that the development of paints that were less sensitive to adverse weather conditions at the time of application would be of great advantage. This is the constant aim of the paint industry and some progress is being made towards achieving it. In our view, zinc rich paint is but a poor substitute for a solid coating of metallic zinc and where it was practicable and economical to apply either, we should prefer the latter. This does not mean that zinc rich paints are not valuable materials for special purposes where ordinary zinc coatings cannot be used; e.g. they have given good service on keel strakes, which are relatively inaccessible once a ship has been launched.

We are glad that Mr. Manley has referred to Mallet's paper to the Institution in 1872, because this gentleman was one of the pioneers of practical corrosion research as we know it to-day. Thirty 30 years before that date he described in a series of papers to the British Association how he had exposed numerous pieces of iron and steel to corrosion in Kingston Harbour, in the River Liffey, and outdoors at Dublin. The results were extremely interesting but of little present value because the materials tested were ill defined—necessarily so in the undeveloped state of metallurgical knowledge at that time—and are not typical of modern iron and steel. Mallet seems to have done the work with very little help and certainly without the backing of a Committee or Research Association such as we know them to-day—merely for the love of the thing. Indeed, as a slight tribute to the spirit that animated many of our Victorian forbears, it seems fitting to quote the following passage from one of his reports: "I much regret the many imperfections and omissions, which I might have been enabled to avoid, could I have devoted more time to these researches. That learned otium, however, so necessary to experimental study, is denied to those who, like myself, find every day to come preoccupied with the unavoidable duties of a laborious profession. Hence, most of these experiments have been made and recorded in hours stolen from rest, or with greater difficulty, from business."

The use of long boiled coal tar, mentioned by Mr. Manley, is clearly akin to that of hot bitumen mastics, which have been observed to give strikingly good results in coal bunkers. It may well be that the modern hot applied mastics have stemmed from the old coal tars applied in this way.

Perhaps we may be permitted to dissent from Mr. Manley's pessimistic views on what would happen to the steel industry if the problem of preventing rusting were entirely solved. It seems probable that at least for a long period to come the world demand for metals of all kinds will greatly exceed the possible output. The conservation of materials is, therefore, a vital matter of world-wide importance and the winning of the fight against corrosion would constitute an important contribution to the general welfare of mankind.

Professor Telfer's philological comments are interesting and we are grateful to him for his clear explanation of the derivation and meaning of the word "fleet." We note that, like ourselves, he, too, has had resort to the *Shorter Oxford Dictionary* regarding "holiday." Surely, in view of what he found there, he would agree that there can be few more appropriate occasions for the use of the word in the given sense than in a paper written for this Institution? As regards "turbulence," experts in hydrodynamics, such as he, must naturally be most careful and precise in their use of terms. We, as novices in these matters, merely use the word in its popular sense, as denoting a condition of violent and irregular motion. Perhaps, on the whole, it would be better to permit us to continue to do so, lest we choose an alternative word and fare worse.

Professor Telfer's valuable comments on the phenomenon of "turbulence" itself raise the question as to whether the trouble aft is due to erosion of the steel, i.e. a purely mechanical effect, or corrosion, made possible by the erosion of the paint. We have already touched on this point in our reply to Mr. Barrington Stiles. We join most of those who have studied the subject in the view that the damage results from the combination and interplay of the factors. It would appear from the Professor's remarks that the usual practice of merely providing rounded surfaces or easy lines of no particular calculated shape in this part of the ship is not enough and that the streamlining should be based on more scientific principles.

We agree with Captain Thompson that the damage caused by corrosion is much heavier in tankers than in the general run of cargo ships but, as explained in the introduction, our paper was not intended to deal with this. If his remarks about the premature failure of paints refers to the bottom compositions, then it would appear either that the right types of paint are not being used or, as may well happen in this class of ship, that the performance of the paint is being adversely affected by mechanical damage. It may be categorically stated that anti-corrosive compositions are now available that, under reasonable conditions of use and service, will protect a ship's bottom against corrosion satisfactorily for up to twelve months. The use of coal tar has obvious financial attractions but, rightly or wrongly, we feel that much more research and development work will be needed before entirely reliable coal tar coatings are available. Captain Thompson does not state what metal was used for re-metalling the bilge strakes of the small ship mentioned by him. Either steel or zinc could have been used, according to the degree of damage by corrosion, and be expected to give good results with careful and timely maintenance painting. We have dealt at some length with the problem of "sweating" in our reply to Mr. Jones.

As Mr. Tait remarks, the value of cathodic protection during the fitting out period of a ship may be regarded as established. We agree too that it is unlikely that the provision of cathodic protection for cargo ships in service would affect their performance in the general sense of the word. The thought in our minds when we wrote the paragraph with which Mr. Tait joins issue was that the fitting of cathodic protection apparatus, both inboard and outboard, which would necessarily occupy space, might interfere with the fighting efficiency of a naval vessel. Such a point is irrelevant in the context of the present paper. From a theoretical point of view, it is excellent to use cathodic protection for ships' hulls but, like all other measures, the process must justify itself economically.

We accept Mr. Shirley's correction to our observations on the use of stainless steels in ships. The fifth paragraph of section 1(*c*) of our paper is too sweeping and it would have been better had the first sentence of this paragraph read: "The use of rust-resisting ("stainless") steels . . . fails to solve the *general* corrosion problem under these conditions." There can be no question of the general use of stainless steels for shipbuilding but, as Mr. Shirley rightly points out, they are of good value for certain special details of construction, and we should be sorry if this generalized remark of ours were to prejudice the use of these valuable materials for suitable purposes by shipbuilders.

The comments of Mr. Forbes on corrosion fatigue are relevant. Damage from this cause also occurs in way of hard spots on bulkheads and on certain types of transversely framed corrugated bottoms. In the bulkhead it leads to severe fractures at the edges of welded stiffeners and elsewhere. In corrugated bottoms it must be stifled at once by fitting longitudinal stiffening. Double plate welded rudders also experience corrosion fatigue along the edges of the internal webs. In all these cases, except that of the corrugated bottoms, the primary cause of the damage is panting, as Mr. Forbes suggests.

Several of the questions asked in the written contributions to the discussion have already been answered in whole or in part, but the following additional replies seem desirable to round off the discussion as a whole.

Mr. Slade asks for information about flame-cleaning. The process certainly has possibilities but its use in shipyards has not yet been sufficiently extensive to provide a great deal of evidence as to its economic value under such conditions. It has proved its worth as a method of surface preparation for painting both new and old structures and has been fairly widely used by British Railways.* There is some danger of distortion, particularly of light section, e.g. riveted water filter shells of light steel plate were found to spring leaks after being flame-cleaned, but this damage can be avoided by careful workmanship and systematic procedure. However, it should be noted that British Railways restrict the use of flame cleaning to panels of ¼ in. or more in thickness. The chief rivals to flame cleaning are gritblasting and pickling, the choice between these three processes will be governed by circumstances and no sweeping generalization can be made about their relative merits. It might be argued that for painting ships in dry-dock, where the weather conditions are often adverse and humid, flame-cleaning has the great advantage of producing a warm dry surface on which to paint. Whether this advantage is worth the additional expense involved, remains to be decided. So far as pickling is concerned, there is evidence that its use for the plates of new merchant ships is on the increase.

Although we agree with Mr. Slade that welding up pitted rivets may not be the best practice, this is commonly done particularly where only a small number have to be treated. Except that the procedure may introduce difficulties should subsequent repairs be called for, it is effective and it is certainly much cheaper than riveting.

The electrochemical relationships between several dissimilar metals in close juxtaposition, such as when zincs are fitted near a non-ferrous grating let in to a steel hull, are complex and the problems that arise are best solved by a combination of theory and practical experience. It seems to us that where zincs are ineffective, as is not infrequently the case, some more definite form of cathodic protection, such as fitting magnesium anodes or the imposition of a suitable e.m.f., might usefully be tried. We doubt whether the use of zinc rich paint for such purposes would prove more than a temporary palliative.

The answer to Mr. Lees's question about pickling is that, provided the operation is efficiently conducted, i.e. that the millscale is entirely removed without undue attack on the metal, it is of little moment what particular pickling process is used. In an extensive series of experiments on the surface preparation of steel for painting, F. Fancutt† found that the results obtained by painting over freshly pickled surface were all equally good, whether the acid used was hydrochloric, phosphoric or sulphuric and whether, in appropriate cases, the bath was hot or cold. Where there is a large and continuous throughput of pickled steel, the Footner duplex pickling process might be the most advantageous. In this the millscale is removed by pickling in 5 per cent sulphuric acid at 80° C., then the steel is rinsed with hot water and finally it is dipped in a 2 per cent phosphoric acid solution at 80° C. The last dip puts a very thin film of phosphate on to the steel surface and the priming paint is applied as soon as the steel has dried off and before it has cooled down to room temperature. For intermittent use in shipyards, however, the old Admiralty practice of pickling by prolonged immersion (e.g. overnight) in cold dilute hydrochloric acid may be more economical. Care should be taken to rinse the plates thoroughly with fresh water after pickling. Moreover, it is a wise precaution to add an inhibitor to the pickling bath, in order to reduce both the attack of the acid on the steel itself and the possible absorption of hydrogen by the metal, which may have an embrittling effect, particularly on high tensile steels. It should be added that descaling by blasting gives equivalent results to pickling so far as paint performance is concerned. In view of recent developments in the design of blasting apparatus, e.g. the introduction of the type with a vacuum hood that absorbs its own dust, gritblasting may be regarded as a practicable alternative to pickling in shipyard practice but here again economics must have the final word.

It is true that pickling will tend to reveal any surface or other defects that may be present in the plate but surely, if a fair agreement is reached between the shipbuilder and the steelmaker as to what is a reasonable practical standard of acceptance for surface condition, this is all to the good? In this connection, it may be observed that in 1954 the British iron and steel industry supplied about 300,000 tons of ship plate. This would have a total area of roughly 2½ square miles. It would be as unrealistic to expect the whole of it to be without surface blemish as to imagine that every woman must necessarily be a Venus or every man an Adonis.

We have already discussed the corrosion fatigue of steel in general terms; aluminium structures are outside the scope of the paper.

Mr. Benford is probably aware that one side bulb plates are now manufactured; their use should obviate the difficulty in the design of tank tops to which he refers. His case of the corroded funnel is an excellent example of the extremely damaging effects of abrasion by solid pollution, grit, coupled with corrosive attack by combustion products, which almost invariably contain a high proportion of sulphur dioxide.

It is difficult to comment on the results of the practical trial reported by Mr. Perrin without much more knowledge of the test conditions and data than he gives. It is true that, as he suggests, the relationship between paint performance and film thickness will vary for different paints. In general, however, for the types of paint known and manufactured at present, there is a certain minimum thickness below which, because of unavoidable defects in the paint film itself, effective protection cannot be expected. It is only when this minimum has been surpassed that differences in the efficiencies of rival paints become manifest. For this reason, as mentioned in the paper, it is wise to insist on a minimum total dry paint film thickness of 5 mils., where important structures have to be protected by painting. We may add that, of all the factors affecting paint performance on steel, the one that can do the most harm in the majority of cases is bad surface preparation.

Mr. Waters has made some interesting comments on the difficulties of welding light plating. It may be noted that, in the experience of one of us (H. J. A.) the use of "swedge" stiffness is increasing; moreover, some owners are requiring continuous fillet welding instead of intermittent or scalloped welding. Where the parts are prefabricated, so that the continuous welding can be done by machine, the first coat is probably reduced. Mr. Waters also refers to chlorinated rubber anti-corrosive compositions. No further experimental work has been done on these by B.I.S.R.A. but we have the impression that appreciable progress has been made by the paint industry in developing compositions of this type and that good proprietary anti-corrosive compositions in a chlorinated rubber medium are now available.

Mr. Carter's constructive contribution is a valuable adjunct to the paper itself. We particularly are glad to have his practical confirmation of many of the views that we have expressed ourselves such as, for example, the possible value of neoprene coatings for protecting the after end of ships.

We have already dealt with Captain Duckworth's query about the effect of the weight of paint applied to a ship.

In conclusion we should like to associate ourselves with Mr. Pemberton in his expression of thanks to all those who have taken part in the discussion. We have learnt a great deal from their remarks and we feel that these will add considerably to the value of the paper.

* See Fancutt, F.: "Painting and Protection of Steel Structures." Paper read at a Symposium of the Corrosion Group of the Society of Chemical Industry on the Protection of Structural Steel, 1955. *Chemistry and Industry*, 1955, No. 47, November 19th, pp. 1492–1502; or in the Symposium volume to be published shortly by the Society.

† Fancutt, F.: "The Effects of Different Methods of Pre-treating Iron and Steel before Painting." Iron and Steel Institute, Special Report No. 31, 1946.