CORRESPONDENCE

ON

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"Corrosion of Iron and Steel."

By Sir ROBERT ABBOTT HADFIELD, Bart., D.Sc., D.Met., F.R.S., M. Inst. C.E., and SIDNEY ARTHUR MAIN, B.Sc.

Correspondence.

Mr. WILLIAM BENNETT, of Philadelphia, observed that it was of interest to note how well Halifax came out relatively in the series of tests carried out at that port together with those at Colombo, Auckland, and Plymouth. A statement on p. 10 required some modification or explanation. The Authors said that "A further important discovery of recent times, and one which established a direct and previously-unsuspected effect of corrosive action on the strength of metals, concerns what is known as 'corrosion fatigue.' The weakening of structures due to actual loss of metal through corrosion is obvious, but it was not so clear that corrosion to a degree short of that which causes a reduction in the section of metal can cause a marked reduction in strength, in many cases by as much as 50 per cent." That statement made Mr. Bennett think of the many cases of badly-corroded oil-tankers, whose plating was, in addition, say 30 per cent. less in thickness than when the ship had been built; it gave rise to thoughts as to how such oil-tankers managed to survive heavy winter storms, and in many cases even full gales and hurricanes. His impressions of the Paper were: (*a*) The cause (or causes) of corrosion, as evidenced by the Paper, appeared to be more elusive than ever. (*b*) Ordinary mild steel was the basic all-round metal from the engineering standpoint; that was to say, both on account of its satisfactory physical qualities and its good riveting and welding qualities. (*c*) It was, perhaps, a matter for thanks more than for regret, looking at the question purely from the ship-repairers' point of view, that the so-called rustless and stainless steels were not at present producible at a price at all comparable with ordinary mild Mr. Bennett.

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[1] p. 3 (June).

Mr. Bennett. steel; nor had they proved to be "rustless" in actual practice in salt water.

Dr. Desch. Dr. C. H. **Desch** thought that the extensive results brought forward by the Authors served to emphasize the complexity of the process of corrosion. It was evident that the many factors which were concerned interacted in a complex way, so that it was exceedingly difficult to draw conclusions which would hold good over a wide range of conditions. The results would have to be compared with those that had been obtained by the Corrosion Committee of the Iron and Steel Institute, most of which, however, covered a shorter period. The present results were of especial interest on account of the long period of exposure.

The totally-submerged specimens showed comparatively small differences (the highly-alloyed steels being excluded), and under such conditions it would seem that chemical composition exerted only a small influence on general corrosion; much greater differences were, however, found in the extent of pitting, in which texture played an important part. It was natural that ingot iron, a highly-oxidized steel low in carbon, should differ in its resistance to local attack from wrought iron, which was very little oxidized and had the property of deflecting pits on account of the linear arrangement of the cinder inclusions. It was rather surprising that the difference in that respect was not even greater. Atmospheric and half-tide specimens naturally showed greater variations, both among similar specimens at the same station and between the same steels at different stations. Under such conditions it would appear that protection would have to be given by painting, and that inherent resistance to attack, short of using highly-alloyed steels, was not to be expected, although the advantages of adding copper to mild steel exposed only to the atmosphere were confirmed.

The results of exposure in the Gulf of Paria were of particular interest, and it was to be hoped that the mechanism of pitting in the highly-alloyed steels would be further studied. The extent of the organic growths on those specimens was unusually great, and the different degree of adhesion of barnacles and similar organisms to nickel and chromium steels might deserve study. In view of the complexity of corrosion under marine conditions, it seemed desirable that an analysis of the results obtained by the several committees should be examined by strict statistical methods, provided that the number of check specimens were sufficient; the body of results presented by the Authors ought to form most valuable material for such an investigation.

Mr. Elliot. Mr. T. G. **Elliot** observed that it had been a great pleasure for him to have assisted in the analyses required in the research. There

Mr. Elliot. was a point in the Paper that might usefully be stressed, namely, the evidence afforded against the still prevalent idea, referred to on p. 7, that each metal possessed an inherent "corrodibility." That property was now proved to be dependent upon the particular circumstances in each case. It might also be useful to mention again the distinction between general corrosion and pitting, and especially to draw attention to the suggestions made on pp. 19 and 20, which might be found useful in the consideration of later parts of the Paper.

Dr. Evans. Dr. ULICK R. EVANS observed that an authoritative review of the extensive results of the corrosion researches of The Institution was of great value. The calculations of Tables IX and X, which showed clearly that mill-scale led to pitting, although on the average it had no appreciable influence on the corrosion as a whole, were particularly valuable. The remaining Tables in which materials were compared were also of great interest. In applying the data, however, it would have to be remembered that the order of merit of materials, when used in the painted state, might not be identical with the order of the same materials when tested in the unpainted state. Under atmospheric conditions, the two orders were not very different, as shown in a recent 2½-year test by Mr. K. G. Lewis and himself.[1] There was reason to think, however, that under marine conditions the two orders would show greater divergences. If the paint were applied to a weathered surface, the relative behaviour of different types of steels was likely to be determined mainly by the state of the mill-scale reached after the normal period of weathering. Probably the ideal marine steel would be one which would lose its scale very quickly on weathering. The state of the mill-scale at the moment of painting was apt to be more important than the composition of the steel as such. Another series of tests,[2] in which specimens had been weathered for different periods before painting (including also specimens completely descaled, mechanically or chemically), indicated that, under atmospheric conditions, the worst results occurred where the scale had been removed locally by the weathering, the main areas remaining covered with scale at the time of painting. Intense attack occurred at the breaks in the scale, and the rust formed forced away scale and paint together. On plates completely descaled by weathering before painting, the paint remained firm for long periods. That accorded with the general electrochemical principles governing the intensity of attack at breaks in a "cathodic coat" upon steel,

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[1] K. G. Lewis and U. R. Evans, Iron and Steel Institute Corrosion Committee Report, vol. 3 (1935), p. 177.

[2] *Ibid.*, p. 173.

Dr. Evans. whether that coat were copper or mill-scale.[1] The strength of the electric current flowing between the coating as cathode and the exposed steel as anode was largely determined by the cathodic reaction. If the cathode were a large one (that was to say, if the coating were nearly continuous), the current would be strong. The attack would be concentrated on the bare steel (as anode) and if the exposed areas were small, the intensity of attack (namely, the attack per unit area) would be high, leading to pitting. It should be remembered that on high-chromium steel the invisible oxide-film formed at ordinary temperatures would prevent attack over the greater part of the area ; if attack should occur, it would be severely localized and therefore intense. That explained the pitting to which the Authors referred. On ordinary steel, the invisible film was too porous to localize the attack under the same conditions, and localized attack (pitting) only occurred if mill-scale were present.

The pitting at breaks in mill-scale was to be expected even if the oxygen-concentration were uniform. If the oxygen-concentration at the break were lower than that over the scale, there might be a slight increase in the current-strength, but such differences in oxygen-concentration were not needed. He did not remember that he had ever used the differential-aeration principle to explain pitting at interruptions in a mill-scale coat, as the Authors seemed to imply.

The differential-aeration principle did not seek to provide an explanation of all cases or types of corrosion, but it did explain the distribution of attack in salt solutions under conditions where oxygen had better access to some parts than to others. The distribution certainly seemed to call for explanation, since, although oxygen stimulated corrosion, the part nearest to the source of oxygen was frequently seen to be immune. That was explained, not only qualitatively but even quantitatively,[2] by the differential-aeration currents which flowed between the relatively aerated part as cathode and the relatively unaerated part as anode, producing attack on the latter. But, as he had frequently pointed out in various Papers, quite different distributions, involving corrosion at the water-line, were also met with, and, furthermore, corrosion-currents could be set up by factors other than differences in oxygen-concentration.

Dr. Footner. Dr. H. B. **Footner** observed that there were definite indications in the Paper that rolling-mill scale had been the cause of serious pitting of steel plates, but that there was very little difference between the general wastage of specimens originally carrying mill-

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[1] U. R. Evans, " The Corrosion of Metals at Joints and Crevices." Journal Roy. Soc. Arts, vol. LXXV (1926–27), p. 544.

[2] U. R. Evans and T. P. Hoar, " The Velocity of Corrosion from the Electrochemical Standpoint." Proc. Roy. Soc. (Series A), vol. 137 (1932), p. 343.

Dr. Footner.

scale and of others which were previously descaled. The fact that general wastage had been similar, and, if anything, less on the plates from which the scale had not been removed, did not seem material, since it was to be expected that, under the conditions of exposure, unprotected mild-steel plates would have a marked tendency to rust. What was clearly brought out, however, was that the presence of mill-scale led to marked pitting. That indication was fully borne out in practice, and an illuminating instance of the effect might be quoted. At a petroleum installation in the Near East the contents of different tanks from a certain date consisted of a semi-refined oil having an appreciable organic acidity. In all the tanks a salt-water bottom was carried. After from 18 months to 2 years it was found that the bottoms of some tanks were actually holed, whilst others showed no pitting at all. Those tanks in which the bottoms were not pitted had been in other service for 5 or 6 years, so that the mill-scale had been gradually and completely removed, whereas those in which the bottoms were pitted were new and carried mill-scale when they were first filled with the semi-refined oil, other conditions being identical in all the tanks.

Apart from its tendency to cause pitting, the presence of mill-scale had a most pernicious effect on such structures as petroleum tanks or gas-holders, which had to be painted. If paint were applied to plates carrying scale the protection obtained was almost invariably bad. That was due to two causes, the action between the oxide scale and the metal, which led to rusting, and the poor adhesion of the paint on surfaces covered with scale.

The latter point had generally been overlooked, but he had seen tank plates, some years after painting, on which the paint adhered well and was quite elastic where the steel was free from scale but was brittle and lifeless on the surfaces where mill-scale still remained. There was a certain amount of rusting on the surfaces carrying scale, but even where rusting had not yet begun the paint had definitely perished. In that respect a surface carrying scale resembled a newly-galvanized plate which, as was well known, gave poor adhesion to paint, the effect being noticeable under the action of sunlight.

It was now generally recognized that steel should be freed from mill-scale before being painted, and various methods of descaling were available. One method was to expose the steel to the effects of the weather, but there were several objections to that simple practice. It was often undesirable, for commercial or æsthetic reasons, to leave structures unpainted for an indefinite period which might, in some climates, be as long as 2 or 3 years. Furthermore, after weathering, plates were covered with rust and dirt, as well as salt deposits in a maritime location, and very careful scraping was

Dr. Footner. necessary before the application of paint. It was a common fallacy that wire-brushing was sufficient after weathering, but cleaning in that manner certainly did not sufficiently free the plates from rust or other deposits. Another method of descaling was by sand-blasting, which certainly provided an excellent surface for painting. It was necessary, however, to paint very soon after blasting, as the exposed surface was very liable to corrosion. In addition, the process required somewhat costly equipment and a supply of suitable sand. Another objection was its effect on the health of workmen, as it was liable to produce silicosis after a comparatively short period.

Descaling could also be effected by acid pickling. Until recent years that process had been open to the objection that traces of acids or salts were left on the surface of the steel, which were liable to cause corrosion and breakdown of a paint film, but methods of acid pickling had now been devised and adopted in the petroleum and other industries which were free from that objection, and were at the same time entirely economical in practice. Mr. J. P. Pheiffer had described[1] a method of pickling steel plates or tubes, which consisted, briefly, of immersing the steel in a hot 10–15-per-cent. solution of phosphoric acid and then in a dilute bath containing in solution about 2 per cent. of free phosphoric acid and 0·5 per cent. of iron, and maintained at 85° C. The first bath effected the descaling, whilst the second bath functioned as a wash bath and at the same time deposited on the steel surface a very thin film of ferric phosphate, which had a definite inhibitive effect against corrosion in the atmosphere. That method of pickling had been adopted with success by certain petroleum companies, but its cost was somewhat high. The process was cheapened by a discovery, covered by a French provisional patent, that the phosphoric acid in the descaling bath could be regenerated by sulphuric acid with no deleterious effect on the pickled plate. Further investigation in Great Britain had shown that completely satisfactory results were obtainable by descaling the steel in a 5-per-cent. solution of sulphuric acid, followed by washing in hot water (65° C.) and final immersion in the hot dilute phosphoric acid bath described above. Actual practice on steel tank plates had shown that that method of pickling completely removed mill-scale and left the steel in an ideal condition for painting. Plates pickled in that way showed no more tendency to corrode than when the scale was removed by phosphoric acid alone. The process was economically sound, and cost considerably less per square foot of surface than sand-blasting.

With any of the above pickling processes it was good practice to paint immediately after pickling and, if possible, whilst the plate

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[1] "Pickling Wrought Iron and Steel by means of Phosphoric Acid." World Petroleum Congress Proceedings, London, 1933. Vol. I, p. 542.

Dr. Footner.

was still hot, since the paint penetrated better and was more easily worked into the surface of the plate. Actual practice during 2 years had shown that tank plates which were pickled and immediately painted with red-lead primer could be transported abroad and erected with no more than 5 per cent. damage to the paint film. That surprising result was no doubt due to the good adhesion of the film, since on corresponding plates which had been shop-painted over the scale the paint was invariably damaged during transport and erection.

The methods of pickling mentioned above had been given a thorough trial in the petroleum industry, and had been the means of preventing pitting of tank bottoms and roofs; they would result in a very considerable saving of repainting costs, since scraping to bare metal would no longer be necessary when repainting, the only requirement being a periodical renewal of the finishing coat. The process had recently been extended to the shipbuilding industry, the complete hull of a 7,000-ton ship having been pickled and shop-painted at a yard in Amsterdam. The red-lead paint applied to the hull after pickling had remarkable tenacity, and it was probable that the usual hull corrosion found on a new ship would be completely eliminated.

The most important points to be noted about the methods of pickling described above were that the steel surface after pickling was in an ideal condition for painting, and that there was nothing left on the surface which could cause corrosion or deterioration of the paint film. The thin film of iron phosphate was not resistant to corrosion by water, but had some inhibitive effect on atmospheric corrosion. Plates pickled by those methods, when left unpainted and exposed to the weather, showed even rusting after some time but no tendency at all to pitting. It should be mentioned that the process of pickling in sulphuric acid, followed by washing in water and immersion in the dilute phosphoric acid bath, was entirely free and was not covered by patent.

Dr. Newton Friend.

Dr. J. NEWTON FRIEND wished to call attention to the very great services which Sir Robert Hadfield had rendered to the Sea-Action Committee in its various activities. In the course of preparing and examining the metals to be exposed by the Committee at various stations, Dr. Friend had had occasion to spend many days at the works of Messrs. Hadfield's Ltd., in Sheffield, and he was glad to have the opportunity of publicly thanking Sir Robert and his staff, more particularly Mr. S. A. Main (one of the present Authors) and Mr. T. G. Elliot, for their unfailing kindness, courtesy and assistance. Without their generous co-operation the work of the Committee could not have been so efficiently carried out. The close concordance which had been found between the results at different stations and over different periods of exposure was in a large measure due to the

Dr. Newton Friend.

great care with which the iron and steel bars were manufactured in Sheffield; had the specimens not been prepared with the greatest skill it was obvious that the results obtained could not have been satisfactory, even if the later experimental technique had been perfect.

The researches of the Committee had already extended over a period of nearly 20 years, and during that time enormous progress had been made by various associations in the study of corrosion; the great value of the data before them lay in the fact that they were not the results of short-period exposures of merely a few hours, days, or even weeks, which might give very conflicting results. The data under consideration were the product of 5 and 10 years of testing, and were therefore worthy of most careful consideration.

He would like to support Dr. Vernon's plea for the avoidance of the possibly ambiguous use of the term "scaled" to indicate steel from which the scale had been removed. Dr. Vernon had also mentioned, giving reasons therefor, that if the Committee's bars had been exposed inland very different results might have accrued. A similar idea had occurred to Dr. Friend, and upon his request in 1921 Sir Robert had generously placed at his disposal bars of ten varieties of iron and steel, nine of which were specimens left over from the Committee's research. The bars measured 12 inches in length and had otherwise the same dimensions as the Committee's bars, and were exposed in the "blue" condition, namely, with mill-scale still adherent, except at the ends, which were machined and stamped for identification. The bars were placed in a rectangular wooden frame, their ends being embedded in a thick layer of putty let into grooves in the frame. (Concrete, which had been found to be an excellent embedding material in the Committee's experiments, could not well be used with a wooden frame.) The frame was laid horizontally on a flat portion of the roof of the Technical College, Birmingham in May, 1921. At intervals it was turned over to give both sides comparable treatment. It should be remarked that the College was situated unpleasantly near to the L.M.S. railway station and goods yards, so that it received no small quantity of smoke and soot from the engines. In May, 1927, after an exposure of 6 years, the frame was dismantled; the wood had rotted seriously and the frame readily fell to pieces, but the hardened putty adhered to the ends of the bars like cement and had to be chipped off. The metal protected by the putty was bright where it had been originally machined, and the identification lettering was clear and free from rust.

After careful cleaning the losses in weight of the bars were determined, using the same balance and weights as those employed in the Committee's research, so that from a manipulative point of view the results were strictly comparable. The results were given in Table

Dr. Newton Friend.

XXXIII of Sir Robert's Paper (p. 96). It was, however, instructive to compare the relative corrodibilities of the metals with those found by exposure at three of the Committee's stations. Table XXXIX gave that comparison, the Colombo station being omitted, as the aerial tests, owing to excessive spraying from the sea, closely resembled the half-tide tests. As no wrought irons were exposed it was convenient to choose the mild steel bar E as standard, its loss in weight being taken as 100, the losses of the others being expressed relatively thereto.

TABLE XXXIX.

Bar.	Type of steel.	Relative corrosion.			
		Birmingham, 6 years.	Halifax, 5 years.	Auckland, 5 years.	Plymouth, 5 years.
E	Mild steel, low S and P.	100	100	100	100
B	Mild steel, low Mn; high S and P.	161	163	152	136
F	Mild steel, 0·7 per cent. Mn.	114	122	87	124
D	0·40 per cent. C steel.	122	98	118	122
G	Mild steel, 0·6 per cent. Cu.	66	63	46	78
H	Mild steel, 2·2 per cent. Cu.	70	46	30	44
K	3·75 per cent. Ni steel.	41	27	26	17
L	36·55 per cent. Ni steel.	6	2·7	3·5	1·4
J	13·6 per cent. Cr steel.	1·5	11	9	2·6

Consideration of the Table showed that, except for the steel H, the results were reasonably concordant; although bar L had lost more than bar J in the Birmingham tests, the losses of both metals were small and a few grams made all the difference.

Had the data been available it would have been interesting to compare the behaviour of those metals towards typical country air such as that of the Sussex Downs, and moist air such as that of Borrowdale, Cumberland.

In the aerial tests pitting was not usually serious and the cast irons did not suffer appreciable graphitization; hence the losses in weight might be regarded as fairly accurate measures of the extents of corrosion.

In the half-tide and immersion tests, however, both pitting and, in the case of the cast irons, graphitization were appreciable and rendered the problem more complex. The cast irons proved very disappointing in their resistance to sea water; they underwent serious graphitization, and were often internally corroded, so that their external appearance was deceptive, giving little or no indication of their weakness. The experimental results were in complete accord

Dr. Newton Friend.

with the observations recorded[1] of the corrosion of the landing stage of the Birnbeck Pier at Weston-super-Mare. The introduction of alloying elements such as copper, chromium and nickel might tend to reduce the losses in weight of the steels exposed to sea-action, but in the Committee's experiments there appeared to be an increased tendency for those steels to undergo localized corrosion or pitting. That result was evidently supported by the observations of the Authors on the specimens immersed in the Gulf of Paria. The 36-per cent. nickel steel and the 18–8 chromium-nickel steel would, of course, be extremely expensive, and their superiority over ordinary steels and low alloy steels would have to be overwhelmingly great for them to receive more attention.

Dr. Hatfield.

Dr. W. H. HATFIELD, Chairman of the Joint Corrosion Committee of the Iron and Steel Institute and the British Iron and Steel Federation, observed that the analysis which the Authors had prepared of the results of the Sea-Action Committee's tests on unpainted bars should be of considerable utility as a general survey of those tests. Even with a limited series of irons and steels, a very large number of tests would be required to cover fully all the possible variations in conditions of exposure and pre-treatment of the materials which were of practical interest, and there were directions in which it would have been of considerable interest to extend the work under consideration. Nevertheless, the tests had produced a number of very interesting observations which should not only assist those responsible for the choice of materials for marine structures, but also stimulate interest in further tests.

The long time usually required for the completion of corrosion tests was particularly unfortunate where tests on the special alloy steels were included because in that rapidly developing field the steels tested were liable to be superseded by improved types long before the final results became available. The research under discussion had, in fact, suffered in that way, notably in the case of the 13-per-cent. chromium steels, which for marine work had now been almost entirely superseded by the higher chromium materials, usually of the 18/8 chromium-nickel type.

Another difficulty encountered in such tests was in the design and carrying out of sufficient tests to show clearly the influence of any particular factor. Taking, for example, the present tests with carbon steels, the results suggested that under aerial conditions the steel low in manganese and high in sulphur and phosphorus was inferior to the other materials, whereas under immersed conditions it was the least corroded. Before it would be possible to say whether or not

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[1] Fourth (Interim) Report of the Committee on the Deterioration of Structures exposed to Sea-Action, p. 28. London, 1924.

those results were in any way related to, say, the sulphur and phosphorus content, it would be necessary to carry out a series of tests to explore various other possibilities. For instance, the increased corrosion might well be connected with the condition of the oxide scale resulting from the particular rolling treatment given during production, and might have little or no relationship to the composition of the steel. It would be appreciated, therefore, how difficult and complicated a matter it was to obtain specific information as to the influence of the various factors, and why it was that the Corrosion Committee of the Iron and Steel Institute and the British Iron and Steel Federation had already found it necessary to expose nearly two thousand specimens and was actively engaged in the preparation and exposure of some hundreds of further specimens, in addition to the planning of new series of tests, whilst, as yet, its work had scarcely touched the higher alloy steels. Again, it was very desirable that tests such as those under consideration should be supplemented as far as possible by a study of the behaviour of steels under actual service conditions. That was a necessary phase of the work, since it was often impossible to allow for all the various factors which might operate in service. **Dr. Hatfield.**

Considering the detailed results, the indicated advantage resulting from the addition of 0·6 per cent. of copper to the carbon steel continuously immersed in sea-water was decidedly interesting, especially in view of the general indication from other tests that small additions of copper were not beneficial under such conditions. In that connection it would have been useful to have included a similar steel with 0·2 to 0·3 per cent. of copper, which would have permitted the direct checking of the Authors' suggestion that, whilst 0·2 to 0·3 per cent. of copper was fully effective in industrial atmospheres, a larger amount was required before the influence became apparent in sea-water. In the circumstances, it would be particularly interesting to study the comparative behaviour of strictly comparable 0·2-per-cent. copper steel and 0·5-per-cent. copper steel specimens which the Corrosion Committee of the Iron and Steel Institute had arranged to expose to marine conditions very shortly.

In the tests which the Authors had carried out in the Gulf of Paria, the conditions of exposure had certainly been very drastic and had evidently been such as to hinder seriously that reasonably free access of oxygen to the surface of the various austenitic chromium and chromium-nickel steels which was necessary if they were to maintain their full corrosion-resistance in media such as sea-water. It had been amply demonstrated that the 18/8 chromium-nickel type of steel behaved excellently in marine service where oxygen-shielding was not a serious factor; that applied even under static conditions

Dr. Hatfield. of exposure, as, for example, in the case of the rods driven into the Reef as survey-stakes by the Great Barrier Reef Expedition of 1928–9. The Authors implied that the relatively small attack obtained with the pickled sample of the 10-per-cent. chromium, 20-per-cent. nickel steel No. 3765 in the Gulf of Paria tests might have been due to its lower chromium and higher nickel content in comparison with the other steels in the group. That seemed rather improbable, particularly in view of the much higher loss shown by the 36-per-cent. nickel steel. It would seem much more probable that the sample in question had a particularly passive surface, since considerable variability in the passivity of pickled samples of such material could occur. Undoubtedly, the most generally useful special steel for marine work was the well-known 18/8 chromium-nickel type.

Drs. Honda and Endo. Drs. KOTARO HONDA and HIKOTO ENDO, of Tôhoku University, observed that, although many metallic and environmental factors were involved in the corrosion of iron and steel in salt solutions, the possible actions of each factor had now been sufficiently clarified by various investigations. In laboratory experiments those factors were comparatively limited, but in the more complex conditions of exposure-tests important factors might be revealed. The results obtained from such tests often contradicted conceptions formed from laboratory work; that was undoubtedly due to the predominance of those factors which acted only under marine exposure. Hence, also, it was generally true that the same results would not be obtained from the same material if there were differences in the exposure conditions, location, character of sea-water at different seasons, and so on. The amount and character of the corrosion observed were the results of a combination of factors, each of which might be different in different locations or under different circumstances. It was, therefore, important and significant that authentic results should be accumulated from practical exposure-tests made in various locations, one of the major objects of such tests being to find out the predominating factors affecting corrosion and their mutual accelerations and retardations at each location.

The results of the Author's extensive investigation would be very instructive to engineers; to laboratory men they suggested many important problems to be studied, especially with regard to pitting. According to the Authors' results, the amount of pitting did not seem to follow any systematic relationship with respect to locations or methods of exposure, but seemed to be affected by many factors and to be caused by complicated reactions. For example :—

(i) At Halifax, the extent of pitting was extraordinary under half-tide conditions, in spite of the fact that it was very slight under total

Drs. Honda and Endo.

immersion and aerial conditions. The character of the sea-water and the molluscs at Halifax apparently contributed some special corrosive feature causing that excessive pitting under half-tide conditions only. The contamination of water with oil at that port might perhaps be responsible. It was therefore desirable that the mechanism of the reaction of oil-contaminated sea-water on iron and steel—for example, whether a colloidal action of oil was an accelerating factor or whether an oil layer acted as a protecting film—under half-tide conditions, should be investigated.

(ii) At Colombo, the pitting on a steel surface was greater under half-tide than under aerial or total-immersion conditions, whereas for iron it was less than in the latter two cases. That great difference in results between iron and steel might be attributed not merely to the difference of carbon content but perhaps also to factors of environment. Perhaps the Authors would be able to give an explanation.

(iii) In general, the rusting of iron and steel in air in winter, when the mean relative humidity was comparatively high, was greater than that in summer, when the mean relative humidity was small; also, the velocity of rusting of iron on which rust already existed accelerated greatly over the critical humidity-range between 60 and 70 per cent., as confirmed by Dr. Vernon. On the contrary, however, the rusting in air at Colombo, in a hot climate, was greater than that at Halifax, in a cold climate. In that case the relative humidity was not the major factor, as the surface of a specimen near the sea was maintained in a wet condition by salt spray, but the difference of air-temperature between the two places was an important factor, as an increased temperature accelerated the reaction-velocity. The nature of the sea-water, and other factors, had also to be taken into consideration.

(iv) It was a widely accepted view that the corrosion-velocity of iron and steel in alternately wet and dry conditions was larger than that in total-immersion or aerial conditions. In the tests described in the Paper, however, the loss in weight of the large majority of ordinary steels and rolled irons under the half-tide conditions was intermediate between the losses experienced under aerial and total-immersion conditions. The above result might be due to the salt-spray, which maintained the surfaces of the specimens in a wet condition, and also to the character of the sea-water at the locations where the experiments were made. That view, however, did not apply to the results of the half-tide tests on rolled irons and steels at Auckland and Plymouth, where the loss in weight was usually less than that under either aerial exposure or total immersion. The

Drs. Honda and Endo.

causes of that difference might need further experiments for their elucidation.

Although there were many at present unaccountable results, such as those mentioned above, Drs. Honda and Endo were gratified to find that most of the results could be explained by their own findings on the following principles :—

(1) In total-immersion conditions :—

(*a*) Additions of small amounts of special elements to iron and steel had a very small effect, which could safely be neglected in comparison with other factors in neutral salt-solutions. The corrosion of iron specimens in those conditions was affected chiefly by the metallic factors (i) surface condition, (ii) presence of different phases, (iii) design (form) of structures, (iv) protective film; and by the environment factors (v) concentration of oxygen, (vi) concentration of hydrogen ions, (vii) adhesion and distribution of corrosion-products, (viii) electrical conductivity of solutions, etc.

A small addition of special elements had a large effect on the dissolution of iron by acid in total-immersion conditions, and also in aerial and wet-and-dry conditions, but it had almost no effect under total immersion in neutral salt-solutions, and the total wastage of ordinary iron and steel was almost the same if the concentrations of chlorine ions and of oxygen and acidity in solutions were almost equal, as was seen in *Figs. 4* (p. 25). However, it was natural that when the content of special elements was increased to more than 7 or 8 per cent., as in 13-per-cent. chromium steel, 18/8 chromium-nickel steel, or 36-per-cent. nickel steel, the added element had a considerable effect even in the neutral solution under total-immersion conditions.

(*b*) It had been ascertained by their own experiments that the loss in weight of iron and steel in water and sodium chloride solution was greatest at temperatures between 60° and 70° C. The effect of climatic temperature was very small in that experiment, as the temperature-difference for all locations from the hottest to the coldest climates was not so large under total-immersion conditions. The character of sea-water in that case seemed to be a more important factor than the temperature, but in aerial and half-tide conditions the effect of temperature was clear, indicating that it was a predominating factor; for example, the loss in weight in aerial conditions at Colombo was greater than that in the colder climate of Halifax.

(*c*) It was also well known that if the form of specimen were very complicated, the velocities of corrosion at various parts would be different owing to the difference of oxygen supply, and hence the results obtained would not be the same as those found from a specimen

Drs. Honda and Endo.

of simple form. Another important factor was the position of specimens with respect to the current, as changes of position might affect the adherence of corrosion-products to the surface of the specimen.

(*d*) The chemical character of sea-water at a location had a predominating influence on the corrosion of iron and steel; it might be affected by substances discharged from ships and also by molluscs or other fauna which adhered to steel structures. If the composition and seasonal change of sea-water were more thoroughly investigated, the curious results might be effectively explained. It was interesting to find that the character of sea-water at Halifax was such as to cause greater corrosion of iron than that occurring at other ports.

(2) In aerial conditions :—

(*a*) As the chemical composition and adherence of corrosion-products depended upon the amounts and properties of added elements, a small amount of special element added might have an appreciable effect on the rusting of iron and steel in air. In the case of copper-bearing steel, for example, the small content of copper formed a protective layer of copper oxide during the progress of rusting. The effects of such small amounts of added elements and impurities were evident in *Fig. 11*, p. 59.

(*b*) The mill-scale of iron and steel had a protective power against rusting and corrosion, and the total wastage of scale-covered iron was smaller than that of de-scaled iron. If there were fissures or rents in the scale, pitting would easily occur on the defective portions. The character of the scale varied with the amount of the added element and also with the heat-treatment employed.

(*c*) As the mean relative humidity in winter was greater than that in summer, the rusting of iron and steel was greater in winter than in summer. That experimental result appeared to be contrary to the fact that the rusting at hot Colombo was found by the Authors to be greater than that at cold Halifax; the difference, however, was probably due to the temperature-effect, which was the major factor in deciding the reaction-velocity between iron and sea-water.

(*d*) It was reasonable to consider that the content of sulphur dioxide (produced by the combustion of coal) in the air acted as an important factor in aerial corrosion.

(3) In wet-and-dry or half-tide conditions :—

(*a*) Small amounts of added elements had also an influence on the corrosion.

(*b*) They had often found in their own experiments that alternately wet and dry conditions were more favourable to corrosion than total-immersion or aerial conditions. The wastages under half-tide conditions obtained by the Authors, except in the case of cast iron

Drs. Honda and Endo.

at Colombo, were intermediate between those experienced under aerial and total-immersion conditions. The results could be partly explained by the consideration that under aerial conditions at Colombo the rusting was very large owing to the high temperature, and that under total-immersion conditions at Halifax the wastage was also comparatively large owing to the character of the sea-water. The corrosion under half-tide conditions of the rolled iron and steel at Plymouth and Auckland, however, was generally less than that under either aerial exposure or total immersion, and at Auckland it was particularly small. That difference could not be clearly explained.

(4) Pitting :—

(*a*) Pitting was generally produced by the formation or the previous existence of fissures and rents in the protective films, such as mill-scale or the very thin oxide film which might be found on stainless steel. Accordingly, the nature of mill-scale, and the influence of added elements and heat-treatment on its chemical and physical properties, was worth a thorough study. It was well known that the number and the depth of pits produced on the surface of a stainless steel changed with the relative contents of chromium and carbon and with the tempering temperature. Likewise, the corrosion-resisting properties of all kinds of protective films on various ferrous alloys required further study in the laboratory.

(*b*) It was readily understandable that complete immersion in sea-water definitely favoured pitting as compared with aerial or half-tide conditions, because sea-water was an efficient electrolyte. When anodic areas were very small as compared with cathodic areas on the surface of a specimen, the depth of pitting became large as the current-density increased. The direct contact of iron with sea-water for a long time was therefore a necessary condition for the occurrence of severe pitting. The moisture which collected on a specimen exposed to the air, or small amounts of sea-water brought on the surface by salt-spray, were not so effective.

(*c*) In general, the total wastage of specimens due to mill-scale or very thin oxide film was very small, notwithstanding their tendency to induce pitting. When the total wastage was small, the pitting was deep, and when the total wastage was large and pitting occurred at the same time, the pitting was generally very shallow. Most of the results obtained by the Authors could be explained by the above conceptions. The fact that the depth of pitting at Auckland was shallow, in spite of the small total wastage, might be explained by the small ratio between the anodic areas and cathodic areas and also by the electrical conductivity of sea-water at Auckland. The depth of pitting under half-tide conditions at Auckland, however, was less than under total-immersion or aerial conditions; the explanation of that fact seemed to require a further investigation. Drs. Honda and Endo.

(*d*) The temperature had also an influence on the occurrence of pitting, which was severer in a hotter than in a colder climate. In fact, the pitting of steels increased, on the average, in the order of Halifax, Plymouth, Auckland, and Colombo. Irons, however, suffered less pitting at Colombo than at Auckland; the cause of that result was not clear.

(5) Special steels:—

According to experiments made by Drs. Honda and Endo, copper had no effect on the corrosion of iron in neutral salt solutions under total immersion, but when a small amount of aluminium was added to copper-bearing steel, it became more resistant against corrosion in neutral solutions. The addition of 0·35 per cent. of copper (which was the solubility-limit of copper in α-iron at room temperature) increased the resistance to dissolution in hydrochloric acid of various concentrations and sulphuric acid of various concentrations below 50 per cent. The experiments and their explanation would shortly be published by Dr. Endo.

Their experiments had also confirmed that 36-per-cent. nickel steel was very resistant against corrosion in neutral salt-solutions, and had almost the same resistivity as pure nickel against dissolution in 10-per-cent. sulphuric acid. Although the 36-per-cent. nickel steel was one of the most resistant alloys, it did not escape corrosion by sea-water. The 18/8 chromium-nickel steel and 36-per-cent. nickel steel were easily attacked by solutions of mercuric chloride, ammonium chloride, hydrochloric acid, and sulphuric acid. The alloy which they considered the most resistant consisted of 15 to 20 per cent. chromium, 7 to 10 per cent. molybdenum, 10 to 20 per cent. iron, 1 per cent. manganese, and the rest nickel, but as it was more expensive than those mentioned just above, it was not suitable for use in large structures. As a cheaper alloy, they adopted a steel containing aluminium, chromium, silicon, and copper, of which the total addition was below 8 per cent., as in "Chromador"; under total-immersion conditions that alloy was more effective than "Chromador."

Mr. Kewley. Mr. JAMES KEWLEY observed that the attention paid to corrosion problems at the present time was reflected in an exhibition on corrosion which had been arranged by the Asiatic Petroleum Company, and had been held in London. Although one of a series of exhibitions primarily intended for the education of the staff of that Company, it had afforded a very valuable opportunity for the discussion of

Mr. Kewley. corrosion problems of vital importance to the petroleum industry with some of the authorities on corrosion, and with suppliers of equipment for oil-refineries.

The exhibition dealt with the factors affecting corrosion and with means adopted to avoid or reduce corrosion in air, water, and soil, and under refinery conditions. Particular attention was paid to the selection of the proper grade of paint and to the necessity of treating steel plates before painting. A section of the exhibition dealt with the results of galvanic action between dissimilar metals, which was strikingly illustrated by the use of the ferroxyl indicator. Other features included were the methods of protection of pipe-lines (by coatings and electrical methods) the detection of pinholes in coatings, and the effects of anaerobic bacteria on steel. A collection of specimens of corroded refinery equipment emphasized the particular problems confronting the oil industry.

Although the exhibition had now been closed and most of the exhibits returned to their owners, a complete catalogue was being prepared, and might be found of assistance to any research association or institution considering an exhibition along similar lines. The Asiatic Petroleum Company would be very glad to offer any assistance in that direction that might be required.

Dr. von Wolzogen Kühr. Dr. C. A. H. VON WOLZOGEN KÜHR, of Bloemendaal, Holland, observed that, besides the ordinary or aerobic corrosion of iron (with oxygen from the air) causing the formation of yellowish-brown rust, the anaerobic corrosion of iron (without oxygen from the air) in the soil was of great significance. With the first-mentioned process the iron in the product of corrosion was characterized by the ferric state, but with the second by the ferrous state.

The anaerobic corrosion of iron had been studied in the Netherlands since 1922, and was found to be principally of a micro-biological nature. The primary iron corrosion process:

$$Fe + 2H^{\cdot} \rightarrow Fe^{\cdot\cdot} + 2H$$

continued uninterruptedly only when a depolarizer (hydrogen-acceptor) was present. Suitable depolarizers were found to be:—

(i) The sulphate reduction of Beijerinck (1895), according to the equation by Baars:

$$H_2SO_4 + 8H \rightarrow H_2S + 4H_2O$$

The reaction of the iron corrosion was:

$$4Fe + H_2SO_4 + 2H_2O \rightarrow 3Fe(OH)_2 + FeS.$$

The curious fact that that frequently very severe corrosion process took place in an approximately neutral medium (pH value = about 7) was explained by the formation of FeS and $Fe(OH)_2$, which had a neutral nature.

(ii) The carbon dioxide reduction of Söhngen (1906): Dr. von Wolzogen Kühr.

$$8H + CO_2 \rightarrow CH_4 + 2H_2O.$$

> The corroded iron forming in that case passed into $Fe(OH)_2$, so that the *p*H value of the medium again remained about 7.

In the case of sulphate reduction the bound sulphate oxygen was the hydrogen acceptor, and in the case of the carbon dioxide reduction the oxygen from the carbon dioxide was the hydrogen acceptor. The sulphate reduction occurred quite generally everywhere, whilst the carbon dioxide reduction occurred in boggy and marshy districts. The two processes might also occur simultaneously. The anaerobic corrosion process was entirely the same for steel and for cast-iron pipes. In the case of steel pipes it resulted in pitting, whilst cast-iron pipes also showed graphitization owing to their higher carbon content (about 3·5 per cent.).

The anaerobic iron corrosions referred to were to be considered as electro-biochemical processes. Since, therefore, with both the aerobic and the anaerobic corrosion of iron pipes in the soil the attack of the iron had to be ascribed to the anodic solution of the iron by means of a depolarizer (hydrogen-acceptor), there existed, from an electro-chemical point of view, no fundamental difference between the two corrosion processes just mentioned. The unity manifested itself by the invariably present and essential hydrogen-acceptor. It was always possible, in cases of iron corrosion in the soil, to explain conformities and nonconformities by the prevailing conditions under which the iron corrosion took place. The integral parts of the mechanism of the anaerobic corrosion of iron were not by any means novel. On the other hand, the bond uniting the whole gave a novel insight into the process.

Mr. Maurice.

Mr. F. J. MAURICE observed that under all the various test conditions discussed in the Paper, the ingot iron exhibited a resistance to corrosion appreciably lower than that normally shown within his experience and generally demonstrated under service conditions. The explanation of that difference, however, was apparent from the range of analyses of ingot iron given in Table IV, Appendix II. At the time when the test-pieces were procured, British-made ingot iron was in its infancy, although it had regularly been made in the United States during the previous decade, and was now in regular production both in Britain and in all the leading Continental steel countries. The analyses given in the Table cited showed a total of the five major impurities ranging between 0·168 and 0·202 per cent.,

Mr. Maurice. but the current typical analysis of the metal as produced to-day in Britain was :—

Carbon	0·015 per cent.
Silicon	0·005 ,,
Sulphur	0·035 ,,
Phosphorus	0·005 ,,
Manganese	0·020 ,,

the total being only 0·08 per cent. It was understood that British ingot iron was now manufactured to a guarantee of 0·10 per cent. of the elements listed above.

Professor Portevin. Professor A. M. PORTEVIN, of Paris, observed that the Paper by Sir Robert Hadfield and Mr. S. A. Main constituted one of the most valuable contributions which had been made to the important problem of the corrosion of steel. Having himself, in collaboration with Mr. E. Herzog, studied that problem for several years at the steel works of Pompey, he presented the following notes and ideas with a view to comparing some of the results with those given in the Paper.

It had been found necessary to systematize and regularize the results of the various corrosion-tests carried out in the laboratory at Pompey by defining and laying down the working conditions and by introducing standards of comparison based on a Martin-type steel.

The comparisons which he proposed to make dealt with the following points :—

The rapidity of the average attack.
The distribution or type of attack.
The effect of the state of the surface and of scale.
The effect of the temperature.
The effect of the composition of steel, for :—

    Nickel steels.
    Copper steels.
    Chromium steels.
    Ordinary steels and rolled irons.
    Steels with the addition of other elements.

The Rapidity of the Average Attack.

The rapidity of attack obtained with the three methods of testing used (salt mist, intermittent immersion, and total immersion) was as shown in Table XL, and compared with the results of the corresponding tests quoted by the Authors.

Professor Portevin.

TABLE XL.—AVERAGE LOSS IN THICKNESS: MILLIMETRES.

	Place of test.	Duration of test.	Saline mist or sea air.	Half-tide conditions or intermittent immersion.	Total Immersion.	
					Still liquid.	Agitated liquid.
Standard Martin steel [1]	Laboratory at Pompey	1 month	0·025	0·057	0·009	0·035
		2 months	0·044	0·109	0·016	0·065
		2½ ,,	0·081	0·154	0·024	—
		5 years (extrapolated).	1·38	3·00	0·480	1·8
Average ordinary steels and rolled irons	Halifax	5 years	0·140	0·388	0·513	
	Auckland	,,	0·300	0·186	0·430	
	Plymouth	,,	0·951	0·414	0·478	
	Colombo	,,	1·834	1·014	0·495	

[1] The standard Martin steel for the laboratory tests at Pompey (sheet from middle of ingot) had the following analysis:—

C	0·07 per cent.
Mn	0·41 ,,
Si	0·02 ,,
S	0·024 ,,
P	0·018 ,,

The laboratory tests gave, in increasing order of rapidity, the following classification:—

	Coefficient.	Loss in weight: grams per square metre per month at 30° C.
Total immersion in calm liquid	1	60/70
Total immersion in agitated liquid	3–4	180/240
Salt mist	3	200
Intermittent immersion	6	400/430

The practical results given by the Authors furnished a grading which was not the same; besides, it varied from one testing station to another. In general, the grading for increasing loss in weight was:—

(1) Salt air (either first or second, varying with the testing station).
(2) Half-tide conditions. (,, ,, ,, ,, ,, ,, ,, ,, ,,).
(3) Total immersion.

In the laboratory, corrosion was slowest under total immersion in still liquid. That was different from the results of tests in the sea, where currents and aeration probably intensified the attack. The figures derived for a 5-year period from those obtained in still liquid in the laboratory agreed with those obtained in the sea. In that

Professor Portevin.

test, therefore, there was no acceleration in the rate of corrosion. It was difficult to work out how much more rapid the laboratory tests were than the practical tests.

Taking the highest figures, which were those for Colombo, and the lowest, as observed at Auckland, the rates of corrosion in the laboratory tests relative to each of them were as given in the following Table; for still liquid the rates were found to be in agreement.

	Colombo.	Auckland.
Salt air	0·7	4·5
Intermittent immersion	3·0	16·0
Total immersion (agitated liquid)	3·6	4·2
,, (still liquid)	1·0	1·12

The Distribution or Type of Attack.

In the laboratory tests on total immersion in still liquid and on alternate immersion and exposure, the ordinary Martin or Thomas steels showed a smooth surface hardly grooved at all. The attack was practically uniform. The test in salt mist exhibited fine pitting when the dimension of the droplets was of the order of 10 to 30 thousandths of a millimetre, provided that the spraying was intermittent, followed by periods of drying. On the contrary, if the drops were larger, for example, several tenths of a millimetre, or if the spraying were continued without drying, the attack showed itself in fairly large cavities or grooves, the distribution of the corrosion becoming fairly uniform.[1]

The depth of the pitting obtained in fine mist was about 0·10 to 0·12 millimetre per month for the standard Martin steel. A cupping test on a specimen showed a reduction of 15 per cent. in the cupping pressure; as the loss of weight was only 4·2 per cent., that reduction was to be attributed to the local corrosion.[2] The ductility of the steel, as shown by the stretching of the surface in that test, was not diminished by 1 month's exposure to corrosion; the pits, although very fine, were rounded in form and their notch-effect was not appreciable.

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[1] A. Portevin and E. Herzog, "Quelques conditions à réaliser dans les essais de corrosion des aciers en milieu humide," Comptes Rendus de l'Academie des Sciences, vol. 199 (1934), p. 789.

[2] E. Herzog and G. Chaudron, "Sur l'alteration des propriétés mécaniques des tôles de duralumin après corrosion par l'eau de mer," Comptes Rendus de l'Academie des Sciences, vol. 189 (1929), p. 1087.

Professor Portevin.

In the tests in the sea, pitting was in fact general. That result differed completely from the results obtained by laboratory tests, and research into the cause of the difference would deserve most careful study. The average depth of the pitting in 5 years in salt air was from 0·8 to 1·2 millimetre, in half-tide conditions from 0·45 to 2·5 millimetres, and in total-immersion tests from 0·5 to 2·8 millimetres.

Condition of the Surface, and Influence of Scale.

In the intermittent-immersion tests and in salt mist, the standard Martin steel, when covered with scale, was attacked 20 to 30 per cent. less than the same steel with the surface polished with emery paper (No. 00 Denis-Poulot). The corrosion by pitting was, however, more pronounced. At the end of 1 month's test in the presence of scale the pitting was as deep as 1 millimetre. With a polished surface in salt mist, however, the pitting was only 0·1 millimetre deep, and it was not measurable in the case of the intermittent-immersion tests. That observation was in agreement with the results of practical tests, which showed that the depth of pitting was doubled in the presence of scale. It should be noted that the favourable effect of small additions (1 to 5 per cent.) of nickel, chromium, silicon, etc., disappeared if the samples tested were covered with scale. With polished surfaces the addition of those elements gave a diminution in the general attack varying from 20 to 30 per cent., in accordance with the composition and conditions of attack.

The scale—iron (magnetite—iron) couple had been the object of study in the laboratories of the Pompey steelworks, where Mr. Herzog had introduced a new technique for measuring the potentials and currents generated by the couples formed between iron and its compounds with sulphur, phosphorus, and oxygen. The difference of potential between magnetite and iron in salt water was 1 volt, the current being 0·002 ampere per square centimetre. The formation of pitting was explained by the large size of the cathodic surfaces in relation to the small anodic surfaces which existed on steel covered with cracked or discontinuous scale. The magnetite, which acted as the cathode, was formed by reaction between the yellow rust (Fe_2O_3, H_2O) and ferrous hydrate (FeO, H_2O). According to the results obtained by Mr. Herzog, it was a semi-conductor, its resistance in a wet state being from 3 to 4 ohm-millimetres. The rust (Fe_2O_3, H_2O) was an insulator, but it assisted the oxidation of hydrogen at the cathodes, acting as a depolarizing agent.

Professor Portevin.

Effect of Temperature.

Professor Portevin and Mr. Herzog had found [1] that for extra-soft standard Martin steel in sea-water the temperature-coefficient between 20° and 40° C. was :—

(*a*) 0·20 to 0·30 in the tests of total immersion in calm liquid.

(*b*) 2·0 in the tests of alternate immersion and exposure. The considerable activity of the attack was due to the drying of the wet flakes in the air.

The practical results given in the Paper were in excellent agreement with their findings.

(*a*) In total immersion, corrosion differed little between the four testing stations, where the temperature varied considerably, from 28° to 33° C. at Colombo (Ceylon), to 10° to 12° C. at Halifax (Nova Scotia). In fact, the depth of general corrosion ranged only from 0·43 to 0·5 millimetre between the two testing stations.

(*b*) In specimens exposed to half-tide conditions and to salt air the influence of the temperature was very marked. The testing station at Colombo, situated in the hottest area, showed the greatest attack.

The pronounced variations found in the tests with specimens exposed to half-tide conditions and to salt air were probably also related to differences in the humidity, the rhythm of immersion and exposure, and the wind-velocity—factors of which the influence had been shown in laboratory tests—and other well-known factors, such as dusts and gases (sulphur dioxide, ammonia, or others pointed out by Dr. Vernon) would also play an important role.

Effect of the Composition of the Steel.

(*a*) *Nickel steels.*—Tests made in the laboratories at Pompey had given the following relative losses of weight :—

	Intermittent immersion.	Salt mist.
Standard Martin steel	100	100
2·3 per cent. Ni ; 0·08 per cent. C	50–65	75–70
5·6 ,, ,, ,, ,, ,, ,, ...	50	65–70
33·5 ,, ,, 0·17 per cent. C	4·4	3

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[1] See footnote (1), p. 634.

Those results applied for the conditions described by Professor Portevin and Mr. Herzog in 1934[1] for a temperature of 30° C. They were in agreement with previous studies carried out by Mr. Herzog in the laboratory of Mr. G. Chaudron at Lille, where the improvement in the intermittent-immersion tests was 40 per cent. for 2 per cent. nickel and 50 per cent. for 6 per cent. nickel.

Professor Portevin.

The tests of the Sea-Action Committee at four ports gave the following relative losses :—

	Immersion.	Half-tide conditions.	Salt air.	Pitting. (all three conditions.)
Standard steel (0·40 per cent. C)	100	100	100	100
3·7 per cent. Ni., 0·2–0·3 per cent. C	75	63	54	77*
36 per cent. Ni	46	20	1·1	33

* Results from three ports only.

The improvement varied with the testing station and the method of testing. Thus, in the salt air at Colombo it was only 20 per cent., but at Plymouth it was 86 per cent. with 3½ per cent. of nickel. The favourable effect of nickel was especially notable in reducing the tendency to pitting. The comparison between the laboratory and practical tests was sufficiently satisfactory for steels with small percentages of nickel. Laboratory tests showed greater improvement than practical tests in the case of larger percentages of nickel, especially for intermittent immersion (half-tide conditions).

(*b*) *Copper steels.*—Laboratory tests did not show any advantage with 0·5 or 1 per cent. of copper. Sometimes even a 10 to 20 per cent. more rapid attack took place than for steels without, or with only 0·2 to 0·3 per cent. of, copper.

On the other hand, the tests of the Sea-Action Committee in certain cases showed appreciable decreases in the corrosion of steel through the addition of copper. Table XLI (p. 638) gave the relative losses compared with those of a standard steel containing 0·4 per cent. carbon, which were taken as 100.

In connection with the tendency to pitting, copper steels behaved as ordinary steels ; sometimes they were even more pitted.

It would be seen from Table XLI that copper decreased the attack, especially in salt air, at all the testing stations with the exception of Colombo. At Auckland and Halifax copper steel still showed an advantage in the case of intermittent immersion (half-tide conditions). In total immersion the improvement from copper steel was not so marked. Summing up, it might be said that in salt air

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[1] See footnote (1), p. 634.

Professor Portevin.

TABLE XLI.—RELATIVE GENERAL CORROSION OF STEELS WITH COPPER, EXPRESSED AS PERCENTAGES OF CORROSION OF CARBON STEEL.

	Total immersion.	Half-tide conditions.	Salt air.
(1) *Halifax.*			
D—standard with 0·4 per cent. carbon	100	100	100
G—soft steel with 0·5 per cent. copper	95	44·5	65
H—soft steel with 2 per cent. copper	97	50	47
(2) *Auckland.*			
D—	100	100	100
G—	84	61	39
H—	82	100	26
(3) *Plymouth.*			
D—	100	100	100
G—	87	98	64
H—	90	77	36
(4) *Colombo.*			
D—	100	100	100
G—	73	102	95
H—	87	114	83

the addition of 0·5 to 2 per cent. of copper gave better results than for immersion in sea-water. With 0·2 to 0·3 per cent. of copper there was no record of any decrease of corrosion.

All experimenters were in agreement that in sulphurous atmospheres a copper-content of 0·3 to 0·4 per cent. definitely decreased the attack. Atmospheric-corrosion tests carried out in the neighbourhood of the blast-furnaces of Pompey had in fact shown 25 to 35 per cent. decrease in corrosion (after 1 year of exposure) with the addition of 0·3 to 0·5 per cent. of copper or 0·5 per cent. of copper with 0·5 per cent. of chromium. The tendency to pitting was very pronounced, being probably aggravated by the large quantities of dust. The local attack reached 0·5 millimetre in depth after 1 year's exposure whether the steel contained copper or not. The general attack in the tests was of the order of 0·025 millimetre only, so that the problem of pitting was the more important.

(*c*) *Chromium steels.*—Tests given in the Paper showed that the use of steels with a high percentage of chromium (13 per cent., or 18 per cent. with 8 per cent. nickel) was specially to be recommended for protection against corrosion in salt air, but was not at all satisfactory for immersion in salt water. The liability to pitting of such steels in contact with salt water was particularly marked, and was not reduced by polishing. A higher chromium content (12 to 14 per cent.) reduced the general attack in salt air to 4 to 5 per cent. of the amounts for ordinary steel, though, as the Authors pointed

Professor Portevin.

out, the rusty appearance usually gave a wrong impression ; pitting was slight, even insignificant. Even with small additions of chromium the attack in salt water was diminished.

For comparison the results of the laboratory tests carried out at Pompey were detailed in Table XLII, the results being expressed as the loss of weight relative to that of the standard steel (of the composition given previously) which was taken as 100.

TABLE XLII.

	Tests in saline mist at 3½ months.	Inter-mittent-immersion tests at 2½ months.	Depth of pitting with intermittent-immersion tests.
Steel with 1 per cent. Cr.	85	85/80	0·05 to 0·1 mm.
,, 2 ,, ...	74/70	50/55	
,, 3 ,, ...	60/55	45/50	
,, 4½ ,, ...	50/45	32/35	0·3 to 0·4 mm.
,, 13 ,, ...	1·9	2·3	0·2 to 0·3 mm.
,, 18 ,, and 8 per cent. nickel	0·3	0	—
Standard steel	100	100	—

Those tests showed the favourable action of small additions of chromium.

Some previous studies (by Dr. Speller, Messrs. Herzog and Chaudron, and Professor Portevin) had established a reduction in the corrosion of steel in saline solutions by the addition of 2 to 3 per cent. of chromium. The tendency to pitting in intermittent-immersion tests was small with 2 to 3 per cent. but very evident with 4 to 5 per cent. of chromium. In salt mist the tendency to pitting was not more pronounced than with ordinary steels. The difference between laboratory tests and practical tests was especially marked in the case of the steels with 13 per cent. of chromium and with 18 per cent. of chromium and 8 per cent. of nickel.

The general corrosion of chromium steels was insignificant in laboratory tests ; in practical conditions it was fairly high when in contact with sea-water. The conditions of use had a large effect upon their resistance to corrosion. The Authors indicated that sheets of 18/8 chromium-nickel steel had a high resistance in clean water in movement. It would seem, therefore, that good aeration was an essential condition for the stability of the protecting film of chromium steels. If parts of that film should disappear through lack of oxygen (due, for example, to organisms) or by any deposit preventing access of the air, the attack would proceed rapidly, and would result in a tendency to pitting at those places.

Professor Portevin.

(*d*) *Ordinary steels and rolled irons.*—According to the results of the Authors, the composition of the various materials played only a secondary part in total-immersion tests, the composition and temperature of the sea-water being of greater importance. In salt air the temperature of the testing station was the dominant factor. The coldest climate (Halifax) gave the minimum and the hottest (Colombo) the maximum attack.

For specimens immersed under half-tide conditions the influences were more complicated; it was not yet clear what factors came into play. It would appear that the differing periods of immersion and exposure and the height of the tides were concerned. At Halifax the action of molluscs was marked by an inclination to pitting, but, in general, the formation of pitting showed such anomalies that it defied interpretation.

For comparison with those conclusions, the following results had been obtained at the Pompey laboratory. The rhythm of immersion and exposure had an influence on the attack; Table XLIII gave some new figures confirming those published in 1934.[1] The composition of steel would be seen to be of importance.

TABLE XLIII.—DURATION OF IMMERSION EQUAL TO THAT OF EXPOSURE—TEMPERATURE OF 30° C.—ATMOSPHERE CONTINUALLY AGITATED.

	Loss in grams per square metre in 15 days: Rhythm of			Difference: per cent.
	10 seconds.	30 minutes.	6 hours.	
Standard Martin steel . . .	278	285	375	33
Steel with—				
2·3 per cent. Cr	80	130	153	90
1·3 ,, Al				

The importance should be emphasized of two other important factors for the aeration and the renewing of oxygen; namely, the stirring-up of the solution and the speed of the wind. The stirring-up of the solution increased the speed of corrosion; for example, at 30° C. the standard steel lost:—

168	grams per square metre	after 30 days	with	20 stirs per minute.
240	,,	,,	,,	60 ,,
60–70	,,	,,	,,	without stirring.

The total corrosion diminished by 20 to 25 per cent. with rapid drying of the test-piece after each immersion. On the other hand, rapid drying increased the tendency to pitting; a pitting of 0·10 to

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[1] See footnote (1), p. 634.

0·15 millimetre in depth was obtained with standard steel after 30 days of intermittent tests, whereas with slow drying it was attacked uniformly. **Professor Portevin.**

In natural conditions, currents and winds certainly played a considerable part. The resistivity of the products of corrosion varied greatly with the degree of humidity. According to Mr. Herzog, dry rust had a resistivity of 200,000 ohm-centimetres, whilst wet rust had only 1,000 ohm-centimetres. The hygroscopic properties of the products of corrosion had to be considered, as had been shown by Mr. J. C. Hudson.[1]

Laboratory tests in sea-water did not show appreciable differences between Martin and Thomas steels and Armco iron. A high sulphur-content (0·18 per cent.) did not increase the attack; 0·3 per cent. of phosphorus lessened the attack by 20 to 30 per cent. (Table XLIV).

TABLE XLIV.—TESTS CARRIED OUT AT POMPEY ON THE CORROSION OF ORDINARY STEELS: LOSS OF WEIGHT IN GRAMS PER SQUARE METRE.

Steel.	Essential elements:			Salt mist, 30 days.	Intermittent immersion, 20 days.
	C.	P.	S.		
Thomas, before addition of ferro-manganese . . .	0·03	0·08	0·036	197·5	349
Thomas, after addition of ferro-manganese, and poured into ladle . .	0·04	0·06	0·034	194·5	341
Standard Martin . . .	0·08	0·02	0·018	199·0	309
Armco iron	0·02	0·014	0·009	202·0	331
Cutting steel	0·09	0·06	0·176	197·0	328
Steel for screws	0·05	0·35	0·032	181·0	237

In an acid medium sulphur and phosphorus considerably increased the attack, which was increased ten times by a rise from 0·02 to 0·20 per cent. The study of couples showed that iron sulphide and iron phosphide (26·1 per cent. P)[2] gave intense currents of 0·12 to 0·16 ampere per square centimetre in a sulphurous medium, and weak currents of 0·001 to 0·004 ampere per square centimetre with a neutral normal solution of KCl, in accordance with a recent research in the Pompey laboratory.[3] The opinion of Skapski and Chyzewski that manganese sulphide would be more active than iron sulphide

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[1] J. C. Hudson, "Atmospheric Corrosion of Metals," Third (Experimental) Report to the Atmospheric Corrosion Research Committee, Trans. Far. Soc., vol. 25 (1929), pp. 177 and 475.

[2] U. R. Evans and T. P. Hoar, "The Velocity of Corrosion from the Electro-chemical Standpoint, Part II," Proc. Roy. Soc., vol. 137 (1932), p. 343.

[3] Footnote 1, p. 634.

Professor Portevin.

appeared to be deduced from electro-chemical measurements, which were liable to error on account of bad contacts at their non-metallic electrodes; that appeared to be inevitable with the conditions used when testing. It was for that reason that they found very weak currents (10^{-6} ampere) with iron sulphide, which was a good conductor. It was rather the beginning of corrosion which would be increased by the sulphides, as Messrs. Mears and Evans [1] had indicated.

The Authors' tests at Birmingham showed that sulphides increased atmospheric corrosion. That was in agreement with theoretical investigations, which suggested that iron sulphide ought to increase the attack in an acid atmosphere as found at Birmingham.

(*e*) *Effect of other additional elements.*—In addition to the elements referred to, there are others which, when incorporated with steel, furnish interesting results in connection with salt corrosion, at any rate in laboratory tests. In particular, the addition of aluminium, silicon, and especially the association of chromium with silicon and chromium with aluminium were of interest, and had given the following results :—

	Relative losses of weight.	
	Alternating tests.	Salt mist.
Standard Martin steel	100	100
Steel with 1·2 per cent. Al	60	75
,, 2·6 ,, ,,	35	45–50
,, 3·2 ,, ,,	25–30	35–40
,, 12·0 ,, ,,	5	8
,, 2·2 ,, Si	80	85
,, 3·6 ,, ,,	70	75
,, (2+1) per cent. Cr+Si	40–45	50–60
,, (2+1) ,, Cr+Al	25–30	30–40

Messrs. Sykes and Bampfylde [2] had given the results of tests in salt mist of a series of aluminium steels containing up to 50 per cent. of aluminium. The improvement was clear, but difficult to compare with Professor Portevin's results, in view of the fact that they had used various terms of comparison, sometimes steel with

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[1] R. B. Mears and U. R. Evans, "The 'Probability' of Corrosion," Trans. Far. Soc., vol. 31 (1935), p. 527.

[2] C. Sykes and J. W. Bampfylde, "The Physical Properties of Iron-Aluminium Alloys," Journal Iron and Steel Inst., vol. cxxx (1934, Part II), p. 389.

Professor Portevin.

0·8 per cent. of aluminium, at other times with 1·12 per cent. of aluminium, and again with 5 per cent. of nickel.

Dr. Speller.

Dr. F. N. Speller, of Pittsburgh, observed that some significant data on the Delhi Iron Pillar were presented on p. 101, which confirmed the conclusion that he and others had previously expressed; namely, that that unique example of ancient craftsmanship in wrought iron possessed no inherent qualities that would make it more durable than modern wrought iron. Dr. Speller had examined and tested a small sample of Egyptian wrought iron, with the same results; it was a clasp taken from an Egyptian monument said to be 2,000 years old, and contained some copper. When exposed, together with modern wrought iron and open-hearth steel, to outdoor atmosphere, humid atmosphere, and aerated hot water, it showed the same behaviour as modern copper-bearing iron.

A number of forged iron armour-scales, dating back to A.D. 240, had recently been obtained. They were unearthed at Dura-Europos, on the river Euphrates, by the Yale University Archæological Expedition in 1929, and most of them were only slightly corroded. They measured about 3 inches by 1¾ inch by 0·022 inch thick. Test-pieces 1 inch by 1¼ inch were cut, surface oxides removed, and the specimens insulated and suspended in Pittsburgh City water heated to 160° F. Eight specimens each of three modern wrought irons and eight each of three basic open-hearth steels, 0·14 per cent. carbon, of the same dimensions, were also included. The specimens tested had the following percentage composition:—

	C.	Mn.	S.	P.	Si.	Cu.
Dura-Europos*	0·09	0·01	0·007	0·114	0·013	Nil
Wrought-Iron .	0·03	0·06–0·07	0·019–0·021	0·153–0·160	0·20–0·25	0·020–0·024
Steel .	0·13–0·14	0·54–0·55	0·027–0·028	0·006–0·008	0·20–0·23	0·012–0·016

* The Dura-Europos sample was free from Ni and Cr.

After 3 months in the water some of the ancient iron samples were perforated, so the test was discontinued and the specimens weighed. Stated as average penetration in inches per year, the loss in the three types of metal tested was:—

Steel	0·0140
Modern wrought iron	0·0143
Dura-Europos iron	0·0137

The ancient specimens of iron were much more heterogeneous in structure than modern wrought iron, but showed no essential

Dr. Speller.

difference in durability. When cleaned and exposed to the atmosphere, they rusted rapidly and lost far more in 3 months in water of average domestic quality, as indicated above, than they had suffered in 1,700 years of exposure to the dry conditions where they were found. Further details in regard to the metal had been given elsewhere.[1] The quantitative tests described substantiated the conclusions expressed by Sir Robert Hadfield and other investigators that the remarkable durability of certain specimens of ancient iron was due to their favourable environment, and not to any superior inherent durability.

More recent tests, conducted by the American Society for Testing Materials in various waters, and by the National Bureau of Standards in forty-seven different types of American soils, indicated no material difference in corrosion-resistance between wrought iron and the various grades of commercial pure irons or steels under those conditions. The differences in life of those metals in service under such conditions had evidently been controlled mainly by factors external to the metal. However, it was found recently that certain low-alloy-steels designed to form more resistant films in certain kinds of water or air showed superior durability.

Colonel Trinham.

Colonel J. S. Trinham observed that the Paper was of special interest to manufacturers and users of genuine wrought iron made by the puddling process. There were still nineteen or twenty firms in Britain making good wrought iron in considerable quantities, and that iron would give results in service as satisfactory as those mentioned in the Paper. The 36-per-cent. nickel steel and the high-chromium stainless steels, though of high corrosion-resistance, were naturally beyond practical comparison with wrought iron, as they were commercially expensive, but what might be called the "general commercial mild steel" was in a comparable category.

The data given by the Authors relative to the distinctly different types of corrosive attack found to have occurred during the long-duration tests of iron and steel samples in conditions of aerial, half-tide and total-immersion attack at the four posts geographically wide apart were of particular interest. They had made it possible to compare the behaviour of wrought iron, ingot iron, and mild steels in their relative resistance to corrosion, general and local, more closely and more satisfactorily than had hitherto been practicable. From those data he had tabulated the estimated mean depths of general corrosion, waste, and pitting produced so as to indicate the resistance to corrosion of the ingot iron, mild steels, and copper steels relatively to that of wrought iron. In Table XLV the relative

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[1] *Metals and Alloys*, August, 1936. [New York.]

resistances, taking that of the wrought iron as 100, were estimated on the basis that the depths of corrosion attack were inversely proportional to the resistance to corrosion possessed by the corroded metal. Colonel Trinham.

TABLE XLV.—MEAN DEPTHS OF GENERAL WASTAGE AND OF DEEPEST PITS: AVERAGES FOR ALL FOUR PORTS.

Material.	General wastage: millimetres.	Relative resistance.	Maximum depth of pitting: millimetres.	Relative resistance.
Wrought iron N	0·499	100·0	1·16	100·0
Swedish charcoal iron P . . .	0·573	87·1	1·35	86·2
Ingot iron M	0·664	75·2	1·62	71·5
Mild steel B, 0·21 per cent. carbon	0·617	80·8	1·91	61·0
Mild steel F, 0·24 ,, ,,	0·607	83·0	2·19	53·0
Mild steel E, 0·34 ,, ,,	0·630	79·4	2·10	55·2
Steel D, 0·40 ,, ,,	0·599	83·3	2·16	53·8
Copper steel G, 0·21 per cent. carbon with 0·63 per cent. copper .	0·499	100·0	2·18	53·2
Copper steel H, 0·22 per cent. carbon with 2·19 per cent. copper .	0·472	105·3	1·96	59·2

The authoritative results given in the Paper, and arranged in comparative form in Table XLV, corroborated previous findings to the effect that genuine puddled wrought iron resisted ordinary corrosive attack more satisfactorily than mild steel, ingot iron, or Swedish iron, and was much less prone to the far more serious "pitting" action experienced in both underground pipe service and marine practice. The Authors had duly recognized the seriousness of the pitting type of corrosion, and had shown in Table XXIV (p. 88) that even in the stainless type of chromium steel the deepest pits had a mean depth of 1·74 millimetre in the averaged tests (aerial, half-tide, and total immersion) whilst in the wrought iron (Table XIV, p. 78) the mean depth was only 1·16 millimetre. In the case of the copper steels it would be noted that, whilst the depth of the general corrosion wastage approximated to that of wrought iron, the depth of the average maximum pitting was from 69 to 88 per cent. more than that of wrought iron. It was interesting to read that "the Sea-Action Committee's research had clearly shown that, for conditions such as those of total immersion in the sea, alloy steels, while in general showing a superiority over plain carbon steels, are not so effective in reducing wastage as they are under half-tide or aerial conditions."

Table XXXVII (p. 106), given by Mr. Wilson, did not bring out the superior corrosion-resisting properties of wrought iron, as ingot iron, Swedish iron, and wrought iron were grouped together, giving the relative corrosion figure of 112, whilst the adjacent figure for steel

Colonel Trinham.

was also 112. Separately considered, the wrought iron had shown less general wastage and less pitting than the other irons with which it was grouped.

If, as shown in the foregoing Table, the depth of the local pitting and of the general corrosion wastage was less in wrought iron than in ingot iron or mild steels of the plain carbon type, there would have to be, as a result of the authoritative findings of the Institution's Sea-Action Committee's research, a recognition of the fact that genuine wrought iron retained its character of resisting sea-water corrosion in the widely different conditions operating in the four ports and for long periods. Moreover, the tests proved that wrought iron had withstood such corrosive attack more satisfactorily than ingot iron or mild steels. As the wrought-iron samples were descaled before the tests, further tests might show wrought iron in a still better light.

Dr. Tutin.

Dr. JOHN TUTIN observed that such a comprehensive Paper would be of great interest and value to the shipbuilding and shipping industries, particularly as ships represented a very large proportion of the world tonnage of steel exposed to sea-action. Even an ordinary tramp ship of 9,000 tons deadweight might carry as much as 200 tons of steel in excess of that required for normal structural purposes, solely to provide a margin of material available for destruction by the various processes which were detailed in the Paper. For that burden the shipowner had to pay not only the extra first cost of material and labour (roughly £3,000 for the small vessel in question), but also the annual cost of propelling 200 tons of otherwise useless material, which also robbed him of the freight earnings on 200 tons of cargo for the entire life of the ship. The corrosion problem, therefore, justified constant attention by naval architects if the shipowners' expenses in that direction were to be mitigated, and the present research embodied the results of observations on such a wide range of specimens, under such a wide range of conditions, that it ranked as one of the most important single contributions ever made to the subject. Attention had been drawn to the progress of the research in a Paper entitled "The Corrosion Problems of the Naval Architect,"[1] but, unfortunately, in that Paper the Institution of Civil Engineers' programme of research had been referred to as "falling short of the ideal" in several respects, so that it might carry less conviction in shipbuilding circles than it was entitled to. For example, it was stated that "duplicate specimens were not exposed." From the Paper now under discussion it was seen that not only duplicate but triplicate specimens were provided for the whole of

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[1] W. H. Hatfield, "The Corrosion Problems of the Naval Architect," Trans. Inst. N.A., vol. lxxvii (1935), p. 158.

the main series of tests. Furthermore, it had been stated that the effect of scale on the specimens had not been properly taken into account, particularly for the chromium steels. It was, however, evident from the present Paper that throughout the tests adequate provision had in fact been made in that respect. Dr. Tutin.

Mr. H. E. YERBURY was gratified to observe that the line of demarcation originally defined between chemical and electrical processes was nearly broken down. In his opinion the subject of corrosion in general could better be understood when electrical processes entirely supplanted what was called "chemical action." Nothing in the Paper falsified the views which he had previously expressed.[1] From a practical view-point, there was no doubt that corrosion of ferrous metals had increased greatly since steel—as used in commercial work—had replaced iron. All commercial steels, whether Siemens or Bessemer, had manganese added for the sake of good working under the press, and that greatly increased their tendency to corrode. Unfortunately alloy steels were too expensive for heavy engineering work, with the result that more attention was being paid to the protection of structures from corrosive influences. The simple fact remained that, whatever medium was employed as a coating, if it remained impervious to moisture (an electrolyte) no corrosion could take place. Mr. Yerbury.

The AUTHORS, in reply to the Correspondence, observed that both it and the Discussion had shown the high value which was placed by other workers in the field of corrosion on the data so far provided by the extensive researches of the Sea-Action Committee regarding the corrosion of iron and steel. That, they felt sure, would be taken by the members of the Committee as some reward for their labours of the past 20 years. The Authors.

They were pleased to find that their Paper had evoked such a wide discussion, in which many of the most prominent authorities on corrosion had taken part. The contributions from abroad were especially welcome; giving as they did authoritative and up-to-date accounts of the progress in the subject being made in their respective countries, they would be found particularly helpful.

Several contributors had taken the opportunity afforded of comparing the results of their own laboratory tests with those of practical exposure-tests, and it might be said that on the whole the degree of agreement was most encouraging. Not many years ago such agree-

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[1] "The Effect of Air and Water on Materials used in Engineering Work," Supplement to vol. 57, Journ. I.E.E. (1919), p. 118. "The Electrolytic Action of Return Currents in Electric Tramways on Gas- and Water-Mains; and the Best Means of Providing against Electrical Disturbances," Min. Proc. Inst. C.E., vol. cc (1914–15, Part II), p. 62.

The Authors. ment was uncommon, for two reasons: firstly, that authentic data on corrosion under practical conditions for an extended period, such as those now provided by the Committee, were scarce; secondly, that the same effective control was not then exercised in laboratory tests as was now the case. It would appear from the degree of agreement now obtained that the effects of at any rate the principal factors operating, including temperature and oxygen-supply, were becoming better understood, and that the field for further investigation was being narrowed to those cases where important differences occurred between the results of laboratory and practical exposure-tests. Although therefore, as Dr. Desch pointed out, the complexity of the process of corrosion was becoming more apparent, the Authors did not take the rather pessimistic view of Mr. Bennett that the causes of corrosion appeared to be more elusive than ever. To such a degree, in fact, had knowledge advanced that in the planning of subsequent researches of the kind undertaken by the Sea-Action Committee it had been found necessary to take account of many more factors, both in the manufacture of the test material and in the environment during exposure, as explained by Dr. Hatfield with regard to the researches being made by the Joint Committee of the Iron and Steel Institute and the British Iron and Steel Federation.

The special attention paid by the Paper to the particularly vicious form of pitting corrosion suffered by the high-chromium steels in sea-water had brought useful comment and suggestions from a number of correspondents. The Authors agreed with Dr. Hatfield that the 18—8 chromium-nickel type of steel might behave excellently in sea-water where oxygen shielding was not a serious factor, but unfortunately such conditions could not be relied upon except in rare cases, especially with stationary structures. Local restriction of oxygen-supply might be caused in many ways by natural agencies such as molluscs and other marine growths, or by the settling of any particles in suspension on to the surface of the steel. Also, those immersed steel members which were necessarily in an upright position were not so accessible to the aerial oxygen at their lower as at their upper portions. Even in the most favourable cases, to ensure uniform supply of oxygen the avoidance of corners and crevices was involved, thus putting serious restrictions on design.

There seemed to be much evidence in favour of the explanation of the serious form of pitting put forward by Dr. Evans and based on actual measurements of anodic voltage and current. Vigorous and localized electrical action did seem to be at work. The protective film which was characteristic of the modern "stainless steels," and which gave them such excellent and useful properties for many purposes, was an armour which was vulnerable under

The Authors.

certain forms of attack, namely, where anodic conditions were set up in the presence of a suitable electrolyte, such as sea-water. All explanations pointed to chromium as being the basis of that protective film, and the Authors' suggestion that the comparatively low chromium-content of specimen No. 3765 (chromium 10 per cent., nickel 20 per cent., tungsten 2 per cent., copper 2 per cent.) helped to account for its superior behaviour as regards pitting in the tests conducted in the Gulf of Paris was well borne out by the results of other exposure-tests. Passivity of the surface caused by pickling, as suggested by Dr. Hatfield, could not be expected to operate for any length of time under such conditions ; the chief effect of pickling was to be attributed to the uniformity of surface which it effected by the removal of all scale.

The appearance of the chromium and nickel-chromium " stainless " steels at the onset of pitting had often given a strong impression that the pits were formed at centres provided by non-metallic inclusions, but that impression might now be finally dismissed. Apart from the fact that such steels were among the cleanest made, close investigation of cases of pitting in their initial stages had been made in the Authors' laboratories, and in no case had any connection with inclusions been established.

With the suggestion of Dr. Desch that the mechanism of pitting in the highly-alloyed steels should be further studied, the Authors, who had experimental work in hand on that question, heartily agreed. Regarding the adhesion of barnacles, experience in the Committee's researches seemed to show that it was not materially influenced by the composition of the steel.

The possibility of biological action by molluscs promoting corrosion had been mentioned both in the Committee's reports and by the Authors ; present evidence seemed to show that it was not an important factor in most cases. Dr. von Wolzogen Kühr called attention, however, to the importance of bacterial action in promoting corrosion in certain cases where attack would not ordinarily be expected, owing to the exclusion of atmospheric oxygen. The Authors understood that such " anaerobic " corrosion, although occurring more particularly on iron and steel buried in soil, had been associated also with the attack on piles of piers where embedded in the mud of river-beds. Sulphide of iron was one of the products of the bacterial action, and the interesting information provided by Drs. R. B. Mears and U. R. Evans and referred to by Professor Portevin as to the part played by that compound in corrosion-processes might therefore be usefully studied in that connection.

With regard to the rather thorny subject of the relative merits of wrought iron and ordinary steel, the Committee's programme

The Authors. intentionally included specimens for the purpose of providing reliable comparative evidence on that question. While wrought iron of good quality was shown to behave rather better than ordinary steels, the superiority was not very pronounced, and, further, it could not be hoped by such means to set up a court of appeal, to which protagonists of steel or iron could refer in settlement of their friendly differences! It was shown that the relative performance depended on environment, and the variety of conditions under which those materials were actually employed was too wide for any one research to cover. Nevertheless, the practical evidence provided on the question by Mr. M. F-G. Wilson,[1] Dr. Speller, Colonel Trinham, and Mr. Yerbury would be read with interest.

It was probably true that, as mentioned by Dr. Desch, wrought iron owed something to its texture or fibrous character resulting from slag. The characteristic appearance of corroded wrought iron certainly seemed to indicate a directive influence of the slag on the corrosion. Texture as well as chemical composition was in many cases an important factor in the behaviour of metals, and the Authors were reminded of Dr. Desch's instructive lecture on that subject,[2] which was well worth studying.

With reference to Mr. Yerbury's remarks in regard to the possible influence of manganese in comparatively small percentages (up to about 1 per cent.), researches by many authorities did not seem to show it to have any material influence on the corrosion of ordinary steel, or, at any rate, to be of such prominence as to prove the determining factor in its characteristics as compared with those of wrought iron.

In reply to Professor Honda and Dr. Endo, the Authors were unable to make any suggestions in explanation of the contrasting behaviour of iron and steel with regard to pitting under half-tide conditions at Colombo, other than those given in the Paper.

It was pointed out by Professor Honda and Dr. Endo that 0·35 per cent. was the limit of the solubility of copper in iron at ordinary temperature, and the inference might possibly be drawn that no more than that amount could usefully be added. It should, however, be noted that that percentage applied to conditions of complete equilibrium in the steel, and that ordinarily more than that amount would be found in solution. Even, therefore, if solution of the copper were a necessity in order that it should improve resistance to corrosion (which was by no means established), there was no anomaly in the fact that larger percentages than 0·35 had been found to be

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[1] Discussion, p. 104 (June).

[2] "Texture and Chemical Resistance," Trans. Inst. Chemical Engineers, vol. 12 (1934), p. 198.

advantageous in the Committee's researches. It had recently been stated that a proportion of the wagons being ordered by the London, Midland, and Scottish Railway and the London and North-Eastern Railway would be built from steel containing 0·25 to 0·45 per cent. of copper. It would be particularly interesting to learn in due course how they behaved in service. The Authors.

Special attention should be called to the useful practical information placed at the disposal of engineers by Dr. Footner regarding experience with pitting, and methods of pickling to remove scale.

The Authors were indebted to Dr. Tutin for his remarks on the thoroughness with which the Committee's researches had been planned, and particularly on the fact which those studying the subject should bear specially in mind, namely, that adequate provision had been made in the way of duplication of specimens and in the inclusion of specimens for the investigation of the effect of scale.

The interesting information which he gave regarding corrosion and its economic bearing on ship-construction was an indication of the importance of the subject.

One of the Authors showed [1] in 1922 that the annual losses from corrosion, at a conservative estimate, amounted to the large sum of £700,000,000. Whilst the researches by the Sea-Action Committee and by the Joint Corrosion Committee of the Iron and Steel Institute and the British Iron and Steel Federation—in which two Committees, with 43 individual members, were at work—and also other organizations throughout the world, had not as yet solved the problem completely, yet the increased knowledge brought to bear was certain to prove of the greatest value in its economic results. Whilst the labours of the Sea-Action Committee were largely drawing to a close, those of the Iron and Steel Institute continued, and all would wish every success to their efforts. If proof were needed of the widespread importance of the subject, the many valuable contributions to the Discussion and Correspondence from Great Britain, the United States, France, Japan and Holland, would provide it in full.

In conclusion, the Authors would like to express their thanks to the contributors for their appreciative remarks in the Paper, and especially to Dr. Newton Friend, whose kind remarks regarding their very friendly relations in the work allotted to them in the Committee's Research programme were most welcome and were heartily reciprocated.

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[1] Sir Robert Hadfield, "Corrosion of Ferrous Metals," Minutes of Proceedings Inst. C.E., vol. ccxiv (1921–22), p. 83.