Discussion.

Sir Robert Hadfield.

Sir **Robert Hadfield** said that the Paper had been prepared some considerable time ago, and in the period which had since elapsed some progress had occurred which the Authors would have liked to have taken into account, but that had not been possible. He would like to say how indebted he had been for the very kind help and encouragement given to him, during his 20 years' membership of the Sea-Action Committee. He would also like to express his indebtedness to his colleague, Mr. S. A. Main, who had rendered him yeoman service with the preparation of the present Paper, and to the many willing helpers in his firm's research department in Sheffield. Next, he would refer especially to the late Sir John Wolfe Barry, Past-President Inst. C.E.; one of the things Sir John had wanted to know was whether the 12- to 14-per-cent. chromium steel could safely be used for cutlery. Sir John had heard that owing to the formation of certain oxides the steel was liable to be poisonous. Sir Robert Hadfield had given him the assurance that, so far as was then known, he had no need to fear, and had, at Sir John's request, written him a letter to that effect. The best answer on that point was that millions of cutlery-articles made from chromium steel were now in daily use throughout the world, and great credit was due to the manufacturers of those special steels. He would also like to refer to the Department of Scientific and Industrial Research; the sea-water corrosion-research could not have been initiated and carried on but for the timely assistance given by the Department, which had given £10,600. A further sum of £11,700 had been given privately, making a grand total of £22,300. Those donations had materially assisted the work, and most important additions to the knowledge of the subject had been made. He was confident that the research would be of the greatest use to the world. He did not wish to compare the work of the Sea-Action Committee with that of other Committees, which were also doing splendid work, but it had done work in certain directions not included in other researches.

One of the first of the various ferrous materials to be examined by the Committee was wrought iron, one of the commercial materials approaching most nearly to pure iron. He was able that evening to exhibit what was probably the most remarkable specimen of wrought iron in the world, from that wonderful example of the work of the metallurgist of about A.D. 300, the Delhi Iron Pillar; that pillar dated from some 1,600 years before the introduction of the modern forge, steam hammer or hydraulic press. There were all

Sir Robert Hadfield.

kinds of strange things connected with that pillar, and many which were not understood. In view of the early date at which it was produced, it was especially remarkable on account of its extraordinary size and weight, being 23 feet 8 inches in length and about 6 tons in weight. The special point, however, was not its size and weight, for there were still larger specimens in India dating from a later period, but that everyone who had in any way examined or dealt with it had been baffled to know how a pillar of such considerable size and weight had been manufactured. It had gained the admiration of the world by its beauty of form and by its extraordinary resistance to corrosion, the latter being probably largely due to the dryness and cleanliness of the atmosphere in which it was located. The legend that its composition was of some special nature which would resist corrosion was not correct, because it was, in fact, made of what was known to-day as wrought iron. In 1912 he was fortunate enough to be entrusted with about 2 ounces of material taken from the pillar, through the kind help of Sir John Marshall, then Director of Archæology in India. From that specimen he had been able to obtain interesting analytical and other data, including chemical composition, hardness and microstructure. The actual composition of the pillar was shown to be :—

Carbon, 0·080 per cent.; silicon, 0·046 per cent.; sulphur, 0·006 per cent.; phosphorus, 0·114 per cent.; manganese, nil; iron, 99·72 per cent.; total, 99·966 per cent.

The Brinell ball hardness-number was 188, and the specific gravity 7·81. Although this enabled the material of which the pillar was composed to be identified, the method of manufacture of the pillar was still unknown. Its largest diameter was 16½ inches, tapering to the smallest diameter of about 12½ inches at a height of 22 feet above the ground. The bulbous underground portion of the pillar was no less than 28 inches in diameter by 20 inches in depth, and was anchored to the ground by crossbars which were also of wrought iron.

The specimens from the pillar sent to him were tested in the ordinary way for resistance to corrosion, and a small sample weighing a few grams was left in the laboratory atmosphere overnight; the next morning it was found covered with red rust, as any other wrought-iron specimen would have been. He could definitely state that the wrought iron of which the pillar was made had no qualities different from those possessed by ordinary wrought iron, such as the modern specimens used in the research dealt with in the Paper. There was thus obtained an exact comparison between the wrought iron of to-day and that made 1,600 years ago. There was another point of particular interest which he had elucidated. Included amongst, Sir Robert Hadfield.

and attached to, the specimens received from Sir John Marshall were scales taken from the surface of the pillar at its base, and described as "rust-scales." Whilst not wishing to throw any doubt on that description—the scales in question were undoubtedly from the pillar—it was not clear whether they were produced by the heat-treatment of the pillar for forging-purposes or were actual rust from contact with the ground, which was occasionally damp. The present belief was that they were heat-treatment scales. At the present time an X-ray examination was proceeding to ascertain their true nature. There were several other extraordinary facts which were being discovered with regard to the pillar, and it was hoped that they would shortly be embodied in a Paper on the subject.

Sir Robert Hadfield then showed on the epidiascope (for the loan of which he expressed his gratitude to Sir William Bragg, and for the operation of which he thanked Mr. W. J. Green, Sir William's assistant), six specimens, including three from the Delhi Iron Pillar.

It might be asked what was the use of the research, and he would therefore like to give a practical instance of its utility. About 10 or 12 years ago, when the research had been in progress for some time, he decided to try to use in a practical way the information which had been gained, and a large number of different kinds of iron and steel sheets were made into roofing. The atmosphere at Sheffield contained a great deal of smoke, some of which was sulphurous. His firm had something like 60 acres of buildings, and consequently they found the cost of replacing roof-sheeting to be considerable. They put down four special specimens, including some very pure iron and steel and also steel containing 0·35 per cent. of copper. The tests had not yet been completely finished, but it would appear that the copper steel was easily the best; he did not claim that as a novelty, because in America a large number of tests had been carried out, and no doubt such tests had been made elsewhere in England, but roofing sheets of that composition would, he believed, prove highly beneficial to his firm. When further buildings were erected, as was anticipated, a large number of sheets would be required, and he thought that steel containing 0·35 per cent. of copper would undoubtedly be specified. He did not infer that that copper steel would be of use in resisting corrosion due to sea-water, but the Sea-Action Committee's tests included an aerial test and the above results therefore came within the scope of the research. He mentioned that fact to show that, as a result of the research work which had been done, his own firm had benefited, as could any other firm which cared to look into the matter, by saving money in the cost of roofing-sheets by using a 0·35-per-cent. copper steel.

Mr. Main.

Mr. S. A. **Main** remarked that, for the most complete appreciation

Mr. Main. of the work which had been done by the Committee of The Institution, it was necessary to refer to the reports of the Committee; only in that way could the details be studied. It would be found in the Paper that the bars which had had their scale removed before exposure were referred to as "scaled bars," which was the ordinary term used in such circumstances by the engineer; in metallurgical circles, however, it was customary to refer to such bars as "descaled." If that point were appreciated, no confusion should arise in the discussion.

He would also like to say that his examination of the results had impressed him very much with the efficiency of the research as a whole. Each specimen had been chosen to answer a particular point, and every one of those points was something that the engineer wanted to know; for instance, the influence of climate and method of exposure, and the effect of rivets and bolts, had all been investigated. He thought it could be said that no single bar in the research had failed to yield the result that was expected of it. That was a very great thing to say of such a big research, and it might be expected to be true for the remaining bars, which had yet to be taken out after 15 years' exposure.

Mr. Wilson. Mr. M. F-G. Wilson remarked that he was especially interested in the Paper, as it dealt with a section of the investigations of the Sea-Action Committee (of which he was an original member, and of which for some years he had been Chairman), that had been carried on for many years, and it also gave him an opportunity, which he was very glad to take, of thanking Sir Robert Hadfield for the very great trouble he had taken to assist the investigations of the Committee. Sir Robert had advised the first Chairman, the late Sir William Matthews, Past-President Inst. C.E., on the general scheme of the tests and as to how they should be carried out, and Mr. Wilson thought it would be agreed that the tests had been arranged so as to overlap and check each other in a very satisfactory manner. Taking, for example, any one bar, say the wrought-iron "N," and one station, say Plymouth, three bars were exposed above high water-level for 5 years, 10 years, and 15 years; at half-tide level three more such bars were exposed, and three more were placed below low water-level, making in all nine "N" bars at Plymouth. The whole of the experiments were repeated in three situations abroad, the same method of exposure being followed. A similar set was sent to Colombo, where the conditions were tropical and very moist; in fact, the half-tide specimens might almost be said to be under water, seeing that the tide rose only about 2 feet. Another set was sent to Auckland, in New Zealand, where the conditions were semi-tropical, and another set to Halifax, Nova Scotia. It would be seen that the experiments overlapped each other, and enabled a very comprehensive set of results to be obtained. In addition, a **Mr. Wilson.** further set of fresh-water experiments was carried out at Plymouth.

In regard to the half-tide and complete immersion experiments, he had tried to determine by comparative figures an order of merit for the metals with regard to their resistance to corrosion, and he had adopted the method used by Dr. Newton Friend in his report. Sir Robert Hadfield had taken the actual thickness of the corrosion in decimals of a millimetre, but Mr. Wilson thought that Dr. Newton Friend had adopted a somewhat simpler method; he actually weighed each bar before and after exposure, and called the difference in weight the amount of corrosion; that was, the corrosive loss. Having obtained that for the whole set of experiments in one place, Dr. Friend took the wrought-iron bar " N " and called the value of its loss 100, and worked out all the rest accordingly, so that all the losses came out as a percentage of that of the standard bar. Mr. Wilson thought that those figures might be of practical use to engineers; they were set out in Table XXXVII (p. 106).

The best steel of all, as would have been gathered from the Paper, was the 36-per cent. nickel steel " L," and, again, taking the figure for wrought iron as 100, the figure for that steel was 36. The cost, however, of that steel would probably be very high. He did not know whether the Authors would give in their reply the comparative costs for that nickel steel as compared with the other steels. If, for purposes of economy, the nickel steel were used only in special positions, it would necessarily be in contact with other steels, and thus give rise to the electrolytic action to which the Authors had referred. The result would then be that the other steel would corrode away very much more quickly than normally, and that fact would have to be put against the value of the nickel steel. The next steel in order of merit was the 13·57-per-cent. chromium steel " J," with the relatively high figure of 51. That, so far as general corrosion was concerned, was very satisfactory, and it was exceedingly good in the air; in the water, however, it corroded badly, and very severe pitting took place; many of the bars were completely perforated, so that the use of that steel could not be considered for the purpose which the Committee had in mind. Next came the 3½-per-cent. nickel steel, whose comparative value was 72. That steel was very satisfactory in the air, and it had some advantages in the water, but it was not entirely reliable, seeing that there were several cases where bad corrosion had occurred, although on the whole it might be looked upon as being fairly satisfactory. The best steel for general purposes appeared to be the copper steel to which Sir Robert Hadfield had referred. The average figure for the 0·5-per-cent. copper steel was 90, which showed an appreciable advantage

Mr. Wilson.

over the rolled iron, whose figure was 112. Generally speaking, Mr. Wilson thought that that would be the most useful steel for engineers to consider for use in sea-water, and he presumed it would not entail much extra cost. Another interesting fact which emerged was that, taking the rolled irons "M," "N," and "P," their average loss came out at 112, while the rest of the steels "A," "C," "D," "E," and "F," taken together, averaged 118. That, he thought, was very interesting as showing how small was the difference between the rolled irons and the steels. That was a point which was also referred to in the Paper.

TABLE XXXVII

AVERAGE GENERAL CORROSION FOR HALF-TIDE AND COMPLETE-IMMERSION CONDITIONS OVER 5 AND 10 YEARS. COMPILED FROM TABLE XXIV OF THE SEA ACTION COMMITTEE'S XVTH REPORT. WROUGHT IRON "N" TAKEN AS 100.

Material.	Mark.	Relative corrosion.	Remarks.
36-per-cent. nickel steel	L	36	
13½-per-cent. chromium steel. . .	J	51	Severe pitting.
3½-per-cent. nickel steel	K	72	
Mild steel with ½ per cent. copper .	G 90	95	
Mild steel with 2 per cent. copper .	H 99		
0·4-per-cent. carbon steel	D	108	
Medium carbon steel, with low S & P (scale on)	E 114	112	Considerable pitting.
Mild steel with 0·7 per cent. manganese (scale on)	F 111		
Ingot iron (scale removed) . . .	M 121	112	
Wrought iron (scale removed) . .	N 100		
Swedish charcoal iron (scale removed)	P 115		
Medium carbon steel with low S & P (scale removed)	A 135	129	Moderate pitting.
Mild steel with 0·7 per cent. manganese (scale removed)	C 123		

In that connection he might say that, when he first came to London, about 30 years ago, engineers used to fight very shy of steel for jetties, piers, or similar structures in sea-water. Later on, when the use of steel greatly increased and wrought iron was more difficult to obtain, sleeves of wrought iron were placed over the piles where the corrosion would be worst, and the space between filled up with concrete. That was an expensive arrangement, was troublesome to carry out and interfered somewhat with the fixing of the bracing. Now, however, that precaution might seem unnecessary, because the steel was almost as good as the wrought iron in resisting corrosion.

There was a difference between the steels "E" and "F," from which the rolling-mill scale had not been removed, and the steels

"A" and "C," which had been scaled. The steels which were not cleaned had a figure of 112, whilst those cleaned had a figure of 129. As against that, although the general corrosion was less with the unscaled steel, the cleaned steel was much less liable to pitting and was therefore a more reliable metal to use. He did not know what it cost to clean steel properly and to remove the scale, but when that was done it was clearly of great benefit. Mr. Wilson.

He might refer to one point not mentioned in the Paper, but which was referred to in Dr. Newton Friend's report on which the Paper was based, and which affected the value of the cement-coating to the steel where it was buried in the concrete; the point might be of interest to those who used reinforced concrete. When the Committee sent out the bars originally, a difficulty was how to distinguish them after the experiments were finished. It was clearly of little use merely to stamp the bars, and so a series of holes was drilled in the top and bottom to indicate the number of the bar and the type of metal. The holes were drilled completely through the bars, and when the latter were to be exposed, they were fixed in concrete frames, the holes being buried in the concrete. When the bars were cleaned for examination the holes were found just as clean as though they had been recently drilled, showing that the steel had been completely protected by the concrete.

Mr. Ellson. MR. GEORGE ELLSON observed that reference had been made on p. 10 to the effect of corrosive action on the strength of metals. He could say from personal observation that those members of structures subject to the highest stress corroded the most readily. He agreed with, and would emphasize, the necessity in the design of metallic structures of allowing some margin above bare requirements, and also of avoiding members of a slender and a flimsy nature, using preferably members with as little exposed superficial area as possible. In other words, it was desirable to employ sectional material which was stout and rigid, and this was a point which was often overlooked.

Another point to which he desired to make special allusion concerned the removal of mill-scale. On p. 21 it was stated that steel with its scale left on had the advantage in fourteen cases out of twenty-four under corrosion tests. Later in the Paper, however, allusion was made to the question of the pitting of iron, it being stated that the specimens had had the advantage of having had their scale removed, while a remark was also made as to the advantage of cleaned steels over the steels which had their mill-scale untouched. The Authors had also commented on the beneficial effect on the pitting of ordinary iron and steel produced by previously removing the scale. Those remarks appeared somewhat contradictory, and he was unable to follow them in view of the first state-

Mr. Ellson. ment which he had quoted, namely that in fourteen cases out of twenty-four the advantage was with steels in which the mill-scale had not been removed.

His own experience was that it was entirely injudicious and harmful to remove the original scale of the metal. The fallacy of the benefits of removing the scale had persisted for a number of years. Some 30 years ago, when the renovation of the roof of Cannon Street station came under his personal supervision, a certain amount of rust had taken place on some of the members, but he had noticed that in every case where identification marks had been painted on to the skin of the metal at the works they stood up in relief, and in no case had corroded. To stop the corrosion, the surface of the metal had to be almost polished bright, and this was done at a very heavy cost. If corrosion were once allowed to commence, either by the pickling process to remove the mill-scale, or from any other cause, it was difficult and costly to remove the rust in order to get the protective coat of paint on to the metal itself, and, if the paint was put over any rust, its protective qualities would be heavily reduced, as the corrosion would still go on underneath the paint. His own practice was to specify a coat of red-lead paint to be put on at the maker's works, thus protecting the skin of the metal. After erection it was wire-brushed and given the final coats of paint, generally three in number. In that process a small amount of mill-scale was removed, but very little, and a clean surface was obtained on which to put the final coat, with a very satisfactory general result.

In the case of Charing Cross bridge, which was completed in 1863, the original paint was put on what was known as the mill-scale, or, as he preferred to call it, the original skin of the metal. The paint-work had been removed a number of times during renovation-work, but the skin of the metal was still as good on the great majority of the area as it was on the day when the bridge was completed. Similar remarks applied to Cannon Street bridge and to the other river-bridges of the Southern Railway.

It was stated in the Paper that, of all the ordinary steels and wrought irons, steel "D," with its rather high sulphur- and phosphorus-contents, was the only one to contend effectively with a specially energetic pitting action such as occurred under half-tide conditions at Halifax. He hoped that no one would deduce from that that a high sulphur-content was in any way helpful in reducing corrosion. On the Southern Railway it had already been necessary to renew conductor-rails which were laid down in the years 1915 and 1916 and which should have had a life of upwards of 30 years; that was entirely due to rapid corrosion arising from a high sulphur-content. A typical analysis showed that their composition was approximately as follows :— Mr. Ellson.

Carbon, 0·07 per cent.; manganese, 0·28 per cent.; silicon, trace; sulphur, 0·14 per cent.; phosphorus, 0·05 per cent.

At the present time, the conductor-rails, of which the Southern Railway employed many thousands of tons, were made of steel of which the sulphur-content was not allowed to exceed 0·04 per cent., and the corrosion of that steel was very small indeed.

A corrosion-test had been made recently in Sevenoaks tunnel of copper-bearing steel rails of the following analysis :—

Carbon, 0·61 per cent.; silicon, 0·16 per cent.; phosphorus, 0·0029 per cent.; sulphur, 0·038 per cent.; manganese, 0·10 per cent.; copper, 0·34 per cent.

At the end of nearly 4 years, consecutive lengths of that copper-bearing steel rail and of ordinary steel rails were taken up and weighed. The average loss of weight was found to be as follows: the copper-bearing steel had lost 7·5 lb. per yard, and the ordinary steel had lost 9·45 lb. per yard. That test, however, was carried out on only about 50 tons of rail, and, therefore, too much importance should not be attached to the result; but it seemed to confirm to some extent the results found in the various experiments which had been carried out by the Sea-Action Committee.

Under conditions where sulphurous fumes existed in the atmosphere, as, for example, in enclosed stations under steam-traffic conditions, he had found that the best protection was given by graphite coatings rather than by lead paints, and that was particularly noticeable in Cannon Street, Charing Cross, Victoria and Dover Marine stations. Coatings of coal-tar had also been found to be very satisfactory. He had referred to that question in a Paper[1] which he read in 1921, and in that Paper he gave particulars of the mixture used, which was still standard on the Southern Railway for coal-tar coatings, and gave excellent results.

He had read with considerable interest each of the Committee's reports as they had appeared, and had distributed them to all his divisional officers; he attached great value to them. At the same time, he wished to say, with all deference, that there was still, he thought, a great field for research in the matter of the protection of metallic structures, and in his view the value of the work would have been considerably enhanced if the co-operation of engineers who were concerned with structures had been obtained, so that data could be accumulated as to the best methods to be adopted under actual

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[1] "Cannon Street Bridge Strengthening," Minutes of Proceedings Inst. C.E., vol. ccxi (1920–21), p. 305.

Mr. Ellson. working conditions. Such co-operation would, he was sure, have been willingly given, but he was afraid that it would be necessary to wait at least 20 years before anything of value was obtained. A record of the value of different protective coatings applied under suitable conditions at different places in varying circumstances would be very useful, bearing in mind the great amount of ordinary commercial steel which existed in metallic structures. That was where the investigations would be of value. It would appear that perhaps the most hopeful results, from an economic and practical point of view, for the reduction of corrosion had been those obtained from the copper-bearing steel. As a result of those tests, he had used about 1,000 tons, and was hoping for good results. He had not used any "Chromador" steel, but, according to the results given, it appeared to have very good non-corrosion properties. An investigation had been carried out under the auspices of the Iron and Steel Institute by Dr. W. H. Hatfield,[1] and Mr. Ellson thought that that pamphlet should be studied.

The general practice on the Southern Railway for the maintenance of metal structures consisted of giving two coats of coal-tar, wherever it was practicable and æsthetically permissible. For the bulk of the remainder, a reliable lead paint was employed. The Southern Railway manufactured its own lead paints, but he did not mean to imply by that statement that it was not possible to buy reliable lead paints, because, in fact, very excellent lead paints could be bought. In other cases, zinc-oxide base-paints were used, and a certain amount of experimental work with lithopone had been done, but nothing had been found which was an improvement on the standard practices which he had previously mentioned. In terminal stations, subject to sulphurous atmosphere, graphite paints were used. For new works, wherever it was possible to do so the steelwork was embedded in concrete, and in other cases the exterior of the steelwork was as far as possible also encased in concrete.

Dr. Hudson. Dr. J. C. Hudson congratulated the Authors on their Paper, and particularly on their analysis of the corrosion-tests conducted by The Institution; those tests served a very useful purpose. The particular point to which he wished to refer concerned the relative corrosion-resistance of wrought iron and steel. He thought it possible that the recent results obtained by the Corrosion Committee of the Iron and Steel Institute and the British Iron and Steel Federation, to which Mr. Ellson had very kindly referred,[1] might throw a little additional light on the points raised by the Authors.

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[1] "The Work of the Corrosion Committee," Special Report No. 11, The Iron and Steel Institute, London, 1936.

He would like to make it clear that when, in the course of his remarks, he referred to "the Corrosion Committee" he would be referring to the Corrosion Committee of the Iron and Steel Institute, and not to the Sea-Action Committee. Dr. Hudson.

There could be no doubt that the Authors' conclusion that, of the ordinary rolled materials, the Low Moor iron was distinctly the best as regards general wastage was perfectly justified by the experimental data, more particularly perhaps in the intermittent and the total-immersion tests. So far as the relative behaviour of wrought iron and mild steel was concerned, the researches of the Corrosion Committee were tending to show that any difference between those materials was due to one or both of two factors: firstly a difference in the character of the rolling-mill scale, and secondly a difference in macrostructure.

With regard to the first point, it had been found in the research-work of the Corrosion Committee that when wrought iron and steel were exposed side by side to the atmosphere, the rolling-mill scale adhered much more tenaciously to the wrought iron. A specimen of Scottish wrought iron had been exposed to the atmosphere of Llanwrtyd Wells for 1 year, and at the end of that period only 21 per cent. of the scale on the front had been removed by weathering. Even after the specimen had been vigorously scratch-brushed, all the loose scale being removed, 55 per cent. of the mill-scale was still adhering to the front of the specimen, and had afforded complete protection over that area for 1 year. That result had been confirmed by observations made at other stations selected by the Corrosion Committee; in the tests on as-rolled specimens at Sheffield, the loss in weight on exposure for Staffordshire wrought iron was 58 grams,[1] whilst the Scottish wrought iron lost 15 grams, and ordinary commercial mild steel 148 grams. After the scratch-brushing (that was, the removal of loose scale and rust), the figures were 76 grams for the Scottish wrought iron, 91 grams for the Staffordshire wrought iron, and 159 grams for the mild steel. It was the practice of the Committee to remove all rust from its specimens by pickling them in the presence of an inhibitor in an acid-bath. That placed the wrought irons at a disadvantage, because the loss observed naturally included the mill-scale which was still adhering to the specimens; but, in spite of that, the figure for the Staffordshire wrought iron was 179 grams, for the Scottish wrought iron 201 grams, and for the ordinary mild steel 214 grams. It was interesting to note that a much purer material, Swedish wrought iron made in Lancashire, lost 331 grams, and was, in fact, the most corroded material of those

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[1] The losses in weight referred to specimens measuring 15 inches by 10 inches by $\frac{3}{8}$ inch, freely exposed to the atmosphere for 1 year. A loss of 100 grams was equivalent to 0·0024 inch of metal.—J. C. H.

Dr. Hudson.

tested. The beneficial effect of copper, which had already been referred to by Sir Robert Hadfield, was shown; it reduced the loss of Swedish Lancashire iron from 331 to 176 grams. Those two irons were identical; he had seen them made on behalf of the Committee, and the only difference was the copper-content. The corrosion of mild steel, ordinarily 214 grams, was reduced to 167 by the presence of 0·2 per cent. of copper and to 165 by 0·5 per cent. of copper. Those three steels were absolutely identical apart from the copper contents, and were made from the same cast. There did not appear to be any marked difference in the effect of 0·2 and 0·5 per cent. of copper, which was an interesting and practical observation.

Those results showed that the rolling-mill scale on British wrought irons (but not on the Swedish), certainly afforded the metal some protection, at any rate during the early stages of exposure. Wrought iron was rolled at what was relatively a very high temperature, starting at about 1,500° C., and at that temperature the slag in the metal was liquid. It seemed probable that that slag was smeared over the surface during rolling, and constituted a very crude form of enamel. In confirmation of that view, the fact that the Swedish Lancashire iron, which contained very little slag, had behaved rather worse than the mild steel would tend to show that it was the scale, or the slag and scale, which was primarily responsible for that difference in the corrosion of the wrought iron and the mild steel over the short period of 1 year.

The Authors had stated on p. 35 that the superiority of the Low Moor wrought iron was not due to the fact that the rolling-mill scale was removed from it before test. He thought it might be said that the superiority was manifested in spite of the fact that the scale had been removed. That was, perhaps, rather an important point, because if that protective scale were removed from the wrought iron a factor was introduced which would not obtain under normal commercial conditions; such structural materials were used as they came from the mill, and therefore the wrought iron had the rolling-mill scale on it.

The second possible difference between the two materials lay in their macrostructure. Wrought iron, at any rate in the case of British iron, contained a large number of slag particles oriented in the direction of rolling. Those originated from the piling process, and also from the puddling process itself. According to a conception developed by Dr. Ulick R. Evans, it was possible that those slag particles acted as a mechanical barrier, and tended to obstruct the penetration of corrosion into the material. That was an interesting point, and, although he believed that Dr. Evans had recently modified his views to a slight extent, the Corrosion Committee had that theory under test in various ways. In particular, they had prepared a wrought-iron wire from a pile made by building together wrought-iron sheets; the pile was then rolled down to a wire rod and drawn into wire. The size of the pile was about 4½ inches square. The theory was that all the slag particles resulting from the piling and from the manufacturing process would be arranged tangentially, so that the final wire would have the structure of an onion and would produce maximum obstruction to corrosion. If the theory was correct, that wire would give good results; if it did not, it would be necessary to change the theory. In a year or two results would be obtained from tests on that type of wire. **Dr. Hudson.**

There was one other matter which might be of general interest in illustrating the effect of rolling-mill scale. Ingot iron was a peculiar material, inasmuch as there was a brittle range between approximately 900 and 800° C., where it developed a tendency to brittleness, and it was not practicable to roll it. It was, therefore, necessary to complete the rolling of ingot iron above a temperature of 900° C., or alternatively to roll it partly above that temperature and then to allow it to cool through the brittle range before finishing the rolling. It was interesting to find that the normal scale produced at the high temperature would adhere to the specimen for from 3 to 6 months, whereas the scale produced at the reduced rolling temperature would be entirely removed in the space of from 2 to 3 weeks. The normal rolling-mill scale with the process finished at 1,060° C., was about ten times as thick as the low-temperature scale, when rolling was finished at 780° C.

Dr. FRANK WORMWELL said that Dr. G. D. Bengough regretted his inability to be present that evening, and had asked Dr. Wormwell to read a joint statement which they had prepared. **Dr. Wormwell.**

The question of the estimation of the amount of corrosion was discussed on p. 19. The results were originally stated by Dr. Friend as grams of metal lost per 1,000 square centimetres of surface. Dr. Wormwell considered that that did not give a true idea of the penetration of corrosion, even when converted by the means proposed in the Paper. To obtain a fair idea of the average depth of penetration the area of the metal actually corroded should have been measured, and the loss of weight divided by that area; such a measurement was often possible, especially in sea-water, and with carbon steels and wrought irons. When corrosion was mainly in the form of severely localized pitting, as, for example, with some alloy steels, the area-measurement would be difficult, and the behaviour of the material would be best expressed, as the Authors had said, by measurement of the number and depth of the pits.

The next point to which he desired to refer was the corrosion of

Dr. Wormwell. composite specimens; that was, the coupling of chromium steel with an ordinary mild steel or with cast iron. It was really necessary to consider one or two general principles which applied in those cases. He was considering metals completely immersed under sea-water at appreciable depths. A mild-steel test-piece of given area corroded at a definite rate, chiefly determined by the rate of oxygen-supply to the whole specimen. If, however, another specimen were taken of the same total size, but copper-plated over half its area, the total corrosion in a given time would be the same as if the whole specimen were bare, because the catchment-area for oxygen was unaltered; the amount of corrosion per square centimetre of the bare steel would, therefore, be approximately doubled. Thus, the increased initial electromotive force due to the presence of copper would have no effect on the total amount of corrosion, which would be determined by the catchment-area for oxygen. The copper might be regarded either as a hydrogen or as an oxygen electrode, *its potential depending on the rate of supply of oxygen.* If a specimen, half of which was covered with scale instead of copper, were considered, the result would be similar if the scale were a good electrical conductor; if, however, it were a bad conductor, the rate of corrosion per unit area of the base metal would be less than double that from the scale-free specimen. Dr. A. McCance, in a recent paper,[1] had expressed the view that scale on steel could be regarded as a non-conductor of electricity, and there seemed some support for that view. For example, in the present Paper it was shown (p. 21, and Appendix III, Table IX) that steels exposed with mill-scale suffered less total corrosion or wastage than steels exposed in a scale-free condition, whereas if the scale were a very good electrical conductor the total corrosion should have been the same both for the scale-covered and scale-free specimens. The total amount of corrosion on a test-piece was not generally directly proportional to its area, owing to the diversion of the oxygen-conveying convection-currents into different paths when the size of the specimen was changed. In order, therefore, to show correctly the effect of contact between dissimilar metals, the size of the composite specimen had to be identical with the size of the single specimen of each metal, a condition frequently overlooked in practice.

Those principles led to the conclusion that the contact of dissimilar metals was serious only when one of them was relatively resistant to corrosion, and was of large area relative to that more rapidly attacked. Accordingly, Dr. Wormwell had re-arranged

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[1] Dr. A. McCance, "The Corrosion Problem in Steel," Trans. Inst. Engineers and Shipbuilders in Scotland, vol. 79 (1935–36), p. 329.

Table XXVI (Appendix V) of the Paper, as shown in Table XXXVIII, on the assumption that the "contact specimens" were made up of two single specimens of similar size.

Dr. Wormwell.

TABLE XXXVIII.

CORROSION OF CHROMIUM STEEL (SOFT GRADE) BY RIVER-WATER, WHEN IN CONTACT WITH MILD STEEL OR CAST IRON. (DATA FROM APPENDIX V, TABLE XXVI, OF THE PAPER.)

Col.	Loss in weight: milligrams.					
	(1)	(2)	(3)	(4)	(5)	(6)
	Material exposed alone.	Calculated for double size.	Actual total loss of dual specimen.	Values for separate metals added together.	Ratio (3) : (4).	Ratio (3) : (1).
	Chromium steel 181	362	—	—	—	—
	Mild steel 853	1,706	1,363 + 35 = 1,398	1,034	1·35	1·64
	Cast iron 961	1,922	1,456 + 10 = 1,466	1,142	1·28	1·53
	Mild steel and cast iron in contact.					
	Mild steel 853	1,706	782 + 829 = 1,611	853+961 =1,814	0·89	1·89
	Cast iron 961	1,922				1·68

Considering first the upper part of the Table, which referred to chromium steel in contact with either mild steel or cast iron, it would be seen that the actual experimental results of Col. (3) were less than the calculated values of Col. (2), no doubt because doubling the size of test-piece did not necessarily double the amount of corrosion, as Dr. Bengough and himself had shown in 1933. Col. (6) showed that the corrosion of the composite specimen was either 1·64 or 1·53 times that of the single specimen. The reason why the values of Col. (4) were lower than those of Col. (3) was merely that the chomium steel separately did not use as much of the available oxygen as did the mild steel. When the metals were placed in contact the oxygen reaching the chromium steel became available for assisting the corrosion of the mild steel or cast iron, the latter being the anode and the chromium steel the cathode of an electrolytic cell. The total corrosion in the system was therefore increased either 1·35 or 1·28 times by placing the metals in contact, as was shown in Col. (5).

In the tests with mild steel in contact with cast iron, the lower value of Col. (3) as compared with Col. (4) was due to the fact that doubling the size of the specimen did not double the total oxygen-supply. That was shown by the ratio in Col. (5) being less than unity. Col. (6) showed again that placing two specimens in contact gave less than double the corrosion of a single specimen.

Dr. Wormwell. The three-dimensional diagrams of *Figs. 4, 5,* and *6* of the Paper showed that the effect of a particular location was much less marked for metals completely immersed in the sea than for metals exposed to aerial attack. It was very satisfactory to read the statement on p. 47 that " Apparently the corrosive action of salt water is such as to render the constituents, structure and physical conditions of ferrous materials much less important than they are under atmospheric conditions," as that was precisely the conclusion that Dr. Bengough and himself had reached in their laboratory tests at the Chemical Research Laboratory, Teddington, on different ferrous materials, such as a highly-purified iron, acid and basic mild steels, 0·5-per-cent. copper steels, wrought iron, 0·9-per-cent. carbon steel, badly segregated steels containing 0·95 and 0·235 per cent. sulphur respectively, and a 5-per-cent. nickel steel. Their tests were made in all cases on specimens which were free from scale and which had been given a finely-turned surface, and were conducted in solutions of N/2 sodium chloride, N/10 potassium chloride, Teddington tap-water, and natural sea-water, and under atmospheres of oxygen or ordinary air. The results were set out in detail in Section D, Part 3 of the Third Report of the Corrosion Committee of the Iron and Steel Institute.[1]

The Authors' conclusions on the behaviour of copper steels appeared rather surprising in one respect. On pp. 37 and 38 it was stated that 0·5 per cent. of copper was beneficial both as regards general wastage and pitting, even in conditions of complete immersion. At first sight that seemed to differ both from the results of American tests [2] and from the laboratory tests in N/2 sodium chloride conducted by Dr. Bengough and himself. An examination of the Authors' comparison between copper steels and similar carbon steels (p. 37 *et seq.*) showed that they used steel " D," with 0·40 per cent. carbon, as a comparison-material. That was done because steel " D," according to the Authors, " is, on the average, the best of the carbon steels as regards wastage, and better than " F " as regards pitting. . . ." That statement appeared to be based on the average figures for pitting for all four ports and all three conditions of exposure, given in Appendix III, Table XVI. The figures given there were 2·16 for " D " as against 2·19 for " F," which was probably not a significant difference. Dr. Wormwell would suggest, however, that it was best to consider the relative merits of different materials for each exposure-condition separately. He only wished to discuss

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[1] Published in 1935.

[2] V. V. Kendall and E. S. Taylerson, " A Critical Study of the A. S. T. M. Corrosion Data on Uncoated Commercial Iron and Steel Sheets," Proc. Am. Soc. Test. Mat., vol. 29 (Part II, 1929), p. 204.

Dr. Wormwell.

the results for complete immersion, which were comparable with the laboratory tests carried out by Dr. Bengough and himself; referring to Appendix III, Table XVI, for total-immersion conditions the average pitting for all four ports for steel " D " was 3·19 as against 2·58 for steel " F," so that it would appear better to take steel " F " as a basis of comparison for the effect of copper in conditions of total immersion. Again, from Appendix IV, Table XX, the corresponding figure for 0·635-per-cent. copper steel " G " was 2·64, practically identical with that for the ordinary steel " F." As regards general wastage, however, the copper steel " G " was superior (0·420 millimetres loss) both to steels " F " (0·487) and " D " (0·500) in totally immersed conditions, as well as on the average for all conditions, as had been stated by the Authors on p. 38. The Authors stated on p. 65 that in their tests in the Gulf of Paria on steels which were exposed, like the mild steel, with their scale untouched, the 0·29-per-cent. copper steel No. 3714 " again shows rather less wastage than the mild steel. In the present instance the copper steel has also shown a propensity to localized attack." Those results might be due to the better adherence of scale to the particular copper steels tested than to the ordinary steels; whether, however, that was a general property of copper steels had yet to be shown. Laboratory measurements made by Dr. Bengough and himself threw no light on the matter, since scale-free materials were used. In the tests of the American Society for Testing Materials[1] the specimens were exposed with mill-scale in situ, and for those total-immersion tests in Severn river-water (brackish), Washington city-water and Calumet mine-water, Kendall and Taylerson deduced by statistical analysis that the influence of small additions of copper, up to 0·7 per cent., had a negligible effect on the resistance to corrosion. The latter tests also agreed with the tests performed by Dr. Bengough and himself and with those of the Sea-Action Committee in showing that the effect of up to 0·08 per cent. of sulphur has no appreciable effect on the corrosion of steel under conditions of total immersion. It could not, therefore, be too strongly emphasized that, for steels exposed to aerial attack, additions of copper up to 0·5 per cent. had been conclusively shown to be beneficial. That fact emerged clearly from the work of the Sea-Action Committee and was supported by other exposure tests in Great Britain, the United States, and Germany. The difference between the response of materials to aerial exposure and immersion under water was very important, since it meant that conclusions from one set of data could not be applied to the other. For that reason it was often dangerous to

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[1] **Footnote 2, p. 116.**

Dr. Wormwell. compare different materials from the average results for all three conditions of exposure. The results for each condition should be analysed separately.

Dr. Vernon. Dr. W. H. J. VERNON said that the large amount of valuable information which the Authors had set out in their Paper was clearly a tribute both to the planning of the main investigation under the Corrosion Committe of The Institution and also to the thoroughness with which the experimental part of the work had been carried out by Dr. Newton Friend. The wideness of the investigation had inevitably led to a vast amount of data, and in making an independent survey, the Authors had undoubtedly performed a valuable service. The use of three-dimensional diagrams, which brought out very clearly the relationships between corrosion, climatic conditions and the materials under examination, was particularly helpful.

The Authors' use throughout the Paper of the term "aerial conditions" was likely to give rise to some confusion, even although it was difficult to see what other term they could have used to distinguish such conditions from those of partial or complete immersion. In all cases in the main investigation the specimens had been exposed in very close proximity to the sea. Inasmuch as the work was being carried out for the Sea-Action Committee clearly no exception could be taken to that procedure. It should be emphasized, however, that such conditions were not typically aerial, and very different results might have been obtained had the specimens been exposed inland, even at only a comparatively short distance from the sea.

That point was of some importance, first because the corrosion values of a series of comparable specimens served to compare the corrosivity of the several atmospheres concerned, and secondly because differences in behaviour of various materials were brought out far more markedly, as the Authors had very rightly emphasized, under atmospheric conditions than under conditions of complete immersion. The second aspect was of much significance, but he would confine himself to remarks on the first.

The importance of defining clearly the conditions of exposure when assessing the climatic factor was clearly seen by comparing the present results with those which had been recently published by the Corrosion Committee of the Iron and Steel Institute.[1] In both cases the available data had permitted the different corrosion-stations to be placed in a fairly definite order of merit, but in so far as the stations were representative of comparable climates that order differed very materially in the two investigations. In the Iron and Steel Com-

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[1] Dr. J. C. Hudson, "The Committee's Field Tests on Atmospheric Corrosion." Third Report of the Corrosion Committee (1935), Section B, p. 49.

mittee's research the stations fell, with only one exception, into two groups; those comprised six overseas stations, of relatively low corrosivity, and five stations in Great Britain, of relatively high corrosivity. The first group included such widely differing climatic conditions (particularly as regards temperature) as Abisko (within the Arctic circle), Khartoum, and Singapore. The inclusion of Singapore in the group of relatively low corrosivity (Llanwrtyd Wells and Calshot gave corrosion values approximately four times greater, and Sheffield nearly eight times greater) was rather remarkable, in view of the fact that Colombo, which was on very nearly the same latitude and presented a very similar type of atmosphere as Singapore, was by far the most destructive of the atmospheres included in the Sea-Action Committee's investigation. In fact, on the question of climatic influences there was no correlation whatever between the two investigations. Dr. Vernon.

What then was the explanation? Some light appeared to be thrown on the matter by the examination of results recently obtained at Teddington.[1] When a specimen of iron was exposed to purified air, the relative humidity of which was increased gradually with time from zero to very nearly saturation-point, the rusting that occurred at the higher relative humidities was very small in amount and not at all serious in character. If, however, traces of impurities were admitted into the atmosphere, then very remarkable changes occurred. If, for example, the air contained traces of sulphur dioxide, primary and secondary critical humidities might be recognized. When the relative humidity reached the primary value (about 50 per cent. relative humidity), rusting commenced; when, however, the secondary critical humidity was reached, at about 80 per cent. relative humidity, the rate of attack suddenly increased in an extraordinary manner, and rusting proceeded rapidly.

It was important to observe that those effects might be reproduced in just the same manner if, instead of admitting gaseous impurities into the otherwise pure atmosphere, the specimen itself were "inoculated" at the outset with particles of solid impurity in very small amounts; particles of hygroscopic salts were very efficacious in that respect. Again, very great increase in the rate of attack was produced at the secondary critical humidity, an increase which appeared to be associated with the physical properties of the first-formed rust.

The bearing of those experimental results on the results of field tests was now apparent. So long as the climatic influences were confined either to differences of temperature or to differences of relative

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[1] Dr. W. H. J. Vernon, "A Laboratory Study of the Atmospheric Corrosion of Metals," Part III, Trans. Faraday Soc., vol. 31 (1935), p. 1678.

Dr. Vernon. humidity (the atmosphere being otherwise pure) comparatively small differences in rates of rusting were to be expected. If, however, the specimens were situated in such a position that they could become " inoculated " with salt particles, then very great differences in the rates of rusting might be expected at the higher relative humidities. The rate of attack in a relatively pure atmosphere might then approximate to that produced in a polluted atmosphere in the absence of salt particles. The greatest rates of attack were to be expected in industrial districts, such as those in Great Britain, where the presence of both gaseous and solid pollution coincided with conditions of fluctuating and generally high relative humidity. Under tropical conditions, however, the influence of particles and humidity alone might outweigh the added effect of gaseous pollution under milder conditions of temperature. That appeared to be the case with the " aerial " tests at Colombo as compared with the one example of a British industrial atmosphere included in the present results (Birmingham, as shown in *Fig. 11*).

The results dealing with the influence of scale initially present on the specimen were particularly interesting. (Incidentally, the Authors' use of the term " scaled steels," to indicate steels from which the scale had been removed, was confusing, and Dr. Vernon would suggest that it should not be used. The word " descaling " had recently been criticized, but if the substitution of the word " scaling " were advocated, he would ask what term was to be used instead of " scaling " when that word was used, in its legitimate and more obvious sense, to imply the formation or acquisition of scale ?) The results showed, in most cases, the greatest general corrosion on those steels from which the scale was not originally removed. The maximum effect was observed at Plymouth; at Colombo there was practically no difference in the results. Presumably, the greater corrosion given by the steels with scale initially on was due to the de-scaling that usually occurred on exposure to the atmosphere, the loss of scale adding to the total loss of weight; there was a certain amount of undermining and the scale tended to peel off. No doubt the process was hastened by temperature changes, owing to the unequal coefficients of expansion of scale and metal. It was perhaps rather unfortunate that the copper-bearing steels were all exposed with scale on, because the beneficial effects of copper were probably directed, at least in part, toward modifying the properties of the first-formed rust on exposure to the air.

Finally, he would like to refer to Sir Robert Hadfield's remarks concerning the Delhi Iron Pillar, in respect to its notable freedom from corrosion. The results of the X-ray examination of the surface layer, to which Sir Robert had referred, would certainly be awaited with great interest. Meanwhile, it might be pertinent to mention that, in the light of recent work, there was nothing inconsistent in that freedom from corrosion with the climatic conditions which the Delhi Pillar had enjoyed, more particularly in the earlier stages of its 1600 years' exposure. Those conditions involved a generally low humidity, a freedom from sulphur-dioxide pollution, and an absence of " inoculating " salt-particles. Under such conditions iron either did not rust at all (if the humidity were below the " critical humidity "), or, even if the critical humidity were exceeded, the rust which formed would be small in amount and actually protective in character. The presence of carbon dioxide, so far from increasing the rusting, actually depressed it.[1] Dr. Vernon.

Earlier work [2] had shown that in the absence of particles (for example, when screened within a muslin " cage "), iron developed an invisible film of oxide which showed marked resistance to rusting on subsequent normal exposure. It had formerly been thought that that invisible oxide-film ceased to thicken soon after its formation, but recent work [3] had shown that such was not the case; on the contrary, a progressive increase in thickness occurred. The rate of attack certainly decreased with time (depending approximately on the relation $W^{2 \cdot 5} = kt$ in early stages where W denotes thickness of film, and t denotes time), but in the course of centuries the film would undoubtedly reach appreciable dimensions, and would almost certainly be sufficient to account for the resistance to mild conditions of atmospheric corrosion for which the Delhi Pillar was famous. Very probably a thin scale formed during manufacture would contribute its quota of protection, and the X-ray examination might decide whether that was the major factor; it might, however, be fairly safely surmised that even in its absence nature would still have produced, in course of time, an efficient substitute.

Mr. H. D. MANNING asked permission to refer to one point which, although not specifically mentioned in the Paper, might, he thought, be regarded as coming within the scope of the discussion. Engineers responsible for the design of sewerage and sewage purification-works would all be familiar with the problem of corrosion of such works. The subject was of increasing importance owing to the more widespread use of steel pipes for sewerage purposes and to the way in which modern purification-plants were becoming mechanized. Mr. Manning.

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[1] Footnote 1 on p. 119.

[2] Dr. W. H. J. Vernon, Second Report to the Atmospheric Corrosion Research Committee (British Non-ferrous Metals Research Association), Trans. Faraday Soc., vol. 23 (1927), p. 159.

[3] Dr. W. H. J. Vernon, " A Laboratory Study of the Atmospheric Corrosion of Metals," Part II, Trans. Faraday Soc., vol. 31 (1935), p. 1670.

Mr. Manning. The fact that the Ministry of Health would now sanction loans for 30 years on steel sewers had lessened, but had not removed, the doubts which were felt as to their ability to stand up to sewer-conditions. In that connection, it was necessary to distinguish between pumping-mains and gravity sewers. In the former the pipe was normally full of sewage under pressure, and it was to be assumed that the danger of internal corrosion was not great. In a gravity sewer, however, the water-level was constantly changing, and the ventilation was often poor. It was said that, in practice, a layer of grease formed over the sides of the pipe and protected the metal from attack. That might be the case, but it was curious that, in the case of concrete or brickwork sewers, where a similar grease-film might be expected, the cement was sometimes very seriously attacked on the top half of the arch and along the wind-and-water zone.

The principal causes of corrosion in sewers were presumably the damp conditions, coupled with the presence of such gases as sulphur dioxide, sulphuretted hydrogen, carbon dioxide and carbon monoxide. Possibly, also, the grease-film, instead of forming a protection, was actually a danger owing to the formation of fatty acids resulting from its decomposition. There was also the danger of external attack due to ground-waters containing sulphates in solution. Whilst it was common practice to protect the outside of steel pipes with bituminous wrappings, the danger of external attack could not be overlooked, especially if those wrappings were omitted. No doubt a great deal of independent investigation had been carried out on the subject, but, so far as he was aware, the published information was scanty.

With reference to the increasing use of steel in sewage-purification works, until recently it had been possible to make most of the fittings required on such works in cast iron, wrought iron, or gunmetal. To-day the average sewage-works included mechanical screens, cleaning mechanisms for sludging the tanks, and stirring mechanisms and gasholders for digestion-tanks. Such apparatus involved the use of large quantities of steel, and time had yet to show what the life of those structures would be.

The use of steel gasholders for sludge-gas was of particular interest. Gasholders containing ordinary town's gas were protected, he believed, by the formation of a tarry deposit on the internal surfaces, but that would not apply in the case of sludge-gas. He believed that that gas had been found to be most destructive of brass and copper fittings, such as meters and valves, more especially where water was present. In some large gasholders recently constructed for sludge-gas, use was made of copper-bearing steel having a copper-content of about 0·25 per cent., in the hope of resisting corrosion. In the absence of practical results or comprehensive experiments, designers were greatly handicapped, and he would like to ask the Authors whether they could express any opinion as to the suitability of copper-bearing or other special steels for purposes such as he had mentioned. The importance of the subject might be realized when it was stated that, on a typical modern sewage-purification works, about 25 per cent. of the cost might be debited to machinery and steelwork as distinct from normal constructional work in concrete and brick. The Paper showed the complex nature of marine corrosion, and it might well be that the conditions arising in sewers and on sewage-disposal works were even more varied than marine conditions. He felt sure, however, that the results of a full investigation of the problem would be of very great value. **Mr. Manning.**

Mr. Barclay. Mr. W. R. Barclay expressed his thanks, as President of the Institute of Metals, for having been invited to attend the meeting. Although the Institute of Metals was mainly concerned with the non-ferrous metals, corrosion was one of those general subjects with which both sections of metallurgical science were concerned.

Sir Robert Hadfield. Sir Robert Hadfield thanked the speakers for their kind comments on the Paper. It might be of interest to mention that no one had yet succeeded in producing a ferrous alloy of the same high resistance to corrosion as Michael Faraday had done. Faraday had made an alloy of 50 per cent. rhodium and 50 per cent. iron which seemed practically incorrodible under almost any conditions; Sir Robert had described it fully elsewhere.[1] He had desired to recommend the inclusion of some rhodium-iron specimens in the experiments of the Sea-Action Committee of the Institution, but had found that each bar would cost something like £1,600, so that it was not possible to pursue the matter further in that direction.

The Authors. The Authors, in reply, thanked Mr. M. F-G. Wilson, the present Chairman of the Sea-Action Committee, for his very kind remarks regarding the help which one of them (Sir Robert Hadfield) had tried to give to the investigations of the Committee since its commencement 20 years ago. Sir Robert had always found it a great pleasure to do anything he could to assist the work of the Committee.

They agreed with Mr. Wilson as to the usefulness of a percentage basis in comparisons of the various materials, and had themselves found useful the comparisons made in that way in the Committee's Reports. The method adopted in the Paper had been used rather as a means for conveniently and systematically carrying

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[1] "Faraday and his Metallurgical Researches," pp. 214 and 216. London, 1931.

The Authors. out the examination made of the influences on corrosion of the different climates concerned, and of the different conditions of exposure.

With regard to steels containing copper, the results of the Committee were, as had been stated by some speakers, in agreement with those of other past and current researches, and with the practical experience so far obtained with those steels. The present research had, it was believed, gone further, in showing that for marine conditions the beneficial addition of copper might extend beyond the small amount, namely about 0·3 per cent., which appeared to be the limit of useful addition for steels exposed to ordinary atmospheric conditions. The Committee had thus been justified in its decision to include steels containing larger percentages of copper, namely 0·6 and 2·2 per cent.

Copper steel was undoubtedly of value in contending with corrosion, but its choice for any particular purpose should be the result of careful consideration of its capabilities ; while no dangers seemed in any case to be attached to its use, it was only in particular circumstances that copper steel offered advantages. In sea-water 0·50-per-cent. copper steel was worthy of consideration for practical trial, as had been suggested by Mr. Wilson. Such practical experience was the only way to determine the merits of copper steel, and the same was true of the steel containing 36 per cent. nickel, referred to by Mr. Wilson.

A subject which had been referred to by several speakers was the influence of the previous removal of scale. The direction, favourable or otherwise, of that influence depended on circumstances. There was not necessarily any conflict between the experience in that respect of Mr. Ellson and the Committee's results referred to in the Paper ; an important point of difference was that Mr. Ellson was concerned with painted structures. Dr. Hudson's results referred, as did those in the Paper, to unpainted steel, and the two series were in marked agreement. The most marked influence of scaling was, however, shown, not under atmospheric conditions, but in its favourable effects on the pitting which occurred in sea-water. There was undoubtedly room for a closer study of the bearing of the actual character of rolling-mill scale on its influence as affecting corrosion, and the results in that direction provided by Dr. Hudson were of decided interest.

Mr. Ellson's remarks were of much practical value ; the Authors agreed with his suggestion that there was still a great field for research in the matter of the protection of metallic structures. Naturally, the subject was complex, dividing itself into (*a*) the type of steel employed, (*b*) its heat-treatment, as the same steel under different conditions might give quite different results as regards corrosion, (*c*) the method of manufacture and the care taken in its production into finished forms. Mr. Ellson had pointed out that to determine corrosion-qualities thoroughly required a long time; the researches of the Sea-Action Committee were coming to a close, but those of the Iron and Steel Institute and other bodies would be continued for many years, and would probably help to provide an answer to Mr. Ellson's queries.

The Authors.

The Authors were glad to have the confirmation provided by the work of Drs. Bengough and Wormwell as to the levelling influence of actual exposure to sea-water on the relative merits of different ferrous materials; that was one of the most noticeable features both of the Sea-Action Committee's and of the Authors' own results. In particular, the behaviour of Steel "B," with a high sulphur and phosphorus content, was especially striking, and left no doubt that the effects of those impurities in ordinary steel were much less harmful in sea-water than in air. The point, however, was for the present one rather of scientific interest, and the Authors would be the last to advocate the use of impure steel. Further, under marine aerial conditions steel "B" had been shown to be definitely inferior to purer steels, thus agreeing with Mr. Ellson's experience with conductor-rails; presumably, however, the latter were mostly exposed in a rather different kind of atmosphere.

In the large majority of cases the Sea-Action Committee's specimens were corroded over their whole area between the concrete supports, and the method adopted of assessing penetration would thus for the most part appear to be identical with that suggested by Dr. Wormwell. The exceptions were mainly provided by the chromium steels, which were subject to severe localized pitting and for which, therefore, the method proposed would be unsuitable.

The description by Dr. Wormwell of the principles underlying the corrosion of dissimilar metals in contact was of great interest. Contact-effects could not altogether be avoided even with the use of ordinary materials, and they were responsible for many cases of excessive corrosion. By the intelligent application in practice of the knowledge afforded by fundamental research, it should be possible to minimize such effects with advantage.

The adoption of different carbon steels in each separate type of exposure as a basis of comparison for the performance of the alloy steels would have introduced an undesirable complication into the Tables of results. It was doubtful, too, whether such a course would be justified, since true comparison could only be on the basis of composition, in which respect steel "D" was chosen by the Authors as being the best. Desired comparisons in other ways

The Authors. could, in any case, readily be made, as had been shown by Dr. Wormwell. The Authors' conclusions that the copper steels were subject to pitting to about the same extent as carbon steels, while their total wastage was less, appeared, however, to be correct even for under-water conditions if comparison were made alternatively with steel "F."

They were especially interested in Dr. Vernon's remarks, which did much to justify their own prediction in the Paper as to the eventual importance in the solution of the corrosion-problem of the kind of fundamental research in which Dr. Bengough and his colleagues were engaged. It was apparent that connections were now steadily being established between the results of laboratory research and field tests systematically conducted, and through them with practical experience. One of the Authors (Sir Robert Hadfield), having visited Singapore, would not have been surprised if the climatic conditions there had been found to be particularly corrosive to iron; Dr. Vernon, however, threw considerable light upon why the corrosion there was actually relatively low in amount as compared with that at Colombo, which had a similarly hot climate. Dr. Vernon's observations regarding the Delhi Iron Pillar, especially as to the possible part being played by a protective film in its freedom from corrosion, were particularly interesting and were valued as showing that modern scientific knowledge at any rate did not find it necessary to suppose any special virtues in the material of which the pillar was made which were not shared by other high-quality wrought irons.

In conclusion, the Authors would like to say how much they appreciated the information provided by Messrs. Wilson, Ellson and Manning, and based on their practical experience of corrosion. In presenting their Paper the Authors felt that its chief purpose would best be served by the collaboration in discussion of practical engineers and those interested in the scientific study of corrosion; they trusted that the written contributions to follow would show the same gratifying results in that respect as the discussion had done.

A large selection of specimens, from both the Sea-Action Committee's and the Authors' researches, was shown at the Institution during the meeting.

⁂ The Correspondence on the foregoing Paper will be published later.—SEC. INST. C.E.