kept in repair to save undue impact on the structure. With the smaller type of bridge, there is a tendency to leave the operation to one man, with probably a road lengthman on call. Although such a scheme appears to be economical, it does not, in the long run, pay dividends, since the operator will be discouraged by having to work long hours, whilst many little points of day-to-day maintenance will be neglected and will build-up, finally leading to a breakdown. Such things as uneven bearings of the bridge, which cause rocking when carrying road traffic, could be eliminated by steel wedging, etc.

ACKNOWLEDGEMENTS

The Author is indebted to Mr E. B. Hugh-Jones, M.C., B.Sc., M.I.C.E., Chief Engineer, Ministry of Transport, for permission to publish Part (*b*) of the Paper, and to many colleagues within the Ministry for the supply of information and for assistance in preparing the MS.

The Paper is accompanied by eleven photographs and seventeen sheets of diagrams, from which Tables 4–10, the half-tone page plates, and the Figures in the text have been prepared.

Discussion

The Authors introduced the Paper with the aid of a series of lantern slides.

Mr C. S. Chettoe thought it opportune that the Paper should be presented at a time when so little money could be spent on new construction; it was all the more important, therefore, to consider the economics of maintenance in order to ensure that the bridges of Great Britain were maintained in the most efficient way. In the past, when there had been enough money for new bridges to be built, insufficient attention had been paid to maintenance. There were masonry bridges which had not had any attention for 50 years, and there were wrought-iron girder bridges which had holes in the webs—the bridges were evidently working on the Vierendeel principle. Regular inspections and forms which had been carefully worked out beforehand were very important because they enabled defects to be traced throughout the years and remedial measures to be recorded.

With regard to the preparation and painting of steelwork in bridges, the general position seemed to be that for an old steel bridge which was in bad condition flame cleaning was probably the best way to deal with it, if it were bad enough to require such treatment, but in the case of new steelwork there was much in favour of either grit or sand blasting, or pickling. If metallizing were used, the steel had to be carefully prepared first. It might be worth while considering metallizing for bridges built in polluted atmospheres.

From the economic graph, *Fig. 16*, p. 186, *ante*, pickling and painting seemed to be a very good method of dealing with the protection of steel. Could Mr Davies say whether more might be done in the way of pickling and how far a limitation was imposed by plant and apparatus in the fabricator's works?

He agreed with Mr Davies's statements regarding the importance of impervious surfacing of bridges, both steel and concrete. Most concrete bridges did not have an impervious surface and water got through; that was something to which special attention should be paid.

Referring to the diagrams showing the lives of different test specimens which had been treated in different ways, Mr Chettoe thought that it might be difficult in practice, in interpreting those tests, to be sure of what was meant by "good," "fair," "serviceable," "failure," and so on. His own impression from seeing the results of tests on steelwork which had been both metallized and painted was that some rather inconsistent results had been obtained. One reason given for that had been that it was difficult to determine accurately when a surface ceased to be "good" or "serviceable" or actually failed.

Referring to Part (*b*) of the Paper, it was arguable whether cement mortar should be used in masonry facing. It was probably better to use a mortar of lime or, perhaps more commonly, lime and cement mix, because there was a good case for the mortar not being harder than the main material, the stone.

With regard to the coating of the stone for protection, mentioned by Mr O'Malley, reference had been made to magnesium silico-fluoride, and there had been some argument whether, if a coat of that sort were put on the masonry face, it should be something which would allow the stonework to breathe and not be an impervious coat, or whether it should be impervious. If an impervious coat, such as "Cementone," were used there might be greater danger owing to dampness, and ultimately the face would come off.

Mr F. M. Fuller, in endeavouring to check some of Mr Davies's figures, had found the results so confusing that he had concluded that those figures could be used only as a general guide and that every locality, and in fact every bridge, should be treated on its merits. His remarks, therefore, referred to London conditions only.

Mr Davies had emphasized the fact that detailed design had a great influence on maintenance. The tendency would be to spend more on the construction of a bridge—which would run counter to the present proposals of the Ministry of Transport, for reducing expenditure—and less on subsequent maintenance. In dealing with the details, however, Mr Davies had not emphasized the trouble experienced with expansion joints, which probably gave more trouble than anything else. On certain concrete bridges in London, the only maintenance expenditure which had been incurred since construction had been on the expansion joints.

Reference had also been made in the Paper to the pickling process, to flame cleaning, and to various other processes which in general were more applicable to new bridges than to maintenance. Soon after the 1939–45 war, he had suggested to the leading bridge manufacturers in Britain that in future pickling or some other process might be specified; he had been told that they were not equipped for the purpose. At present he was adopting the procedure of scraping, patching, and painting for maintenance and, in spite of the present Paper, he thought that he would continue to use that process.

He did not agree with Mr Davies that flame cleaning was the most significant development in the maintenance of steel bridges in recent years. He did not wish to disparage flame cleaning; he had used it in special circumstances with good results. However, the London County Council had just finished repainting Hammersmith Bridge by the method of scrape, patch, and paint and it had been necessary to get down to the bare metal on only 3 per cent. of the total area of the bridge. If flame cleaning had been used, it would have been necessary to clear that 3 per cent., but that would have destroyed the paint on the other side of the plate—making another 3 per cent. to be scraped off; the paint immediately surrounding the areas which had been flame cleaned would also have been destroyed—making another 5–7 per cent. It would therefore have been necessary to repaint 15 per cent. of that bridge instead of 3 per cent. Where bridges had deteriorated so much that it was necessary to clean the whole structure, he thought that flame cleaning might prove its worth.

Mr Davies had stated that 67 out of 157 steel bridges had been flame cleaned, with an area of 18,500 square yards: that worked out at not much more than 250 square yards per bridge. Were the bridges very small or had only very small areas been attacked? How would Mr Davies deal with the possible damage to the paint on the far side of the plate and in surrounding areas, and had he any experience of cleaning bridges by grit or sand blasting and maintaining traffic at the same time? That might present difficulties, and the process seemed to be more applicable to new bridges than to existing structures.

Mr Fuller could not agree with several of the figures given by Mr Davies. It was just possible that costs in London differed from those in other parts of the country, but on p. 178 it was stated that "figures for maintaining steel bridges were from 1*s*. 9*d*. to 2*s*. 3*d*. per square yard every 5 years." Present-day costs in London were from 3*s*. 0*d*. to 3*s*. 6*d*.; Mr Davies had also stated that the cost per ton of steel was equivalent to 5*s*. per annum; that was very low, judging by London experience. In Table 11, item 4 was a bridge costing roughly £500,000, which might be equivalent to a Thames bridge, and the average annual expenditure on maintenance was £500. The average annual maintenance cost of the Thames bridges varied from £1,000 to £1,300.

Mr Fuller had some information relating to five large bridges in the London area. The first time that Wandsworth Bridge had been repainted, which was after a period of nearly 10 years, owing to the war, it had been necessary to scrape 20 per cent. of the area to get down to the bare metal. In the case of Westminster and Lambeth Bridges it had been necessary to scrape down 10 per cent., largely owing to leakages through the conduit routes of the trams, but in the case of Hammersmith Bridge, which had been painted many times, it had only been necessary to scrape down 3 per cent., as stated on p. 203. That suggested that the problem of maintenance, if carried out in accordance with that principle, became less with the age of the bridge.

Fig. 16 showed that, considering a 50-year life for a bridge, whatever process was adopted the cost was nearly the same; that was a convenient argument and suggested that all the methods were correct.

In London the reinforced-concrete bridges under the control of the L.C.C. were more modern than those referred to by Mr Davies, and, apart from expansion joints, no serious trouble had arisen.

Mr P. S. A. Berridge observed that a lot of money could be saved by paying proper attention to the preparation of the surfaces of the mild steel in a new bridge. Mr Davies had stated that 11 years of life was expected of the paint when the steel had been pickled. That compared with only 3 years when the mill scale had been removed by weathering. On the Western Region of British Railways the removal of mill scale by pickling was specified. The steel was immersed in a bath of dilute hydrochloric acid, in the proportions of one part of acid to nineteen parts of water, for not less than 15 hours, care being taken to see that the acid had free access to all surfaces during the whole period. On removal from the bath, all surfaces of the steelwork were well hosed with fresh water and scrubbed with stiff wire brushes before a second complete immersion in fresh water. In bridge-work the pickling of the steel was comparatively novel and experience had shown that many of the fabricators in Great Britain were reluctant to install the necessary acid baths. Certain fabricators who appreciated the seriousness of that specification for the removal of mill scale by pickling did undertake to do that at an extra cost of £3 per ton. On a bridge containing 50 tons of steelwork the extra outlay of £150 was very small, when it meant the saving of repainting the bridge three times in the first 11 years of its life. Mr Berridge hoped that more steel fabricators would lay themselves out to give that service. At present few, if any, of the rolling mills would oblige by pickling the steel before delivery to the fabricators.

Attention to details of design for a new bridge could pay large dividends. In all except the very short spans the superstructure of the steelwork, including the hand-railing, should have no contact with the masonry, abutments, pilasters, etc., except through the bearings of the girders on the bedstones. On spans in excess of 120 feet consideration should be given to the provision of proper expansion joints in the roadway. An example of that was in the self-cleaning comb joint at the end of a 230-foot-long span of the Sukkur Channel bridge.

Where the road bridge carried a railway on the same deck as the road, special provision had to be made to facilitate easy access to the rail fittings without disturbing the road metalling. The space between the rail and the road metalling should be bridged with continuous steel plates held in place with set screws. In the Sukkur Channel bridge a flat-bottom rail was secured to steel stools with Mills jaws, the space between the stools being left open so that water and dirt would fall clear.

Steel bridges over steam-operated railways should have smoke-plates to protect the underside of the girder-work against the abrasive effect of engine blast. The maintenance of such smoke-plates was greatly improved if in the fastenings the bolts were in shear and not in direct tension. A smoke plate of recent design was secured to a girder flange by a notched wedge tightened by a cotter; it was protected on the underside with " Densotherm " (a hessian-based fabric), secured by " Bostik " adhesive.

Mr E. K. Bridge observed that the Authors had rightly emphasized the importance of giving full consideration to the question of maintenance in the preparation of the design of structures. Many maintenance problems of the present day would not have arisen had the engineers of the past given that aspect of design more thought. For instance, the ends of many bridge girders had been built around so closely that proper access was difficult, and water and mud were held around the bearings.

On metal structures with plate or troughing floors, drip pipes which were not long enough frequently caused corrosion in the surrounding portions of the structure through the draught, which was often present under a bridge, and which blew the drip from the end of the weep pipe on to the adjacent steelwork. Corrosion had also been caused in other cases by shallow rainwater gutters being placed too close to the underside of the steelwork, where they not only made it difficult to paint the steel but also tended to increase its corrosion.

Mr Davies had emphasized the undesirability of having timber in contact with steel or iron bridge structures : the danger of that was illustrated by a fairly recent case where timber decking, resting on the bottom flange of a plate girder, had seriously corroded the web just above the bottom flange angle, and corrosion fatigue had formed a crack extending for the greater part of the girder's length.

The hand-railing on the Tay Bridge was a good example of the rust forcing that could occur between plates when the rivet pitches were too far apart, although in that case the structure of the bridge itself had not been affected.

Mr Bridge agreed with the Authors in regard to the effectiveness of flame cleaning in preparing the surface of iron or steel for painting, but thought that that method should be used with caution where the opposite side of the girder web or deck plate had concrete bonded to it.

Tests had been carried out a year or two ago to compare the effect of power wire-brushing with flame cleaning; after the wire brushing had apparently satisfactorily cleaned the steel, the flame cleaning had been applied and had removed a surprisingly large further quantity of scale and rust. More recent attempts had been made to use that method as a preparation for metal spraying, but the very limited tests had indicated that the metal spray applied to such a surface did not have a long life under severe conditions; possibly, that was partly due to the surface being smoother than that obtained by shot blasting.

In most bridges, corrosion occurred much more rapidly at certain points in the structure, such as round the bearings on the abutment or at the junction of the deck with the main girders, and it was economical to clean off and patch-paint those points at comparatively frequent intervals, leaving such points as the upper portions of the girder webs and the underside of the top flanges for painting at much longer intervals.

Bearing in mind that the cost of cleaning off the rust—so that a proper rust-inhibiting coat of paint could be applied direct to the metal—was much higher than the cost of applying the paint, it would seem to be economical to repaint such portions of the bridge structure before that priming coat had been penetrated.

When steelwork was delivered to the site coated with linseed oil, the oil should be removed before painting commenced; otherwise the red lead or other inhibitor in the priming coat could not function, because it was insulated from the metal by the oil coat.

In the maintenance repainting of a large dock gate, it had been found advantageous to use a large vacuum cleaner to remove the dust and old paint after it had been brushed from the surface. That had the advantage of keeping the air clear in the inner pockets of the gate, and it had been very effective in cleaning out fine dust from corners which would otherwise have been painted over with the dust in place.

The grouting of brick or masonry bridge structures could frequently add appreciably to their strength, and the use of small quantities of a dispersing agent could help the penetration of the grout considerably without reducing its strength. In many of the older brick arch bridges, however, the sand used in the mortar was very fine, and where water percolating through the joints had washed out most of the lime, it was difficult, even with a dispersing agent, to get the cement grout to penetrate that fine sand and reform it into a mortar. There were probably a large number of old brick structures whose mortar was deteriorating, and a solution to the problem of saturating the fine sand in the joints with some substance which would give it back its original strength as a mortar would be a notable contribution to bridge maintenance.

In cases where the ground water behind abutments and wing walls contained chemicals detrimental to the mortar, grouting with aluminous cement had proved effective.

Most bridge abutments and retaining walls had weep pipes to drain the fill at their back, but in many cases the inner end was surrounded merely by hard core before the fill was placed against it; and where that fill was of clay, it was not long before it worked into the voids in the hard core and the weep pipes ceased to function. That could be avoided by covering the hard core with a few inches of suitably graded ballast and sand.

Mr Ernest Bateson said that the bridge designer could undoubtedly contribute a great deal towards the satisfactory subsequent maintenance of a structure by avoiding water traps and narrow inaccessible gaps, such as steel sections with very small spaces between batten plates, lacing bars, and so on, which were completely inaccessible. Facilities for easy access for subsequent painting should also be considered in the design of new bridges.

With regard to surface preparation, his assessment of the various processes was as follows. Weathering and wire brushing, even it it were carried out efficiently, was an erratic process. It could not be related to planned production and it involved the dangerous effects of early corrosion, which Dr Vernon and others had often emphasized. It could not be considered as a satisfactory process for plain material and was even worse for fabricated steelwork. Pickling and phosphating provided a good and reasonably cheap process for plain material, but should not be used for fabricated work. Flame cleaning was good but fairly expensive for existing steelwork and in-situ preparation of steelwork when sand blasting was impracticable. Sand- or grit-blast treatment was the best method of preparing steelwork and was imperative for work which was to be metal-sprayed.

Reference had been made in the Discussion to metal spraying on flame-cleaned steel. He suggested that that was entirely wrong and that it was not an acceptable procedure. Sand blasting was not merely the cleaning of steel or the removal of foreign matter: it was a question of surface preparation and of producing a proper texture which would subsequently provide the necessary adherence for the sprayed metal.

A few years ago, he had seen some tank plates treated by the three-tank method—pickled, washed, and phosphated. Since those plates were afterwards to be welded, they had been painted round the edges with a 3-inch-wide band of linseed oil and the central part with red lead. The plates had been left lying in the yard and after several months were definitely rusty on the oil area, whereas the central part was intact. Incidentally, the same works had been pickling bundles of angles, but the pickling was very indifferent; the angles nested together and there had been a considerable shielding effect, so that when they were removed much wire brushing and scraping was necessary, which could have been avoided if the angles had been treated separately.

Mr Bateson mentioned some exposure tests which had been carried out recently in a locomotive shed, where there was a fairly vicious atmosphere. The specimens had been of mild-steel plate, some sprayed with aluminium by the wire process and some sprayed with aluminium by the powder process; some with a dual coating of aluminium powder on zinc powder, and some with zinc powder only. Contrary to the results of Dr Hudson's earlier experiments, there was little difference between the aluminium powder and the aluminium wire coatings, although the wire coating seemed to adhere better than the powder. All the aluminium coatings, contrary to expectations in such an atmosphere, were inferior to the zinc, which had been expected to disintegrate fairly quickly owing to the sulphur fumes.

The specimens had also been painted with zinc chromate in chlorinated rubber, and after 10 months the paint on the sprayed specimens had suffered appreciably, but the plain steel plates could hardly have been more rusty if they had been exposed in the unpainted condition. He did not offer that as a criticism of the paint, but it showed the definite value of a sprayed metal coating.

Referring to the considerable number of figures of costs given in the Paper, Mr Bateson said that he had become very tired of quoted works costs, because he was always concerned with the cost to the man who had to pay the bill, and he had had rates quoted varying from 4*d.* to 3*s.* 4*d.* per square foot for flame cleaning, and from 2*s.* to 6*s.* per square foot for sprayed steelwork. As Mr Fuller had inferred, the structural steelwork trade did not favour anything but the old-fashioned scrape and red oxide, but facts had to be faced. Until proper cleaning and protection were organized on a productive basis, it would not be possible to protect steelwork in such a condition as would gain favour subsequently from the maintenance engineer.

Dr J. C. Hudson asked what depth of cover was regarded as desirable for the steel reinforcement and the steel meshing underneath concrete, as in guniting? Mr O'Malley had stated that the material was put on in 2-inch layers, but he had not specified a minimum depth.

Dr Hudson emphasized, as had Mr Bateson, the importance of design in preventing localized corrosion, and also the desirability of providing, from the beginning, suitable facilities for future maintenance. Although Dr Hudson was not in a position to comment on the information regarding costs given in Tables 11–17, it was clear from the remarks of previous speakers in the Discussion that there was some divergence of opinion as to what the costs were; he thought it valuable, therefore, that an attempt should be made to present such comparisons and to put the whole subject on a practical basis, which was necessary if the processes concerned were going to be used in industry.

Reference had been made by Mr Davies to research which had been carried out on the correlation between the atmospheric corrosion of metals and the meteorological conditions. Ellis,[1] in the United States of America, had recently investigated the subject in the case of zinc, and had confirmed the statements made in the Paper, that rainfall, as such, was not of paramount importance and that the determining factors were the atmospheric humidity and the pollution.

The advantages to be gained from the use of low-alloy steels had also been discussed in Part (*a*) of the Paper, and an advantage of about 20 per cent. had been suggested for a copper-bearing steel; quite rightly, that was a conservative estimate, and Dr Hudson would put the figure higher. The British Iron and Steel Research Association had found, for example, that steels of the copper-chromium type (containing about 1 per cent. of chromium and 0·5 per cent. of copper) and some of the nickel steels, with 2 to 3 per cent. of nickel, which would be used only for special constructional purposes, had a resistance, when exposed in the bare condition, of from three to four times that of ordinary mild steel. They still had to be painted, and therefore the advantage of using those steels for a painted structure was not so great.

With paints of the conventional type generally used for engineering purposes, there was a rough general relationship between the efficiency of the paint and the paint-film thickness. Individual paints might deviate from that relationship, but the application of inadequate thickness was a severe handicap to any painting scheme. Judging from the experimental data obtained by the Association, Dr Hudson thought that it would be unwise to put into service in Britain any steel structure carrying a paint film which was thinner than about 0·005 inch. That, of course, corresponded to good engineering practice—the application of three or four coats.

With regard to metallic coatings, he agreed with Mr Davies that zinc and aluminium were the two most generally useful metals for that purpose. Perhaps lead could be added to the list if a way could be found of overcoming certain difficulties associated with application on the one hand and the toxic properties of lead on the other. Before the 1939–45 war, the German State Railways had treated a bridge by covering it with electrically-deposited lead and had obtained good results. Lead coatings had good properties in an industrial atmosphere, and the only difficulty was to get them on.

If linseed oil were used as a temporary protective coating, it should be put on thinly. Mr Bateson had made the point that if there were a linseed-oil film underneath the inhibiting paint, there was obviously no contact between the inhibitor and the steel. Dr Hudson thought that linseed-oil films, if rubbed on or brushed on very thinly, at the rate of 2,000 square

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[1] O. B. Ellis, "Effect of Weather on the Initial Corrosion Rate of Sheet Zinc." Appendix to Report of Committee B–3 on Corrosion of Non-Ferrous Metals and Alloys. Proc. Amer. Soc. Test. Mater., vol. 49 (1949), p. 152.

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feet per gallon, were of value. In normal circumstances they would protect steel for 2 or 3 months, which was a reasonable time. At the end of that time the attack would be sufficient to enable the oil film to be removed by the ordinary scraping methods, without any difficulty. If a thick oil film were applied, any attempt at scraping would result in skidding of the tool along the surface, which would lacerate the oil film and render it unsatisfactory for paint applied on top of it. The best use of linseed oil was for relatively thin plates, such as those used for gas-holders, which would have comparatively thin mill scale. A heavy section, such as a joist with a $\frac{3}{8}$-inch web, would, in general, have a rougher mill scale, which might interfere with the efficiency of the linseed oil.

Mr J. Barrington Stiles welcomed the collated research into zonal conditions of exposure which Mr Davies had made. The Metallizing Equipment Co., Ltd had just published a series of eighteen different specifications to cover the various conditions of exposure normally encountered. Those systems took into consideration the factors envisaged by Mr Davies, and recommendations had been made not only with regard to the preparation and appropriate metal and thickness but also, which was equally important, with regard to the sealers or paints to be employed. With both zinc and aluminium, wide use was made of vinyls, although chlorinated rubber was preferred as a sealer for certain zinc-sprayed steelwork.

Table 10 should be studied carefully; it represented the most realistic of the tests, since it dealt with a painted metallic coating which was normal and recommended practice. It showed clearly that the appropriate metal, when sprayed and suitably painted, was the best treatment that could be applied. It would be noted that in a polluted atmosphere, such as that of Sheffield, aluminium should be the obvious choice, whilst painted sprayed zinc of approximately the same thickness behaved much better than the painted galvanized samples. Even one-third of the quantity of sprayed zinc, when painted, was superior to the painted heavily galvanized sample.

Tests and experience in the field had proved that in zones where zinc was preferred, as for instance in rural areas, although sprayed zinc behaved in much the same way as hot-dipped zinc when not painted, the spray method was outstandingly the better when both were appropriately painted. That was largely due to the excellent key for paint provided by the sprayed surface. Zinc or aluminium coatings, selected to suit local conditions and given intelligent after-treatment in the form of appropriate sealers rather than conventional painting, provided a means of ensuring long-term protection at minimum cost.

Mr Stiles emphasized particularly the havoc wrought by long periods of neglect, as during the 1939–45 war, and the heavy cost of attempts to stem temporarily the toll of corrosion. The incidence of damage caused by such emergencies should be much less when a treatment was selected such as properly-sealed metal spraying, which did not require such frequent maintenance. Another point arose there, in that, by the methods used to achieve shorter periods of protection, there was greater risk at all times of some attack in certain areas of a bridge. Since the painting period should be based on that, and sometimes was not carefully adhered to, a slight attack in that area might give rise to pitting, which would accelerate further corrosion, and the problem would become worse rather than better.

Mr Davies had been unduly conservative in his speed-of-application figures for wire-metal spraying and, as would be expected, his costing for hand metal spraying—which he had not defined as zinc or aluminium in Table 17—would be heavy for the former and very heavy for the latter. Shot-blast and metal spraying work comparable to that indicated in Table 17 was being undertaken for about half the costs indicated. If 50 per cent. were added to the actual figures to allow for less economical work, or for any other objection which might be envisaged, an initial cost would be established which would keep the curves given in the Paper, for metal spraying, lower than the others, on a 50-year basis. If the cost were still considered high, only those areas most subject to corrosion would need to be metallized.

Bridge owners and designers should be interested in the relative maintenance costs, taking into account the extra capital outlay. Mr Davies, however, had given an erroneous picture of metal spraying by over-estimating the initial costs. If in place of the resin solution mentioned, the appropriate vinyl were employed, at slightly higher cost, the curve would level off to show even greater economy.

Also, Mr Davies had not emphasized the financial advantage associated with the process which, he had acknowledged, required the least frequent attention. Since labour costs increased inexorably, the maintenance costs given in the Paper were likely to be much too low. All the curves, therefore, should be compensated for that, when again the advantages were with metal spraying. Mr Stiles was convinced that the money spent to-day to save labour in the years to come was a wise investment, and it was for that reason that he emphasized the longer period of protection which was afforded between the periods of repainting.

With reference to *Fig. 12*, item 3, the unusual increase in roughening of a grit-blasted surface by subsequent painting would be expected only if the surface being treated were inverted and the paint were too thin. From his own experience, he did not think that that was a normal effect.

He was unable to understand the economics of the flame cleaning given in Table 16, and in particular why No. 3 cost less than No. 5, which, unless he was wrongly interpreting the Table, suggested that the more flame cleaning was necessary, the cheaper was the job. His company's experience of flame cleaning was that it was extremely slow and cost much more than abrasive blasting, whilst producing inferior results.

Reference was made in the Paper to experimental evidence regarding the phenomenon of immediate cathodic potential peculiar to sprayed aluminium in certain circumstances, and to early rusting. Although of academic interest, in practice that had no significance if proper sealers were used. It was stated in the Paper that solutions considered suitable for the prevention of that rust staining had been developed, but Mr Stiles would point out that Mr Tolley's suggestions [13]—the application of either dilute sulphuric acid or a salt solution—were not only unreliable but also were dangerous in practice. There was no necessity for destructive treatment of the aluminium coating, costing part of its life, and engineers would normally prefer to seal their coatings by a method such as the application of an appropriate paint, which would add to rather than detract from the value of the metallic coating. Scratch tests for those who preferred laboratory methods, and the evidence of mechanically damaged aluminium coatings in the field, bore witness that in service aluminium behaved anodically with respect to the steel with which it was in contact and protected it by sacrificial action. The need to make the initial sacrifice suggested did not, therefore, arise.

It would be interesting to know why Mr Davies recommended copper guttering. It had often been employed, but Mr Stiles had heard it referred to as a source of accelerated corrosion.

The skilled labour that Mr Davies had said was necessary for metal spraying was not, in Mr Stiles's opinion, required, except in the sense that a painter had to be a skilled operator. Mr Davies had said that the metal-spraying operator should be responsible for the quality of the metal, but Mr Stiles considered that the operator would have no more responsibility for the quality of the metal than would a painter for the quality of the paint which he was brushing.

Mr G. A. Wood thought that no one should be allowed to design a bridge until he had had long experience of the maintenance of bridges, because some features of design were impossible from the maintenance point of view. Mr Bateson had mentioned one of them, namely, steel surfaces such as angles back to back about ½-inch apart, which made painting and cleaning impossible. The paint could not be made to adhere in such places, which became rapidly choked with mud, dirt, and damp and suffered badly. In concrete bridges the cover of concrete over the steelwork was sometimes, in the interests of economy, dangerously low; that showed itself some 20 years later by extensive failure of the concrete cover on a structure originally intended to have a long life without requiring much maintenance.

An unsatisfactory feature that Mr Wood had seen in a steel bridge was that of girders partly encased in concrete. The joint where the concrete met the steel was always difficult to deal with; corrosion started and got inside the concrete, and it was impossible to reach it without ripping the concrete away. The extra money spent in completely encasing the steelwork was well repaid. Another fault, common in girder bridges, was the footpath of a highway bridge which came tight up to the web of the girder. Corrosion started along the edge of the footpath and went on for about 3 inches up. The only way which he knew of dealing with that was to take out the side of the footpath down to the concrete decking or the top of the steel decking, to put in a concrete fillet extending to 6 inches above footpath-level, and to coat the joint between the concrete and steel with about 6 inches width of asphalt (3 inches up and 3 inches down), or, which would be cheaper, to spray on a hot bitumen of the type used for road emulsions.

With regard to the roughening of inverts, plain inverts often resulted in an abnormal scour hole at the bottom of the invert. The placing of stones in the invert had surprising results, and it would be of interest to anyone with aesthetic leanings to know that a much better appearance was thus imparted to flow of water. It was important, however, that the upstanding stones should not catch sticks and litter : there should never be a vertical face or corner on the stones, and they should be so low that anything swept in among them would be swept out by the first rush of water in the next spate.

Referring to repairs to masonry arch bridges, he was surprised that no mention had been made of saddling rather than putting a layer inside a failing bridge. His experience had been that arch bridges failed in the spandrels rather than the arches, and the saddle made it possible to strengthen the arch and strengthen the spandrel walls.

It was amazing how many bridges had aprons which had no cut-off wall, but it was not surprising that it was never possible to find the person responsible for putting them in, because presumably he had been sacked long ago ! Even a light sheeting of timber piles would give protection to the edge of the invert, and such sheeting was probably put in for construction purposes, so it was surprising that it was not left. Mr Wood thought that in any hole scouring round a bridge it was better to place large stones—perhaps restraining their movement by light timber piling —than to try something solid like a concrete apron, because whatever happened the stone was comparatively cheap and could not be underscoured.

*** **Mr D. E. Hennessey** regretted, but thought it inevitable, that Mr O'Malley's Paper, whilst dealing admirably with repairs necessitated by defects in design and construction, failed to give the items and cost of maintenance proper.

If the economics of maintenance of concrete bridges could have been presented and analysed in a manner comparable with the figures for steel bridges, the Paper would have been of considerably greater value. A more statistical approach to the subject of the failures and deterioration of early concrete structures would have been welcome. He believed

*** This and the following contribution were submitted in writing.—SEC. I.C.E.

that the Ministry of Transport had felt concern about the extent of repairs necessary to reinforced-concrete highway bridges. Could Mr O'Malley, therefore, give some information about the proportion of such bridges which had needed repair since their construction, the money spent (expressed as a fraction of the original cost), and the principal causes of the defects?

Mr Hennessey considered that most of the faults found in concrete structures should be eliminated at the time of construction. More up-to-date knowledge and technique and particularly improvements in cement manufacture, specifications, supervision, and systematic site-testing of materials and finished concrete were now contributing to that process. Unfortunately, the most important factor, site workmanship, would improve only if the trade of "concretor" were raised to the same status as the other primary building trades.

Whilst guniting and the application of cement mortar raised problems of their own—such as shrinkage, cracking, and imperviousness—that medium, combined with the use of tensioned wires, provided they were well bonded and protected, might afford a useful method of repairing or strengthening bridge beams.

The efficacy of preventing scour by roughening the concrete invert of river bridges was doubtful. If the water had to get through the bridge opening, the only effective way of slowing it down was to widen the opening.

Allowing stream estuaries to silt up might conceivably be justified if the equilibrium of the regime were assisted. On the other hand, it might easily lead to meandering in the lower reaches, causing the river bed to widen or even to outflank its bridge sites. Not all estuarine shoals were formed simply by the deposition of river-transported material. Other factors—for instance, sewage or mussel banks—might be responsible and should be dealt with according to the scale on which they occurred.

Mr F. A. Rivett compared the figures given in Part (*a*) of the Paper with those which had been the experience of Schori Metallising Process Ltd—one of the few companies with large-scale experience of the sand-blasting and metal-spraying of bridges, both in sections before erection and in situ some years after erection, including large-scale bridgework in Great Britain, Denmark, and Africa.

With reference to *Fig. 16*, which showed a comparison of estimated total cost of maintenance employing different methods of protection over a 60-year period, he disagreed completely with the results shown. He thought that the main error had arisen in assuming that steelwork which had been grit-blasted and zinc-sprayed 4 mils thick, and subsequently painted with one coat of zinc chromate paint and two coats of finishing paint, would require repainting once every 12 years. The evidence was that the period was likely to be in excess of 20 years, which produced a fundamentally different result in the graph. For example, the suspension links of the Menai Bridge, which had been zinc-sprayed and painted in 1939, were exposed to a heavy marine atmosphere and had not yet been repainted, nor was there any intention of painting them at present. He had visited the bridge recently and had found that the deck steelwork, which had required frequent attention because it had not been rust-proofed, had been repainted dark grey and that the outside links in the suspension chains had also been painted the same colour in order to give the bridge a uniform appearance. The inner surfaces of the links, which were 18 feet long and in groups of six with considerable gaps between, had not been touched and it was very easy to examine the condition of the paint film. A thorough examination had shown no sign of failure.

Mr Fuller's statement that it would be difficult to sand-blast an existing bridge without closing it to traffic was incorrect, provided that reasonable precautions were taken by sheeting up to prevent sand and dust from falling on passers-by. For example, sand-blasting and zinc-spraying of the large Oddesund road-and-rail bridge in Denmark had been going on for about 2 years and would be completed by the end of 1951. At no time had it been necessary to close the bridge, although occasionally half of the roadway was closed. In general, so much experience in the blasting and metal-spraying of various types of steelwork in situ had been gained that it was most exceptional to encounter any difficulty which could not be surmounted.

Mr Davies, in reply, said that Reference No. 12 concerned research carried out by Mr Tolley[13] on the action of sprayed aluminium when exposed to various media, and also the research work done by the Corrosion Committee, including that of Dr U. R. Evans of Cambridge. The reference was to that subject as a whole, not to the laboratory use of sulphuric acid in accelerated tests to simulate the effect of sulphurous atmosphere on sealing up the pores of aluminium-sprayed coatings. Some criticism had been made on the effectiveness of those coatings on structural steel and it was considered questionable whether the use of aluminium was worth the extra expenditure, because after it was put on the whole surface rusted. That happened because the porous nature of the coating allowed rust to come out from the initial phase in the oxidation of the steel, due to moisture penetration through the porous coating; but that stopped after a time, when aluminium hydroxide was formed, and sealed the pores. However, people did not like to see an expensive surfacing smeared with rust. The coumarone synthetic resin paint had, therefore, been introduced as a sealer to overcome that problem. In fact, however, the coating eventually sealed itself by the products of corrosion. There was good reason to believe that, during that phase, the aluminium, which was originally cathodic to steel, became anodic, that was to say, sacrificial to the steel.

Aluminium was often stated incorrectly to be anodic to steel, but its peculiarity was that in hard water it was cathodic and in sea water anodic whilst during the course of weathering it changed again with change in its chemical behaviour.

With regard to the speed of metal spraying, Mr Davies had been told by one of the specialist firms that the figures which he had quoted were far too high. The matter really depended on the diameter of the wire which was used. Mr Stiles no doubt thought that $\frac{3}{16}$-inch-diameter wire should be used; but other authorities limited it to 2 millimetres and, if a greater diameter than that were used, a very porous coating might be obtained.

In answer to the remark that the initial costs given in the Paper were too high, those were actual costs of bridge jobs built or projected in Britain, so that there was really no case for argument. If they were considered high, then the answer was for metallizing firms to co-operate in reducing them, and in due course that should be possible.

Mr Stiles had referred to the increase in roughening of a grit-blasted surface by subsequent painting. The ridge shown in *Fig. 12* was probably due to the paint itself. Ridges were formed when painting, and on the Golden Gate bridge there was a strict instruction that the final coat should be done up-and-down, at least where the steel was open to the weather; Mr Davies did not know if that precaution had been insisted upon elsewhere.

The use of copper for gutters was a time-honoured procedure, and he saw nothing wrong with it provided any possible electro-chemical action with other materials was not set up. The copper was cathodic to steel, to which it was not attached, being fixed to the concrete forming the bridge deck. He did not think that engineers made a point of putting it on the steel; it was usually attached to the deck concrete.

So far as the use of skilled labour on metal spraying was concerned, probably many people who were engaged on maintenance would feel that the man who painted bridges ought to be a skilled man; and Mr Davies's own view was that a man who metal-sprayed bridges should also be a skilled man. The question of coating thickness was important, and unless the operator were conscientious and maintained the correct nozzle distances and so on, the results would not be satisfactory. Metal spraying involved considerable expense, and the man who did the work should be more skilled and reliable than the ordinary painter. In any case, the view of the maintenance engineer was that a painter should be a skilled man.

More information on synthetic sealers, apart from that mentioned earlier to which Mr Stiles had referred, would be useful. Such sealers should be the subject of research by nationally known authorities, in so far as the claims made by Mr Stiles were concerned.

The case put forward for the advantages of sprayed metal coatings when neglect of painting, inforced or otherwise, took place, was sound, but perhaps open to abuse. For instance, such neglect might be treated indifferently, judging by some examples of maintenance encountered, so that the next step taken would be either to renew the disappeared original metal-spray coating, in situ, or forego that and rely in the future on paints only.

Alternatively, if repainting were necessary at, say, 8- to 12-year intervals (the full effective paint life), it would be found that a copper-bearing mild steel or, better still, a suitably constituted low-alloy steel, pickled and painted, would corrode so much less rapidly than plain mild steel that repainting at precise time limits would, within reason, be unnecessary.

Mr Stiles's suggestion of metal spraying vulnerable parts of a bridge was certainly worth closer attention, and Mr Davies was not in disagreement with him on the advantages offered. It was sound sense to test out the process on certain items before tackling bigger work.

Mr Stiles had stated that shot blasting and metal spraying were being done at about half the rates quoted in Table 17. Perhaps he had overlooked the wording in the title to that Table, which stated that the costs were for hand operation. Further, the costs quoted were those which would be entered in a priced schedule for processed steel-work as it left the works, a further schedule item having to be priced for any necessary processing at the site, for instance, damaged coating and site joints. Considering the lowest cost given in the Table—13*s.* per square yard—Mr Stiles's statement meant that he could do the type of members used in bridges, of the weight for that item, at say 7*s.* per square yard, and that would be his price to the purchaser f.o.r. works. As low a cost as that was not forthcoming from the mechanized plant in Britain processing plain material; Mr Stiles appeared to be in serious error in his statement.

Mr Stiles's had said that if, in *Fig. 16*, his cost for aluminium spraying 40-ton bridge girders were increased 50 per cent. to cover the cost of handling, labour, and plant, curve number 9 would be the lowest on the chart at a 50-year period. That meant that the total initial cost for curve 9 (ordinate at 0) would be 28*s.* 9*d.*, less the difference between the ordinates of curves 9 and 11 at 50 years, or 36*s.* 11*d.*—29*s.* 5*d.*=7*s.* 6*d.*; that was, a total initial cost of 21*s.* 3*d.* Hence Mr Stiles's all-in cost for grit blasting and metal spraying of that class of work, excluding cost of use of buildings, cranes, and labour on cranes, etc., was equal to $\frac{2}{3}$ of 21*s.* 3*d.*=14*s.* 2*d.* per square yard. That seemed a reasonable cost until one realized that it also included erection of scaffolding at the site, shot blasting and metal spraying of all site splices in situ, and a certain amount of repair work to parts of the shop-applied metal-sprayed coating, damaged in delivery to site and during erection, together with the cost of two coats of paint after completion of site metal spraying. That site work would cost not less than 3*s.* 6*d.* square yard, leaving 10*s.* 8*d.* square yard for the total cost of grit blasting, metal spraying, and a sealing coat of resin solution at the works—a cost which Mr Stiles would know was about 7*s.* 6*d.* too low.

In reply to the inquiry why curve 5 was lower than curve 3 after 50 years, and Mr Stiles's remark that that seemed to indicate that the more flame cleaning done the cheaper the maintenance would be, the answer was that he had forgotten to look at the last column in the tabular key to *Fig. 16*. He would see from that that the repainting intervals were 5 years for curve 3 and 7 years for curve 5.

When quoting relevant factors affecting the quality of metal-sprayed coatings, Mr Davies's wording had been couched in terms of the supervising engineer's responsibility, rather than upon associating labour with responsibility for the quality of the metal used for spraying.

It was reassuring to know that Mr Stiles had been thinking on the same lines as the Author in that specifications should be attuned to the conditions of exposure.

Mr Davies agreed with Mr Chettoe that bridges had been neglected to a great extent in earlier days, when more emphasis had been given to building new bridges. Nobody would let his own house go for 15 or 20 years without any maintenance, and it seemed a shame that structures which were publicly owned should be allowed to suffer in that respect. He believed that it would be prudent if some independent well-informed person or authority were authorized to take the necessary steps to prevent structures going too long without attention.

There was evidence to show that the pickling process was being more widely used for the removal of mill scale. Mr Berridge had also mentioned that in connexion with his own recent experience. What was important was that for some years many works engineers directly concerned with the fabrication of steel bridgework had recognized the merit of efficient mill-scale removal, either by the chemical process of pickling or by the mechanical process of grit blasting. In fact, certain works had been equipped for several years with plant for dealing with either process, whilst other works had been using one or the other process for some time. It should not be assumed, however, that for the moment an unlimited tonnage could be processed in a short time by the plant at present in use at various works, nor that the capacity of pickling plant be overlooked when considering the dimensions of the plain steel material to be dipped. Tanks capable of pickling material, 40–50 feet length and in any rolled width, had been in use for some years. By the use of double dipping the length and width of tanks did not need to be anything like those of the biggest pieces to be treated.

The removal of mill scale had often enough been stipulated as a *sine qua non* if the protective coatings applied on the steel surface were to be given the opportunity of developing their full useful lives. Experience had shown also that scale removal by the weather, and then applying paints on the cold steel surface after hand preparation, gave unreliable and often poor results, so far as paint life was concerned. Therefore mill scale removal at the works or at the site by some efficient process had been receiving growing attention. That concerned, for the present, only the most efficient method for removing the mill scale, and not the idea of altering the nature of the base metal upon which the protective paint coatings were to be applied.

If the efficient removal of mill scale was the objective to be achieved, then there was little argument as to which process was cheapest. Some chemical processes of pickling would remove mill scale much more efficiently, rapidly, and economically than, for example, hand grit blasting. Pickling cost about 1*s.* 10*d.* per square yard of surface, compared with about 4*s.* to 5*s.* per square yard for grit blasting. If the pickling process were accompanied by a corrosive inhibited phosphoric acid treatment (in heated chemical baths)—certain industrial firms were equipped for pickling and phosphating—and one coat of inhibitive primer applied on the hot steel after chemical treatment, the cost was 2*s.* 3*d.* to 3*s.* 6*d.* per square yard of surface. The maximum cost of complete plant for chemical treatment, for instance, by the pickling/phosphating process, had been estimated by Mr Davies in 1948 at £60,000, of which £27,000 was for a building equipped with three 10-ton cranes. Plant of that type was capable of dealing with average rolled steel material at the rate of about 500 tons per week, pickled, phosphated, and painted. Much less costly pickling plant was in use where tonnage output was governed by shop fabrication output at smaller works.

Plant for automatic grit-blasting of the type of structural steel common in heavy bridge-work, if eventually constructed, would no doubt give a production rate equal or possibly greater than that of the chemical process.

From the results of research so far available on the lives of paints on a variety of surface preparations, including the use of sprayed non-ferrous metal undercoatings exposed to a heavily polluted industrial atmosphere, as at Sheffield, it would be seen from *Fig. 16* that four coats of paint (two red lead plus two red oxide) on pickled and phosphated steel was the most economical treatment.

That assessment, it should be made clear, was based on the life of the paint only, and not on the combined life of the paint plus any undercoat of sprayed non-ferrous metal, as used in some of the procedures. To allow a sprayed metal undercoat to suffer direct attrition from an atmosphere of the Sheffield type, by neglect of timely renewal of paints, would be a poor return on the initial relatively high expenditure in applying the metallic coating. From Table 9 it would be seen that after breakdown of the paint the metal coating would have a life to grade " fair " (5 per cent. surface rust) of about 4 years at Sheffield for aluminium and of more than 5 years for zinc (see Reference 9, p. 189, *ante*). For that reason the life of the paint on sprayed metal undercoats (see Table 10) should be taken as the criterion. For three coats of paint on non-ferrous metallic sprayed coatings, the intervals between re-paintings had been taken as 12 years at Sheffield ; and those for two coats of paint as 10 years.

Since much of the information given in Part (*a*) of the Paper was based on the research work already completed and still being carried out in

Britain, the opportunity should not be lost of following up the lead given here, by reference to additional results of research as those were published in the future.

The question of whether sprayed metal undercoats should be used in polluted atmospheres therefore depended upon: (*a*) the type and intensity of pollution, for instance, industrial, marine, or a combination of those; (*b*) the life of the metal undercoat when painted and when the paint had failed (as might happen should enforced or inadvertent neglect of maintenance take place); (*c*) the return on initial investment as compared with, for example, the pickling and painting process in combination with corrosive retarding elements in the steel (principally copper); and (*d*) the desirability of basing choice of treatment upon the longest intervals between repainting rather than upon the overall cost of maintenance (for instance, stainless steel would not need protection coatings, but the initial capital investment would be prohibitive). Mr Davies believed that the answer to those points would be found by economic assessment of the research results which would finalize the interim information tabulated in the Paper, taken in combination with the financial and practical facilities offered by the purchaser and by industry respectively.

The definition of the serviceable life of the paint given in Tables 5–7 inclusive, was given in the Fifth Report of the Corrosion Committee (Reference 3, p. 188, *ante*). That graded the condition of the paint by the allocation of adverse marks according to the type and number of paint failures on the surface areas of exposed specimens.

The standard grading given in that Report was reproduced below for quick reference, and was based on specimens of steel plates having 150 square inches surface area each side.

Adverse marks	Type of fault	Remarks
0	No fault	Perfect condition
1	Pin-head blisters	
2	Coarse blisters	
3	5 faults or less	
4	6–10 failures	End of serviceable life
5	11–25 ,,	
6	26–50 ,,	
7	51–100 ,,	
8	Over 100 ,,	

Grading of (1) represented about 1 per cent. of the area of painted surface, whilst grade 4 represented 4–5 per cent. and had been taken as the limiting valuation for serviceable condition of the painted surface as a whole.

It was of interest to mention that certain standards in use in France were employed in testing the serviceability of painted steel work. They prescribed that when the paint had broken down over an area of 3 per cent. of the painted surface its serviceable life had been reached. Those specifications referred to the use of graph paper and also employed sample photographs of paint conditions for the purpose of facilitating the assessment of painted work.

Mr Fuller had stated that the prices quoted in Table 11 on the maintenance of existing structures did not agree with his own experience in London. Those costs were only a few of a great many which Mr Davies had, and it was perhaps the case that in certain instances Mr Fuller was concerned with more costly maintenance than any mentioned in the Paper. Mr Davies's figures, covering structures which cost from £4,400,400 down to £30,000, had been taken from a whole group of bridges with a view to their being fairly representative.

It was perhaps not surprising to hear of the difficulty experienced by Mr Fuller in trying to check the comprehensive information given in Part (*a*) of the Paper; Mr Davies had himself spent several years following up research and the results of experience both at home and abroad before getting down to the preparation of the Paper. The subject was one of some complexity and, in view of conflicting opinions so freely expressed by many concerned with maintenance, he felt it timely that attention be drawn to the wealth of information available from fundamental research, including field tests, and from a wide survey of the practical application of different procedures and techniques concerned with maintenance of bridge steelwork. If the information presented were in conflict with opinions held by individual engineers, then the Paper had achieved a useful purpose in stimulating an active interest in facts and events encompassed by their own sphere of activity. For example, it might well happen that, whilst methods employed in the past had given general satisfaction, certain limited instances of a local nature causing troublesome maintenance might be rectified by one of several procedures described. Since much of the research referred to was still in progress after several years of testing, it should not be necessary to emphasize the importance of keeping in touch with the results of completed research, as they were released.

In commenting on the influence that detail design had on subsequent maintenance, Mr Davies mentioned the extra capital cost which that would entail and questioned whether such extra cost would conform to present Ministerial policy. In certain respects improved detail design might entail higher initial costs, for instance, a bridge-deck of concrete would be much heavier than a timber deck and would therefore require more robust construction to support it, resulting in higher capital expenditure. That fact had not, however, been allowed to outweigh the advantages in the wider use of materials more durable and impervious than timber for bridge-decks. Admittedly, that was perhaps an extreme example where initial extra capital investment was justified, and compared with that the vulnerable items mentioned in the Paper were relatively insignificant. It did not follow, in any case, that all improvement in detail would result in increased capital expenditure. For example, a nest of multiple bridge-bearing rollers, complete with oil-bath and hood, was more expensive than the less vulnerable type of bearing, which employed a much smaller number of segmental type rollers or robust struts, well spaced apart for ease of access for inspection at all parts of the bearing.

The importance of correct detail for expansion joints in road decks had not been given specific emphasis in the Paper, although deck joints were of course mentioned. Further amplification was not possible within the confines of the Paper, but it was believed that more attention would be given to that aspect of maintenance at some future date, when a Paper might be presented on the subject.

In dealing with bridge maintenance, Mr Davies felt obliged to contribute information which would be useful on the maintenance of existing bridges, as well as information affecting the maintenance on new bridge-work. *For example, in the case of maintaining existing bridgework, the information* given in the Paper on the effectiveness of a wide variety of paints, climatic effects, flame cleaning, and shot blasting were all of importance. Again, in the case of new bridge-work the information quoted included surface preparation, controlled weathering, metal spraying, design details, and so on.

Flame cleaning had been used on new bridge steel-work, but to a much smaller extent than on existing bridges where the use of that process had been justified on the score of previously excessive maintenance costs.

Mr Fuller's comments regarding the pickling of steel had been answered by Mr Berridge. As Mr Chettoe had previously raised that point, the matter had been adequately dealt with in the appropriate reply.

The opening paragraph of the Paper stated clearly that the information had been collated with the object of indicating how research and experience of certain processing could help maintenance engineers who were alive to the possibilities of improvement upon the performance compared with past practice, where the results had not been up to the average standards desired, whether the performance related to local features of a bridge or to the job as a whole. Where he was satisfied that the *ad hoc* practice employed by him in the past had given the results desired, then surely that was testimony to a long-standing appreciation of how to get the best out of a pot of paint.

It was quite evident from the interesting figures quoted by Mr Fuller that flame cleaning of defective paintwork would be unsatisfactory from the economic point of view, since the defective paintwork at the time of re-painting was only about 3 per cent. It was obviously cheaper, in those instances, to adopt spot scraping and re-painting rather than to employ more punitive methods. Mr Fuller had agreed, however, that where the percentage of paint deterioration warranted flame scouring, then its employment might be justified. Instances of that justification included maintenance programming for large numbers of bridges where paint deterioration had been serious, owing to enforced neglect of maintenance as the result of wartime and post-war restrictions. The resulting effect of cumulative maintenance arrears, labour shortages, and rising paint-price trends had favoured the use of flame cleaning as more expeditious, less dependent upon atmospheric conditions for paint application, less dependent upon muscular effort of the operators—and therefore more conducive to sound workmanship. The recognized merit of dehydration of the damp steel surface before the primer was applied was also a consideration.

The explanation for the apparently low average of 276 square yards or area flame-cleaned and painted per bridge was readily explained by the type of bridge, its size, and the area so treated. For the example referred to in the Paper, the sixty-seven bridges were of the short-span type and varied in form of construction, a number having only the bottom steel flanges exposed under concrete encased construction, others having concrete decks or steel girders, and still others having steel trough flooring. The areas flame cleaned depended upon the condition of the old paintwork, and that varied generally from 10 to 50 per cent. of the total of existing paintwork.

Questions as to sound paint damage could be answered only after an assessment had been made of the relative areas between deficient paintwork on both sides of a number of girders and the frequency with which breakdowns had occurred after repainting.

With regard to the use of sand blasting at site and the question of maintaining traffic while that was being done, the railway maintenance engineers were more qualified than Mr Davies to give an opinion as the result of recent trials.

For blasting, sand was preferred for in-situ site work and examples of its use on existing bridge work included the Storstrøm Bridge; whilst steel grit-blasting was preferred (owing to higher recovery and re-use factors) on new steelwork before its erection.

The rates quoted on p. 178 applied to the date given in the same paragraph, 1940. Present rates, as Mr Fuller had pointed out from his experience, were substantially higher. Those rates varied quite widely according to the type and size of bridge. For short to medium single-span girder road bridges the costs at present rates for repainting varied from 3*s.* to 6*s.* per square yard of surface painted.

The figure taken for pre-war cost per annum for painting bridge work could be seen on p. 178 to average 2*s.* per square yard and had purposely been taken to cover the higher costs charged on many short-span bridges just before the war. Much lower rates had been experienced in certain instances, including those for big bridges. An average of 12·5 square yards of painted surface to the ton of steel gave 25*s.* per ton for the cost of painting every 5 years; that was 5*s.* per ton per annum, pre-war, as stated in the Paper. Mr Fuller had referred to that as a low figure from his own experience, but, in fact, it was much higher (for reasons mentioned above) than the average pre-war rates on the larger Thames bridges, some of which had cost about 2*s.* 6*d.* per ton per annum, whilst certain short span bridges had also achieved that lower rate. Mr Fuller must therefore have been thinking of the latest post-war re-painting costs on Thames bridges.

The valuations given in the third column of Table 11 were, quite logically, those for the cost of construction of the whole of the bridge-work, and not only the spans themselves. The capital investment protected was therefore the total cost, and on that basis it was suggested that the total pre-war value of a Thames bridge would be nearer that given for item 3 of the Table. With regard to the annual cost of maintenance of that item, assuming that the bridge had been painted twice before the war at 4- or 5-year intervals, and once during or since the war, after a further interval of 10 years (owing to force of circumstances), then Mr Davies submitted that the average cost to date for painting, found by dividing all costs of maintenance since the bridge was built, by the total number of years to the next future repainting, would be not more, but less, than the figure of £680 per annum quoted in Table 11. His figures were based on one repainting contract only—the most recent.

For the purpose of estimating near-future painting costs, Mr Davies considered Mr Fuller's higher figure of £1,300 for item 3 in Table 11. Pre-war, the comparable figure would have been about £500 per annum for a Thames bridge. Then, neglecting capitalization on maintenance, the pre-war and post-war entries in the seventh column of Table 11 would read 0·0532 and 0·0508 respectively; that was to say, the capacity of maintenance financing to safeguard capital investment had not deteriorated compared with pre-war years. The comparable average figure for the life of the bridge—realizing that paint used from the beginning to the end had contributed to the increased valuation of the property protected—was seen to be 0·0264.

The percentage areas of scraping to bare metal quoted by Mr Fuller for the most recent repainting on four Thames bridges made interesting reading and demonstrated the gradual decrease of paint failures with time. Although it was not mentioned, the time interval between the last and previous repaintings must have had a direct influence on those percentages. In addition, depreciation of the protective coatings in certain of the bridges had no doubt stabilized at a very gradual rate, in which case the intervals between repaintings of those bridges could, with safety, be increased. Compared with the time intervals between bridge repainting in other large cities, apart from those in atmospheres with heavy industrial pollution and humidity, the 4- to 5-year intervals implied by Mr Fuller's earlier remarks appeared short, at least for older bridge-work. For example the repainting intervals using good paints, had been given as follows: Newcastle on Tyne (Tyne Bridge), 6 years; Sunderland (Wearmouth), 6 years; Middlesbrough (Newport Tees Bridge), 5 years; and New York, 7 years.

In the last-mentioned case, the Port of New York Authority owned and maintained the following bridges :—

Bridge	Type	Steel tonnages : long tons
George Washington	Suspension	92,000
Bayonne	Arch	26,800
Goethals	Cantilever	10,500
Outer Bridge Crossing. . . .	do.	14,400

Their own paint crews did the work which started about the 1st May and ended about the 15th November each year, no painting being done below 40° F.

Red lead paint was used for priming coats and red lead paste for spot priming, followed by a full coat of aluminium paint. The paint vehicle preferred was of the varnish type, which had a shorter drying time than linseed oil.

The amount of chipping and scraping was stated to be normally confined to small areas, whilst red lead paint was applied over about 20 per cent. of the area as an average, when repainting at 7-year intervals. As the result of wartime interference, the repainting intervals were nearer 10 years.

The widest variation in total cost of maintenance, between the eleven procedures shown graphically in *Fig. 16* and based on a 50-year period of time, was given in graphs 7 and 11—between the dearest and the cheapest on that reckoning. The difference was 8*s*. 10*d*. per square yard, or 30 per cent. on the lower figure of 29*s*. 5*d*. per square yard. Assuming that a new 3,000-ton steel bridge was under consideration, then the 8*s*. 10*d*. saving per square yard would represent a total saving in maintenance over 50 years of £16,000, or £320 per annum, and was therefore substantial enough to encourage attention.

Comparing the graphs for procedures 1 and 11, the saving over 50 years amounted to 3*s*. 11*d*. per square yard, or £7,300 total—£146 per annum. That was not so large a saving as for the extreme comparison, but the intervals between repainting were almost doubled, and so the demand on labour was halved.

Since *Fig. 16* applied to the worst type of polluted industrial atmosphere, some adjustment would be necessary for a less destructive atmosphere. Judging from the experience mentioned on Thames bridges, it would not be over-optimistic to expect an increased saving between items 1 and 11 if the graph were adjusted to the London atmosphere.

Mr Berridge had confirmed, from his experience, the importance he attached to efficient surface preparation and the great saving in maintenance costs that could be achieved.

It was interesting to note that Mr Berridge had not been unsuccessful in getting bridge steelwork pickled by certain structural firms, although he had not been so fortunate to date with his inquiries to the rolling-mills.

Referring to Table 4 giving the comparative lives of paints on various surface preparations, the reliability of the pickling process mentioned above appeared to be satisfactory for a 10-per-cent. acid solution and less satisfactory for a 2-per-cent. acid solution. Since a 5 per-cent. solution was the one in question its effectiveness would presumably lie between the valuations plotted.

Taking up the arithmetic in the example mentioned by Mr Berridge, where he had compared paint lines for 50 tons of bridge steel pickled in one case and hand wire brushed and painted as an alternative, Mr Davies estimated that for four coats of paint the total cost of future painting at 3-year intervals would be 16*s*. 6*d*. per square yard or, at 12 yards to the ton, £495 over an 11-year period. For the pickling treatment the cost of pickling was, as mentioned, £150 and the cost of first painting could be taken as £180—or a total of £330, which gave a saving of £165.

Wrought iron had often been favoured in the past for road bridge parapet railing and manufacturers had produced many attractive designs. Higher corrosion resistance had in the past been claimed and accepted when specifying wrought iron for that type of work. It was useful therefore, to get confirmation of that viewpoint by examining *Fig*. 7, which showed the relative corrosive velocities of various wrought irons and steels.

Bridge-deck expansion joints had previously been mentioned in the discussion, and the further remarks by Mr Berridge emphasized the importance of employing suitable designs, with particular reference to longer spans. A point which should also be kept in mind was that of the relation between the basic design of the bridge structure, in the case of multiple spans, and the number of deck joints that were required, whether of the expansion or the stationary type. That was a matter of considerable importance in relation to (*a*) the traffic riding quality of the deck wearing surface, (*b*) the maintenance of the road surfacing at joints, (*c*) wear and tear on the joints themselves, (*d*) maintenance below deck-level, and (*e*) the cost of providing joints, not forgetting the influence the number of deck joints had on the design and cost of the bridge bearings. Forethought in design of the fundamental structure of the bridge was therefore essential.

Mr Berridge's remarks on smoke plates were welcomed.

It was reassuring to have Mr Bridge's endorsement, as the result of his experience, of the relation between detail design and maintenance.

The remarks on flame cleaning were worthy of note, and Mr Bridge had sounded a warning regarding the heating of steelwork when concrete was against, say, the far side of a vertical plate or bar. The same objection had not applied in the past where concrete or masonry rested on the top flange of a steel girder being flame cleaned.

It was interesting to have the comparison between descaling by power wire-brushing and by the flame method. That demonstrated one of the claims made for effective de-scaling by flame, upon which some engineers had been sceptical.

On a number of occasions the question had arisen of metal-spraying steel surfaces without previous grit blasting. From Mr Bridge's remarks on the testing of metal spray on flame-cleaned steel, it was clear that results were not satisfactory.

Emphasis had been given in the Paper to the importance of correct detail, since that affected maintenance. Was it not equally important, in view of Mr Bridge's remarks on the more frequent painting of vulnerable items of construction, that the maintenance engineer should contribute his quota towards greater maintenance economy? It was common knowledge that certain features in a bridge had a voracious appetite for paint. Would it not be a good thing for maintenance engineers to prescribe one of several courses of treatment to cure those local ailments, either before the bridge was built or even when it was up? By that means a balance in performance of all parts was achieved and over-frequent erection of staging to deal with errant members was avoided.

In his remarks on surface preparation, Mr Bateson had favoured sand or grit blasting, over all other methods, but it was evident that he was thinking not merely of efficient mill-scale removal but also of the additional process of metal spraying. Mr Davies agreed entirely that metal-sprayed coatings, if used, depended for their full efficiency upon sand- or grit-blasted surface preparation, other methods of surface preparation being much less satisfactory. But surely the point to be kept in mind was that, for many years, the root of the problem of keeping down maintenance costs, particularly in the eaily life of a bridge, had been loose mill scale and pitting, caused by allowing the weather to remove some of the scale before paint was applied. The renewal of mill scale on erected bridgework by hand or by power-driven tools was arduous and unreliable and could be very expensive if thoroughness of workmanship were insisted upon—so much so that bankruptcy of the paint contractor might ensue. Scale removal should be regarded as one issue, and protective coatings as a separate issue, to be decided only after a thorough investigation of the conditions of exposure for the bridge in question.

The only methods of efficient scale removal which competed with each other were the chemical process of pickling and the mechanical process of grit blasting. As mentioned in the Paper, the former applied only to steel-work which had not been built up; that was to say, it would not be permitted on fabricated material consisting of more than one plate or rolled section. Grit blasting, on the other hand, would preferably be done after fabrication; but since no mechanical plant capable of dealing with heavy fabricated bridge-work had ever been built, the process would have to be done by compressed-air hand-guns, each de-scaling about 60 square feet per hour—about 25 tons of fabricated steel per week per gun. If the rate of dispatch of fabricated steel were 125 tons per week, then five guns would have to be in continuous operation; but extra guns, grit hoppers, extraction and screening plant, compressors, and so on would be required to take over and allow for maintenance.

Comparing the two methods, the chemical process was much cheaper to operate, as Mr Bateson had conceded, and was also quicker when hot acid was used, compared with hand grit-blasting, but, as the above figures showed, the latter process could readily be adjusted to production requirements. Initial investment in new plant was likely to be a good deal higher for the chemical process, depending upon the particular process in mind, compared with hand grit-blasting equipment. Mechanized grit-blasting plant, however, would cost substantially more than the average type of pickling plant.

Summarizing, chemical treatment for de-scaling was cheaper, but the material had to be processed before fabrication of built-up pieces, and precautions taken against corrosion before the site painting was done. Grit blasting by hand was substantially dearer but permitted de-scaling to be done after fabrication; for that reason it had the advantage of independence of all other workmanship except, of course, the application of the protective coating immediately the surface was de-scaled. It had the further advantages that the plant was mobile, the installations had to be only temporary, and parts of a bridge—girder ends, bearings, and so on—had to be treated only if so desired.

Mr Bateson had also mentioned that if pickled steel were left improperly protected for several months in the stockyard it would rust—which was true. Firms employing the process prior to their own works fabrication would take precautions against that. Where margins of plates left unpainted after pickling got rusty before assembly at site, the fine powdery rust was usually removed by swabbing with a phosphoric acid wash, leaving the metal quite clean. The possibility of defective acid de-scaling owing to bundling of material in the dip could be avoided so easily that it would be in the interests of the processors to run the risk of rejection of treated materials.

The tests of sprayed-aluminium and sprayed-zinc coatings exposed in a locomotive shed were interesting, if only for the fact that the results seemed to contradict research elsewhere.

Suitable paints for atrocious indoor polluted atmospheres were difficult to prescribe, and for that reason Mr Bateson's reference to two paints tried in a loco-shed was very instructive.

Mr Davies concurred with Mr Bateson on the usefulness of all-in prices as a guide to the purchaser or bridge owner. Where it had been possible to give such costs, based on tendered prices for work actually carried out, that had been done in the Paper. In other cases that had not been possible, simply because complete costs were not available—for instance, metal-sprayed heavy girders for new bridge-work.

Metal spraying had only in recent years been seriously considered on bridge-work and so far the few jobs done had served the useful purpose of giving some sort of yardstick regarding practical application, costs, and the protection offered.

Compared with alternatives it was expensive, and caution was necessary before prescribing metal-sprayed coatings on future bridge-work. Comparison should be made with other processes regarding capital to be invested by the bridge purchaser in the treatment, and also with the return of investment he could expect in terms of lower maintenance costs.

Mr Bateson's sweeping statement that the costs in the Paper were for shopwork only was quite wrong. In one part of one item alone—Table 17—were shop costs quoted. If he could have given the Meeting " all-in " costs to pair with the items in the Table, that would have contributed to the value of the discussion. As it was he had no knowledge of completed work which paired up, and had therefore been able to include only those costs which it was estimated the bridge owner would pay, up to the stage when the members for the bridge left the manufacturers works. Thereafter the treatment would have had to be completed at the site, on repairing damage to the metal-sprayed coating during handling, transport and erection, and the in-situ treatment of site joints. That latter stage of the treatment should be only a small proportion of the total all-in costs.

Mr Davies said that he was not qualified to speak for the steel trade on the subject of the Paper, but that did not deprive him of the right to rebut Mr Bateson's criticism of its lack of interest. The latter could surely not have forgotten that the research sponsored by the steel trade—research in which Dr Hudson had taken a leading part—had provided the first real foundation upon which to prepare specifications for improved corrosion protection.

Research of that nature depended for reliable results upon exposing specimens of various steels and irons—with surfaces prepared in various ways and coated with paints, sprayed metals, etc.—for a sufficient number of years under natural conditions. During that period, other processes, treatments, or protective coatings had been brought forward for testing. To date many test results of a valuable nature were available, whilst other results would be made known when available.

With regard to the practical development side of the picture, during the past 10 years, 5 of which had been years of total war, a number of applications of all the processes or treatments had been tried out by research, flame cleaning and surface dehydration before painting, pickling of bridge steelwork, metal spraying of bridge-work and building work, and so on, and a lot had been learnt from them. From that information the purchaser of new bridge-work should be able to satisfy himself which of the procedures would give him a profitable return on the capital he invested in processing or treatment of the steel-work. For that purpose a chart of the type shown in *Fig. 16* should be prepared for the particular bridge site in question, employing the authentic results of research on the lives of various protective treatments.

It was not surprising that Dr Hudson had seemed nonplussed by the "cut and thrust" of the discussion, where speakers had expressed opinions which were contested by others. Mr Davies would, however, like to reassure Dr Hudson that the references made to costs in the discussion assumed quite a different complexion in the light of his replies. In considering the information in the Paper dispassionately, Dr Hudson had been able to rise above the level of dispute on detail and to view the subject matter as an entity. Mr Davies was therefore glad to have his view that the Paper was of value in that an attempt had been made to reconcile the results of research with practical economic considerations.

Throughout the Paper Mr Davies had preferred a conservative assessment of values, whether they were from research or from experience on practical applications. He suggested, however, that since *Figs 6*, *7* and *8* were direct plots from research results, they should also be examined.

With regard to the use of low-alloy steels for reducing the corrosion rate, apart from considerations of stress requirements, it was clear from Dr Hudson's remarks that choice of those steels would depend upon the type of protective coating employed. Their use would hardly be justified, for example, if a relatively expensive non-ferrous metal coating were projected, as the steel was then never intended to be exposed directly to the atmosphere. However, if paints in contact with the steel were to be used as a protective coating, more serious consideration to the use of those steels might be justified.

The minimum thickness of paint coatings which should be used was very important, so that Dr Hudson's remarks on that were most helpful. That had been amply demonstrated by the much longer lives for protective paint coatings when four coats were applied as compared with two (see Table 5). On the Golden Gate Bridge electric buzzer instruments were used to test paint thickness.

Dr Hudson's remarks on the use of temporary coating of linseed oil were a useful contribution. Since that oil had assumed a very high price in recent years, there would appear to be no excuse for extravagant usage. In fact the use of synthetic media developed in recent years to replace linseed oil might possibly have a useful application as temporary protective coatings.

Mr Rivett's complete disagreement with the results shown in *Fig. 16* was due to Mr Davies's assessment of the repainting intervals as 12 years. That life had been based on the life of the paint—not necessarily of all the coats of paint but only of the outer protective coats. The reason for that was that the paint immediately in contact with the sprayed metal coating should in no circumstances be allowed to perish, since the sprayed metal is too valuable to sacrifice to naked attack from a Sheffield type atmosphere. Mr Rivett had suggested that the interval of 12 years should be increased to 20 years—and in a Sheffield atmosphere at that. Research had already shown that the lives of paints (that was, the serviceable life) in Sheffield, were not much longer than 10 to 12 years.

Mr O'Malley, in reply, referred to Mr Chettoe's remarks on the use of magnesium silico-fluoride for the protection of stone. If the coat were applied after a spell of dry weather, the risk of it affecting the breathing of the stone, with consequent damage to the face of the material by moisture in the stone forcing the coat off, would be reduced. Other materials were available which, whilst acting as a water repellant, did not seal off the pores in the stone and left a layer of entrained air which then acted as a non-conductor and prevented the penetration of frost. To be effective, all such protective coatings should be renewed at intervals.

In masonry and brickwork, it was now generally agreed that the mortar should have a strength approximating to that of the materials with which it was used. The Building Research Station had issued pamphlets making recommendations as to the mortars which should be used in particular cases, lime being mixed with cement in various proportions.

Deflexion cracks in parapets were a particularly unsightly feature and the use of a lime cement mortar or the provision of vertical joints would help to eliminate them.

Expansion and deflexion joints in concrete bridges could cause almost as much trouble as the lack of them. The development of cracking in the road slabs adjacent to those joints could be minimized by the use of metal comb joints.

Where an open-type joint was used, the deck opening should be made so that it widened out downward, thus preventing small stones from binding in the joint and also the collection of debris. Adequate provision should be made in the surface drainage to trap water before it could run through the open joint; any gullies where there was a gradient should be placed up-hill from the joint.

Mr O'Malley agreed with Mr Wood that bridge designers should have some years of experience in the maintenance of bridges before embarking upon design. That idea could very well be applied to other branches of engineering, particularly highway construction and research. There was a danger, however, that a young engineer might easily lose his facility for quick mathematical analysis and calculation if he spent too much time in the field. It would be better if design and research were not divorced from actual maintenance work as they were at present, and more opportunity should be given to the engineer to obtain practical experience concurrently with office work.

On the other hand, all bridge design was subject to the approval of senior officers and no doubt the latter's experience would be drawn upon to enable the designer to incorporate in the drawings any modifications suggested by maintenance needs.

The joints between footpath and parapet walls should be made thoroughly waterproof and should have an upstand of about 9 inches in concrete or, preferably, asphalt. On bridges where the carriageway almost abutted on to the parapet, there was often rapid deterioration of the steel, concrete, brickwork, or masonry, owing to wheel splash throwing up mud which created damp spots; the only proper cure was to widen the guard curb sufficiently to reduce that to the minimum.

Wherever an arch required attention, the construction of a saddle bonding into the extrados had been used, especially where it could be done easily, but the replacement of the fill by weak concrete should prove equally effective.

Mr Hennessey had regretted the lack of statistical data on the cost of repairs to masonry and arch bridges. The occasions, however, when maintenance to those types of bridges was normally carried out were at such long intervals that detailed information on costs was seldom available in a useful form.

Not all of the earlier concrete bridges had failed and, where they had, the failure could not always be attributed to the materials; faulty workmanship, or carelessness, had both contributed to such failures. Other reasons were probably too light design, or lack of appreciation of the necessity of providing for temperature effects, etc. Many mass-concrete arches and walls built more than 50 years ago were still in a very good state of repair; but a number of reinforced-concrete bridges between 20 and 30 years old now required attention.

A large reinforced-concrete viaduct had recently been repaired at a cost amounting to about one half of the original cost of construction—but which, comparing the original costs with present-day prices, would amount to about 10 per cent. Careful consideration had been given to the possibility of replacing the structure, in the light of present-day shortage of materials, before the decision had been taken to repair it. (The cost had been increased by having to fit in with railway workings and it would be found that, in all railway bridge repairs, the costs of the work were considerably increased and did not reflect the true costs.) The deterioration in that case had been attributed to too great a proportion of fines; lack of cover to the reinforcement and exposure to sea air had been contributory causes. In another case, the whole of the facing of a concrete bridge had deteriorated in about 20 years to such an extent that it had become necessary to repair by guniting at a cost of about 15 per cent. of the original construction costs. The deterioration had been attributed to bad concreting and to the use of elaborate sloping surfaces which held water.

Defects could usually be found in reinforced-concrete structures after about 20 years of life, but few of them were very serious and, when dealt with in good time, they could be quickly and cheaply rectified. Many of the older structures, however, were in a worse condition, whilst some of those built before the 1914–1918 war might be said to be underdesigned by modern loading standards and over-stressing might be a prime cause of deterioration. Experience with such concrete bridges had shown that it was, in the long run, unwise to economize on supervision during the construction period.

Mr Hennessey's suggestion regarding some form of pre-stressing or post-loading was worthy of further investigation, but the main difficulty would lie in devising some simple method of tensioning the wires. The present method of using a welded wire-mesh reinforcement assisted the guniting process and helped to reduce cracking.

It was often neither practical nor economical to provide sufficient opening in a bridge to cater for all conditions of flow in a stream or river, and there might be other conditions which governed the span of the bridge ; it was then advisable to ensure that, in certain conditions, the flow should be broken up, the idea being to simulate the condition of the river bed by embedding similar stones in the invert. Where stream estuaries tended to silt up, Mr O'Malley suggested that such conditions should be preserved and that dredging of the bed for materials should not be encouraged. Many of the old river bridges were protected by weirs downstream.