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The Protection of Structural Steelwork against Atmospheric Corrosion

Protection contre la corrosion des constructions en acier

Der Korrosionsschutz an Stahlbauten

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1. Introduction

To members of this Association the importance of protecting steelwork against corrosion needs no emphasis. The point has frequently been made but may usefully be reiterated here that the rusting with which the engineer has to contend is not a capricious infliction but a perfectly rational phenomenon. It merely represents the natural tendency for the metal iron to revert to a state of combination akin to that of the ore whence it is derived. The same tendency is manifested to a greater or less degree by most other common metals, such as aluminium, copper and zinc.

As will be discussed later, iron is liable to rust whenever it is in contact with oxygen and water. Consequently, unless suitable preventive measures are taken, trouble from rusting will generally be experienced whenever structural steel is exposed to the elements, to natural or salt waters, or is buried in the soil. However, the bridge and structural engineer will be predominantly concerned with land structures and this paper will, therefore, be mainly devoted to the rusting of iron in the atmosphere and to practical methods of preventing this.

To begin with, the results of research on the subject will be presented and discussed, with special reference to recent British work. This part will comprise a short exposition of the mechanism of atmospheric corrosion and a statement of the rates of wastage caused by rusting in various parts of the world when ordinary structural steel is exposed outdoors without protection. The effect of the chemical composition of the steel on the rate of rusting will then be considered. Finally, the whole range of available protective measures, in-

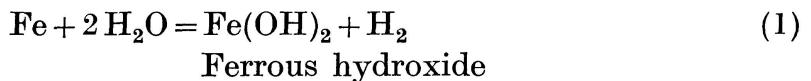
cluding the adoption of good design details conducive to corrosion prevention and the use of protective coatings, more particularly of paint or non-ferrous metals, will be discussed in the light of experimental data.

The last part of the paper is essentially practical in character and is a review of current British practice in the field concerned. This is based primarily on the experience gained by one of the Authors (F. F.) during many years' experience of the structures belonging to the British Transport Commission.

2. Research on the Rusting of Iron and Steel in the Atmosphere and its Prevention

2.0. *Mechanism of rusting in the atmosphere*

For a proper understanding of what follows, it is desirable that the reader should have a rudimentary knowledge of the mechanism by which atmospheric rusting takes place. Certain metals, of which sodium is a good example, are capable of reacting directly with water, hydrogen being evolved. Although the direct reaction of iron with water resulting in the formation of gaseous hydrogen can only be brought about under artificial laboratory conditions, for the present purpose the reaction



may be regarded as representing the first stage in the rusting of iron in the atmosphere¹⁾. If this reaction is to proceed, the hydrogen, which cannot usually be evolved as gas, must be removed from the system. This is done through the influence of oxygen, derived from the air, which may be loosely regarded as oxidising the hydrogen to water. Secondary reactions between ferrous hydroxide, water and oxygen lead to the formation of a whole gamut of hydrated hydroxides and oxides of iron, the final product being hydrated ferric oxide, $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$. It is noteworthy that this compound, which is the major constituent of ordinary rust, occurs naturally as the iron ores lepidocrocite and göthite.

This mechanism requires that both water and oxygen should be present if appreciable atmospheric rusting of steel is to occur. But fundamental knowledge of the subject goes further than this. The classical researches of W. H. J. VERNON²⁾ have shown that, for serious rusting, it is also necessary that a definite level of humidity, termed the "critical humidity", should be

¹⁾ The direct attack of atmospheric oxygen on steel, in the absence of condensed moisture, results in the formation of a very thin, impermeable surface film of iron oxide, mainly Fe_2O_3 , which retards corrosion and, in the case of rust-resisting steels (see section 2.2), may prevent it entirely.

²⁾ W. H. J. VERNON, "A Laboratory Study of the Atmospheric Corrosion of Metals", Transactions of the Faraday Society, 1935, 31, 1668—1750.

reached or exceeded. This fact is demonstrated by curve *B* in figure 1, which depicts in simplified form, some of Vernon's experimental data. The exact value for the critical humidity is difficult to determine and indeed may be a function of the temperature but, as will be seen from figure 1, it lies between 70 and 80 per cent relative humidity. For practical purposes, therefore, a rusting hazard will exist whenever steel is exposed to atmospheres with a relative humidity exceeding about 70 per cent; below this degree of humidity rusting will normally be inappreciable³⁾.

The second fundamental fact established by Vernon and illustrated by curve *A* in figure 1 is that, even when the atmospheric humidity is propitious for rusting, serious rusting will not occur in pure air. For this it is necessary that the air should be polluted as well (curves *B* and *C*). The most damaging component of atmospheric pollution in industrial countries is sulphur dioxide, or its oxidation product, sulphuric acid, which is present to some degree in all combustion products, particularly those of coal or fuel oil. Joint investigations by the British Iron and Steel Research Association and the Fuel Research Station have demonstrated, as is shown in figure 2, that in England, where the atmospheric humidity exceeds the critical value for the greater part of the year and does not vary much from one locality to another, the rusting of steel is directly proportional to the sulphur pollution of the air.

It is desirable to add that when steel is in contact with liquid water, as distinct from the atmosphere above the dew point, corrosion takes place by an electrochemical process. The surface of the metal becomes divided into

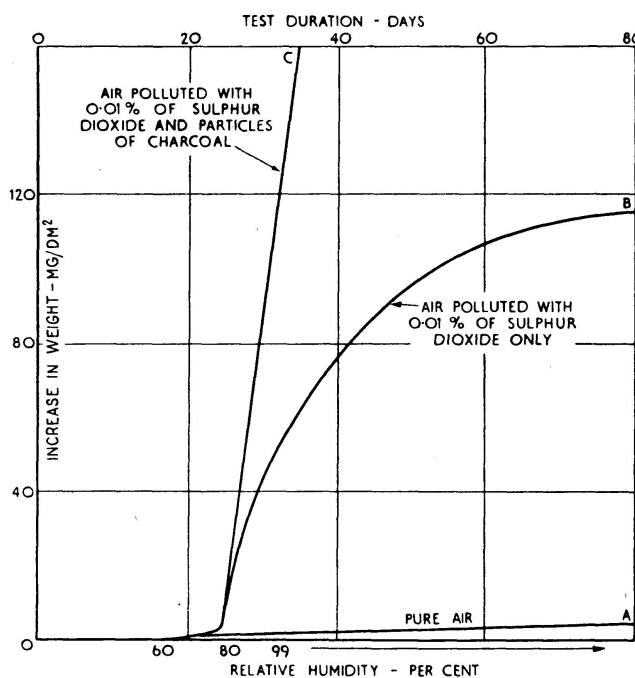


Fig. 1. Atmospheric rusting of iron (W. H. J. Vernon).

³⁾ See also section 2.5.

areas that are corroded, the "anodes", and areas that are not, the "cathodes". Similarly corrosion cells are set up when two dissimilar metals in contact with each other are also in contact with an "electrolyte", i. e. an aqueous solution capable of conducting electricity. In the corrosion cell steel /electrolyte/ zinc, the zinc is the corroded pole or anode, the steel being protected, whereas in the corrosion cell steel /electrolyte/ copper, the steel is the "anode" and is corroded.

2.1. *Influence of climate on the severity of atmospheric rusting*

In conformity with the principles discussed above, the rate at which unprotected steel rusts in different parts of the world varies between very wide limits. Some typical figures obtained in the course of researches by the British Iron and Steel Research Association are given in table I. The data bring out in a practical way the inter-play of atmospheric humidity and atmospheric pollution in determining corrosion⁴⁾.

In Great Britain, where the humidity is relatively high, some degree of rusting will take place everywhere. The rate of rusting is determined, as already shown in figure 2, by the atmospheric pollution and varies from about 2 mils⁵⁾ per year at rural and marine sites, such as Llanwrtyd Wells or Brixham, to nearly 7 mils per year at industrial ones, such as Derby.

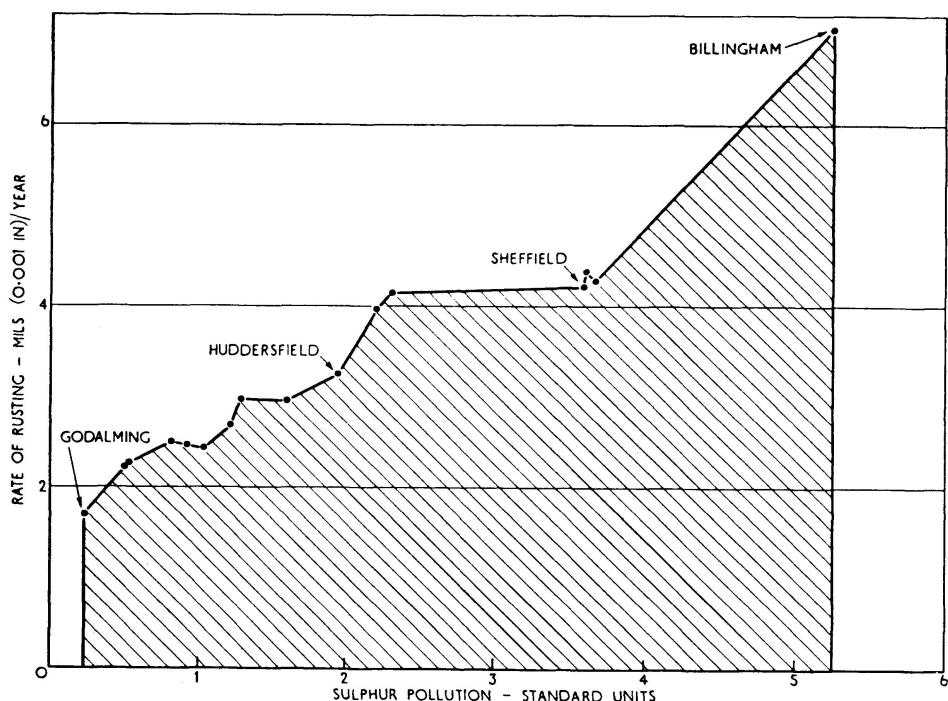


Fig. 2. Correlation between rusting and atmospheric pollution.

⁴⁾ This subject is discussed in greater detail in the following papers: J. C. HUDSON and J. F. STANNERS, "The Effect of Climate and Atmospheric Pollution on Corrosion". Journal of Applied Chemistry, 1953, 3, 86—96. J. C. HUDSON, "The Delhi Pillar". Nature 1953, 172, Sept. 12, 499.

⁵⁾ One mil equals 0.001 in., 0.025 mm., or 25 microns.

At places overseas where the humidity is low, for example Delhi and Basrah, steel suffers little corrosion in the open. This is also true for places where the humidity is high, provided that the local atmosphere is not artificially polluted; for example, rates of 1.1 mil per year or less were observed at Apapa, in Nigeria, and Singapore. On the other hand at Congella, near Durban in South Africa, where there is considerable industrial activity, the rate of rusting was 4.5 mils per year, which is comparable with the results obtained in industrial areas in Great Britain.

It would be inappropriate to elaborate this discussion here but two other

Table I. Rate of rusting of steel in different climates

Exposure site		Rate of rusting
Type of atmosphere	Place	Mils (0.001 in.) per year
<i>Great Britain</i>		
Rural	Llanwrtyd Wells	2.5
Marine	Brixham	2.1
	Calshot	3.1
Industrial	Motherwell	3.8
	Woolwich	4.0
	Sheffield	5.4
	Frodingham	6.4
	Derby	6.8
<i>Overseas</i>		
Rural or urban	Khartoum	0.1
	Abisko, North Sweden	0.2
	Delhi	0.3
	Basrah	0.6
	State College, Pa., U.S.A.	1.7
	Berlin-Dahlem	2.1
Marine	Singapore	0.6
	Apapa, Nigeria	1.1
	Sandy Hook, N. J., U.S.A.	3.3
Marine/Industrial	Congella, South Africa	4.5
Industrial	Pittsburgh, U.S.A.	4.3
Marine, surf beach	Lagos	24.4

These results refer to small specimens of ingot iron, a steel with the lowest practicable carbon content, that were freely exposed in the open, except that at Delhi a copper-bearing mild steel was used (see section 2.2). The Delhi result has been corrected for the effect of the difference in composition of the test material.

points should be made before leaving the subject. The first is that, in assessing the potential corrosiveness of the atmosphere at a given site, a study of the variation in the relative humidity there throughout the year is much more helpful than a knowledge of the average value of the relative humidity for the whole year. This point may be illustrated by the diagrams shown in figure 3. Here are indicated, for Kew (England), Khartoum, Pittsburgh (U.S.A.) and Singapore, the hours of day, averaged for each month, at which the relative humidity of the air lies below, between or above the limits of 70—80 per cent. If 70 per cent relative humidity is assumed to be the critical value for rusting, then the diagrams show that the conditions are conducive to rusting in Great Britain for about 80 per cent of the year and for 99 per cent of the year at Singapore. The corresponding figures for Khartoum and Pittsburgh are nil and 49 per cent respectively. It is of interest to note that the humidity at Pittsburgh and similar observations for other American observatories indicate that the climate of the United States is drier on the whole than that of Great Britain, and, therefore, less dangerous as regards rusting. It is probable that the lower humidity at Pittsburgh is counteracted by the presence of a relatively high degree of high atmospheric pollution, just as, at the test site at Singapore, referred to in table I, the absence of serious pollution results in relatively slight corrosion despite the high humidity.

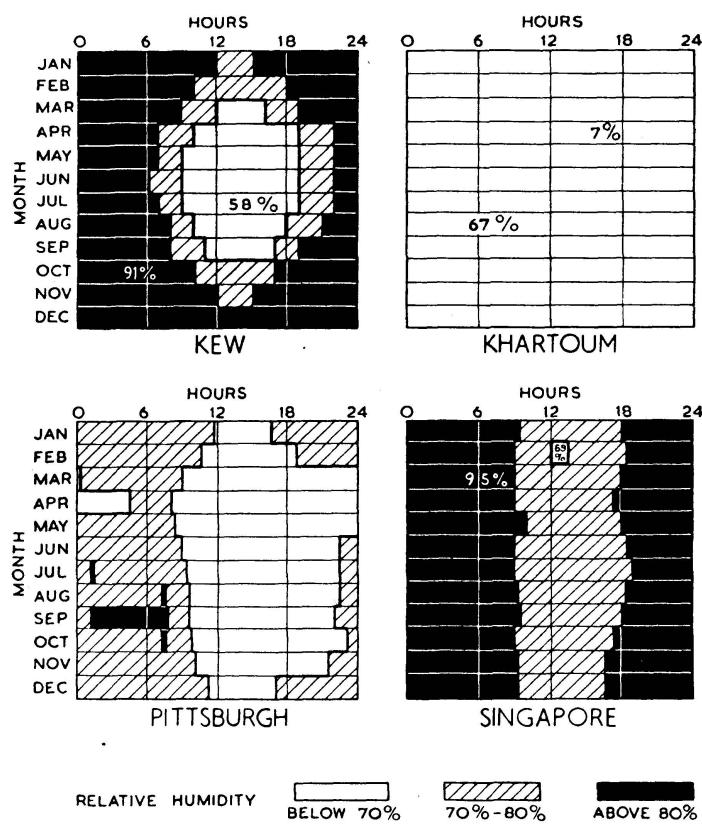


Fig. 3. Annual variation in atmospheric humidity at Kew, Khartoum, Pittsburgh and Singapore.

Secondly, it should not be concluded from the results quoted that corrosion in the tropics is negligible. Unfortunately, experience has shown only too clearly that very heavy rusting of steel can occur there. There is one example of this in table I, the figure of 24.4 mils per year recorded on a surf beach at Lagos, which incidentally is but a few miles away from Apapa where the rate of rusting was only 1.1 mils per year. In this particular case the very rapid rusting was due to the continuous presence of a cloud of sea-water spray round the specimens. Rusting from this cause decreases very rapidly with increasing distance from the ocean, as is shown by the following figures obtained at or near the site in question:

Distance from surf	Rate of rusting mils per year
50 yards	37.7
200 yards	14.9
400 yards	2.2
1300 yards	1.6
25 miles	1.9
37 miles	0.2

In the interior of Nigeria, 60 miles from the coast, at Aro, a rate of 0.5 mil per year was recorded.

It should also be emphasised that all these figures relate to simple pieces of steel plate hanging vertically, from which condensed moisture can evaporate freely. Such specimens are not fully comparable with fabricated articles of complicated shape, which may suffer serious corrosion, because condensed moisture remains entrapped in them, whereas it evaporates freely from the flat plates.

2.2. *Effect of steel composition on rusting*

In respect of their resistance to atmospheric corrosion structural steels fall into three main groups:

- I. Ordinary unalloyed steels.
- II. Low-alloy steels.
- III. Rust-resisting steels.

Within the first group minor differences in the composition or the nature of the material have no marked effect on the resistance to atmospheric corrosion. Thus the process by which a mild steel is manufactured, Bessemer or open-hearth, acid or basic, has no pronounced influence on the rate at which it rusts. It is true that the old types of British wrought iron rusted at about two-thirds of the rate of mild steel but the point is of academic interest only, for it would be impracticable to produce this material in sufficient quantities nowadays.

The second group of steels, the low-alloy steels, are of fairly recent origin. Practical attention was focused on the prototype, copper steel, by the researches of the American investigator, D. M. BUCK⁶). As shown in figure 4, he demonstrated by field exposures that progressively increasing additions of copper to steel reduce the rate at which it rusts in the open air until a content of about 0.15 per cent of copper is reached. Further additions do not increase the corrosion resistance much more but for safety it is customary to add about 0.3 per cent of copper to modern steels of this type. Other elements, particularly chromium, nickel and molybdenum have since been found to exert a similarly beneficial effect and a whole family of low-alloy steels has now been developed. One of the best known of these, an American proprietary product, contains about 1 per cent of chromium, 0.5 per cent of copper, 0.5 per cent of silicon and 0.15 per cent of phosphorus. Its loss in weight after exposure in the open for several years in an industrial atmosphere is about one-third of that of ordinary mild steel exposed under similar conditions.

The third group, the rust-resisting steels, possess a high degree of corrosion resistance and the best of them are virtually incorrodible in the atmosphere.

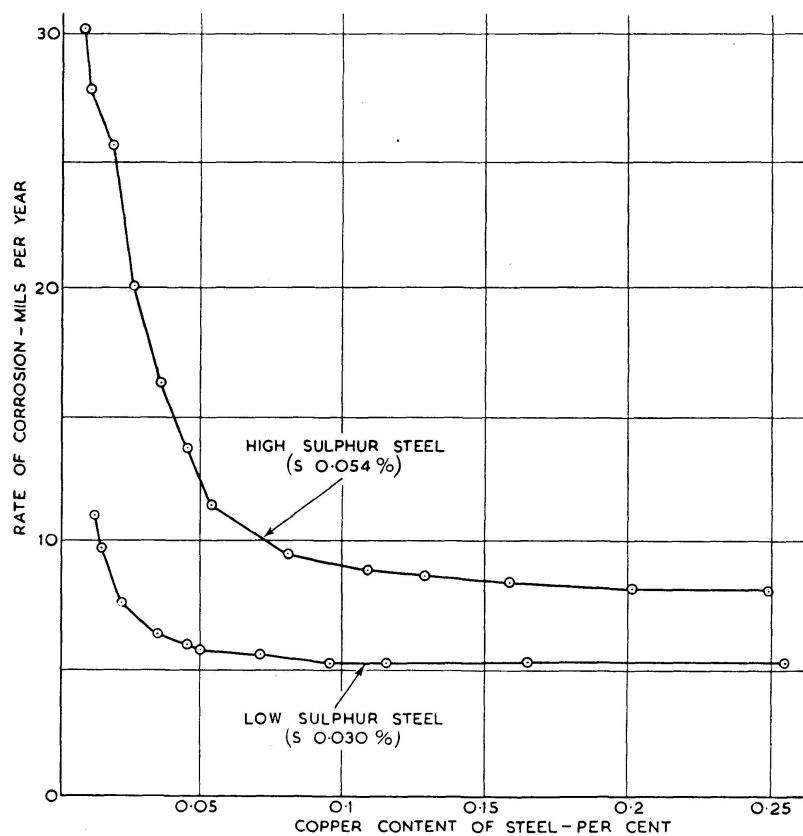


Fig. 4. Effect of copper in steel on the resistance of steel to atmospheric corrosion (D. M. Buck).

⁶) D. M. BUCK, "The Influence of Very Low Percentages of Copper in Retarding the Corrosion of Steel". Transactions of the American Society for Testing Materials, 1919, Vol. 19, Part 2, 224—237.

For example, in a test made at Sheffield by H. T. SHIRLEY and J. E. TRUEMAN⁷), a polished specimen of 18/8/2 $\frac{1}{2}$ chromium-nickel-molybdenum steel retained its original reflectivity almost unimpaired after five years' exposure (see figure 5). Its loss of weight was only 0.03 per cent of that suffered by ordinary steel.

The use of rust-resisting steels for general engineering purposes is, however, inevitably restricted. Apart from the question of cost, a ceiling is imposed by the limited supply of alloying elements available. The British steel industry alone produces nearly 20 million tons a year. To make this entirely of rust-resisting steel would consume 1 $\frac{1}{2}$ million tons of nickel; this is several times the world output, which has to serve many other essential purposes besides steelmaking. There can, therefore, be no question of the general replacement of ordinary steels by rust-resisting steels for bridge building, although the latter may be usefully employed in key positions where maximum rust resistance is imperative.

This leaves the structural engineer with the choice between ordinary steels and low-alloy steels. It has to be admitted that corrosion resistance generally has little influence on his decision; he is usually most concerned with the comparative mechanical properties of the steels, in relation to his design requirements and, ultimately, the cost of the project. Fortunately, however, many of the low-alloy steels possess, in addition to greater resistance to atmospheric rusting, enhanced mechanical properties, e. g. a tensile strength of 40 tons or more per sq. in., as compared with 28 tons per sq. in. for ordinary steel. Indeed, it was the search for better mechanical properties rather than

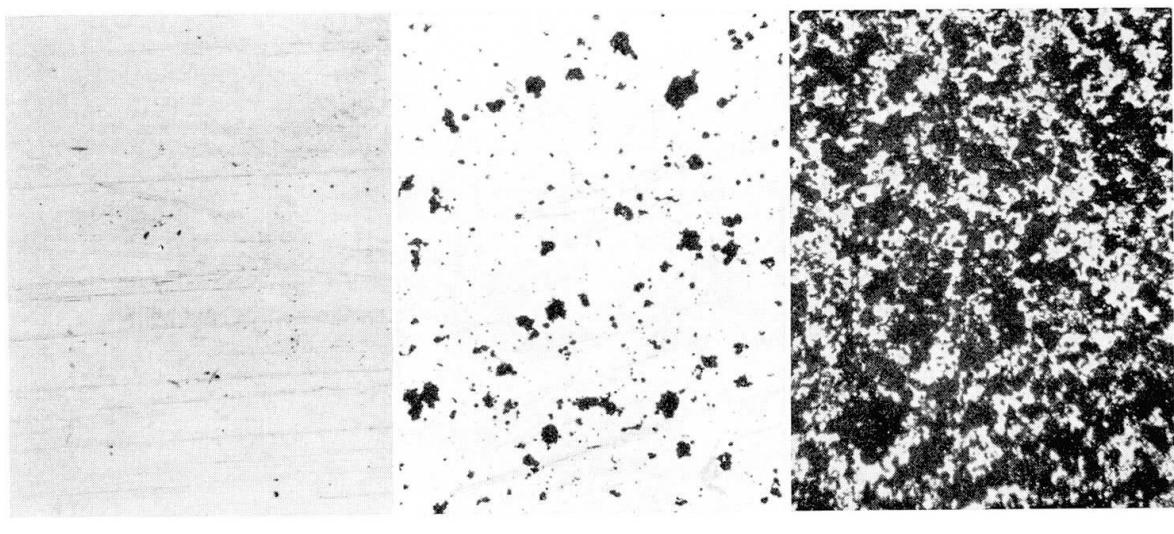


Fig. 5. Comparative resistance of various rust-resisting steels to atmospheric corrosion.

⁷) H. T. SHIRLEY and J. E. TRUEMAN, "A Study of the Corrosion Resistance of High-Alloy Steels to an Industrial Atmosphere". Journal of the Iron and Steel Institute, 1948, 23, Dec., 367—375.

the desire for enhanced corrosion resistance that largely paved the way for the development of low-alloy steels.

The pertinent question arises, therefore, "If we make use of high-tensile low-alloy steel for our structure, shall we gain any incidental benefits or economies from its greater resistance to corrosion?". To answer this, it is necessary to consider the mechanism whereby low-alloy steels⁸⁾ gain their increased resistance to atmospheric attack.

First, it should be said that the rust-resisting steels proper owe their immunity from rusting to the extremely rapid rate at which they combine with atmospheric oxygen. Their surface is covered with a very tough and impermeable oxide film, which reforms immediately should it become damaged in any way. This film has been isolated and shown to be about 3 ten-millionths of an inch⁹⁾ thick or, something like five thousand times thinner than a coat of paint. Rust-resisting steels will only function satisfactorily when there is free access of air to their surface. If for any reason this access is impeded, as when a barnacle settles on a stainless steel plate immersed in sea water, repair of the oxide film at that point is prevented and local corrosion may set in at a catastrophic rate. For example, 0.080 in. thick sheets of some types of rust resisting steel have been observed to become perforated in sea water within six months.

A different mechanism operates for "slow-rusting" steels. Here no protective oxide skin is formed and in the early stages of exposure the rates of rusting for these steels differ little, if at all, from that of ordinary steel. Gradually, however, as time goes on differences in appearance manifest themselves between the "slow-rusting" and the ordinary steels when they are exposed outdoors. Both become covered with a layer of rust which may be as thick as 50 mils or more¹⁰⁾ but the rust on the slow-rusting steels is darker and of finer grain. The enhanced rust-resistance of the slow-rusting steels is closely associated with the more compact texture of the rust formed on them, which offers a greater resistance to the ingress of the corrosive medium, moisture and oxygen. The reasons for the difference in the properties of the rust have not yet been fully elucidated. In general terms, it is believed that the small amounts of alloying elements present in the steel, chromium, copper, nickel, etc. are converted to sulphates when the steel corrodes and are precipitated in the pores of the rust, which consists mainly of hydrated iron oxides, as basic sulphates. These compounds may loosely be regarded as serving to plug the channels through the rust film and thus decrease its

⁸⁾ It has been suggested (private communication from Mr. T. H. TURNER) that the steels concerned should be called "slow-rusting steels". The use of this term in the present connection seems appropriate.

⁹⁾ I. e. 7.5 millimicrons or 75 Ångstrom units.

¹⁰⁾ The figure refers to adherent rust. Flaky rust may accumulate on steel at times to a much greater thickness than this. (One mil equals 0.001 in., see Footnote 5, p. 4.)

permeability. In conformity with this it has been found, both in the United States¹¹⁾ and in Great Britain¹²⁾, that the percentage of sulphate present in the rust on a steel increases *pari passu* with the resistance of the steel to atmospheric corrosion.

This mechanism only seems to operate when the rusting steel is fully exposed to the rain and the weather; perhaps a leaching process is involved. The experimental fact is that in closed environments, to which rain has no access, the low-alloy additions fail to have any marked effect and slow-rusting steels do not show to advantage. For example, in tests over 5 years made inside the highly polluted Dove Holes steam-railway tunnel in Great Britain the rates of corrosion of ordinary steel and of copper steel were identical within the experimental error.

With these facts in mind the answer to the original question is clearly as follows:

I. If the structure is to be used bare, the use of slow-rusting steels will greatly prolong its life, particularly under highly corrosive conditions. Although the increased corrosion resistance only applies to the freely exposed parts of the structure, these are often the parts that are most affected by rusting¹³⁾.

II. If, as is most common, the structure is to be provided with a protective coating, much will depend upon the character of the coating itself and the efficiency with which it is or can be maintained. Assuming, for example, that a bridge were sprayed with zinc and then painted, it would be immaterial from the corrosion aspect whether the steel were of ordinary or of slow-rusting quality.

Again, if a bridge were properly painted after correct surface preparation of the steelwork, if the paint suffered no damage in service and if repainting were invariably carried out at the proper time — quite a large number of “ifs” — no difference would be expected between the performances of slow-rusting steel and of ordinary steel. Although some investigators have claimed that paint “lasts better” on slow-rusting steels, in tests by the British Iron and Steel Research Association no such general observation has been made. It seems probable that for painting schemes that are identical in all respects, i. e. as regards surface preparation, composition and number of coats and film thickness, the duration of protection to the first signs of failure will be substantially the same for both types of steel. This conclusion is supported by the data shown in table II, which were obtained by the Swedish Corrosion

¹¹⁾ H. R. COPSON, “A Theory of the Mechanism of Rusting of Low-Alloy Steels in the Atmosphere”. Proceedings of the American Society for Testing Materials, 1945, 45, 554—580.

¹²⁾ J. C. HUDSON and J. F. STANNERS, “The Corrosion Resistance of Low-Alloy Steels”. Journal of the Iron and Steel Institute, 1955, 180, July, 271—284.

¹³⁾ But see also section 2.4 Importance of Good Design.

Table II. Effect of composition of the basis steel on the durability of a protective painting scheme. (I. V. A.: s korrosionsnämnd.)

Copper content of steel ¹⁴⁾ Per cent	Test duration to failure years ¹⁵⁾	
	At Stockholm	At Gothenburg
0.01	11.3	5.6
0.13 ¹⁶⁾	11.1	5.9
0.30 ¹⁷⁾	11.1	5.7
0.45	11.1	4.9

Committee¹⁸⁾. When, however, failure is allowed to proceed — and this seems to be the point of practical importance — further deterioration of the paint film and rusting of the basis steel take place more slowly on the slow-rusting steel. In other words, the use of the steel with the superior corrosion resistance acts as an insurance policy and palliates the detrimental results of oversight by prolonging the period within which repainting of the structure is practicable without resorting to the costly necessity of removing the old paint and cleaning down to bare metal.

To sum up, therefore, in the words of the Atmospheric Corrosion Sub-Committee of the British Iron and Steel Research Association: "This superiority (of slow-rusting steels) may be of value for thin sections, structures exposed to industrial or marine atmospheres, or structures on which maintenance painting is difficult." It should be emphasised that this remark refers to outdoor atmospheric corrosion only, since, for reasons which need not be elaborated here, slow-rusting steels do not show to appreciable advantage under other corrosive conditions. When totally immersed in fresh or salt waters, when buried in soil or when exposed in an enclosed atmosphere, they corrode at practically the same rate as ordinary unalloyed steel.

2.3. General survey of protective measures

Practical measures for preventing the corrosion of steel may be classed under four heads:

- I. Design.
- II. Composition of the steel.
- III. Treatment of the corrosive medium.
- IV. Protective coatings.

¹⁴⁾ The steels were prepared for painting by pickling.

¹⁵⁾ Corrections have been applied for differences in paint film thickness.

¹⁶⁾ Average for three steels.

¹⁷⁾ Average for two steels.

¹⁸⁾ Private communication from Mr. KURT F. TRÄGÅRDH, of that Committee.

The effect of the composition of the steel has been discussed in section 2.2. Before passing on to consider the other three types of measure, it is important to enunciate one guiding principle that applies over the whole field. This is that it is foolish to economise unduly on the cost of protective measures, for the cheapest coating initially is not necessarily the least expensive in the long run.

2.4. *Importance of good design*

It is now recognised that the design of a structure may play a decisive part in determining how far it is vulnerable to corrosion. It has been said that "corrosion begins on the drawing board". The point will be taken, although it might have been better expressed by saying that the drawing office is the first place where consideration should be given to the effective prevention of corrosion. This aspect of the subject is capable of lengthy treatment but the essential postulates can be reduced to two, namely that the designer should take all possible steps:

- I. to minimise the liability of the structure to corrode, and
- II. to facilitate the effective application both of the initial protective scheme and of subsequent coatings applied for maintenance.

In the first place due regard should be paid to the choice of the structural materials themselves. Here, apart from the composition of the steel (see section 2.2), it is important to avoid what may prove to be harmful contacts between the steel and other materials, both metallic and non-metallic. It is bad practice, for example, to permit direct contact of steel with wood; the steel deck plates of a ship may be prematurely perforated by rusting where planking is laid on them unless the planks are properly embedded in a thick layer of bitumen, as they should be. Again, although contact between steel and non-ferrous metals will not commonly occur in bridges and similar structures, it should be realised that this is often an undesirable practice, because in the presence of an electrolyte, such as sea-water, the juxtaposition of ferrous and non-ferrous metals constitutes an electrolytic corrosion cell, in which the corrosion of the former may be greatly aggravated. For example, a case has been reported in which the proximity of a bare copper-cable and galvanised steel led to serious corrosion of the latter, because leachings from the copper fell on to it, thereby setting up local corrosion cells. As a rule, however, contacts between steel and most common non-ferrous metals should be safe when exposed solely to normal atmospheric corrosion¹⁹.

¹⁹) Detailed information regarding the possibility of galvanic corrosion resulting from metal to metal contacts will be found in a paper by K. G. COMPTON, A. MENDIZZA and W. W. BRADLEY, "Atmospheric Galvanic Couple Corrosion", Corrosion, 1955, 11, September, 383t—390t, and in a pamphlet published by H. M. Stationery Office in 1956: "Corrosion and its Prevention at Bimetallic Contacts", by U. R. EVANS and (Mrs.) V. E. RANCE.

The main features of design conducive to the corrosion of structural steel-work can be illustrated by the following examples:

Figure 6 shows some sheet steel litter baskets in use in London. The basket in photograph A was open to the rain at the top and was particularly vulnerable to corrosion at an outer horizontal seam running round the bottom. As will be seen from photograph B, taken about a year later than A, the bottom rusted through rapidly. The design of the basket in photograph C is much better in all respects. Incidentally the material used for the corroded basket was also at fault. It was made from ordinary black thin-gauge steel sheet;

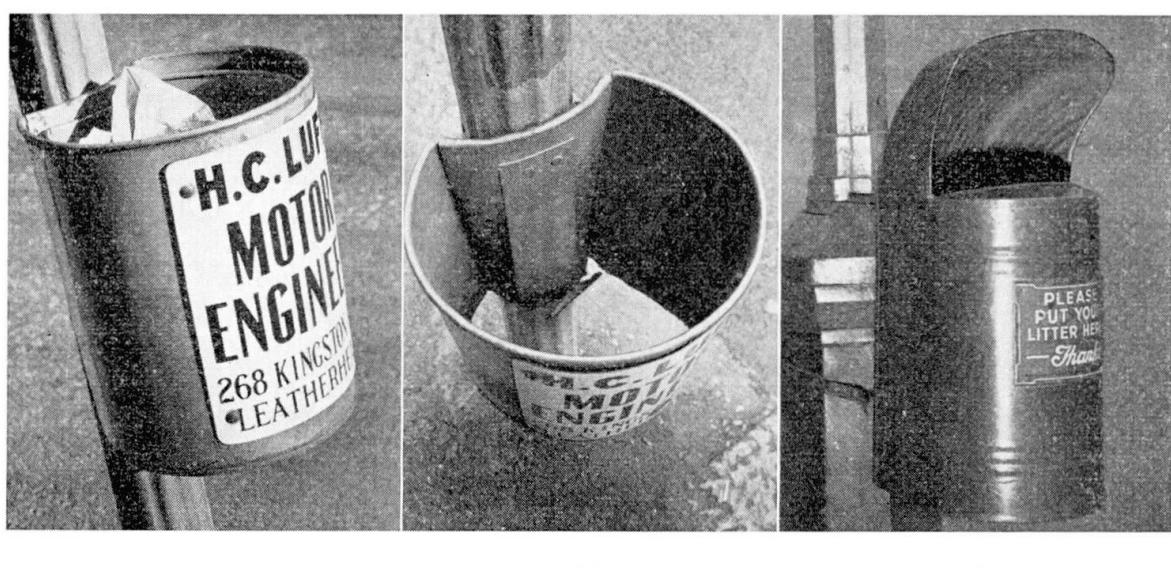


Fig. 6. Influence of design on corrosion. Effect of seams (litter baskets).



Fig. 7. Influence of design on corrosion. Rusting at lapping surfaces (Palm House, Kew).

galvanised sheet should always be used for the fabrication of light-gauge articles exposed outdoors.

The photograph in figure 7 is a detail of a component of the Palm House at Kew Gardens, London. When this building was fabricated a century ago from cast iron and wrought iron, it was necessary to build up some of the sections. As is shown in the photograph, rust has formed in the crevice between the component members of the bar and has grown in volume over the years to such an extent as to disintegrate them; the same effect is frequently observed in some designs of steel railings, as is illustrated in figure 8. The internal structure of the Palm House is exposed to exceptionally corrosive conditions, because it is necessary to spray the tropical plants within it daily with water and in addition the air is heated. At the moment (September 1955) the Ministry of Works is undertaking a complete overhaul, repair and maintenance painting of the building; it is of interest to note that where necessary and practicable the vulnerable seams of built-up components will be closed by welding.

As an example of the introduction of undesirable difficulties in maintenance

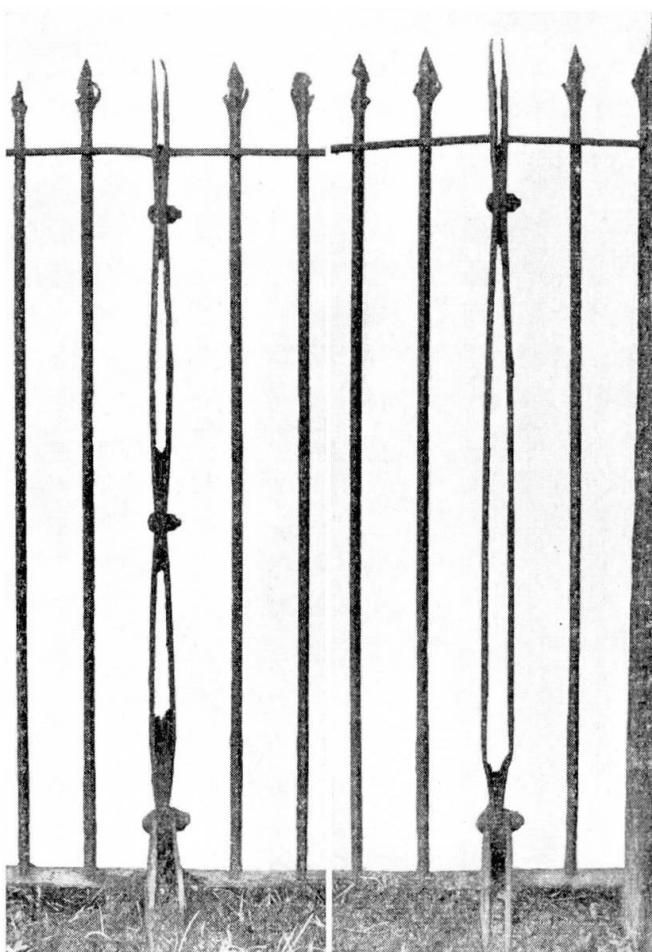


Fig. 8. Influence of design on corrosion. Rusting at crevices (railings).

painting, a detail of the railway bridge at Putney is shown in figure 9. This component consists of long double steel links about 2 in. apart and, although their inner surfaces could no doubt be reached by small mops mounted on long handles and there is no evidence of marked corrosion there, the complication seems unnecessary and a cleaner and easily accessible design is to be preferred. In another case heavy steel stanchions were erected so close to the wall — in a pickling shop of all places — that their back surfaces could not be reached. The condition of these stanchions is now causing anxiety and the only practicable method of maintenance seems to be to take them out one by one, clean and paint them thoroughly and then replace them.

Care is also necessary in design details when repairing an old, corroded structure. An example of lack of thought in this respect, which has recently come to light, concerns a pier where some of the web plates in a girder had corroded through. A new plate was welded without removing the perforated plate, in such a way as to leave small pockets between the old plate and the new, which were liable to be filled with sea water but could not be adequately protected. Such an obvious error is improbable today but less obvious ones



Fig. 9. Influence of design on corrosion. Difficult access to surfaces for repainting (railway bridge at Putney).

can be avoided if the matter is given adequate thought when repairs have to be carried out.

It is unnecessary to multiply these examples further. The lessons to be learnt from them can be summarised in two sentences:

I. Avoid all features in design that will or may lead to the local accumulation of moisture or grime and subsequently of rust.

II. Make things as easy as possible for the painters, who will have to maintain the structure in future years.

2.5. Treatment of the corrosive medium

It is clear from the remarks made in section 2.0 that atmospheric rusting can be entirely prevented by drying and purifying the air. Such methods are in fact practised on an industrial scale as, for example, in the holds of cargo vessels or in the finishing and packaging shops of needle factories. In such places, provided that the relative humidity of the air is kept below 60 per cent, little trouble from rusting is experienced. It should be remembered, however, when applying this principle in practice, that under some circumstances the temperature of a steel surface may be lower than that of the ambient atmosphere. The important fact is that condensation should not occur on the steel, bearing in mind that, because of the presence of rust or pollution on its surface, this condensation may be able to take place at humidities well below the saturation point, in accordance with Vernon's observations (see section 2.0). In any case, for obvious reasons it is impracticable to apply these treatments to large structures freely exposed to the atmosphere, which must, of necessity, take the weather as it comes.

Similarly, although "cathodic protection" is extremely useful for preventing the rusting of buried or submerged steelwork, it cannot be expected to provide a solution of the main problem under discussion. This valuable method, which, in simple terms, involves deliberately setting up a corrosion cell in such a way that the steel is its cathode or protected member (see section 2.0), can only function when the corroding medium is an electrolyte, e. g. salt water or fresh water of appreciable conductivity or, in the case of buried structures, a soil of low electrical resistivity. This condition does not obtain for the bulk of steelwork exposed to the atmosphere, although there may conceivably be circumstances under which cathodic protection might be of value, such as for the protection of piers and jetties in the zone of intermittent immersion by tidal waters. Cathodic protection may also be of value for buried or immersed members of steel bridges but it should be made clear that the process is to be regarded as an adjunct to and not as a substitute for orthodox protective coatings. It would be unduly expensive, if not completely impracticable, for example, to protect a buried steel pipeline by cathodic protection alone; the first step should be to apply a good thick protective coating of

bitumen, leaving the cathodic protection to take care of any local gaps or imperfections.

2.6. General principles governing the use of protective coatings

In recent years considerable progress has been made in the development of new and better coatings for the protection of steel and knowledge of the properties and application of the older types of coating has greatly increased. Broadly, there are three main groups of coating, namely:

- I. Paints (see section 2.7).
- II. Metallic coatings (see section 2.8).
- III. Other coatings, notably bitumen, cement and concrete and plastics (see section 2.9).

Before passing on to a detailed discussion of the use of these coatings for structural steelwork, it may be useful to state some general principles that apply to all of them. These are:

- I. The adhesion of the coating must be good.
- II. The thickness of the coating must be adequate for the purpose in hand.
- III. The coating must lend itself readily to overcoating for maintenance.

I. *Adhesion.* Although some of the members of a structure may experience considerable vibration, appreciable permanent change in their dimensions does not occur. The demands on the adhesivity of a protective coating applied to structural steelwork are, therefore, much less severe than those on that of, say, a galvanised mild steel wire, which may have to be wrapped round its own diameter. Consequently, the necessary degree of adhesion can generally be obtained by careful attention to the correct surface preparation of the steel to receive the coating concerned. This surface preparation involves, in the case of protection by paint, the complete removal of all dirt, millscale and rust. Where a sprayed metal coating is to be applied, the steel surface must also be roughened in a suitable manner and to an appropriate degree by gritblasting.

Some attention may also be necessary to the elasticity of the protective coating, particularly in climates where there are marked variations in temperature. In Great Britain and similar temperate climates, however, the usual paint and metallic coatings are sufficiently elastic for all normal purposes.

II. *Coating thickness.* Although properly chosen protective coatings will often possess inhibitive properties, i. e. tend to prevent the corrosion of steel by chemical passivation, they all act as a physical barrier between the steel and the corrosive atmosphere. It is obvious, therefore, that this barrier must be of adequate thickness and that there is a lower limit for each type of coating below which the thickness should not be reduced.

The desirable thickness for any particular coating will naturally vary to some extent with the severity of the local climate. As a general guide,

however, exposure tests under severe atmospheric conditions in Great Britain have shown that metal coatings, e. g. aluminium or zinc, should be at least 3 mils (0.003 in.) thick and that painting schemes should have a total thickness

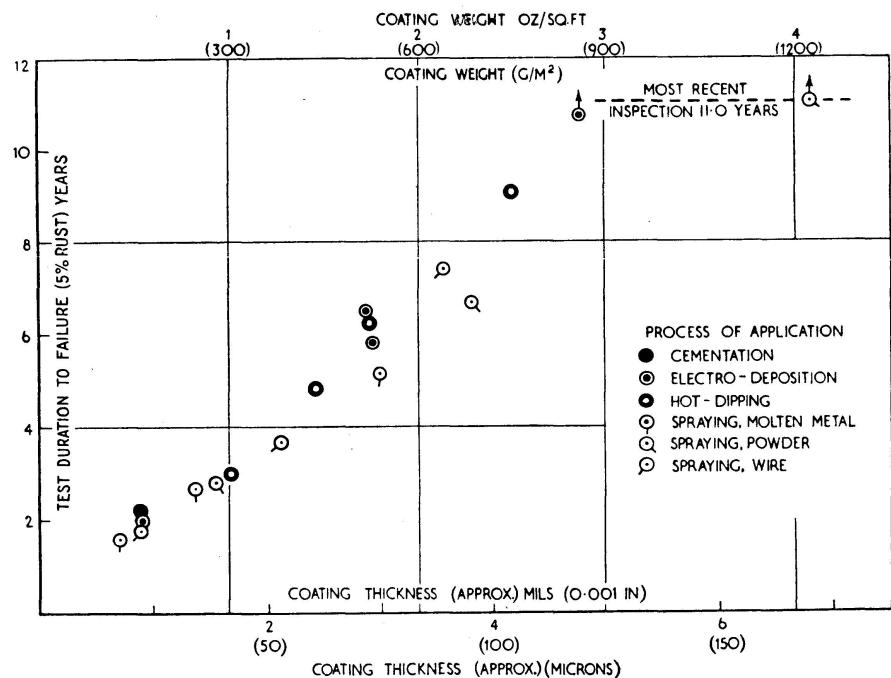


Fig. 10. Durability of zinc coatings on steel exposed at Sheffield.

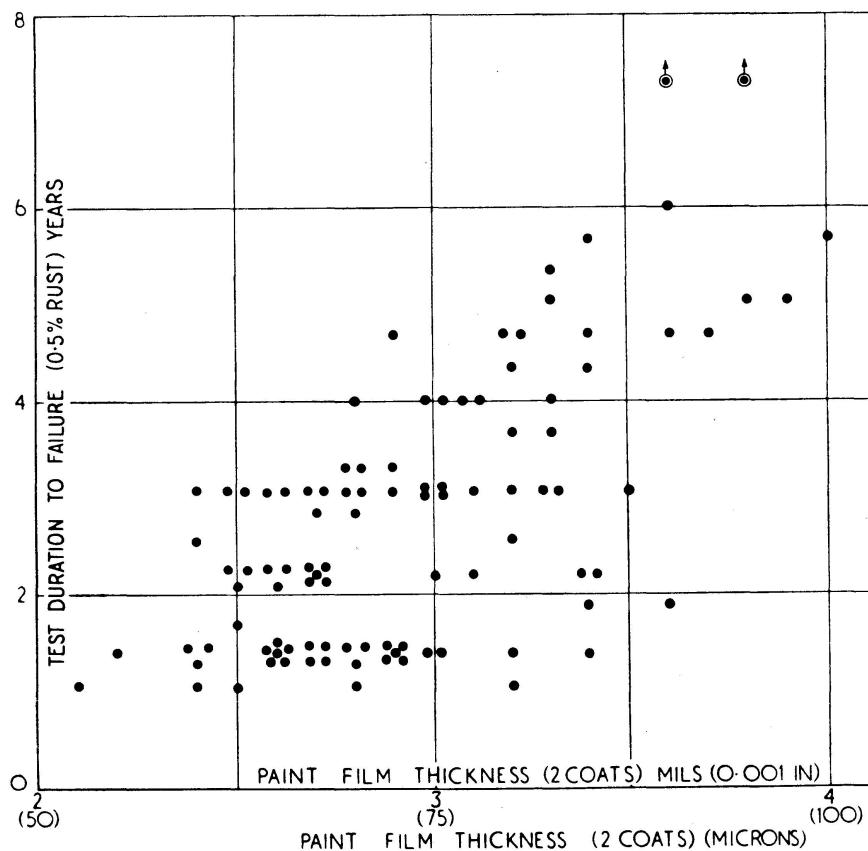


Fig. 11. Durability of painting schemes on steel exposed at Derby.

of about 5 mils. Coatings of these thicknesses might reasonably be expected to protect steel for 5 years at least, except perhaps in the neighbourhood of chemical plant. These conclusions are supported by the experimental results shown in figure 10, for zinc coatings exposed at Sheffield and in figure 11, for painted steel exposed at Derby; both the Sheffield and Derby atmospheres are heavily polluted by industrial smoke. Incidentally, the results of the Sheffield tests show that the protective value of zinc coatings is mainly determined by their thickness and that the process by which they are applied is of secondary importance.

III. *Suitability for Recoating.* It is highly advantageous to attempt to envisage the whole sequence of protective measures, including both the initial and the subsequent maintenance coatings, from the very beginning, before the structure is fabricated. Obvious errors, such as the use of tar or bitumen paint when it may be desired later to overcoat with oil paint, will generally be avoided, but such finer points as whether the finishing coat should be of hard gloss paint or of a paint with a greater tendency to chalk will repay attention. In some circumstances the use of the less-resistant chalking paint may prove more economical in the long run by making it easier to clean down the structure when repainting it (see section 2.7); much will depend on the local conditions, the maintenance schedule and whether this schedule can in fact be implemented. Clearly no generalization can be made about this and similar matters but they will repay thought at an early stage.

2.7. *Protecting by painting*

It would be possible to write volumes on the protective painting of structural steel and in fact the Steel Structures Painting Council, of Pittsburgh, U. S. A., has just published two on the subject, amounting to roughly half a million words²⁰). All that can be attempted here is to set out briefly the main principles that should govern good practice in this field. The exposition will follow the broad lines of a book on the subject recently prepared by the Authors on behalf of the Protective Coatings (Corrosion) Sub-Committee of the British Iron and Steel Research Association²¹).

For success in the protection of steel structures by painting there are three essential factors, namely:

- I. Proper surface preparation before painting.
- II. Proper choice of the painting scheme.
- III. Proper painting procedure.

²⁰) "Steel Structures Painting Manual." Pittsburgh, Steel Structures Painting Council, 4400, Fifth Avenue, Pittsburgh, 13, Pa., U.S.A. Two volumes 1954 and 1955, pages vi+423; vi+292. Price 10 dollars for both volumes; separate volumes 6 dollars each.

²¹) F. FANCUTT and J. C. HUDSON, "Protective Painting of Structural Steel". London. Chapman and Hall Ltd. (to be published early in 1957).

I. Surface preparation for painting. With few exceptions the steel plates and sections used for bridge building are produced from billets by hot-rolling and, therefore, begin their life covered with millscale. This millscale consists of oxides of iron formed by the oxidation of the hot metal during its exposure to the air whilst rolling and constitutes a layer a few mils thick all over the steel surface.

It has been established that, under practical industrial conditions, a surface covered with millscale is not a good one over which to paint. This is partly because some millscales are brittle and are liable to flake away from the steel, carrying the paint with them, but mainly because it is impracticable to prevent damage to the millscale and consequent rusting of the steel, which is often heavy, before the priming coat of paint is applied.

The millscale should, therefore, be removed from the steel and the question arises as to how this should be done. There are three main methods of doing this: weathering, pickling and blasting.

Weathering is the traditional method and is still widely used by structural engineers. The steel is fabricated with the millscale on and is then left outdoors in the builders' yard or after erection at the site for a convenient time. The action of the weather corrodes the steel and the rust formed undermines the millscale and forces it off. Loose millscale and rust are removed more or less thoroughly by cleaning with scrapers and wire brushes just before the painting is begun.

The main objection to this process is that it is uncontrollable, usually incomplete, and that it is impracticable to carry it out properly for each and every member of a structure of any size. Moreover, even if a hot-rolled steel surface were perfectly descaled in this way, a considerable quantity of rust would be left on the steel after the final cleaning and this rust would impair the durability of the paint film applied over it.

It need hardly be explained that *pickling* consists in immersing the steel plates and sections in a bath of acid, hot or cold, until the millscale is removed; in most cases the millscale is loosened by undermining from below rather than dissolved. Solutions of hydrochloric acid or sulphuric acid are commonly used, sometimes in conjunction with a final rinse in dilute phosphoric acid. The attack of the acid on the steel itself can be rendered negligible by the addition of suitable inhibitors to the bath. Apart from this it is advisable to use an inhibitor to minimise the possibility of hydrogen being absorbed by the steel, which may have an adverse effect on the mechanical properties of the steel, particularly if it has a high carbon content.

Blasting is carried out by bombarding the steel with hard abrasive particles, of sand, grit, steel shot, alumina, etc. so as to knock off the millscale. The particles may be impelled by compressed air or slung at the surface by means of an impeller wheel.

When properly operated, both pickling and blasting will remove the

millscale completely from steel but, to achieve the best results, it is essential that the paint should be applied immediately after the descaling process, before the steel has had time to rust again. Thorough rinsing with water to remove traces of acid is essential where pickling is concerned. Probably the best procedure is to dip the pickled steel in a hot dilute solution of phosphoric acid, as in the duplex pickling process developed by H. B. FOOTNER, in which the millscale is first removed by immersion in hot dilute sulphuric acid.

The great superiority of pickling and blasting over weathering and wire-brushing as methods of preparing steel for painting is well brought out by the results of some exposure tests at Sheffield, given in table III. It will be seen that the durability of protection achieved was four or five times greater on pickled or sandblasted steel than on weathered steel. It will be noted, too, that paint performance was slightly better on the sandblasted than on the pickled material. For practical purposes, however, there is little to choose between alternative methods of pickling or blasting, provided, of course, that all the processes are efficiently conducted²²⁾.

When blasting is adopted as the method of surface preparation for painting, due regard should be paid to the choice of suitable blasting conditions, particularly to the nature and size of the abrasive. Blasting inevitably roughens the surface and too great a roughness is undesirable, because the paint will not readily cover the peaks of metal, which may remain insufficiently protected. It is generally considered that the roughness produced by blasting, i. e. the distance between the troughs and the peaks of the steel surface, should be approximately one-third of the thickness of the paint film. If a painting scheme 5 mils thick is used, as already recommended, this means that a roughness of about 1.5 mils should prove satisfactory; there is no difficulty in obtaining this degree of roughness with most blasting processes. Another point to be watched where the steel is appreciably rusted beforehand is that

Table III. Effect of surface preparation on the durability of paint on steel exposed outdoors at Sheffield

Method of surface Preparation	Duration of protection. Years	
	2 coats of red lead paint. 2 coats of red oxide paint.	2 coats of red oxide paint.
Weathering and wire brushing	2.3	1.2
Pickling	9.6	4.6
Sandblasting	10.3	6.3

²²⁾ For more detailed information on this point, see F. FANCUTT, "The Effects of Different Methods of Pre-Treating Iron and Steel before Painting". The Iron and Steel Institute. Special Report No. 31, 1946.

badly adjusted blasting conditions may not remove the rust completely but hammer it into the pits on the surface, where it remains a source of grave danger to the painting scheme applied over it.

Brief references should be made to some ancillary methods of surface preparation: flame-cleaning, chemical surface treatment and pretreatment primers.

Flame-cleaning consists in passing an intensely hot flame, usually oxy-acetylene, over the surface of the steel (figure 12). This has two beneficial effects. First, all *loose* millscale is made to flake off, because of the differential expansion between the steel base and the millscale. Secondly, any rust on the surface is dehydrated and most of it is removed by the wire-brushing that follows the flame-cleaning itself. Moreover, the process has the great merit of warming the steel, so that the paint can be put on to it whilst it is still warm, with all the attendant advantages. One of the latter is that the drying time of the priming coat is considerably curtailed by the slight stoving action of the warm surface, which is of considerable practical importance where time is short.

Although the performance of paint on a flame-cleaned surface is greatly superior to that on a weathered surface, it will generally fall somewhat short of that on a pickled or blasted surface, because in the first case all the millscale and rust are not removed. This is demonstrated by the photographs of a pair of specimens shown in figure 13. One had been gritblasted and the other weathered and flame-cleaned before painting; both had been exposed for nearly nine years when the photographs were taken. After this time the grit-



Fig. 12. Flame-cleaning in operation.

blasted specimen still had not reached the grading, 0.5 per cent of rust, at which the painting scheme is considered to have failed but the flame-cleaned specimen passed through this grade at 6.3 years. The corresponding test duration for a similar specimen that had been weathered but not flame-cleaned, was 4.7 years, from which it is evident that the flame-cleaning produced an appreciable improvement.

Flame-cleaning is particularly useful for certain maintenance purposes; for example, when, because of neglect, an old structure has been allowed to rust excessively and extensive cleaning down to bare metal is involved. The process has also been used for new steelwork in combination with weathering, the structure being erected in the bare condition and allowed to weather at the site for some time before the flame-cleaning and painting are done; as described in section 2.10, excellent results have been obtained by this method on a railway bridge at Spondon.

By *chemical surface treatment* is understood the application of a cold solution of chemicals intended to passivate the steel surface and/or improve the adhesion of the paint to it. Phosphating processes proper, in which the steel is treated by immersion or spraying with a *hot* solution of heavy metal phos-

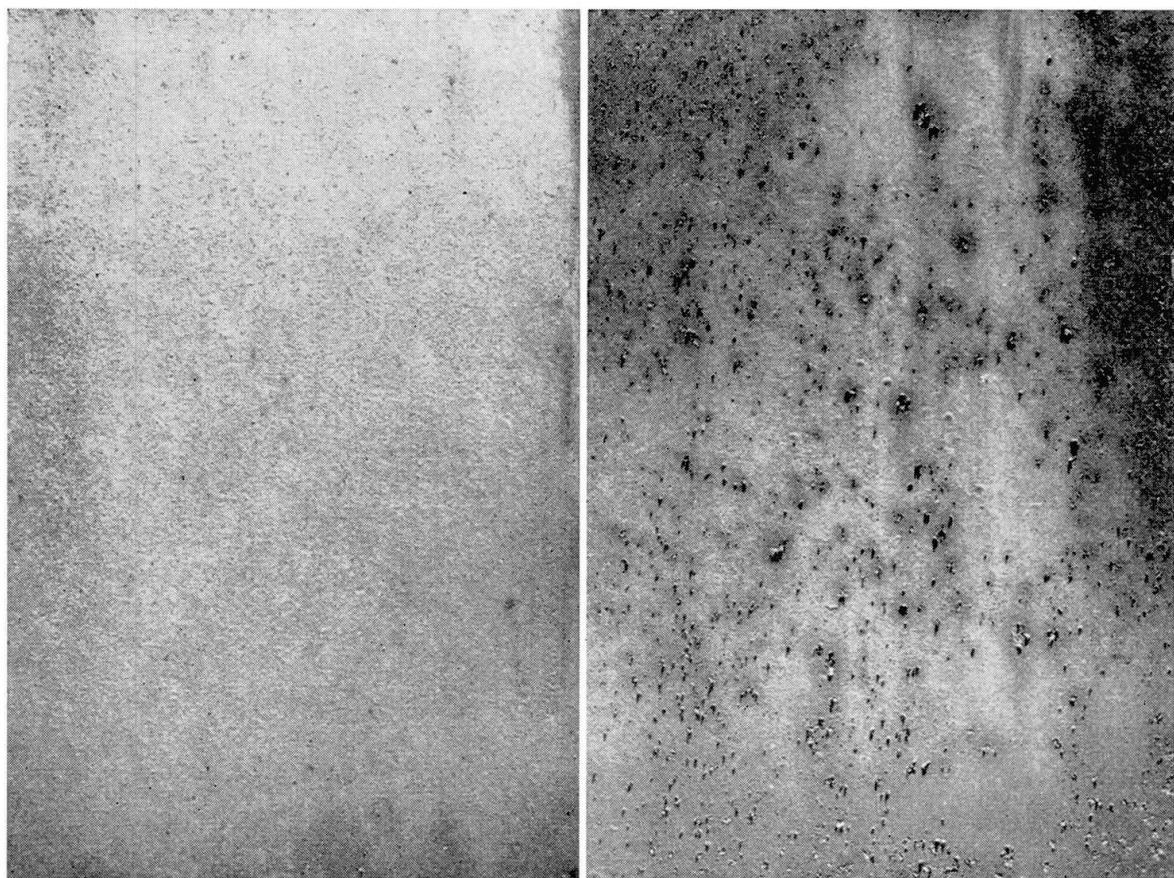


Fig. 13. Comparative behaviour of paint on gritblasted steel (left) and on weathered and flame-cleaned steel (right). (The photographs were taken after 9 years' exposure.)

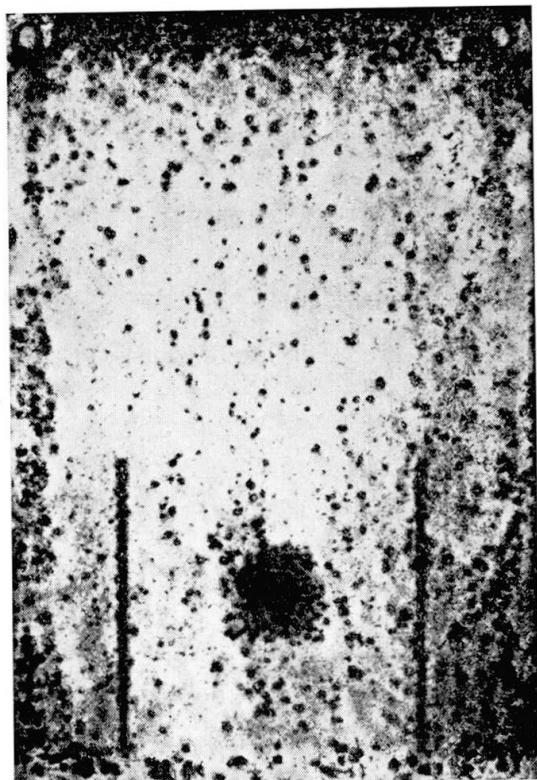


Fig. 14. Effect of a cold phosphoric acid wash on paint performance.

(The photograph was taken after a years' exposure and shows that the use of the wash had failed to overcome the damaging effect of painting over a rusted surface.)

phates, generally those of iron, manganese or zinc, in phosphoric acid, are not included in this definition. There is no doubt that these hot-phosphating processes greatly improve the performance of most painting schemes on steel but in the main they are more suitable, because of the elaborate and expensive plant involved, for the treatment of light-gauge sheet and components, such as motor cars, where continuous production methods can be applied, than for heavy structural steel, with which this paper is mainly concerned.

It is doubtful whether any chemical surface treatment applied in the cold will counteract the detrimental effects on paint performance of a bad surface condition, by which is meant a surface carrying more than a trace of rust with or without residual millscale. Cold washes of the phosphoric acid type certainly fail to do so, as is demonstrated by the photograph reproduced in figure 14. These washes and similar chemical surface treatments, e. g. the application of tannin solutions, are undoubtedly of value when dealing with slightly rusted surfaces, such as result, for example, when bright steel sheets are stored indoors for some time under damp conditions. The washes will react with small amounts of rust but, as stated above, they are unable to cope with gross rusting, produced by exposure outdoors for any length of time.

*Pretreatment primers*²³⁾ are fairly recent development and originated in the United States during the Second World War. In some measure they combine the properties of a chemical surface treatment with those of a paint

²³⁾ These materials are also known as "etch primers" or "wash primers".

film, since they contain both phosphoric acid and organic film-forming materials. The basis formulation, which does not as yet appear to have been improved on, is that given in the following specification of the U. S. Bureau of Ships:

<i>Pigment base</i>	Per cent by weight
Polyvinylbutyral resin	9.0
Basic zinc chromate	8.6
Magnesium silicate	1.3
Lamp black	0.1
Butyl alcohol, normal	20.0
Ethyl alcohol	61.0
	<hr/>
	100.0
<i>Acid diluent</i>	
Phosphoric acid (85%)	18.0
Ethyl alcohol	65.9
Water (maximum)	16.1
	<hr/>
	100.0

The pigment base and the acid diluent are packaged separately and are mixed just before use in the proportions of four parts of base to one of acid²⁴⁾. The mixture is put on by brush or spray and one gallon will cover about 350 sq. ft. It should be emphasised that, as the thickness of the resulting film is only about 0.4 mil, which is several times less than a film of ordinary paint, the pretreatment primer contributes little to the total thickness of the painting scheme. The full number of coats of paint proper should, therefore, be applied over it.

Experience has already confirmed that pretreatment primers are of great value in securing good adhesion of paint to certain non-ferrous metals, particularly aluminium. Good results have been reported, too, from their use on the bottoms of steel ships. Their value for atmospheric steelwork cannot yet be assessed. It is improbable that they will fare any better than the chemical surface treatments discussed above when applied to weathered steel, and how far they would add to the already long life obtainable from good painting schemes applied to properly pickled or blasted surfaces will only be ascertainable by observations extending over a large number of years. As things are, it seems reasonable to conclude that a pretreatment primer is not an essential part of a well thought out scheme of surface preparation and painting.

I. *Choice of the painting scheme.* As already stated, in corrosive climates important structures should be coated, after proper surface preparation, with paint to a total thickness of 5 mils. In practice this means that the steelwork

²⁴⁾ In a useful variant of this specification, Ministry of Supply Aircraft Material Specification D. T. D. 868, "Etching Primer" (Nov. 1953), the compositions of the two components are so adjusted as to enable them to be mixed in equal proportions.

should receive at least three and, more generally, four coats of paint. Two of these coats may well be of priming paint, which will be followed by an under-coat and by a final weather coat. The main characteristics desirable in each type of paint are discussed briefly below.

Priming paints should be inhibitive in character, i. e. they should contain pigments that repress the tendency of the steel to corrode. The best known of these pigments, which has been used from time immemorial for the protection of iron, is red lead. Other inhibitive pigments widely used for the purpose include various chromates, notably those of lead and zinc, white lead, zinc oxide, basic lead sulphate and zinc dust.

The subject of priming paints for structural steel has been extensively investigated by a Joint Technical Panel of the Protective Coatings (Corrosion) Sub-Committee of the British Iron and Steel Research Association with the British paint industry. For details of the conclusions reached to date reference should be made to a recent report of the Panel²⁵⁾ but in brief the main finding is that, when the painting is done over weathered and wirebrushed steel sur-

Table IV. Durability of some linseed oil priming paints on weathered steel

Paint No.	Pigmentation	Duration of protection. Years	
		At Derby (Industrial atmosphere)	At Brixham (Marine atmosphere)
324	Zinc oxide	40	6.9
	Zinc tetrahydroxychromate	40	
	Asbestine	20	
310	Basic lead sulphate	60	6.0
	Zinc chromate	20	
	Asbestine	20	
321	Red lead	40	5.2
	White lead	40	
	Asbestine	20	
300	Red lead	100	4.5
			7.2

The priming paints were tested as single coats beneath a single coat of the same white lead finishing paint.

²⁵⁾ "Painting of Structural Steelwork". Third Interim Report of Joint Technical Panel, J/Pl. The British Iron and Steel Research Association, 11, Park Lane, London, W. 1. February, 1955. Price 5 s.

faces, priming paints made with ordinary linseed oil media give excellent results. When applied over this type of surface they proved superior in the tests concerned to a wide variety of paints in alkyd resin, coumarone resin and other synthetic media. The pigmentation of the linseed oil priming paints does not seem to be critical, provided that it is inhibitive in character. In fact no fewer than eleven paints in this medium — a blend of 30-poise linseed stand oil with one and a half times its weight of alkali-refined linseed oil — have given a better average performance at Derby (an industrial atmosphere) and Brixham (a marine atmosphere) than red lead in linseed oil paint which was taken as a standard of reference. Details of the performance of the three paints at the head of the list and of the red lead paint are given in table IV. One of the best paints No. 321, pigmented with red lead, white lead and asbestine, has been included as Type C in British Standard Specification, B. S. 2523: 1954, "Lead-based Priming Paints for Iron and Steel (Types A, B, and C)". Type A is a straight red lead paint containing only this pigment. The mixed pigment paint of Type C has several technical advantages over this, e. g., it weighs less per gallon and has better can stability. There is, of course, no reason why some of the other formulations found to be better than red lead paint in the tests of Joint Technical Panel J/Pl should not be used instead of a lead paint.

In general, where, as will usually be the case, two priming coats of paint are given to the steel, the second coat may as well have the same composition as the first. It should, of course, be tinted to a contrasting shade, so as to make it easier to ensure that two coats are in fact applied everywhere.

Before leaving this branch of the subject, some further consideration may usefully be given to the value of modern synthetic resin media for the production of priming paints for steel. The superiority of the paints in linseed oil media, revealed in the tests mentioned above and also known from practical experience, is mainly due to two factors. First, they have a better wetting power for rusted steel surfaces and are better able to accommodate the damaging effects of imperfect surface preparation than the paints in a synthetic medium, which dry to a harder film. Secondly, because it is unnecessary to add considerable amounts of volatile solvent to them to bring them to suitable brushing consistency, the linseed oil paints contain appreciably higher percentages of film-forming solids and thus produce a thicker dry paint film.

So long, therefore, as the imperfect method of preparing steelwork for painting by weathering is accepted by structural engineers, their best policy will be to use priming paints in a linseed oil medium. If, however, as is becoming increasingly common, they resort to pickling or blasting, the picture changes. Under these circumstances the use of priming paints in synthetic media, e. g., of a red lead in alkyd medium paint, may well prove advantageous. The paints have the merit, as compared with linseed oil paints, of drying quickly and for practical purposes this is often a great asset, e. g., in badly

polluted industrial areas, where a tacky paint film is very vulnerable to grime and other atmospheric pollution. Unfortunately, these matters take a long time to investigate experimentally and, as the tests of Joint Technical Panel J/Pl did not include many specimens painted over a perfectly descaled surface, no final pronouncement can be made on the subject. It is of interest to note, however, that some American specifications for priming paints are based on a compromise, the medium being essentially a mixture of linseed oil and alkyd media. For example, the Bethlehem Steel Corporation have a specification of this type for a mixed red lead and iron oxide priming paint²⁶).

Undercoats. Until recently the undercoat has been regarded as little more than a link between the priming coat and the finishing paint. Although it is true that a painting scheme consisting of two coats of the same priming paint and two coats of the same finishing paint will give good results, it is well worth while to give some thought to the formulation of the third coat, or undercoat. Low permeability to moisture is of value in this coat and this can be secured by the incorporation of leafing pigments, such as mica or mica-ceous iron ore. The latter pigments have certain advantages for use in painting schemes where the structure is exposed to severe abrasion by wind-borne grit.

Finishing or weather coat. Clearly the outermost coat of the painting scheme must possess the best possible resistance to the weather. Moreover, for many structures, it must be aesthetically pleasing and retain this property for as long as possible; tint retention on exposure is important, for example.

These desired results can be achieved in a variety of ways and there are many satisfactory formulations for finishing paints. It would take very extensive and prolonged tests to distinguish between the best of those available at the moment and it is doubtful whether such an assessment would remain valid for long, as improvements are constantly being made by the introduction of new and better materials, both pigments and media.

In general it may be said that the resistance of paints directly exposed to the weather is determined in the first instance by the nature of their medium. Until about 20 years ago the common practice was to use heat-treated drying oils for the purpose. For example, paints with various pigmentations in a stand oil medium prepared from 3 parts of linseed oil with 1 part of tung oil gave good results in tests by the Dutch Corrosion Committee, which were begun in 1938²⁷). In recent years, however, these paints have been replaced to an increasing extent by paints in synthetic resin media. The use of alkyd resin media and phenolic resin media is especially common and specifications

²⁶) Specification No. 2, "Red Lead, Iron Oxide, Raw Linseed Oil and Alkyd Primer", Jan. 1955, of the Steel Structures Painting Council, 4400, Fifth Avenue, Pittsburgh, 13, Pa., U.S.A., is based on this.

²⁷) Metaalinstituut T. N. O., Afdeling Corrosie, Postbus 49, Delft, Holland. Publicatie No. 32, April, 1955, and earlier publications.

for finishing paints in both types of medium have been drawn up by the Steel Structures Painting Council^{28).}

There have also been considerable changes in the pigments used for finishing paints. Red iron oxide, an admirable pigment for the purpose, albeit an unattractive one as regards appearance, is less commonly used than previously and has been replaced to a considerable extent by newer white pigments, such as the titanium oxides, which can be tinted to any desired shade. Leaf aluminium is also being used to an increasing degree.

A typical modern formulation for a rutile titanium oxide in alkyd medium finishing paint, is given in table V, together with that for a white lead finishing paint, of average merit, of the older type. The alkyd paint will retain its gloss better than the linseed oil one, which will chalk heavily and, in the course of years will literally be washed away^{29).} Chalking, however, is not necessarily an unmixed evil, because it had the effect of making maintenance painting easy. All that is necessary is to wash down the old paint thoroughly, when a smooth and even surface, suitable for the application of a new finishing

Table V. Formulations of a modern and of an older type of finishing paint

Rutile titanium oxide paint in all alkyd medium	Per cent by weight	White lead and barytes paint in linseed oil	Per cent by weight
Rutile titanium oxide	28	White lead	54
Blanc fixe	9	Barytes	14
Micronised talc	5	Acid-refined linseed oil	5
Alkyd resin (medium oil length)	24	Linseed stand oil (15 poise)	22
White spirit	32	White spirit	4
Lead naphthenate solution (24% Pb)	q. s.	Lead cobalt naphthenate solution (7.4% Pb, 1.2% Co)	q. s.
Cobalt naphthenate solution (1% Co)			
Pigment/binder ratio by weight	1.8:1	Pigment/binder ratio by weight	2.5:1
Total volatile content by weight	33%	Total volatile content by weight	5%
Weight per gallon	13.6 lb.	Weight per gallon	21.0 lb.

If desired both these paints could be produced in a range of shades by the addition of suitable tinting pigments.

²⁸⁾ Steel Structures Painting Council, 4400, Fifth Avenue, Pittsburgh, Pa., U.S.A., Paint Specifications, January, 1955. No. 104: White or Tinted Alkyd. Paint. No. 105: White or Tinted Phenolic Paint.

²⁹⁾ It should not be inferred that paints with excellent gloss retention cannot be made in the older types of media.

coat is obtained. On the other hand, if neglected, paints in synthetic resin media may fail by flaking; this gives rise to an uneven surface, which is difficult to clean and to build up again to a smooth even film. The point may be of greater importance where paint is applied over wood, e. g., for domestic dwellings, but at least one seaside Borough Engineer prefers a chalking type of finishing paint for his pier on this account. As in the case of undercoats, leafing pigments are of value in finishing paints and some very durable paints can be produced from blends of leaf aluminium and micaceous iron ore in synthetic resin media.

Tar and bitumen paints suffer from two main disabilities: it is difficult to colour them satisfactorily and they are not freely compatible with oleoresinous paints. Where these disabilities do not operate, e. g., for the protection of certain industrial plant, tar and bitumen paints are a valuable adjunct to protective coatings for steel.

As a rule, coat for coat, the protective properties of tar and bitumen paints are inferior to those of most oil paints, because they have no inhibitive properties and in addition they often yield a thinner film, particularly in the case of paints of the straight solvent type. The best practice is to use them as finishing coats over a foundation of properly inhibitive oil paint. This priming paint must, however, be perfectly dry. When, as is usual, red lead in linseed oil paint is employed for the purpose, this should be allowed to dry for about a month before being overcoated with the tar or bitumen paint. If the latter is put on too soon, the solvent in it affects the priming coat and the whole painting scheme breaks down prematurely.

Although there are several excellent proprietary paints of this type on the market, little systematic research on them has been published. Joint Technical Panel J/Pl has undertaken an investigation to fill this gap and some preliminary results have been published³⁰⁾. The main observation made is that, as is well known to the paint industry, the properties of tar and bitumen paints can be appreciably improved by pigmentation and the incorporation of drying oils. In exposure tests at Derby and Brixham two-coat painting schemes prepared from blends of the natural bitumen, Gilsonite, with several drying oils, showed very little sign of breakdown after six years' exposure on weathered steel and were in somewhat better condition than a scheme consisting of white lead in linseed oil paint over a red lead in linseed oil priming paint. The formulation of one such painting scheme is given in table VI. The priming paint is pigmented with barium chromate, witherite (barium carbonate) and talc and the finishing coat with aluminium powder, which gives it a pleasing appearance. In this particular scheme, dehydrated castor oil was used as the drying oil but equally good results, within the experimental error, have so far been obtained from linseed and other oils.

³⁰⁾ Third Interim Report of Joint Technical Panel J/Pl. (loc. cit. p. 23).

Before leaving the subject of the choice of paints, it may be well to reiterate that a painting scheme should be envisaged as a whole, from the initial surface preparation to the final weather coat. Individual coats of paint should not be matched up in a haphazard manner and, for this reason, it is good policy to entrust the supply of all the paints required for a given scheme to the same paint manufacturer.

Application of the paints. To obtain the best results, it is vital that all paints should be well applied and that the painting should take place under favourable atmospheric conditions. The effect of these two factors will, therefore, be considered below.

Dipping is not used on a large scale for the painting of steel structures and the choice will generally lie between brush- and spray-application. Experimental evidence indicates that, if the comparison is made for films of equal thickness, there is little to choose, as regards protection between hand-brushed and sprayed paint films. Spraying usually has the advantage of being

Table VI. Formulation of a painting scheme based on natural bitumen and drying oil

Formulation	Per cent by weight	
	Priming coat	Finishing coat
Barium chromate	8	—
Ground witherite (barium carbonate)	18	—
Talc	13	—
Aluminium paste (67% metallic aluminium; 33% white spirit)	—	34
Medium as below	48	54
White spirit	13	12
Properties	Priming coat	Finishing coat
Pigment/binder ratio by weight	1.8:1	0.9:1
Total volatile content by weight	39%	51%
Weight per gallon	12.1 lb.	9.6 lb.

Medium. Natural bitumen (Gilsonite) is heated with half its weight of dehydrated castor oil to 370° F, when 0.5 per cent by weight of litharge is added. Heating is continued with stirring up to 540° F for a total period of one hour. The blend is then cooled to 430° F and white spirit and driers are added. After standing for about five days, more white spirit is added to adjust the medium to a suitable viscosity. The total white spirit content of an actual batch was 55 per cent by weight and the batch contained 0.1 per cent each of cobalt naphthenate (6% Co) and manganese naphthenate (6% Mn) driers.

quicker but, against this, it is more sensitive to adverse climatic conditions at the time of application. If the paint is brushed out vigourously, good results can be obtained even when paint is put on to a damp steel surface; it is doubtful whether equally good performance could be obtained by spraxing under such conditions. Moreover, hand application is advantageous when dealing with weathered and rusty surfaces. Probably the best practical procedure, which is adopted by many engineers, is to put on the priming coats by brush and to finish the work by spraying.

It is common ground that painting during bad weather should be avoided, if at all possible. For this reason it is wise to put on the first coat of paint under cover and, indeed, where any considerable and continuous amount of painting is involved, it is worth while to reserve a special shop, which can be warmed if necessary, for painting. Outdoor painting should be carried out under dry conditions, when the air is warm, avoiding temperatures below 40° F where practicable. Admittedly, these may be counsels of perfection, but much can be done by giving a little prior thought to the progress of the work and by consulting the meteorological data for the site where the final painting is to take place. In this connection, humidity records, such as those depicted in figure 3, may prove helpful. It is inadvisable to schedule painting for periods when the relative humidity of the atmosphere is likely to be high, say above 85—90 per cent.

2.8. *Protection by metallic coatings*

Many non-ferrous metals are much more resistant to atmospheric corrosion than iron. For example, taking an average value for a large number of sites all over the world at which tests have been made by the British Iron and Steel Research Association, zinc corrodes about fifteen times less rapidly outdoors than mild steel. The advantage in favour of the zinc tends to be less in industrial atmospheres and greater in unpolluted, rural ones. For example, in the country at Llanwrtyd Wells in central Wales zinc coatings weighing about 2 oz. per sq. ft., which is equivalent to an average thickness of about 3 mils, are still virtually intact after more than 25 years' exposure. Zinc coatings are of much less value, however, in enclosed, polluted and humid places, where the surface is not washed by rain; thus, in the Dove Holes Tunnel zinc was found to corrode at the same rate as steel³¹⁾. This was because the main corrosion product of the zinc, resulting from the attack of the steam and smoke from the locomotives passing through the tunnel, was zinc sulphate, which is deliquescent and literally dropped off the specimens in solution.

Although a wide range of non-ferrous metals is used as protective coatings for sheet steel and small steel components, for application to heavy structural

³¹⁾ It will be recalled that slow-rusting steels also failed to show to advantage under these conditions (see section 2.2).

steel the choice of metals is restricted by economic and practical factors. For example, it is undesirable that the coating metal should be cathodic to the steel (see section 2.0), as this would aggravate corrosion at places where the coating was defective or became perforated by damage. For most purposes, therefore, the choice lies between zinc and aluminium. Zinc can be put on by a variety of processes, cementation, hot-dipping, electrodeposition and spraying, although only hot-dipping and spraying are widely used for structural steel. As yet, except for cementation and hot-dipping processes, which have a restricted application to strip steel and small parts, the only practicable method of coating heavy plates and sections with aluminium is by means of the spray gun³²⁾. Indeed, the use of protective aluminium coatings is a comparatively recent innovation, being intimately bound up with the development of metal-spraying.

The Protective Coatings (Corrosion) Sub-Committee is conducting extensive exposure trials of a wide range of metal coatings for structural steel. Some of these tests have now been in progress for fifteen years. They have already demonstrated the great value of metallic coatings for the protection of structural steel, as is shown by a few typical results for coatings, about

Table VII. Durabilities of metal coatings on steel exposed outdoors at Sheffield

Details of coating			Test duration (5 per cent of rust) Years
Metal	Method of application	Weight ³³⁾ oz. per sq. ft.	
Aluminium	Spraying	1.0	11.9
Cadmium	Electrodeposition	2.2	2.3
	Spraying	2.2	2.8
Lead	Electrodeposition	2.9	11.9
Tin	Electrodeposition	1.8	11.9
	Spraying	1.6	11.9
Zinc	Electrodeposition	1.7	6.4
	Hot-dipping	1.7	6.1
	Spraying	2.1	7.4

³²⁾ Sprayed coatings, both of aluminium and zinc are covered by British Standard Specification B. S. 2569: 1955. "Sprayed Metal Coating, Part I, Protection of Iron and Steel against Atmospheric Corrosion."

³³⁾ 1 oz. per sq. ft. equals roughly 3 g. per dm².

2—3 mils thick and exposed at Sheffield, that are given in table VII; some other results, for zinc coatings at Sheffield, have already been shown in fig. 10.

It will be noted that lead coatings gave good results when exposed in the industrial atmosphere of Sheffield. This is probably because of the formation of a surface film of lead sulphate. Where this film does not form, in purer rural atmospheres or in marine atmospheres, the results given by lead coatings are relatively less satisfactory. In any case, because of difficulties of application, lead cannot be considered seriously for widespread use on heavy structural steel³⁴⁾. For this purpose, therefore, as already mentioned, zinc and aluminium are the most useful materials. Before discussing the performance of these coatings in the Sub-Committee's tests, it should first be stated that, as shown in table VII, zinc coatings gave much better protection than cadmium coatings of equal thickness. There is, therefore, no point in using the more expensive metal cadmium in preference to zinc, except for certain special purposes, as, for example, electrodeposits on articles of complicated shape, where cadmium may give a more uniform deposit than zinc.

There is ample scope for the use of both aluminium and zinc as coating metals for structural steel. Insufficient practical experience is as yet available to distinguish between their respective merits. So far as resistance to general surface corrosion by industrial atmospheres is concerned, the advantage lies with aluminium when the two metals are compared at equal coating thickness (see table VIII). In tests at Sheffield aluminium coatings 3 mils thick protected steel for 10 years or more; a 5 mils thick coating of zinc would have been needed to give equal performance. It cannot be said, however, whether this comparison will hold true for non-industrial atmospheres, as the coatings on similar specimens to those at Sheffield but exposed at less corrosive rural and marine sites have not yet reached the point of failure. Moreover, there is inevitably a difference between the behaviour of coatings on simple pieces of plate hung vertically, such as the test specimens, and on a structure which may comprise a high proportion of sheltered surfaces and edges. In this connection it is pertinent to note that experience at a chemical works has led F. R. HIMSWORTH³⁵⁾ to the conclusion that zinc protects the edges of sections better than aluminium under these conditions, presumably because it exerts stronger cathodic protection (see section 2.5).

Although they are much more slowly affected than steel, metallic coatings are not incorrodible and sooner or later will themselves require protective painting. The question arises as to how this can best be done. A complete answer cannot yet be given to this question and, indeed, the Protective

³⁴⁾ This remark does not apply to the use of lead or lead-alloy coatings for steel sheet, to which they can readily be applied by dipping; the resulting product, "terne plate", shows excellent corrosion resistance to the atmosphere.

³⁵⁾ F. R. HIMSWORTH, "The Protection of Steelwork in Chemical Factories". Chemistry and Industry, 1955, No. 50, Dec. 10th, 1618—1622.

Coatings (Corrosion) Sub-Committee is about to undertake an experimental investigation with a view to providing information on the subject. The following provisional advice can, however, be given on two of the most important features: (I) the painting of hot-galvanised steel and (II) the painting of sprayed metal coatings.

I. *Painting of hot-galvanised steel.* Paint often fails to adhere well to freshly hot-galvanised steel. Where practicable the trouble is best overcome by phosphating the steel, by immersion or spraying, using a suitable process that does not attack the zinc coating itself to a dangerous extent. Otherwise, surface washes based on phosphoric acid, of which several proprietary brands are available, or a coat of the pretreatment primer mentioned in section 2.7 can be used to procure the necessary adhesion.

Another method, where circumstances permit, is to let the hot-galvanised steel weather in the open for some months before painting it. The surface then becomes etched naturally by corrosion; it is advisable to wash it down with hot water before putting on the priming coat.

Tests in the United States and in Great Britain agree in showing that paints pigmented with zinc dust and zinc oxide adhere particularly well to hot-galvanised steel, even if this has received none of the treatments mentioned above. There is an American specification for paints of this type in various media³⁶⁾.

Painting of sprayed metal coatings. As both zinc and aluminium are anodic to iron, they may be regarded as possessing inhibitive properties. Therefore, so far as the steel base is concerned, there is no point in making the priming paint for a metal coating inhibitive in character. On the other hand, it may be an advantage to use an inhibitive priming paint to retard the corrosion of the coating metal itself. In the present state of knowledge, the use of chromates in the pigment mixture is as a promising a step as any.

In their very nature, sprayed metal coatings are rough; there may be a vertical distance of 2 mils or more between their peaks and furrows (see figure 15). Because of this roughness there is generally no difficulty in obtaining good adhesion between the paint and the coating; the physical bond is sufficient in itself and no special chemical surface treatment is needed, as is the

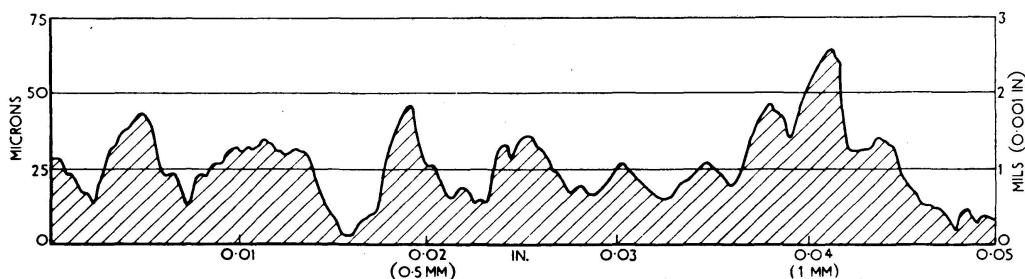


Fig. 15. Roughness of a sprayed zinc coating.

³⁶⁾ U. S. Federal Specification TT-P641. "Zinc Dust-Zinc Oxide Paint. Type I, raw linseed oil. Type II, alkyd. Type III, phenolic." April 20, 1939.

case for hot-galvanised coatings. On the other hand, it is obvious that a substantial proportion of the paint applied will be used in filling up the hollows in the sprayed coating and that, only when this is done, will a depth of cover begin to be built up over the high spots of the surface. It is doubtful whether all this can be done with a single coat of the usual types of paint, so that, for the time being, good practice for the painting of sprayed metal coatings should be regarded as the application of at least two coats of paint. The first of these should be a generous one, designed to fill the pores in the surface. This paint might well contain a proportion of chromate pigment; a good iron oxide pigment mixed with at least 25 per cent of its weight of zinc chromate and in an alkyd medium might be found suitable. The second coat should be a weather coat with a high degree of resistance to breakdown.

The question also arises whether it is better to paint the metallic coating at the time the structure is erected or to wait for several years until the coating is nearing the point of failure. Clearly, much depends on the circumstances. Where access is easy and the conditions are only slightly corrosive, it may be advantageous not to paint over the coating until this is about to become necessary. For example, the galvanised side sheeting of a barn erected in a rural atmosphere might well be left unpainted at first. In contrast to this, where access is difficult, e. g., a lattice wireless mast, or where the conditions are severely corrosive, it is probably advisable to do the painting at once. This applies particularly to structures exposed to industrial atmospheres, where dirt, which is readily retained in the rough surface of the metallic coating and the corrosion products of the coating itself, which accumulate on sheltered

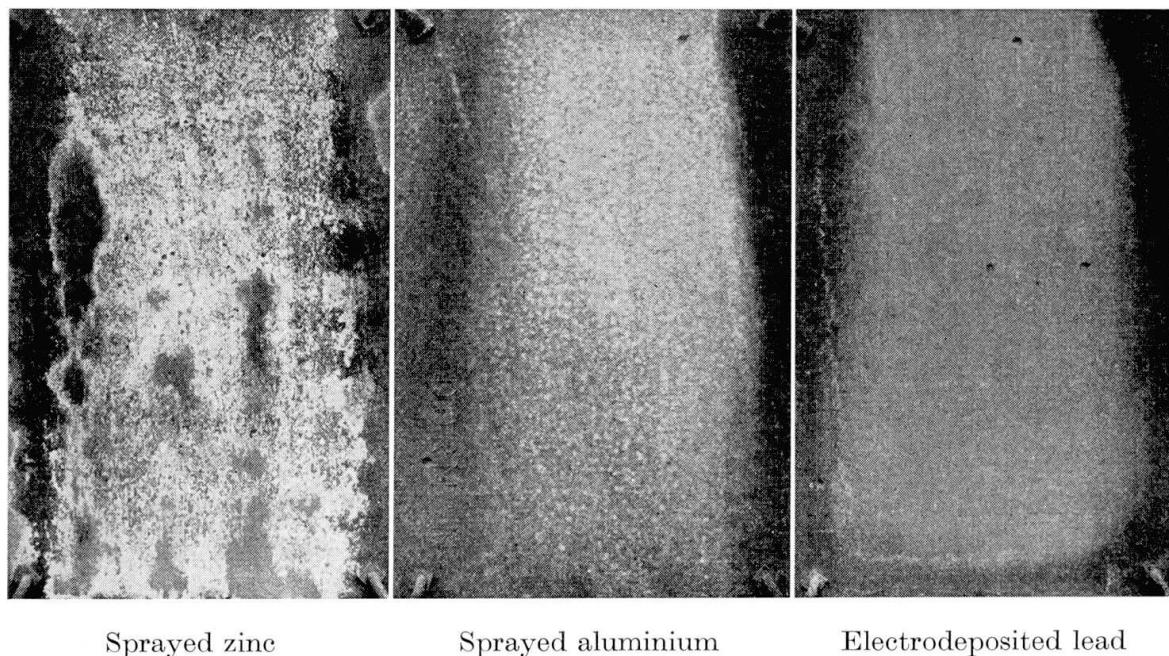


Fig. 16. Condition of paint over metal coatings on steel after $12\frac{1}{2}$ years' exposure at Sheffield.

parts not washed by rain, may have a bad effect on paint applied some time after erection. It should be stressed that the presence of a metallic coating on the steel does not render it permissible to omit the necessary cleaning down of a structure before painting (see section 2.10 on maintenance painting).

The longevity of painted metallic coatings is demonstrated by the photographs reproduced in figure 16, of some metal-coated steel plates that had been given two coats of red iron oxide on linseed oil paint and exposed outdoors at Sheffield for $12\frac{1}{2}$ years. Hot-galvanised steel rusted appreciably at the end of this time, but there was no serious rusting when the steel had been sprayed with aluminium; even better results were obtained by painting over electrodeposited lead.

2.9. Protection by other types of coating

Several other types of coating besides paints and non-ferrous metals are used to protect structural steel. Three of the most important are bitumen, tar and concrete. As with all coatings, there are two essentials for success; good adhesion of the coating to the steel and sufficient depth of cover.

Coatings of tar and bitumen are often applied by hot-dipping or are brushed on hot. They can also be applied in the form of mastics by trowelling in the cold. As stated in section 2.7, straight solutions of coal tar pitches or bitumen suffer from the disability that, after the solvent has evaporated, they yield a comparatively thin film. Adequate coating thickness is essential for these types of coating. For example, in the case of iron or steel buried in an aggressive soil, a sheath of bitumen one quarter of an inch thick is by no means excessive and, because bitumens flow under temperature and pressure, the coating should be reinforced. Inert reinforcements, such as asbestos cloth and woven or felted glass fabric, have taken the place of the older wrapping materials, such as hessian, which are gradually rotted by the soil bacteria. To

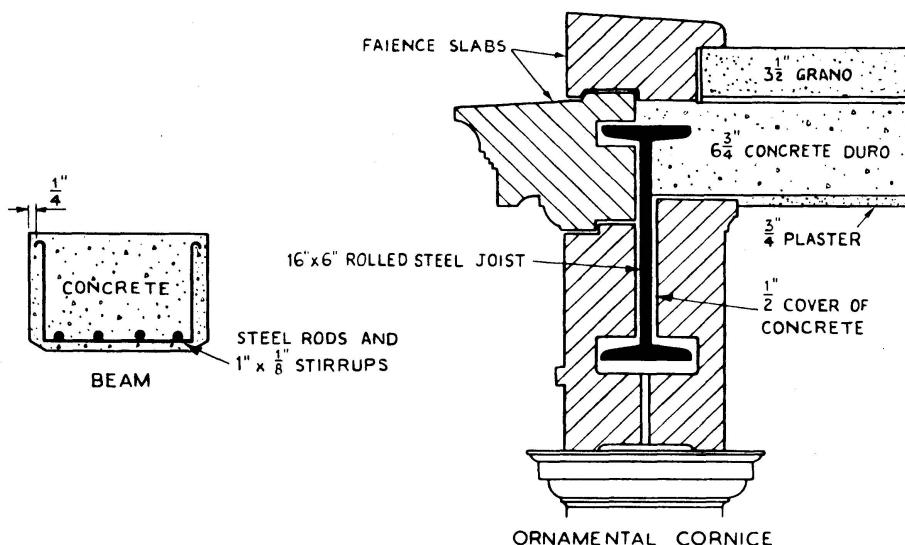


Fig. 17. Faulty designs of reinforced concrete members.

obtain the necessary adhesion of the thick reinforced bitumen coating, it is necessary to apply it in stages, the first coat being usually a thin film of bitumen alone, which is put on by hot-dipping. All these, however, are well known matters of technique, which need not be elaborated.

Insufficient attention is still paid to the importance of depth of cover when protecting steel by concrete. When the concrete is well tamped and of good quality, a thickness of 2 in. should ensure complete protection, but care must be taken that this depth of cover does in fact extend over all points of the section. Designs such as those shown in figure 17 are fraught with danger and should be avoided.

It is probable that in the fairly near future much more use will be made of plastic coatings for the protection of heavy structural steel, as some of these materials possess a high degree of resistance to attack even by the most corrosive media. Clearly the most promising method for large flat surfaces is the attachment of thin sheets of the plastic material. The main difficulties that have yet to be overcome are to ensure the adhesion of the plastic coating to the steel and to produce plastic materials with the same coefficient of expansion as steel. At the moment the large differences between the coefficient of expansion of, say, polythene and steel soon lead to the failure of the coating, which shrinks away from the edges to a marked extent (figure 18). Plastic coatings are, however, already being used for circular sections, such as wires or pipes, to which they can be applied as a continuous sheath by extrusion. Plastics are also used in certain protective wrapping tapes, loaded with grease, which have a range of useful practical applications.

Finally, a word may be said about temporary protective coatings. A thin coating of linseed oil rubbed on by a rag, or applied as a solution in white



Fig. 18. Poor adhesion of polythene coating to steel.

(This bonded polythene coating, 12 mils thick, had been exposed in a marine atmosphere at Brixham for 0.85 years.)

spirit, at the rate of about 3000 sq. ft. per gallon will protect steel outdoors for 3 months or so under moderately corrosive conditions. Lanoline solutions or some of the proprietary sulphonated petroleum compounds will do so for a year or even longer. A bitumen-water emulsion, akin to a paint and applied by dipping, has been observed to protect steel adequately for nearly two years and a half. There may be circumstances in structural engineering in which one or other of these temporary coatings would prove of value. One desirable property of any such coating as that after use it should be easily removable by solvent before the painting proper. Some of the harder lanolin preparations may present difficulty in this respect but most of the materials mentioned should prove satisfactory. Detailed descriptions of nine types of temporary protective now in general use with examples of their applications are given in the British Standard Packaging Code³⁷⁾.

3. Maintenance of existing structures

I. General. The benefits of good design and carefully chosen initial protective schemes might in many cases justify their higher cost if they persisted no longer than the life of the original coating, but great as these benefits are, they are outweighed by the advantages that will accrue throughout the whole life of the structure. To secure these advantages to the full, reasonable maintenance must, however, be carefully carried out.

The proper choice of metals to meet special requirements and the avoidance of corrosion-promoting crevices and ill-ventilated cavities will eliminate danger points that are difficult to protect. The complete removal of scale and rust will ensure that the protective coating will not be prematurely undermined and disrupted by the development of corrosion, which is inevitable when rust and scale are present below the protective film, so that the carefully selected protective coatings themselves, securely anchored to the chemically cleaned and roughened metal surface and applied in the correct thickness under proper atmospheric conditions, will often put up a performance that has hitherto been thought unattainable. Nevertheless, none of the protective schemes envisaged in this paper can be regarded as permanent and the maintenance of the protective system must be carefully considered.

The basis on which the maintenance of a given structure is carried out must, of course, be varied to suit its particular design, function and accessibility, as well as its environment. In all cases the ideal would clearly be the renewal of the protective system before it was allowed to deteriorate to such an extent that corrosion of the basis metal had commenced. The practicability of this objective is greatest when the performance of the protective scheme

³⁷⁾ "The British Standard Packaging Code." Section 3, Clause 346. The B. S. 1133 and 1943.

is uniform throughout the structure, especially in the earlier years of its life. Where the initial protective treatment, including, of course, the surface preparation, has been carried out on the lines suggested in the previous sections of this paper, this will not only eliminate the weak points and enable the original protective coating to give of its best over all, but, under a correct maintenance schedule, will also ensure that the full potential of the coatings subsequently applied is developed. If the initial protective system comprises a metallic coating followed by two or three coats of paint the increased durability of the protective paint will persist throughout the life of the structure and a 7- or 8-year repainting cycle should be obtained under average industrial conditions. Perhaps of equal importance to the increased period between repaintings is the reduction in the amount of work necessary to prepare the structure for repainting since, provided corrosion has not been allowed to commence and the paint coatings are failing by chalking rather than by lifting or flaking, a simple washing down with clean hot water to which a little detergent has been added will be all that is necessary, and considerable savings will be achieved. A suitable criterion of the time at which repainting should be carried out under these conditions is the point at which the undercoating is just beginning to show through the finishing paint. In general, two coats should be applied at each repaint carried out under these circumstances, for in this way the imperfections — incomplete or thin coatings at the first application — will be corrected by the second, the probability of these imperfections coinciding at the two applications being very remote. The nature of the paints to be used will be considered later, but, as an example of what can be achieved it may be noted that a railway bridge at Spondon (figure 19), which was flame-cleaned when newly erected in 1944 and then given two coats of primer and two coats of micaceous iron ore paint, was still in good condition and showing less than 0.1 per cent of rusting in 1955 — eleven years later.

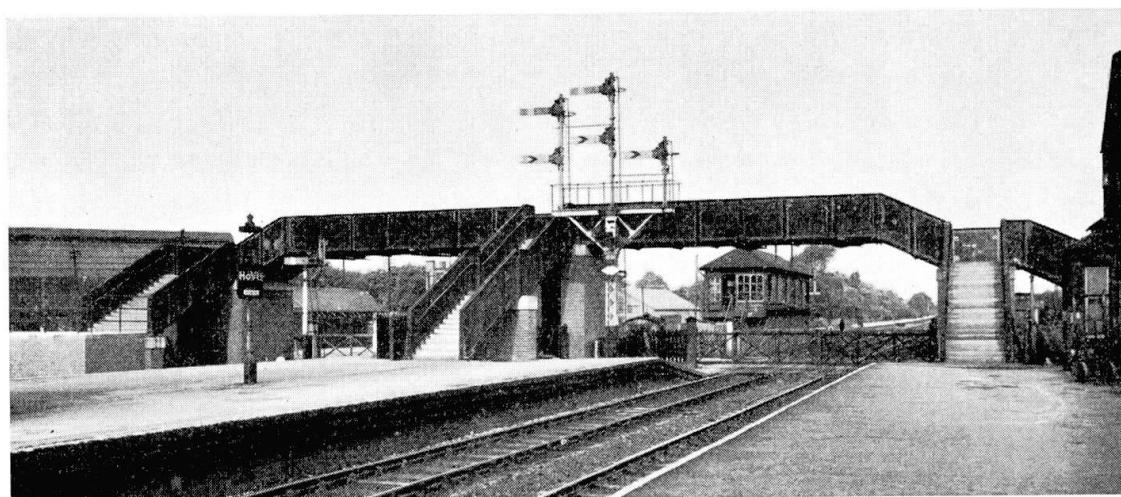


Fig. 19. Spondon Railway Bridge.

II. Surface preparation. Many steel structures exposed to atmospheric conditions in Great Britain have unfortunately been allowed to corrode to such an extent that, before repainting can effectively be carried out, they must be cleaned down to the bare metal over some part at least of their area; often the corrosion has reached the stage where renewal of some members and repair of others have become necessary. Where this has happened, it is essential that all repairs should be effected before the painting of the structure as a whole commences and that they should be carried out with care. Where the preparations for the repair give access to areas normally beyond the reach of the painter, the timing of the operations should be such that the painter can take the opportunity afforded to renew the protective coating at these places. Where welding is carried out, it should be borne in mind that the heat of welding may destroy the paint coating on a hidden surface.

The removal of corrosion product from the rusted and, more particularly, from the pitted areas of a steel structure is essential if a reasonable life is to be obtained from any protective coating applied. This is a difficult and, from the operatives' point of view, unpleasant task to perform by hand and is best carried out by mechanical means. Sharp-ended chipping hammers of the conventional shape, applied indiscriminately, can create weak points in the protective system, because the burrs created at the point of impact with the hammer project through the paint film. Pneumatic chippers held at an angle to the surface can be very effective and do not damage the surface of the metal excessively. If chippers are used, the tool should be of such a size that it can dislodge the corrosion product from the base of the corrosion sores or pits. Mechanical wire-brushing is a useful adjunct to the chipper but is unsatisfactory when used alone. Where the amount of corrosion is widespread and involves continuous areas of considerable size, flame-cleaning is an excellent method and with reasonable care can be used to remove or dehydrate all corrosion products, without distortion and any undesirable metallurgical effects when the plates are $1/4$ in. or more thick. When flame-cleaning is used, the best results are obtained from the subsequent painting scheme if the first coat of primer is applied while the steel is at about 100° F (40° C). If this is done the paint will dry much more quickly, in about 2 hours as compared with 16 hours when applied on a cold surface. The actual technique adopted in flame-cleaning is important and British Railways have laid down a standard sequence of operations for use by their workmen.

The use of blasting with abrasives has been described in section 2.7. On the whole blasting is more conveniently done in the fabricating shop than at the site, because of the difficulty of dealing with dust when sand is used or of the economic necessity of recovering the abrasive when this consists of metallic grit. Another difficulty arises from the sensitivity of the blasted metal to rerusting when exposed to polluted atmospheres. Moreover, it is difficult to ensure that the corroded surface is correctly cleaned. Laboratory and field

tests have indicated that the excellent performance of protective coatings over blasted steel surfaces is not always repeated when the steel being tested has previously been allowed to corrode instead of being new.

The use of vacuum appliances to remove all traces of the debris is an important adjunct to all methods of cleaning. This step can improve materially the success obtained with any of the methods of surface cleaning to which reference has been made.

Under certain conditions the use of chemical washes can give beneficial results, although this must be regarded as an additional treatment to be given to steel that has previously been cleaned free from all loose rust and millscale, and it will not prove effective over rust and old paint. Strict supervision and correct drying conditions are essential for success. The most satisfactory washes are based on tannins or phosphoric acid, and of these the latter has been found to be the more effective.

When preparing well established structures for painting, weak places in the protective system due to design or some feature of environment can generally be recognised, and these should be given special attention. Soil/air boundaries, where the supports of a structure pass into the ground, are a frequent source of difficulty and encasing of the foot of the structure in concrete may prove the best answer to the problem. If this means is adopted, the concrete should be carried well above soil level and be finished off so that no crevices to hold water are created. The use of concrete to protect steel in structures already showing serious corrosion should only be adopted after due consideration has been given to the difficulty of subsequent inspection of areas thus treated. It must also be recognised that at least 2 in. thickness of concrete is necessary and that the concrete may ultimately require to be protected itself.

Where drainage holes have been provided in a structure, care should be taken to ensure that they still function and that the discharge from them is conducted away from any underworks liable to be damaged. Where such holes were not originally provided, experience may indicate that they were, or have become, essential. A not infrequent source of corrosion is the overlaying of the structure with decorative casings and sometimes wooden advertisement hoardings. Where corrosion is seen to be occurring, serious consideration should be given to their immediate removal.

In carrying out the preparatory work indicated, care should be taken not to remove unnecessarily areas of sound paint, i. e. strongly adherent paint showing no sign of deterioration other than surface chalking. On the other hand, in dealing with corroded areas, the paint should be removed right back to the point where the steel is free from corrosion. It will be found to be good practice to chamfer the edges of the sound paint, so that a better transition from the old to the new paint is secured.

III. Painting. An existing structure that has been prepared for painting by the methods indicated above will consist of areas of exposed metal and

adjacent areas with an adequate covering of sound paint. Logically, it would appear that the objective should be to build up the paint film thickness on the corroded areas to the same level as that of the sound paint. On well established structures where the sound paint may have been built up to a thickness of as much as 20 or 30 mils, this procedure is often impracticable, although a paste material, preferably based on white lead and applied with a knife, has been successfully employed to level the surface on occasion. The first two coats of new paint should be based on the inhibitive pigments mentioned in section 2.7 and should be confined to an area overlapping the sound paint by 1 in. to 2 in. only. The completion of the painting process will be governed by aesthetic considerations and will also depend upon the condition of the old paint. For example, if a four-coat painting scheme is used only the under-coat and the finishing coat may be applied all over the structure and the application of the complete painting scheme may be confined to the corroded areas. "Patch painting", as the latter process is called, is a satisfactory procedure only after the structure as a whole has a well established skin of paint; it should not be adopted for structures that have not received at least three complete repaints over the whole surface.

As an example of maintenance painting, it may be of interest to give some details of a well known case — the painting of the Forth Bridge. This structure, which has a permanent staff of 20 painters, is repainted with a single coat of brush-applied red oxide paint based on linseed oil every three years. Until recently the paint was actually prepared on the site from an oil paste, linseed oil and driers. Very little corrosion has occurred but, where it has, a single coat of red lead in linseed oil priming paint is applied after scraping and wire-brushing. The paint film thickness was recently found to be 30 mils and a sample of the film that was removed for examination showed it to be extremely flexible and tough. The remarkable condition of this very exposed structure is an excellent tribute to the care with which it has been maintained and illustrates the advantage of such maintenance.

With regard to the best method of applying paint, as indicated in section 2.7, under outdoor conditions brush application is to be preferred for the first coat. This disturbs any dirt and moisture that may be present on the surface³⁸⁾ and ensures better wetting, whether it be of the metal itself or of the weathered paint, and thus secures better adhesion. The spray application of subsequent coats can give results at least comparable with those of brushing, or where the film thickness of the sprayed paint is greater, even better.

The application of paints under bad weather conditions, i. e. during rainfall or in temperatures below freezing point, invariably yields unsatisfactory results. Painting over damp painted surfaces, especially where the paint contains a lead pigment and is well brushed in, may give results only slightly

³⁸⁾ Admittedly, if the counsels given earlier in this paper regarding surface preparation and painting conditions are followed implicitly, there should be none!

inferior to the results obtained on dry surfaces, but where such paint is applied to rusty metal the results are invariably markedly poorer. Paints containing other pigments are much less tolerant of moisture on the surface and the results obtained are usually bad. The addition of water-displacing amines to such paints may, improve their performance on damp surfaces to some extent.

Consistently good results can be obtained only when the paint is applied under dry conditions and at temperatures above about 40°F (5°C), as has already been indicated in section 2.7.

The choice of paints for maintenance work is similar to that for a new structure although, since most of the metal exposed and needing priming, will be corroded, the use of an inhibitive primer is even more imperative. An old problem regarding the priming of galvanised structures or components from which the zinc coating has corroded away locally leaving the steel exposed, has now been solved by the use of calcium plumbate priming paints which, unlike red lead paints, are equally suitable for use on zinc and on steel surfaces.

An important factor to be taken into account when considering the maintenance painting of a structure is compatibility of the existing and proposed paints. An example of incompatibility has already been mentioned in section 2.7, when a warning was given against the use of tar or bitumen paints, when at a later stage oil paints, perhaps in light colours might be required. Hard-drying short or medium oil length synthetic resin based media may prove incompatible with weathered films of softer paints based on older types of media, particularly where the surface is broken with corrosion. In such circumstances the freshly applied paint may cause flaking from the metal. It should be reiterated that, in general, none of the newer media so far tested is so tolerant of indifferent surface preparation as linseed oil based paint. Consequently, where circumstances prevent adequate surface preparation, paints based on linseed oil will often give the better performance, for old work and new work alike.

In selecting the paints to be used, the performance of the paint already on the structure should be studied and consideration given to the possibility of reinforcing the protective system at areas that are seen to need special protection, such as flanges of girders, which frequently deteriorate at a greater rate than the webs.

Summary

In the contribution the following points and the corresponding results of protection of steel against corrosion are treated:

Results of British researches on the protection of steel against corrosion

1. General survey of protective methods.
2. Effect of design.

3. Effect of steel composition.
4. Effect of corrosive medium.
5. Cathodic protection.
6. Main principles relating to the use of protective coatings.
7. Protection by painting.
8. Protection by metallic coatings.
9. Protection by other types of coating.
10. Maintenance of existing structures.

Résumé

Les points suivants et les résultats correspondants sur la protection de l'acier contre la corrosion sont traités:

Résultats des recherches sur la protection de l'acier contre la corrosion effectuées en Grande Bretagne

1. Examen général des modes de protection.
2. Influence de la conception de l'ouvrage.
3. Effet de la composition de l'acier.
4. Effet du milieu corrosif.
5. Protection cathodique.
6. Principes généraux concernant l'emploi de revêtements protecteurs.
7. Protection par peinture.
8. Protection par revêtements métalliques.
9. Protection par revêtements d'autres types.
10. Conservation des ouvrages existants.

Zusammenfassung

Es werden die folgenden Punkte und entsprechenden Ergebnisse über Korrosionsschutz von Stahl behandelt:

Britische Forschungsresultate über Korrosionsschutz von Stahl

1. Allgemeiner Überblick über die verschiedenen Methoden des Korrosionsschutzes.
2. Einfluß der konstruktiven Ausführung.
3. Einfluß der Stahl-Zusammensetzung.
4. Einfluß des korrosiven Mediums.
5. Kathodischer Schutz.
6. Grundsätze bei der Anwendung von Schutzüberzügen.
7. Schutzanstrich.
8. Metallische Schutzüberzüge.
9. Andere Schutzüberzüge.
10. Unterhalt von bestehenden Bauwerken.