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PROTECTION OF STRUCTURES AND PLANTS FROM CORROSION

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Organized in co-operation with the German Foundation for Developing Countries and the Association of German Machinery Manufacturers (VDMA).

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1. HOW MUCH CORROSION ?

Introduction

Almost all materials are weakened or eaten away by exposure to air or water but not all of them corrode. Wood that has not decayed from fungal attack, yet has been weakened by exposure to the weather, has weathered. Metals and sometimes masonry or concrete corrode. Rusting is the commonest sort of corrosion but applies only to iron and steel.

Corrosion engineering began with the birth of the food-canning industry in the early 1800s. Later, in 1825, a British polar expedition was supplied with canned foods. The ship was lost but some of the cans were saved and their contents eaten nearly a hundred years later by a few adventurous people who suffered no harm. Food cans in the 19th century were massive tinned steel structures to be opened with a hammer and chisel and preferably also a vice. They are now made of steel only one two-hundredth of an inch (0.005 inch or 0.12 mm) thick, covered with a protective coating of tin that may be only one or two hundred-thousandths of an inch (0.000 01 to 0.000 02 inch or 0.0002 to 0.0005 mm) in thickness. The tinning may be thicker but is unlikely to be more than one ten-thousandth of an inch (0.0001 inch or 0.0025 mm) thick.

To the scientist there are two types of corrosion, "dry" corrosion, the direct oxidation of a metal like iron or copper when heated (a slow burning), and "wet" corrosion, of which rusting is one type even though the rusting metal is never in contact with water. This paper will deal mainly with wet corrosion because it concerns all maintenance engineers.

Moisture is present in varying amounts in all air. When the maximum amount is present, in rainy weather, the air is saturated or at 100 per cent relative humidity. In the Sahara desert the daytime relative humidity is always very low, probably well below 40 per cent. The "saturated" value increases with temperature; hot air can hold more moisture than cold air.

Rusting is not appreciable when the humidity in the air is less than 60 per cent of the saturated value for that temperature, that is at relative humidities below 60 per cent. When iron or steel rusts in air, water is drawn out of the air to react with oxygen and form rust on the metal surface.

Rusting, since it can take place in damp air, is probably responsible for most of the direct costs of corrosion. If we limit ourselves to the world's petroleum industry alone, we shall see that there is a very large amount of steel exposed to rusting. In 1967 some 400 000 km of oil pipelines and nearly 1 million km of natural gas pipelines were in existence.

The world's steel industries make a large amount of sheet metal, much of it protected against corrosion by a coating of zinc or tin. The consumption tonnages of galvanized steel sheet and of tinplate show that corrosion prevention is a most important part of industry.

In the US automobile industry, consumption of hot-dip galvanized steel rose from some 45 000 metric tons in 1955 to 670 000 tons in 1966, about fifteenfold in 11 years. In 1968 in the USA alone, [illegible].6 million tons of tinplate (including terne plate) were produced, as well as 4.7 million tons of galvanized steel sheet. World output of these two types of anti-corrosive sheet is probably around 20 million metric tons each.

No less than [illegible] million tons of US steel a year are used in the replacement of corroded parts and products in the USA.

The overall cost of corrosion to the USA alone, according to the US Bureau of Standards, is about $[illegible],000 million a year. But the actual money spent yearly on corrosion control in every form (largely painting and replacement of steel and iron) costs the USA more than $7[illegible] million, Britain about $[illegible] million and the world as a whole about $40,000 million. The British and US corrosion costs are about [illegible].5 per cent of the gross national product of these countries. These are the direct losses from corrosion. But there are other losses from corrosion, not usually accounted against it and therefore called indirect losses, that may well be heavier than the direct costs.

For example, the shutting down of an oil refinery because some tubes have corroded dangerously and must be urgently replaced, may cost about $[illegible] per hour or about $2[illegible],000 per day in lost production. The cost of a shutdown suffered by a generating station for the same sort of reason may be smaller, at least in a developed country, where the power station will be interconnected with others, but the operator will still have to pay about $10,000 per day for the power he buys from neighbouring generating stations. The cost of the components replaced may well be only $[illegible] or so.

Before such a failure, corrosion can cause severe reductions in efficiency and loss of earnings. For example the clogging of pipes with rust or other corrosion products can increase the pipe friction against which the pumps must work and will thus reduce the flow of valuable fluids. The piston rings and cylinder walls of internal combustion engines continually suffer corrosion from burnt gases during working periods and from condensed corrosive water during idle periods, resulting in loss of compression, high oil and fuel consumption, and high transport costs. A small amount of copper lost by corrosion of copper tubing to a fluids circuit may seriously damage a batch of soap worth hundreds of dollars. Pipework and containers in dairies and other food-processing industries have to be made of costly stainless steel because the acids in milk and other foods would damage ordinary steel, quite apart from the possible toxic effects of such reactions. But the intensity of corrosion can vary greatly and there are many circumstances in which corrosion is so slow as to be negligible.

Corrosion is generally severest in seawater, fresh water or wet earth, depending on the corroding influences in the ground or the water. But buried or submerged or partly submerged structures such as pipelines or jetties are usually so large and expensive that it becomes essential to obtain the advice of a consulting engineer on how to protect them since it is then economic to pay for his advice. The consultant must be contacted early, either before or during the design stage because his views will affect the design. The corrosion consultant, who may also be the structural designer, will state what type of metal to use and what surface coatings to apply to it as well as any other protection that may be needed, indicating the most practical, economic or durable combination of methods. But this specialised information, although indispensable for large buried or submerged structures, is not necessarily useful to the maintenance engineer in his daily concern with the pipes, stanchions and tanks around his works, because it would be impracticable and too expensive to treat them all in the same way.

Submerged or buried structures will therefore not be discussed at length in this paper. It will be largely concerned with the prevention of rusting in damp air. Luckily, many figures have been published on the corrosion rate of bare mild steel in air at different places. A corrosion rate is usually understood to be the loss of metal from one side of a metal plate and it is therefore equal to half the loss of thickness. Steel and cast iron have very similar corrosion rates.

Corrosion rates of iron and steel in air

The corrosion rates of iron and steel in the air of his neighbourhood are of the greatest possible interest to the maintenance engineer. He must know whether his area has a corrosive or relatively non-corrosive atmosphere. The rates vary in an extraordinary way from zero in a dry desert or mountain climate to 0.95 mm yearly at a site close to a surf beach in Nigeria.

This is probably because rusting is almost completely non-existent when the air has a relative humidity below 60 per cent. Therefore in most of France and Central Europe there is much less rusting than in the United Kingdom or other western coastal areas of Europe where the relative humidity is often above 70 per cent. In Siberia or the Alps the air is not corrosive because the Alpine or Siberian air contains no industrial impurities, and these, mainly smoke, are important causes of corrosion. In these places the relative humidity of the air also is usually low.

Only 1200 metres inland from the Nigerian surf beach where a bare mild steel surface loses 0.95 mm depth in a year, the corrosion rate drops to 0.04 mm yearly, mainly because there is less salt in the air. Moisture and dirt (including chemicals like salt) are the two most important causes of corrosion in air.

The figure of 0.95 m. of yearly corrosion is worth emphasising because many light-gauge cold-rolled steel sections have a total thickness only a few times as much as this annual corrosion loss. In other words these sections if exposed without protection would probably lose more than half their strength, though not half their metal, after the first year, and in a few years would be worn through.

Annual corrosion rates in the non-industrialised areas of industrialised countries are about 0.05 mm yearly, sometimes as little as half this. In the south of England and in the outer suburbs of Berlin, the corrosion rate is 0.05 mm yearly. In industrialized areas, corrosion rates are at least double, some 0.10 mm (0.004 inch) yearly (Sheffield, England and Pittsburgh, USA). In the heart of industrial England, in Derby, the corrosion rate is even higher, nearly 0.18 mm (0.007 inch) while in the middle of a large chemical works corrosion takes 0.25 mm (0.01 inch) off a bare steel surface every year.

Since such high variations in corrosion rates are possible it is obvimusly important for the maintenance engineer to know what is the corrosion rate in his factory (or on a site for a fubure works). Exposure tests should be made for as long a period as possible, working in a friendly way with a corrosion research organization in one's own or another country. This involves leaving pieces of metal to be tested in the open, marked with some means of identity that cannot be hidden by rust (for example a pattern of drilled holes), weighing them before exposure and afterwards when the rust has been removed by brushing, or some other standard method. Most research organizations, except some of those that are financed by private companies, are happy to co-operate in this way with workers in other countries, sharing their results and increasing their own total of results.

Apart from climate and air pollution, another variation in corrosion rates is caused by the type of steel. A very small percentage of copper in mild steel (only 0.02 per cent) will reduce its corrosion rate to a fraction of what it is without copper. Steels made partly from scrap metal often contain nearly this amount of copper. The extra cost of copper-bearing steel compared with mild steel is small, about 5 per cent or less.

Low-alloy steels have lower corrosion rates even than the copper-bearing steels. They have about 2 per cent of alloying elements excluding carbon. The high-alloy steels have even lower corrosion rates, for example, a common stainless steel is described as 18-8, meaning that it has 18 per cent chromium and 8 per cent nickel. Another stainless steel referred to in this paper is described as 18-10-3, meaning that it has 18 per cent chromium, 10 per cent nickel and 3 per cent molybdenum.

It is also interesting that corrosion is fastest in air containing sulphur dioxide even though the sulphate content of the rust (formed by the sulphur dioxide) is extremely small. Nearly all the rust is iron oxide and water. Another curiosity is that air polluted with pure sulphur dioxide is much less corrosive than air containing the same content of sulphur dioxide contaminated by some particles of charcoal. One would think that charcoal being a reducing agent would oppose oxidation. On the contrary, it encourages it. Evidently it is the smoke in the air of industrial countries that makes for rusting, since the smoke contains both sulphur dioxide and particles of carbon in the form of soot.

Is corrosion-prevention worth while ?

When the maintenance engineer is asked by his employer "Will this metal corrode ?" he must answer "Yes" unless the metal is gold or one of the platinum metals. Even some of these corrode because, like chromium, they are protected from corrosion by a thin, non-porous film of their own oxide that forms in air and sticks tightly to the metal. There are in fact no metals used in industry except these noble metals that are not in some circumstances seriously corroded by water or air. Air consists from this point of view of oxygen, nitrogen, water, carbon dioxide and the usual industrial pollutants, sulphur dioxide, hydrochloric acid, ammonium sulphate and sodium chloride.

The question is better put in this way. "In what conditions of use will corrosion be reduced to an economic level ?" The answers to this question may be found as suggestions in this paper. In greater detail they will be found in publications or from organizations listed in Section 9, or from corrosion consultants.

Corrosion protection rarely costs more than a few per cent of the cost of the structure, and can if the structure is built of ordinary steel, be expected to double or triple its life. It will therefore be well worth while for a bridge or similar structure which has a long expected life but less worth while for a temporary structure. The maintenance engineer's problem is to find out, first of all, the life required for his structure and then to determine the most economic protection to ensure that this life can reasonably be expected.

Let us suppose that the engineer is faced with a construction job that will last two years at most, even if the weather is unfavourable. He has to build a cofferdam in the sea bed to keep out the sea for this maximum of two years. He must first inquire about the useful ife of structures made of similar steel driven into the sea bed in his part of the world. It is unlikely that he would find evidence of serious corrosion in less than five years.

If this is found to be so, the maintenance engineer will need to take no further action for corrosion prevention because whatever anti-corrosion measures he takes will be expensive and unnecessary. Evidently this is quite different from the bridge that should last 100 years. The protection of bridges against corrosion must be investigated very early, in fact before they are designed. Final details of corrosion protection do not have to be decided then but the general scheme of protection must be known at an early stage because it may include the use of a special corrosion-resisting steel. The making of this steel has to be arranged with the steelworks, the steelmaker must plan it months ahead, and the remainder of the protection, including metal coating and probably painting may also be affected.

Low-cost corrosion prevention

When the maintenance engineer is in difficulty with a large amount of exposed steelwork to protect and no paint to protect it with, there is one anti-corrosion material that he should remember, Portland cement. It is alkaline and for this reason protects iron and steel from rusting. There are many ways in which a cement-water or cement-sand-water mix can be applied to steel to prevent corrosion at a fraction of the price of paint. One way is to mix enough water with the cement to produce a creamy grout and to coat the steel with this by brushing. It may perhaps be more easily applied and may spread further if fine sand is mixed with the grout. In most countries, the price of cement is about one fiftieth of the price of the cheapest paint.

2. THEORY OF CORROSION

Chemists believe that "wet" corrosion is electrochemical, in other words that it occurs in the presence of an electric current flowing between two metals dipping into a solution called the electrolyte, through which the current flows. To make a complete electrical circuit, the current flows from the first metal to the second metal not only through the electrolyte but also from the second metal to the first metal, completing the circuit, through some other conductor, usually metallic. The two metals must be different for corrosion to occur, but from the viewpoint of corrosion it is almost impossible for two parts even of a bar of the same metal not to be different. One will have different impurities from the other, forming in an electrolyte an electrolytic cell as explained above.

"Different" here means "at different levels in the galvanic series". The galvanic series is the sequence of the chemical elements in the order in which they dissolve (corrode) in a particular electrolyte, usually seawater or 3 per cent sodium chloride solution. Those at the top of the list dissolve (corrode) most easily, those at the bottom dissolve least easily and are described as "noble". Gold, graphite and platinum are at the bottom of the list.

The two metals dipping in the electrolyte are called electrodes. The electrode that dissolves (corrodes) is the anode; the other electrode is the cathode, hydrogen is released at it or metal is deposited on it, for example in electroplating. Any metal is anodic to all metals below it in the series and cathodic to all those above it.

The galvanic series shows, theoretically, which metals should be used for the protective plating of other metals. Theoretically in commercial practice (not in jewellery) no metal should be used for protectively coating any metal above it in the series. Thus, zinc, aluminium and cadmium are anodic to steel in the series and are used for plating it. Nevertheless, tin which is more noble than steel and is therefore below it in the series, is also used quite effectively for the same purpose though for shorter periods of time and in less severe conditions. It is true that once the corrosion of steel in tinplate has started, it continues much faster than in steel coated with zinc or cadmium or aluminium. Nevertheless for its special purposes in food cans particularly, tinplate is useful (see p. 52).

One instance where two metals should be carefully kept separate is in galvanized steel water tanks. Any pieces of steel or even iron turnings, left in the water tank,will react with the zinc coating and will quickly wear it through.

Zinc or cadmium or aluminium coatings continue to protect a steel surface long after they have worn through and in fact the protection of a zinc coating on steel continues until only 10 per cent of the coating remains. After it has worn through the zinc continues to protect the underlying steel by acting as the anode in an electrolytic cell, and dissolves in preference to the steel. When a tinned surface on steel has been penetrated, the opposite occurs, the steel is dissolved in preference to the tin, and it is therefore destroyed by corrosion more quickly than the zinc-coated steel. This is why it is said that zinc,cadmium and aluminium protect steel"sacrificially".

Cathodic protection

From 1 to 5 per cent of the cost of a structure is not much to pay for probably doubling or trebling its life, and this is the usual cost of cathodic protection. Cathodic protection is generally not used for small structures because of the appreciable amount of engineering design work connected with it, and this 1 per cent is therefore a considerable sum of money. If possible therefore, cathodic protection is not used alone but in conjunction with protective coatings or wrappings over the metal. These reduce the area of metal exposed and thus the bulk of the cathodic protection plant and the current required. The current required is between 10 and 150 milliamps per sq metre of exposed metal but usually from 30 to 60 milliamps per sq metre. Naturally this current is applied only to the exposed metal and the protective coating makes a large saving.

In all types of cathodic protection the structure to be protected is made the cathode. Anodes are placed at some distance away from it in the soil or sea or other corroding medium, and are electrically connected to it, usually by cables. The anodes corrode in preference to the cathode. There are two general methods of cathodic protection, the impressed current method and the sacrificial anode method. In both methods the anode dissolves, though more slowly in the impressed current method, where the anodes may be of graphite which is about as noble as gold. As would be expected, a direct current is forced in at the anodes and out at the cathodes. In the sacrificial anode system the anode material is selected from a metal that is anodic to steel (or to the metal to be protected) in the galvanic series. In other words the anode will quite naturally corrode in preference to the cathode structure.

<u>Part of the galvanic series</u>

ANODIC END	Magnesium
(easily corroded)	Zinc
	Aluminium
	Cadmium
	Steel or iron
	Stainless steel 18-8 (active)
	Lead
	Tin
	Nickel (active)
	Copper
	Nickel (passive
	Stainless steel 18-8 (passive)
CATHODIC END	Silver
(noble metals)	Graphite
	Gold
	Platinum

In the sacrificial anode system the electric current is generated by the electrochemical difference between the two metals, and the main expense is the relatively frequent replacement of the sacrificial anodes. In the impressed current system there is an appreciable expense in the amperage that has to flow permanently through the system, and on large jetties protected in this way a number of power transformers may be needed. The maintenance engineer who considers applying cathodic protection, particularly the use of impressed current, should first make a rough survey of the area of exposed metal. The corrosion engineer who designs the system will need this information to make his estimate. It is important that an experienced corrosion engineer should be employed to design cathodic protection because in a badly designed system the corrosion may be worse than with no protection at all.

The life of bare steel pipes in soil depends on the electrical conductivity of the soil. The higher the conductivity, the more corrosive is the soil. With low resistance (high conductivity) unprotected pipes could be expected to last only two or three years. Soils with low resistivity values, below 500 ohm/cm are highly corrosive. Mildly corrosive soils have resistivities above 2500 ohm/cm and in such soils pipes could be expected to last 20 years without protection. It should be remembered that a soil resistivity depends very greatly on its water content, but if a normally dry soil is flooded it will be more corrosive than a similar soil that is normally wet. Dry soils often contain salts that become highly conductive when wet.

Passivation and anodic protection

The passivation of iron and steel became known nearly two centuries ago. It was noticed that they would not corrode if they were first boiled in strong nitric acid. The metal was then said to be passive or passivated. Later it was found that chemicals dissolved in water would have the same effect and these were called passivators. Passivity is not very permanent and can be removed from iron by knocking it, but in stainless steel it can be more durable. It is believed to be caused by a stable film of oxide that protects the metal from further corrosion. It can also be induced by passing a current into the metal concerned, in the opposite direction from cathodic protection. In cathodic protection the protected metal is the cathode; in passivation the protected metal is the anode, where ordinarily corrosion would be worst, hence the name anodic protection.

Naturally such a system has to be carefully controlled so as to ensure that the current is not so high that metal is lost to the solution. But an anodically protected plain mild steel tank has been used for containing strong sulphuric acid without serious corrosion. A circular steel tank is a relatively easy application because the cathode can be placed centrally at the same distance from all the walls. For the maintenance engineer working in chemical industry this method can be of interest because there is likely to be a chemist or chemical engineer who will supervise the essential instruments and take the readings needed so as to ensure safe working.

Corrosion inhibitors

Very similar to passivators are corrosion inhibitors. Passivators act on the surface of the corrodible metal, but inhibitors act on the liquid, or on the air. Corrosion inhibitors are well known to users of paint and some of them are also pigments used in primers for iron and steel, for example red lead, calcium plumbate, metallic lead, metallic chromates, and when used in high proportions, metallic zinc. Another corrosion inhibitor known to car users in cold countries is the anti-freeze liquid, ethylene glycol, used in car radiators, but this has been known occasionally to decompose and corrode the radiator.

Some chromate inhibitors are poisonous and most of them are costly. It is therefore safer and more economic to use them in a closed (re-circulating) circuit than in a once-through circuit. Normally they are not used in a once-through circuit. All inhibitors for steel act more efficiently in alkaline than in acid solution. In fact merely making the solution definitely alkaline, at a pH of 8 to 8.5* will appreciably reduce the likelihood of corrosion. The solution should thus always have a pH figure greater than 7, except for chromates which can be used even in slightly acid solution.

"Dangerous" inhibitors are so called because if misused they can cause intense local corrosion. The best inhibitors are dangerous, including sodium benzoate, sodium chromate and sodium nitrite. The corrosion occurs sometimes in the presence of dissolved chloride or sulphate. Every inhibitor should be used at a certain minimum concentration which differs with the environment. One way of eliminating the effect of chlorides or sulphates in the water is to provide a molecular concentration of inhibitor that is 15 times as strong as that of the chloride or sulphate. A common inhibitor for closed systems is sodium chromate at pH 8.0 to 8.5 and at a concentration of 500 grammes per tonne. It kills bacteria including sulphate-reducing bacteria, being toxic. An alternative to sodium chromate is sodium benzoate with a small proportion of sodium nitrite

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* The acidity or alkalinity of solutions in water is measured by their hydrogen ion concentration. A neutral solution, one that is neither acid nor alkaline, has a hydrogen ion concentration of 10^{-7}. This is usually expressed by saying that the pH value of the solution is 7; pH values larger than 7 indicate an alkaline solution, those smaller than 7 are acid.

and an appropriate product that kills bacteria but is non-toxic to mammals.

Corrosion inhibitors are regularly used in heating, cooling, hydraulic or refrigerating systems, and in pickling tanks to ensure that the acid attacks the mill scale and not the steel. The steel of the pickling tank itself is usually well protected, for example with 12 mm of sheet rubber, covered with a course of acid-resisting brick.

In cathodic or anodic protection, as well as in the application of corrosion inhibitors, the advice of a corrosion engineer or chemist is needed to ensure that the system is both efficient and safe.

Prevention of corrosion in boilers

Another highly technical subject in which the advice of a chemist is needed is the prevention of corrosion in boilers and the equipment connected to them. As with most corrosion troubles, there are several ways of preventing corrosion. Some of them may be used simultaneously, including feedwater treatment outside the boiler, treatment of the water inside the boiler by injection of chemicals with the feedwater, and treatment of the metal in contact with the steam or water. Almost every maintenance engineer will be concerned with a boiler, and some attempt must be made to mention the main points concerned with boiler corrosion, however incompletely.

Oxygen and carbon dioxide cause most of the corrosion of the steel in boilers. Hydrogen sulphide causes corrosion but is not so plentiful as the other two, and ammonia corrodes copper and its alloys including brass. In power stations, nearly all the steam is condensed to water, pumped back into the boiler and re-used. This has the great advantage of reducing the intake of impurities into the boiler. Condensers and associated pipework are under vacuum and they must be kept tight so that oxygen and carbon dioxide are not allowed to be absorbed. Some water is lost because of leakage and blowdown, roughly 0.5 to 3 per cent of the circulating volume, and a corresponding volume has to be pumped in continuously as make-up water.

All the make-up water must be treated. Most treatment plants include settling tanks, filters, de-aerators to remove oxygen and reaction chambers where the calcium salts, that produce scale, are precipitated by sodium salts. The sodium salts remain in solution in the boiler and do not cause scale. Scale is not corrosive and in fact protects steel from corrosion but it leads to inefficiency of the boiler and to overheating of the scale-covered steel, which may for this reason suffer high-temperature corrosion.

The total amount of salts in the feedwater is not reduced by this method, the calcium salts are merely replaced by the more soluble sodium salts. It will be obvious that the salts concentration in the boiler quickly builds up.(Modern boilers often have a throughput of 100 tons of steam per hour)

Salts concentrations in boilers must not be allowed to build up above certain levels that are known for each boiler. For boilers at pressures above 140 kg/sq cm (2000 pounds per sq inch) the maximum allowable solids are 500 grammes (dissolved) per ton and 5 grammes suspended per ton. For low-pressure boilers operating at pressures below 21 kg/sq cm (300 pounds/sq inch) the conditions are much easier, 3500 grammes per ton total solids including not more than 300 grammes per ton of suspended matter. These maxima must be kept to and this is the reason for blowing down boiler water. Blowdown removes sludge and dissolved salts and in large boilers is a continuous process.

From the viewpoint of the steel, it is important to keep the water alkaline and this may be done by introducing ammonia as ammonium hydroxide to hold the pH figure of the water at about 8.5 . The ammonia reacts with the carbon dioxide and neutralizes it but does not react with the oxygen. All the oxygen must be removed by the de-aerator before the water enters the boiler.

For a high-pressure boiler in use at a site where the natural impurities in the water exceed 500 grammes/ton, it will be necessary to have demineralization equipment in the water treatment, so as to bring the minerals content of the water well below 500 g/ton. An advantage of the use of ammonia is that it does not increase the impurities content of the water since it is removed with the steam but it attacks brass and copper in the condenser and elsewhere. Another reagent used for neutralizing carbon dioxide is morpholine, C_4H_9NO, which does not corrode copper or brass but is expensive. Hydrazine hydrate, $N_2H_4\ H_2O$ or hydrazine phosphate, $(N_2H_4)HPO_4$ have also been used. They react with dissolved oxygen to form nitrogen and water, and at high temperatures the hydrazine decomposes into ammonia and nitrogen. Many of the boiler reagents in existence are used for other purposes than corrosion prevention, such as the prevention of foaming, but they cannot be discussed here.

Prevention of corrosion in idle boilers

A boiler that is out of use for a short period, say less than two months, is kept corrosion-free by filling it with de-aerated alkaline water under pressure so that if leaks occur they are outwards and oxygen or carbon dioxide are thus unlikely to be absorbed. Naturally if there is time the boiler should be cleaned before it is filled. The tightness of the valves and other fittings must be checked. The water must be analysed periodically to make sure that the pH value and oxygen content are no worse than in normal operation.

For a long outage it may be worth while to dry out the boiler. It must be emptied, cleaned and dried out by blowing hot air through it at about 250°C. Steel pans measuring 80 x 35 x 15 cm are placed inside it containing a desiccant* such as calcium chloride, quicklime or silica gel spread uniformly over the floor of the pan. The weight of desiccant needed must be calculated from the volume within the boiler that has to be kept dry. It is usually from 1 to 2 kg per cubic metre of volume. The pans must be periodically inspected and their desiccant changed if it is wet or spent. This method is also worth using for plant or pipes in transit since drums and pipes are not usually difficult to seal. For transit packaging the desiccant is usually silica gel in small plastic or textile bags. Calcium chloride would be corrosive.

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* A desiccant is a drying agent, a substance that absorbs water from the air.

3. DESIGN FOR CORROSION RESISTANCE

A great increase of corrosion resistance can be obtained merely by careful attention on the drawing board to the geometrical shape and layout of stanchions, beams, purlins, tanks, reaction vessels and so on. This work must be done on the drawing board, any later stage is too late and this may be one reason why these important anti-corrosion details are so often omitted.

Geometrical design

Corrosion cannot take place without water and the amount of corrosion depends on the duration of the exposure to water. In the good geometrical design of structures exposed to rain therefore, all exposed surfaces are smooth and shaped to drain easily. Corners whether internal or external, are rounded.

Outside corners are easily knocked and lose paint. Inside corners collect dirt and therefore moisture. Sharp outside corners are always difficult to coat with paint or protective metal and form the starting points for rusting. This is because wet paint naturally forms a rounded surface and the paint thickness on a sharp corner is therefore much less than on a flat or smoothly rounded surface (see stripe coat, p.49)

All this implies that the ideal structural section for corrosion resistance is the cylinder, the tube of round cross-section. This is true but round tubes are a little more difficult to weld than rectangular-section tubes because the roundness makes for curved weld lines. Rectangular tubes can be joined by straight-line welds. Their corners are rounded inside and out, and to prevent corrosion inside they merely need to be sealed, like round tubes, by welding a plate over the end. Such tubes are now available in long lengths, up to about 13.5 metres. Tubular sections, whether round or rectangular have a much smaller external area to be painted than joist or channel or angle sections of comparable strength. Unfortunately they are more expensive than joists of the same beam strength, i.e. they have less beam strength for the same weight per unit length.

Joists , angles , channel or tee sections all have internal corners where dirt can collect and absorb moisture that causes corrosion. Angle or channel sections however have the advantage that if placed with their hollow side down, they have a well drained upper surface and are unlikely to corrode fast.

If drainage is important for structural sections it is even more so for pipe runs and tanks because they should be dried out and cleaned periodically. Small tanks must be built with the bottom sloping towards a drain cock. Large tanks must be built sloping to a sump that must be accessible for emptying. There must be no place where liquid can collect and not be removed. When it is unavoidable to use different metals in the same system , the flow of water should be from the anodic metals in the system towards the cathodic metals, for example from zinc or aluminium to iron.

The undersides of tanks can form typical crevices where corrosion can start. The best way to avoid crevice corrosion underneath a metal tank is to lift it well clear of the floor so that the space beneath is at least large enough for a man to crawl under and inspect it. This may mean that the floor should be lowered . If the tank is to remain for some years the expense of lowering the floor should be worth while. A saddle or pad of metal should be welded to the underside of the tank where it is to be supported. On this pad is welded a bracket to which the stanchion is bolted. In the design of the stanchions it should not be forgotten that they should be shorter at the end containing the drain cock because the tank must drain toward this end.

High-alloy steels

Dilution of welds should be avoided but in addition, weld metals should preferably be more noble than the basis metal. Where stainless or other expensive corrosion-resisting steel is welded to carbon steel, it is wise to weld first on to the joint area a stainless steel weld pad to which the carbon steel is later welded. If the carbon steel is welded directly on to the stainless steel, the stainless steel is likely to be diluted at the weld and corrosion will probably start there. The designer must specify the filler metal (welding electrodes) and the type of weld so as to ensure that the welds are corrosion resistant. The welder should not have to make such decisions himself. On one occasion when a welder had to choose the filler metal for welding an aluminium storage tank to contain nitric acid, the tank had to be replaced because all the joints began to leak. The welds had not been fully specified and the welder had chosen the wrong filler metal.

Inert-gas-shielded welding processes make cleaner welds with fewer slag inclusions than ordinary metal-arc welding processes. Tanks to contain acid are likely to fail at slag inclusions.

Stainless steel, particularly for tanks containing acid, must be protected against attack on the end grain. Properly heat-treated austenitic* stainless steel has good resistance to nitric acid on its rolled surface. Generally thisis the only surface that is exposed but at welds any leak can expose end grain and corrode the plate as a whole. It is therefore vital that welds shall be made absolutely leak-proof. An upright plate that has to be welded to a horizontal plate must be bevelled on both edges before welding, so as to make a full-penetration weld. If the edges of the plte are not bevelled, the weld is likely to be porous and to leak and thus to allow end-grain attack. Full-penetration welds of this type have been watertight , and acid-proof for years.

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* Stainless steels have excellent corrosion resistance but there are several different types, the most corrosion resistant being described as austenitic. These can also resist high temperatures since they do not oxidize at temperatures below 850°C.

Proper heat treatment of joints after welding also helps to increase the corrosion resistance of carbon steel to nitrate solutions for example. The advice of a metallurgist is needed for the proper temperature, duration and type of heat treatment.

Water treatment

The treatment of boiler water to prevent corrosion in the boiler is discussed in Section 2. Similar problems are met with in process water. In every works the water used is likely to be corrosive and should be analysed so that a chemist can determine how its corrosiveness can be simply and cheaply reduced. The carbonate balance can be controlled, for example, so that a film of carbonate is laid on to metal in contact with the water, to protect the metal. The acidity o pH (see p. 20) of the water can be adjusted and the pH value should be kept above 7. The oxygen content of the water can be reduced. If there are no suitable salts in solution to deposit a protective film on metal in contact with the water, a content of sodium silicate amounting to only 20 to 30 parts per million in the water will start the formation of a protective film. After the film has begun to be formed the content can be reduced to 4 parts per million. Other additives such as waterglass or sodium phosphate or sodium metaphosphate can also be used to prevent corrosion but always with the advice of a chemist or corrosion engineer.

Pipe corrosion

Corrosion in pipes may be caused partly by the high speed of the liquid flowing through them. If pipes need replacing too often, it is advisable to try replacing them with pipes of larger diameter. In this report there is no space for discussing pipe-flow formulae and in any case they do not take corrosion into consideration. The maximum pipe velocity should if possible be kept down to a reasonable level, say below 2 metres/second, particularly for acid or alkaline liquids.

If pipe corrosion is troublesome and speeds cannot be reduced, an effort should be made to reduce the temperature of the flowing liquid. This is usually not possible but hot spots can and must be avoided. They are the places where corrosion usually starts. A heating coil should be at or near the centre of a vessel. A metal flue should not be allowed to have flue gases that are so cool that moisture condenses in it. Damp flue gas is one of the most corrosive fluids in existence, particularly if there is sulphur in the fuel, and therefore sulphur dioxide in the flue gas.

Location of the factory

The location of a works is important in anti-corrosion design though it is usually not possible for the maintenance engineer to change it. Sites to which acid fumes or other smoke are brought by the prevailing wind must be avoided and of course the choice of process water is important. The annual penetration by corrosion into steel left unprotected in the open in the UK is usually not below 0.025 mm (0.001 inch) and the loss of thickness on two surfaces will of course be double this. Worse losses can be suffered without disaster but these figures do show the need for some sort of protective coating to steel in an industrial environment. One company however set a figure of 0.075 mm (0.003 inch) annual loss in pipe wall thickness as the design maximum for pipes carrying 98.6 per cent sulphuric acid at 145°C. Many industrial sites do suffer even worse corrosion rates for bare steel exposed to the weather, as pointed out in Section 1.

Crevice corrosion

One of the commonest locations for corrosion is in crevices in tanks or in structures of steel or other metals. Riveted joints that have not been caulked, or lap welds that have not been sealed by a double fillet can collect moisture and will corrode fast. If the crevices cannot be sealed by welding or caulking, they can be filled with one of the fillers used by decorators or by a mastic sealer. Moisture is sucked into unsealed narrow gaps of this sort by capillary action[ø]. Because such water cannot be removed except by boiling, it is certain to cause corrosion. The design of the welds is important, double butt welds should always be used if possible. If lap welds are used they should be double, in other words, welded on both sides.

That crevice corrosion is not caused only by capillarity i proved by the fact that it happens also under water where capillarity cannot exist. Even when an effective corrosion inhibitor is used in the correct proportions in the liquid, its protection usually does not extend to crevices unless additional stirring is used and even this is not usually successful.

An example of the elimination of crevice corrosion is give by the Corrosion Advice Bureau of the British Iron and Steel Research Association (BISRA) in connexion with the re-design of mild steel pit tubs used for carrying coal out of British coal mines. The rounding of the bottom corners of the tubs (eliminatio of crevices) without changing the steel, increased the tub life by 30 to 50 per cent. After the re-shaping of the tubs, investigations were continued into the use of materials with better corrosion resistance.

The original mild steel tubs without galvanizing or other surface protection lasted only six years, resulting

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[ø] The rise of oil or other fluid up a wick, or of any fluid up a thin tube, or the use of blotting paper are all examples of capillarity, which is the sucking of fluids into narrow spaces, often against gravity.

in an annual cost of around ≠11. Using bare Cor-ten copper-bearing steel, the total cost was increased by ≠2.4 or 4 per cent but the tub life was increased to eight or ten years, thus reducing the annual cost to ≠7. With galvanized mild steel the total cost compared with bare mild steel was increased by ≠10 or some 17 per cent but the life was increased to 12 or 15 years, thus reducing the annual cost per tub to about ≠6. With galvanized Cor-ten steel the total cost compared with bare mild steel was some 21 per cent more but the tub life was more than doubled, to 15 or 20 years, reducing the annual cost per tub to only ≠4.5, less than half the annual cost of the original tubs.

Different metals in contact

Care must be taken when different metals are in contact with the same liquid. The introduction of copper water pipes into British houses that had previously had only galvanized steel pipes connected to steel tanks galvanized many years before, resulted in many leaking tanks that had to be replaced. Whether copper pipes are used or not, the inside of galvanized tanks must be carefully cleaned before the tanks are filled. Bits of iron or steel will speed up the corrosion of the zinc.

A stainless-steel cooler was surrounded by cooling brine in a carbon steel tank. The carbon steel tank was protected by an excellent anti-corrosive paint of epoxy resin but this was soon pierced by a galvanic current from the stainless steel, which probably started at pinholes through the epoxy paint. The corrosion "drilled" so many holes right through the carbon steel that the owners suspected sabotage. It would have been much too costly to change the outer tank for one made of stainless steel or some other noble metal so the design was improved by painting the stainless-steel surface that was in contact with the brine. This reduced the area of cathode and the rate of corrosion in proportion. Such holes, apparently drilled, are typical of pitting corrosion.

The same principle applies to different metals that are in contact in air. If the contact cannot be avoided, it may be possible to separate them by insulating washers, with an insulating sleeve round the bolt. But the insulating material also must be carefully chosen. A moist insulator is always more corrosive than a dry one and possibly more corrosive than none at all. The insulation material should be one that does not absorb water, or if it does, it should be tested wet to see whether it still protects against corrosion. Most plastics are both insulating and do not absorb water, like nylon. A simple test is to wet the insulator and then to test its electrical resistance, after its outer surface has been dried. If the resistance is less than it was in the dry state, the material has almost certainly absorbed water. Another, perhaps simpler test is to weigh the material before and after soaking. An increase in weight, after surplus water has been dried off, almost certainly indicates that water has been absorbed.

In connexion with crevice corrosion and the use of different metals in contact, the Society of American Engineers' Committee on the Prevention of Corrosion in Iron and Steel recommends that joints should be completely sealed with mastic sealers to prevent the entry of moisture or air. This applies particularly to welded joints. Different metals, the committee says, should not be used in contact with each other but if they are, a large anode area (aluminium, cadmium, zinc) should be used in conjunction with a small cathode area (steel). The steel should preferably be coated with protective metal. The joint should be insulated, with protective coating on both sections, especially on the steel side and with good ventilation and drainage. Gamma-ray or infra-red inspection is convenient and enables breakdowns to be avoided by detection of corrosion damage at the start when it is limited and replacement is easy.

In this connexion it is worth relating an incident of unexpectedly fast corrosion of aluminium alloy pipe in a circuit connected to steel pipe. Flooding of oil wells that have finished their productive life is relatively common in many oilfields. The water injected into the "empty" well drives the oil to neighbouring wells and increases their output. It is desirable to keep oxygen out of the water so as to decrease corrosion of the steel tubes both in the well and out of it. One source of oxygen-free water is that found in deep wells, which unfortunately is often salty, particularly in the oilfields of the Gulf of Mexico. The oxygen can be kept out of the water when it has been pumped out of the well by keeping circuits closed and sealed and by covering open surfaces with a layer of oil.

For one offshore well on the Gulf coast, a source of oxygen-free water was available that contained 10 per cent salt. It was considered safe to use aluminium alloy pipe with a protective inner lining 0.25 mm (0.01 inch) thick, made of aluminium containing 2.5 per cent zinc. At the first inspection, however, a rusty, metallic-looking deposit which was electrically conducting in places, was found inside the pipe. When sections of the pipe had been cut through it was found that the inner protective layer had been completely replaced by the rust in only nine weeks of use. The 500 metres of pipe had to be scrapped and replaced by plastic pipe in spite of the risks of damage to the plastic on the sea bed.

It would be unfair not to follow such a story with others that have a happier ending. Corrosion at British sea ports is severe, and for many years British Rail have been fighting it at Harwich. Boats from here take trains across to the Continent and back. The bridge connecting the ships to the shore, over which the trains must pass, includes a number of beams that must move relatively to stanchions that are only 3 mm away from them. Rust had filled this space and locked some of the beams so that they could not move. The rust was removed without much difficulty, merely by hacksawing it through. And to insure that the rust did not return was also relatively little work but specialist advice was needed and a preventive maintenance plan had to be started. The stanchions were drilled at a number of points and fitted with grease nipples to enable a heavy-duty grease to be forced in. The particular grease chosen emits an anti-corrosive vapour so that points not reached by the grease do not start to rust.

Corroded gas tanks of sewage sludge digestion tanks at Mauchline, Ayrshire, Scotland were recently saved by a plastics coating and patching treatment that proved less costly than repairs with metal or metal coating. The inner surfaces of the tanks were grit-blasted to remove rust. During the grit-blasting some small holes were made in the tank walls. These holes were patched with fibre glass and resin. The protective coating was a zinc-rich primer followed by two brushed coats of solvent-based epoxy resin, providing a film 0.25 mm (0.01 inch) thick. The film is claimed to have high resistance to abrasion and chemical attack, including dilute mineral acids, alkalis, vegetable and mineral oils, greases, soaps and so on.

It is worth describing here the common measures now used in the UK to prevent the chimney corrosion caused by the burning of sulphurous fuels, particularly oil fuel, now becoming increasingly popular. Chimneys are corroded by acid condensates that attack their inner lining. The only way to prevent this corrosion is to keep the flue gas warm enough to prevent condensation within the chimney. (Preliminary removel of sulphur from oil or coal would be prohibitively expensive).

Within a chimney, the dewpoint of water is about 60°C (140°F) but it is more important to know the temperature at which the acid gases, sulphur dioxide and sulphur trioxide, condense, which is between 115° and 135°C (240 to 280°F). The flue gases can be kept warm either by raising the temperature at which they leave the boiler, which is thermally inefficient, wasting heat and therefore money, or by raising the temperature at which they leave the chimney. This is achieved by insulating the chimney.

In dwelling houses a common way is to line the brick chimney with a plastic tube that has a smaller cross-section than the brickwork and therefore keeps the flue gases warmer and increases the flue gas flow rate. Both of these tendencies together reduce condensation within the chimney but even if it does occur, the plastic lining does not corrode. In industry, chimneys are often made of steel and another method is common. An inner shell of thinner steel is erected within the outer structural steel chimney tube. The ring-shaped gap between them is filled with glass wool or other suitable insulation. The gap must be wide enough for the insulation needed. If the exit temperature of the flue gases is not above 135°C, there is a chance that the point at which acid begins to condense will merely be moved higher up the chimney and the situation may be no better than without insulation. In fact it may be worse, since the condensate can drip down along a greater length of the chimney walls than previously, thus exposing more of them to corrosion.

4. PROTECTIVE COATINGS: PAINT

This section deals with the painting of iron and steel and the metal coatings on them. The prevention of corrosion of other metals is not discussed, mainly because of shortage of space, but they corrode less than steel or iron.

Surface preparation

Before painting starts, the surface to be painted must be so cleaned that the paint will stick to it. For rolled steel, plates, sheets, beams, channel and angle sections and so on, this means removing all mill scale, the black skin of oxide formed in the rolling mill. Casting scale, the skin formed with the sand on the surface of a casting made in a sand mould, does not need to be removed so long as it is tightly held, because it continues to protect the casting after it has been covered with paint. But mill scale does not. If painted over, it will lift and destroy the paint in a very few years.

Proper surface preparation is more important than anything else in the success of a protective coating, whether the coating is paint or plastic or metal. A few modern, quite exceptional paints can be put on to damp or even moderately rusty surfaces but they are unusual. The best method of preparation generally is blast cleaning (shot- or grit-blasting) followed in effectiveness by pickling, flame cleaning and wire brushing, and lastly hand cleaning, the most inefficient and expensive method, even with power tools.

Pickling, the soaking of steel members in acid, to remove scale and rust, was formerly used much more than now. It has fallen into disfavour because it is a wet process and it is difficult to avoid a thin film of rust forming on the steel as it dries. In new installations, pickling (always preceded by de-greasing) is now used chiefly for cleaning thin material. Sheet metal or thin plate below about 2 mm thick cannot be blast cleaned because it becomes dented by the impact of the grit or shot.

A disadvantage of flame cleaning is that the steelwork is usually left to weather in the open for about a year so that slight rusting shall lift the mill scale from the surface of the steel. Flame cleaning must be followed by wire brushing to remove the broken scale. Unfortunately the wire brush cannot remove all the rust, nor will it remove tightly held scale. A further difficulty with wire brushing is that it may be done on an erected steel framework, with all the obstacles to good work that height above ground can bring.

Whichever method is used for preparing the surface, it should be followed as soon as possible, preferably within four hours, by a first coat of protective metal or a priming or pretreatment coat. A well prepared iron or steel surface is in an extremely sensitive condition. It begins to rust as soon as it has been cleaned, and this rusting must be stopped as soon as possible by the first surface treatment. One of the treatments that precedes priming is adequate, for example phosphating or etch priming.

Impact cleaning

It was established some years ago that impact cleaning (blast cleaning) methods were the best surface preparation for iron and steel. Hand cleaning is not only slow but very inefficient and expensive in labour. Even power-operated hand tools, such as vibrating needles, wire brushes and so on are less effective than impact cleaning. These power tools have the disadvantage that if they do remove all the scale and dirt the surface of the metal is likely to be polished and it may be difficult for modern paints to stick to it.

Impact cleaning is the throwing of hard particles of metal or mineral against the dirty surface so as to remove all scale and rust down to bare metal. In one method the abrasive is thrown by a jet of compressed air or water under pressure, in the other method no air or water is used and tho shot or grit is thrown by an impeller wheel. In the United Kingdom since 1949 it has been forbidden to use sand or other mineral grit containing free silica because of the danger to the health of the men who breathe the silica dust. In Britain at least it is therefore no longer correct to speak of sand blasting.

If the operator has to work in the enclosure containing the blast-cleaning machine he must be provided with protective clothing that covers him completely, including a hood with an independent air supply, so that he does not breathe the dust. Zinc or aluminium dust can be highly inflammable and lead pigments removed from old paint are poisonous to breathe.

Good modern practice is to clean plates or sections at the mill where they are rolled, by impeller blasting with shot, commonly of cast steel. Shot blasting has the advantage that dirt can be easily separated from the shot. The shot if used in a plant where it can be recovered, can be of high grade, of regular size and shape, ensuring that the metal surface is not excessively roughened. Cleaning of steel at the rolling mill is of course a factory process and better work can be done at the factory than in the shipyard or on the building site.

Similarly, if the prefabrication primer is applied in the rolling mill, it will probably be applied in better conditions than would be possible elsewhere. The prefabrication primer immediately follows the blast cleaning and must be one that is compatible with the welding or other processes that are to be used on the steel. If the steelmaker is told what fabrication processes are to follow his primer, he will ensure that the primer will suit them. Whether welding is manual or automatic, excellent results can be obtained with the right primer applied in the right quantity. Most of these primers will protect the steel for six weeks, others such as zinc dust primer in epoxy resin, for six months.

Since hull corrosion can increase a ship's power requirements by 20 per cent, it is understandable that shipyards were among the first large-scale users of impact cleaning for steel plate. The shipbuilders understood that the most important single process in protecting steel is the preparation of the surface before painting. A carefully thought out paint system, on a well prepared modern steel bridge, generally has some eight years of life . Exceptionally it may go to 20 years. Such schemes cost more than conventional painting because they include metal spraying under the paint, but the cost of painting the bridge for its first 50 years is expected to be halved.

To prevent corrosion of the steel of the new Severn Road Bridge in the west of England, the de-icing material is not salt but a mixture of urea with sand. It is more expensive than salt but is no more corrosive than tap water. Since the function of a de-icing chemical is merely to lower the freezing point of the water, and this can be done by any chemical with a high solubility in water, the search for a non-corrosive, low-cost de-icing material for roads in frosty countries is continuing. The serious corrosion on car bodies should thereby be reduced.

A blast-cleaned surface must be adequate in two ways. It must be clean enough and must be rough enough, but not too rough. Two British standard grades of cleanliness have been accepted, the first grade being unnecessarily high and expensive for many types of steelwork. The first quality finish, "white metal", is clean metal roughened by blast cleaning everywhere. Its cost is roughly double the cost of the second best surface in which only 90 per cent of the area needs to be clean metal but no single area of 6.25 sq cm (1 sq inch) may contain more than 20 per cent of its area discoloured by continuous scale, rust, old paint, or other dirt. The surface finish to be provided must be agreed between the contractor and the maintenance engineer. A Swedish standard for surface finish of steel was one of the first published standards of this type and its diagrams of the grades required are interesting. The British standard (BS 4232:1967)[ø] also has diagrams showing the grades.

Anchor pattern

The roughness or "anchor pattern" of an impact-cleaned surface is particularly important when the surface is to be protected with modern fast-drying, high-build paints. These often have a lower wetting power than conventional paints and may therefore stick less well. The roughness of a surface can be measured by the height of the peaks. Peaks are always

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[ø] See footnote, page 53

covered with less paint than valleys and they therefore begin to rust first. Shipbuilders regard peaks of 0.075 mm (0.003 inch) as not excessively high for surfaces specified to be 90 per cent clean, provided that the absolute maximum peak heights are not more than 0.1 mm (0.004 inch). It is better for the anchor pattern to be too smooth than too rough.

Grit size is important. Research by a shipowner (Shell) into the use of blasting grits of various sizes for the treatment of ships' rusted plate has shown that only a very small percentage of oversize grit (0.05 per cent by weight) will produce peaks that are much too high. Shot-blasted plates or sections do not have high peaks because the shot is of uniform size and clean. Good practice is therefore to shot-blast at the rolling mill. The results of the Shell research showed that the grit should be accurately sized from 0.2 to 1.0 mm (0.008 to 0.04 inch), a much smaller size than was previously thought correct.

Air pressure is important though perhaps more to the blasting contractor than to the owner of the steelwork, because a drop in air pressure below 6 kg/sq cm (80 pounds/sq inch) greatly reduces the efficiency of the blast and increases the time taken to clean the steel as well as the grit consumption per square metre. Pressure at the nozzle should therefore preferably not fall below 7 kg/sq cm (100 pounds/sq inch) and never below 6 kg/sq cm. This means that the pressure at the compressor should be at least 20 per cent more than at the nozzle, possibly 50 per cent more if the compressor is far from the nozzle. Nozzle operators should be provided with a pressure gauge to fit on to the hose so that they can check the actual nozzle pressure. Below 6 kg/sq cm, blasting should be forbidden except when a low-grade finish only is demanded.

Blast-cleaning plant is expensive and so is grit. Expensive plant of this sort deserves to be protected at least with a shed to keep the rain off, and all blast cleaning should be carefully planned and supervised as the serious engineering operation that it is. Accurately sized grit is more expensive per ton but more economical to use because it cleans the steel better and faster than badly sized grit with a high proportion of dust.

Pre-priming coats

Painting, including priming, can be preceded by a number of rust-inhibiting or temporary protective coatings, one of which is phosphating. The five types of phosphating accepted in the UK are described in BS 3189:1959, which gives general details of treatments including those for creviced components. Other temporary protectives against corrosion are described in the Packaging Code, BS 1133:Section 6:1966. The 118 pages of Section 6 list ten types of temporary protection of metal surfaces against corrosion, divided broadly into the two classes of films and corrosion inhibitors. They are regarded as "temporary" protectives because they can easily be removed from the metal. If not removed they should give protection for an indefinite length of time. Some of the film types can be sprayed on from a pressurized container and do not interfere with subsequent welding. Other films are thick, hard and described as strippable because they can be readily torn off. One particularly interesting type of film dries slowly and is described as "water-displacing" because it can safely be applied to a wet surface.

Corrosion inhibitors

The corrosion inhibitor types are usually not films but greases or oils applied by dipping or brushing or smearing, or (for engine hydraulic systems) by circulating through the system to be protected. Another interesting corrosion inhibitor (contact inhibitor) gives off a vapour which inhibits corrosion on metal surfaces near it in air. Such methods of pre-treating steel or iron parts are more applicable to small pieces than to the considerably larger members found in building or bridge structures.

Contact inhibitors have several uses. They can be used dry or dissolved in water, for example in industrial or domestic or automobile cooling systems to prevent rust. Boiler water is discussed in Section 2. In packaging they are held undissolved on the waxed wrapping paper in contact with the surface to be protected. Some contact inhibitors are sodium benzoate, sodium nitrite and sodium carbonate for steel; soluble chromates may also be used but they are slightly poisonous and may irritate the human skin. Some of these substances need the free access of air so as to be effective in preventing corrosion.

A further help in preventing the corrosion of packaged steel parts is to wrap them in watertight and preferably airtight plastic film and to leave packets of desiccant in the film, that will maintain the relative humidity of the air below 50 per cent. At this relative humidity. rusting is very slow and the growth of moulds is also unlikely, however hot the weather may be. Rusting in fact does not become serious until well above 60 per cent relative humidity. The desiccants used are silica gel, activated alumina or some activated clays. The amount of water that desiccants can absorb is usually less than 27 per cent of the dry weight of the desiccant. The packaging should be as airtight as possible so as to reduce the bulk of the desiccant needed to maintain a low relative humidity within the package.

For structural steelwork that has, like a bridge, to stand for 100 years or so, the painting should be preceded by metal coating of the steel whether in the works by hot-dip galvanizing or on the site by spraying with aluminium or zinc. Metal coatings are expensive and unless thick they are also porous but they do greatly increase the protection given by the paint put on the structure and their rough surface is a good ground for paint.

Many paints will not stick to fresh zinc, whether galvanized or sprayed, but pretreatment primers usually overcome this difficulty and they also dry within a few minutes. The original pretreatment or etch primers, still used, consist of a dispersion of a zinc chrome in an alcoholic solution of polyvinylbutyral resin; or of an alcoholic solution of phosphoric acid. Generally the coat is thin and must be followed as soon as possible by an ordinary primer and a full paint system. Etch primers are also used on bare blast-cleaned steel to help the primer stick to the metal, and to give it some immediate protection. Prefabrication primers have a very similar purpose, for protection during the period of fabrication.

Primer, undercoat and top coat

A conventional paint system usually has three coats, the primer, the undercoat and the top coat, often more than one coat of each. The primer or priming coat is the first coat and is usually put on by brush unless the surface is in first class condition. Brushing pushes the primer into every crevice of the metal and protects it better; ordinarily the primer is followed at least by an undercoat to give colour and a top coat to give gloss. The main function of the primer is to hold to the metal and to stick to the undercoat that is put on over it. The undercoat has to provide thickness, colour, opacity and a good ground for the top coat while filling small depressions in the primed surface. The finishing coat or top coat has to stick to the undercoat and to provide good colour and gloss, though much of the colour may be provided by the undercoat shining through it. Usually a paint with high gloss is relatively translucent and the bulk of the colour must therefore come from the undercoat. The gloss is also protective because rain flows off it easily. When the gloss has disappeared it is usually wise to plan the repainting.

An exception to Airless spraying ~~the rule about~~ brush application of primers is the airless-spray method of priming ships' hulls. To enable the paint to flow it is often applied hot, at temperatures from 71° to 99°C. Airless spraying is done at higher pressures and velocities than compressed-air spraying of paint. The gun throws the primer on to the metal at high speed, enabling it to penetrate the surface as it should. Because there is no compressed air there is no rebound of the paint from the surface and the work is healthier for the painter than spraying with compressed air.

To achieve good atomization, high pressures of 200 kg/sq cm are best. The nozzle bore must then be small and consequently the paint must be uniform and free of bits larger than say 0.1 mm. The nozzle diameter must be watched for signs of wear. Quite small wear and consequent increase of nozzle bore will reduce the velocity disproportionately for the same consumption of paint per hour and the paint also is less well atomized. Plant for airless spraying is expensive, as will be realized from the pressures used, but for the large areas of paint on ships' hulls the method, can be profitable.

Compatibility

Every paint system to be successful must be thought out as a whole and discussed with the paint manufacturer or the painting contractor. If this has been done, the protection given by any paint system is proportional to its thickness, provided that the steel has been shot-blasted or grit-blasted and that all the work is done to specification.

It is necessary to discuss the paint system with the paint maker because it is all-important that paints in the same system shall be compatible with each other. Compatible paints blend perfectly and look well. Incompatible paints may react chemically with each other in an undesirable way, or the upper coat may dissolve and lift the lower coat or may be slow to dry. There are many possible results of incompatibility and all are undesirable. Usually all the paints of one type from one maker are compatible. Therefore the simplest way of ensuring compatibility is to discuss the job with one paint maker and to use only his paint.

High-build paints

Apart from the many types of purely decorative paint, there are three types of protective paint applied to metal. The first and oldest type is oil-based paint containing linseed oil, that dries by reacting with the oxygen in the air. Secondly there are the newer paints that harden by many different chemical processes, including many "two-pack" paints that do not react with air, and thirdly those paints that dry wholly or mainly by the evaporation of solvent and without chemical action.

The most interesting paints for corrosion prevention are found in the last two classes. The maximum thickness of paint that can be put on in one coat of the old oil-based paints is about 0.025 mm (0.001 inch), which means that much work is needed to achieve a thick system and therefore good protection. Specially formulated paints of chlorinated rubber can be applied at a thickness of 0.1 mm per coat or a total thickness of 0.2 mm for two coats with primer. One such paint was successfully applied to damp and rusty steel sheet piling in Belfast Dock, Northern Ireland. A minor disadvantage is that it must be applied by airless spray because it dries by evaporation of its solvent alone. Brushing a second coat over the first would soften and disturb the lower coat. Some advantages of using the airless spray, apart from the greater thickness per coat are that the method is healthier for the painter than compressed air spraying and there is less paint lost by rebound. The advantages of applications of great thickness are that labour charges are greatly reduced and the time taken to do the painting also is smaller.

Two general rules for painting that are broken by this chlorinated rubber paint are that paint should neither be put on in damp air (at relative humidities above 85 per cent) nor on to a damp surface. Both these rules were broken together. The sheet piling was, however protected during painting by scaffolding with sheets hung over it, and warmed with propane gas warm-air heaters inside the sheeting. Excess water was wiped off the piling some hours before the paint was applied.

Paints that allow such large thicknesses to be applied in one coat are called high-build paints. In a chemical works with highly corrosive conditions, the steelwork and operating units were painted with two coats of red lead graphite primer, followed by two coats of epoxy resin paint, giving a total thickness of 0.25 to 0.37 mm. Epoxy resin paints can, however, be applied by airless spray in one coat 0.37 mm thick.

Epoxy resins in the last ten years have also been combined with an old material, coal-tar pitch, that can be applied in coats 0.12 mm thick. Many other high-build paints exist and even more are being developed, and will come into being as the labour costs of painting increase still further. In Section 6, Plastics, some other high-build linings are described.

Application of paint

Paints generally should never be put on at any temperature below 4°C (40°F) and they dry and harden better as the temperature rises. Condensation of moisture (dew or frost) is likely at these low temperatures and this moisture damages wet paint. Since paint dries and hardens slowly at low temperatures, its period of vulnerability at these temperatures is long. The danger to the paint therefore increases as the temperature falls. In any case, the maker's instructions about the method of application should be followed.

Paint systems break down most easily at nuts, bolts, rivets, edges and other projections and in crevices. The paint is always thinner on outer edges because it tends to form a surface that is rounded outside. It is therefore accepted good practice to give an extra coat of priming paint to these areas. The paint has a slightly different amount or type of pigment from the first primer and so is called a stripe coat.

Because black bolts and their nuts need so much more surface preparation and because this is difficult to achieve once they have been fixed, they should not be used as permanent fixings. Other types of bolt should be used, that already have surfaces prepared for painting, for example by sherardizing or galvanising.

5. PROTECTIVE COATINGS OTHER THAN PAINT

Paint is still the commonest type of protection for corrodible metal, but although paint sales continue to rise, other methods of protection are also gaining in importance. Metals can be protected by coating them with plastics or other metals. Electroplating has been in use for many years but it is a factory process and it is only since about 1920 that an outside process, metal spraying, has been available for use on building sites, in shipyards and elsewhere in the open air

In plating, the metal to be protected is submerged in a solution of a salt of the metal to be used for coating. An electric current is passed through the solution which is therefore called an electrolyte. The current enters and leaves the solution by two plates called electrodes. One of these, the anode, loses metal into the salt solution, the other, the cathode is the object to be plated and acquires a corresponding amount of metal from the solution, brought by the electric current. Cathode and anode have the same sense as on p. 15 electrochemistry.

Plating is not practicable on a building site, partly because of the large size of the vats to contain the electrolyte, the cleanliness needed and so on. Other techniques for applying protective coatings include many methods of phosphating, some of which may be applied outside the factory. Phosphating is a treatment usually in a hot solution of phosphoric acid with metal phosphates, slightly etching the metal surface and forming a rust-inhibiting coat on it. It is a pretreatment and inhibiting coat and must be followed by a full paint system including primer. Bonderizing, Coslettizing, Jenolizing, Parkerizing and Walterizing are all phosphating methods.

Metal coating includes many processes, some of which are becoming increasingly important. The oldest method, invented more than 200 years ago in France but now in full commercial use for at least a century, involves dipping iron or steel in molten zinc. Although called hot-dip galvanizing, there is nothing galvanic about the process and the name is misleading. The process by which it protects the steel is, however, galvanic, and is explained in Section 2. Of the other important metal-coating processes, metal spraying can be done anywhere, but electroless plating (chemical plating) and electroplating are factory processes.

Another factory process for zinc coating is sherardizing, tumbling small articles in a heated barrel with zinc dust. Galvanizing is suitable for large or small articles but steel girders may often be too large. In sherardizing, the zinc forms an alloy with the iron and is not a mere coating In galvanizing, the zinc is usually a mere skin, only sometimes alloyed with the iron.

Metallizing or metal spraying has been developed mainly for spraying zinc or aluminium but other metals can be sprayed, including nickel, chromium, copper, cadmium, tin or their alloys. Any metal coating protects the underlying surface if it completely envelopes it. Since sprayed metal is rough, it does not completely seal the underlying surface until the thickness is about 0.075 mm (0.003 inch). This is also a common thickness for hot-dip galvanizing. Even when they are worn through, coatings of zinc, aluminium or cadmium continue to protect iron or steel by acting as anodes and dissolving in preference to the iron. Galvanizing is generally the most economical way of metal coating and is therefore usual for low-cost articles with a short life, such as motor-car parts.

In specifying a metal coating it is important to state the thickness of the metal coating required and whether the surface is to be ground and polished after application. Grinding and polishing will greatly improve the finish but will also make it more expensive though a gloss on the paint will be obtained more easily. The unground, rough sprayed metal is however a good base for paint.

Tinplate and terne plate

In many ways the most interesting of all metal coatings is tin. It can be applied like zinc, not only by dipping in the molten metal (hot tinning) or by electroplating or metal spraying, but also by the tinsmith's and plumber's method of wiping. Peeling or scaling of the coating is practically unknown. Because tin is a valuable metal there is a tendency to reduce the thickness of the coating on tinplate below the smallest thickness possible with hot tinning. The thinnest coatings are not applied by hot tinning but electrolytically. Although the first commercial electrolytic tinning line was built as recently as 1937, 70 per cent of the world's tinplate is now made by electroplating and only 30 per cent by hot tinning.

Terne plate is less decorative than tinplate but has excellent corrosion resistance. It is steel sheet coated with an alloy that is mainly lead, with about 10 per cent tin to make it stick to the steel. It has wide industrial uses in roofing sheet, automobile petrol tanks and so on.

The steel in modern tinplate can be exceedingly thin. A common thickness for the steel in the modern food can is 0.12 mm or 0.005 inch. Previous to about 1950 the thinnest sheet was 0.25 mm or 0.01 inch.

Tinplate is a surprising material. It would not be expected to contain food without serious corrosion because the tin coating is so porous and thin (often 0.0004 mm or 0.000015 inch) that a piece of tinplate left in the rain will rust immediately. Tin also is more noble than iron and cannot be expected to protect it sacrificially in the way that zinc protects iron. Luckily this relationship is reversed by the juices of many canned foods so that iron then becomes more noble than tin and can be protected by it. Rusting also is made unlikely by the absence of oxygen in the can and by the fact that many modern food cans are lacquered inside.

Thicknesses of metal coatings

For severe outdoor conditions in an industrial area or at the seaside, critical loadbearing steelwork should be protected with at least 0.06 mm (0.0025 inch thickness or 1.5 ounce/sq ft) of galvanizing or sprayed zinc, covered with two coats of paint.

Sherardizing is typically for small articles but they can be up to 6 m (20 ft) long, provided that they fit conveniently into the standard box which is 40 cm (16 inches) square. Sherardizing is well suited to the coating of screw threads, since its thickness can be more closely controlled than that of galvanizing. The minimum thickness of sherardizing is from 0.007 mm (0.0003 inch) to 0.05 mm (0.002 inch) for parts subject to heavy corrosion.

Several British Standards use a coding for the thickness of metal coatings that is worth explaining. Thus Ni12S indicates a thickness of 0.0012 inch (0.03 mm) of nickel on steel, a plating suitable for car bumpers and hub caps. Ni4S with only 0.0004 inch (0.01 mm) of nickel on steel is more suitable for indoor uses. BS 1872:1964 ø deals with electroplated deposits of tin of five different thicknesses from 0.005 mm (0.0002 inch) to 0.03 mm (0.0012 inch) on iron, steel, nickel alloys, copper and copper alloys.

Small screws and their threads present a special difficulty in plating. The clearance between corresponding points of the male and female thread is only about 0.025 mm (0.001 inch). The

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ø BS = British Standard. The numbers before the colon are the distinguishing number of the publication. The numbers after the colon are the date of its appearance.

corresponding permissible thickness of coating, however, must be even less, 0.005 mm (0.0002 inch) because of plating tolerance and the slope of the thread. Greater thicknesses than these are liable to prevent the screw passing in to the nut. If it is forced in, the coating will be stripped.

Chemical plating

Many chemical or "electroless" plating processes have been patented for depositing nickel or copper on metal to prevent corrosion, on plastics for decoration and for electronic circuitry. No electric cutrent is used and no electrodes.

In one electroless nickel plating method, the nickel is deposited chemically from solution on to the steel, producing a nickel plate of high quality used on cars, that is much more uniform than electroplated steel. A disadvantage of some electroplates is that areas remote from the anode receive less metal than areas near it. Even on objects with intricate contours, the electroless plating thickness does not vary by more than plus or minus 15 per cent. The metals that can be protected by electroless plating include steel, cast iton, aluminium, copper, titanium amd alloys of these metals, as well as many non-metallic surfaces. The composition of the plate, which might be described as a nickel phosphide, is some 92 per cent nickel and 8 per cent phosphorus. The adhesion to the protected metal is good and the plate is hard and corrosion-resistant. The deposit thickness can reach 0.125 mm (0.005 inch) but is usually less because the plating rate is only about 0.025 mm per hour. The minimum thickness is 0.008 mm (0.0003 inch).

Engineering parts coated with this electroless nickel plate include piston rods, crankshafts, valve inserts, and pump parts. It is also used for applications where iron would contaminate a chemical or a food, for example in dough trays, reaction vessels, petrol tanks, tank waggons, screw conveyors and so on.

Chromizing

Chromizing, sometimes called chromium diffusion, is a heat treatment that puts a layer rich in chromium on the surface of iron, steel and some other metals. The layer resists wear and corrosion at high or low temperatures . Since the chromium has to penetrate the surface of the steel, large thicknesses of chromizing are impossible, the usual economic limit is 0.05 mm (0.002 inch) and the absolute limit almost double this thickness. The resistance to corrosion in tap water or air or many mild chemicals including salt water is good but for any stronger chemicals it is best to use the special "chromizing" steels. In mild steels the chromized layer is not very hard but on high-carbon steels it is excellent and enables the steel to be used for such heavy duties as gear wheels.

Chromium plate and hard plate

Unlike chromizing which is a heat treatment, chromium plate is an electroplate or rather two electroplates, sometimes three. To ensure that the chromium sticks to the metal below it, nickel is first plated over the steel, and sometimes a layer of copper is placed over or under the nickel. Somewhere in this sandwich there must be a polished surface, and it is usually easiest to polish the copper or the nickel because they are soft. Chromium cannot be polished because it is too hard. The chromium thickness is only 0.00025 mm (0.00001 inch), the nickel and the copper are both about 0.025 mm (0.001 inch) thick. Chromium plate is thin and decorative, not to be confused with hard plating or hard chromium plate which is much thicker, deposited direct on the steel and not decorative but very resistant to wear and corrosion-resistant.

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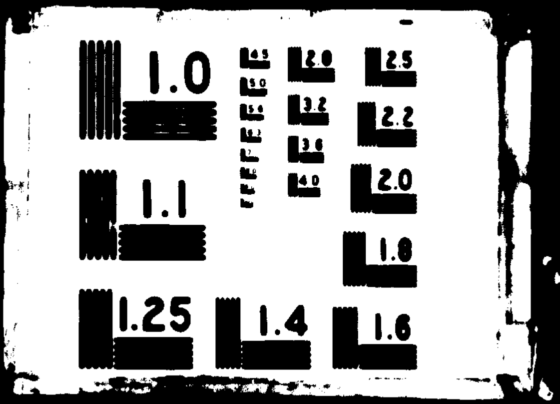

Anodizing

Anodizing is a process for protecting aluminium that is so well known and so often used that it is worth describing briefly. The aluminium article is made the anode in an acid bath and oxygen, as would be expected, is liberated around it because of the electrolysis. The aluminium is oxidized, the oxide film becoming thicker at the rate of 0.001 mm in 3 minutes. For exterior architectural work in Britain the usual thickness required is 0.025 mm (0.001 inch) and for trim on cars about 0.005 to 0.008 mm. The oxide film, after it has been formed in the acid bath, is still soft, so the article is removed and immersed in boiling water. The operation is known as sealing and is a hardening and strengthening process for the oxide film. From the viewpoint of corrosion protection it is as important as the acid bath and the water must be very pure. Sometimes steam at 100°C is used instead of water. The minimum time required for sealing is 4 minutes per 0.001 mm.

Concrete floors

The binder in most modern concretes is Portland cement because this is usually the lowest in cost and the most easily available. It always contains a proportion of free lime, $Ca(OH)_2$. Also called slaked lime, this is an alkali and its alkalinity enables the cement to protect iron and steel from rust. It is therefore worth remembering that its cost is around 25 dollars per ton. Paint is much more expensive, 25 dollars will buy only about 5 gallons. But the disadvantage of concrete made with this cement is that it is relatively easily attacked by acids.

There are two ways of protecting a concrete floor against acids, by giving it a slope, and by using acid-resistant material. Whatever the material, the concrete must be self-draining, pools of liquid must never form on the floor.

This means that the minimum allowable slope over the whole wetted area of floor should be 2 per cent. To prevent ponding in small areas, the lowest spot under a 2.5metre long straight edge should not be more than 3 mm below the edge. For the more corrosive chemicals, the floor should slope more steeply. It slopes either towards a trench in the concrete, that can be covered with a metal grating, or into a central drain

If the chemicals are not too strong, the concrete may need no special coating and the slope alone will be enough to prevent the concrete being attacked. This is particularly true if care has been taken to make ordinary good concrete that is not porous. This can be achieved by paying a little extra for the concrete and ordering the contractor to make concrete with a minimum 14day crushing strength (on 15cm cubes) of about 400 kg/sq cm (5500 pounds/sq inch). This is a relatively high-strength concrete but strength in concrete is achieved by eliminating porosity and this low porosity is required for good corrosion resistance. For a concrete which depends for its acid resistance on a special surfacing, such strength might be unnecessary and about 200 kg/sq cm might be adequate.

For a higher acid resistance than is obtainable with good concrete made from ordinary Portland cement, one of the more expensive cements can be used. Rapid-hardening cement costs about 10 per cent more than ordinary Portland, but is chemically the same cement, ground more finely. Sulphate-resisting cement is a little more expensive again, and high-alumina cement costs about three times as much as ordinary Portland. It is best to obtain specialist's advice on these matters but to find out for oneself the prices of the local materials beforehand. Plastic-coated floors are discussed in Section 6.

Expansion joints, also called shrinkage joints, should be placed at regular intervals in all concrete floors, at least every 6 metres in long runs of floor, and all round the edges. They should be at least 1 cm wide. The joints ensure that the unavoidable shrinkage of the concrete takes place along predetermined lines, and is thus not unsightly nor dangerous to the floor.

Other points to be remembered in the building of concrete floors are: metal pipes passing through a floor should do so in a sleeve (another pipe in which they fit loosely, which does not corrode). The tops of concrete foundation piers should be treated with a sand-cement topping to slope the concrete away from the steelwork. It is sometimes possible now to design the floor so that some of the shrinkage joints run along the line of the drain trenches. Synthetic rubber materials for making the joints can take up the movement and resist the acid without bursting. The movement will in any case be small if the joints are spaced at no more than 6 metres.

If all the joints can be fitted into drain trenches, this eliminates the problem of joints passing through the area of the floor that has a 'finished' surface. The rubber jointing material should prevent leakage through the bottom of the drain trench.

It is fair to say that bare concrete resists no acids but many alkalis, though its life will be very much longer in acid conditions if it is well made and well sloped. Epoxy and polyester floors resist both acids and alkalis and are discussed with other synthetic materials in Section 6, Plastics. Asphalt flooring and polyester flooring are not recommended to withstand solvents or mineral oils. Tiles, bricks and bare concrete are all noisy, plastics relatively quiet.

Concrete as a corrosion preventive

For civil engineering work, concrete is often used to protect steel from the earth, the sea or the weather. It has also been successful as a lining 25 mm thick (1 inch) inside steel water pipes. In these uses it protects the metal mainly against knocks or abrasion since it sticks well to bare steel. Generally the underlying metal is bare and the concrete by its alkalinity acts also as a corrosion preventive. It is suitable in massive structures where its weight is no disadvantage and the inpact- or corrosion-resistance are also needed, as in jetties. The steel should generally be covered with at least 7.5 cm (3 inches) of concrete. This is a considerable expense, not only in concrete but also in formwork and secondary reinforcement, and it also has the disadvantage that a stanchion becomes 15 cm thicker or a beam becomes 15 cm wider, so it is not always cheap. But under this adequate cover, corrosion failures in steel are rare.

Guniting (concrete spraying or cement gunning) is a method of shooting sand and cement mortar through a compressed-air operated gun on to a surface that needs protection. It is commonly used to repair bridges from which the concrete cover has been knocked off or to thicken a concrete cover that is inadequate. For this purpose the cement gun is irreplaceable. It does maintenance work that can be done in no other way. Because the mortar is gunned on, it can be applied to vertical faces or undersurfaces without difficulty. The high pressure of the gun has another advantage. It produces a dense, strong concrete that hardens quickly because it is thrown on at a low water content. This also enables a high thickness to be achieved at each pass.

Another common use of the cement gun that may sometimes help the maintenance engineer is to shoot asbestos mixed with cement and water onto steelwork inside a building so as to increase its fire resistance when the building contains much material that will burn. Like all concretes and all gunites, this protects the steel from corrosion because of the alkalinity of the Portland cement. Its fire resistance comes from the fact that it provides a thermally insulating coating on the steel. But sprayed asbestos, though an excellent material in many ways, is not cheap

Any cement materials gunned on to steel must be held on to it by light reinforcement. Usually chicken wire is used, light steel wire netting with a mesh of about 5 cm (2 inches) square. This must be wired on to the metal before gunning starts.

Anti-corrosion tapes

Anti-corrosion tapes (wrappings) have been in use since the early 1930s in severely corrosive conditions where lighter coatings of paint or metal have been found inadequate, or for protecting metal in an inaccessible position where repainting is not possible and a life of at least 20 years is needed. The tape is wrapped round pipes, stanchions, beams or other metal, overlapping and leaving no metal exposed. Tapes are not beautiful but they are immediately effective, unlike paint which needs time to dry and cannot be put on in any weather. Their chief use nowadays is to protect buried pipes, and for the effective protection that they give they are not expensive.

Most tapes have a textile base, coated with an adhesive, but polyethylene and PVC sheet are also now being used. The textile is usually woven cotton, jute, nylon or glass fibre. If glass-fibre felt or tissue is used it is generally backed with a strengthener. The coating is often a soft grease such as petroleum jelly or wool grease or a soft form of oxidized bitumen or coal tar pitch, though these generally need to be heated before application. The coating can also be a natural or synthetic rubber or resin. The tape also carries fillers and corrosion inhibitors such as chromates, phosphates and tannins as well as stabilizers and anti-oxidants if it contains rubber materials. The bituminous types are generally used only to resist high temperatures.

Grease-coated cotton tapes are the easiest to apply since they can easily be wrapped round awkward surfaces such as bolt heads, rivets, pipe couplings and so on. Bituminous-coated tapes need to be heated with a blow lamp before application; grease-coated tapes have the advantage of no fire risk since they can be put on cold.

If the object to be protected is wet it will need first to be dried either by applying a water-displacing composition or by some other means so as to make sure that the tape is in contact with the whole area. If the pipe is to be buried it may be necessary to protect the tape, especially a greased cotton tape with a tougher outer wrap.

Anti-corrosion tapes generally should be chemically inert and should resist acids and alkalis, soil, seawater and atmospheric pollution. Petroleum jelly fulfils these requirements best. Bitumen and coal-tar pitch are often slightly acid and they have the further disadvantage that they are liable to crack. An exception to the rule about chemical inertness in tapes is that they contain corrosion inhibitors or an alkali such as lime. The purpose of including tannin in the tape is to kill the sulphate-reducing bacteria which are believed to be the main cause of corrosion of buried iron or steel pipe in Britain, though it is not yet proved that tannin has this effect.

Both grease-coated tapes and bituminous tapes have an indefinitely long storage life in any climate, except that bituminous tapes must not be allowed to warm up excessively or they will stick together. Tapes with rubber content should generally be used within 6 to 12 months of manufacture.

Tape is not always the cheapest coating but its long-term protection may make it worth while. For buried pipelines one alternative is to apply a hot bituminous coating in the factory and to coat the joints on site with either tape or hot bitumen. Another possibility for a continuously welded pipe is to apply hot bitumen on the site before burial. Factory-applied coatings are easily damaged in transit and site-applied coatings are difficult to apply perfectly. But site-wrapped, cold-applied tape can cover the pipe without leaving any metal exposed. It is nonconducting and, combined with cathodic protection will reduce the power demand, and may ensure many years of trouble-free operation.

6. PLASTICS

Reactors and other chemical plant made of plastics alone will not be discussed in this paper because almost any shape and size of corrosion-resistant duct or vessel known to chemical engineering can be made by plastics fabricators, including chimneys, fractionating towers and the 350-metre long hose mentioned in the next paragraph. Stationary pipework made of plastics is now so well established that most of the hundreds of miles of pipe installed yearly in the USA for transmitting natural gas are made of plastics

Plastics manufacturers are generally well enough organized to send the inquiring maintenance engineer as much printed material as he needs about chemical plant made of their materials, particularly since most units are made as one-off or small-batch jobs.

A German company, Vredestein, can serve as an example for the uniqueness of many plastics installations in chemical plants. In 1968 Vredestein claimed to have installed the largest rubber hose in the world. Of butyl rubber built on to nylon fabric, it was 19 cm (7.5 inches) in diameter and 350 metres long. A company in the north of Holland had found that its underwater pipeline was too severely corroded to discharge its usual load of waste chemicals at 70°C. The pipe was first cleaned of deposits by pulling a go-devil through it. The hose was then pulled into the pipeline flat and afterwards inflated. Insertion of the pipeline, it was claimed, took only 90 minutes.

A general introduction to linings and coatings will be more useful to the maintenance engineer than a discussion of chemical plant. In the two next headings, coatings are regarded for convenience as being thinner than 0.5 mm (0.02 inch) and linings as thicker.

Plastic coatings (thinner than 0.5 mm)

Generally, plastics are not put on at coating thicknesses less than about 0.15 mm which is the maximum for many conventional paints. Plastic coatings can be applied to concrete as well as to metal and are usually resistant to continuous immersion in many chemicals, being more corrosion resistant than conventional paints. The best properties are obtained by heat treatment. The hardness can be anything between glass-hard and rubbery. The thermal and electrical insulation are usually good but electrically conductive coatings can be made by incorporating conducting filler material. Repairs are often possible on the site.

The coatings that are paint-like are best applied at temperatures above 20°C. Some of them should for best results be stoved at 150 to 200°C, but nevertheless few of them can be used at temperatures above 90°C and this is one serious drawback of plastics. Their cost is also fairly high but this would not be a serious drawback if they had all the desirable properties.

The surface preparation of mild steel for a plastic coating is very similar to that for receiving ordinary paint, possibly rather more rigorous because the chemicals contained are stronger than those usually left in contact with paint. The steel must be degreased with a solvent that is then removed by heating, and the surface is cleaned by grit blasting. It should be remembered that the absolute minimum thickness of steel that can be grit blasted is about 0.5 mm and this is only possible with metal of the highest quality. Dust is removed after grit blasting and the coating is applied as soon as possible but always within four hours. After the coating has been applied it is tested for thickness by thickness meter and any deficiencies are made good by additional coats where needed. To achieve a good gloss, the last one or two coats are usually not pigmented. Stoving may be done between coatings.

Continuity can be tested by some electrical method to ensure that there are no pinholes in the coating. Most plastic coatings are excellent insulators so the design of such a testing method, at least for a coating over metal, is not difficult. Coatings which contain conducting material such as carbon black, like neoprene, cannot be tested in this way. High-frequency alternating current spark testers are not suitable because the spark may puncture a thin coating. For the thinnest coatings a direct current voltage of some 10 to 30 volts can be used, with a sponge as a probe, soaked in brine with a wetting agent. Brine is not always very penetrating and it may not enter the pinholes . A more severe test is a high-voltage direct-current tester with variable voltage from 0 to 5000 volts. For coatings about 0.2 mm thick, a voltage of some 2000 volts has been found suitable. So as to make the overall testing easy and rapid, the probe should be shaped to the contour of the vessel.

Because plastic coatings have to be stoved, there is a limiting size to the articles to be coated, which must be small enough to enter the oven. With coating materials like polyurethane, however, that do not need stoving, objects of any size can be coated. Polyurethane has good resistance to acids and alkalis from pH2 to pH13 as well as to solvents, oils and fuels. In hot water the highest continuous working temperature is about 50°C but higher temperatures can be tolerated for a short time.

Plastic-coated factory-made sheet metal (steel or aluminium) which began to be produced around 1960, is interesting. In Britain the sheet dimensions are about 1.2m maximum width, with a coating on one or both sides, from 0.1 to 0.4 mm thick. Some attractive colours are available. When the steel sheet is coated on one side only, a number of fabrication operations are possible, including deep drawing several centimetres deep, bending, drilling, sawing, punching, shearing and roll forming, and welding after removal of some of the coating. The operations other than welding do not affect the plastic coating. Corrosion in the drilled holes can be prevented by the use of plastic-coated bolts with plastic washers or stainless steel bolts or completely plastic fasteners. The coating ordinarily is polyvinyl chloride (PVC). Some applications of plastic-coated sheet include partitioning in factories in corrosive environments, and the manufacture of refrigerators or laboratory furniture. Some further details about coatings are given later, under "Rubber linings".

Plastic linings (thicker than 0.5 mm)

Plastic linings can be applied in the form of sheet, using adhesives to fix them on to the metal or other material to be protected, and joining the sheets together as needed. Other methods of applying linings are: dipping followed by heat treatment, flame spraying, fluidized sintering, and finally the methods of painting, by spray or brush. The thickest linings are probably about 10 mm thick, anything thicker is probably called a mortar, or if horizontal, a screed or topping, especially when laid over a concrete floor.

Mild steel and concrete are the materials most commonly protected, occasionally nonferrous metals. As usual, careful surface preparation is needed and the surface should be protected as soon as it has been cleaned. Steel articles to be lined should be strong enough not to distort under load. The steel should be smooth, with no rivets or bolts; welded construction is essential and welds must be without porosity and ground smooth. Internal angles must be radiused or chamfered to make them less sharp. All re-entrant corners must be avoided. Concrete surfaces also must be smooth. Projecting fins should be ground flat and holes should be filled with cement mortar. Alternatively, a rubber latex-cement mortar screed or plaster can be applied to the concrete as a backing to the lining. The minimum radius of corners should be 1.5 cm. Brickwork, before coating with plastics should first be plastered or screeded with sand-cement or latex-cement mortar.

Many of the commoner plastics are available in sheet from 1.5 mm to 6 mm thick but some of these cannot be made to stick to other materials. The polyethylenes, unplasticized PVC and polypropylene can, however, be made to stick by laminating them to a backing sheet that will adhere, though this is more expensive. For instance unplasticised PVC has been laminated to plasticised PVC that adheres well.

After they have been blast cleaned, steel tanks are primed with an adhesive primer and then with the adhesive itself. The lining may, if it needs protection from knocks and abrasion, be itself lined with a course of brickwork, as in hot-acid pickling tanks for de-scaling steel.

Synthetic rubber linings

The synthetic rubbers are materials of special interest. There are several types, including neoprenes, butyls, nitrile rubbers, polyisobutylenes, Thiokols, and chlorosulphonated polyethylene, known as Hypalon. Most of them have good chemical resistance but for each application there is likely to be one that is the best.

Neoprene though not highly corrosion resistant, resists seawater and mineral oils and abrasion. It can be applied cold in thicknesses up to 3 mm by brushing, spraying or dipping. The corrosion resistance can be heightened by a top coat of Hypalon which also is obtainable in pleasant colours.

Nylon coatings also can be thick, up to 8 mm (minimum 0.2 mm) and have good chemical resistance except to mineral acids. Their resistance to solvents makes them useful in de-greasing units. The great thickness possible with nylon linings enables them to be placed over rough castings and this eliminates the cost of fettling the casting.

PVC coatings can be applied thickly by dipping. PVC is resilient and not so expensive as most plastics though perhaps more difficult to apply than some of the expensive ones. Sprayed PVC can be put on as a coating in thicknesses from 0.017 mm (0.007 inch) to 0.1 mm (0.04 inch).

Polyethylene (polythene) is the most easily applied of all plastic coatings and is highly corrosion resistant. Coatings are applied as powders by spraying or dipping. Of the two grades available, high-density and low-density, the high-density polyehtylene has the higher melting point, is tougher, less decorative and sticks better to metal than the low-density material. By fluidized sintering, coating thicknesses can be obtained between 0.25 mm and 3.1 mm thick.

Polytetrafluoroethylene (PTFE) though costly, is one of the most interesting plastics now in production, because of its great variety of excellent properties. Unfortunately coatings made of PTFE are porous and thus useless for most anti-corrosion purposes. It has a very low coefficient of friction, is non-wetting and resistant to nearly all chemicals and its properties remain unaffected over the wide range of — 80°C to + 250°C. It can be applied in coatings between 0.012 mm and 0.15 mm (0.0005 inch to 0.006 inch).

Polytrifluoromonochloroethylene (PTFCE) forms a completely non-porous, corrosion-resistant coating in thicknesses from 0.1 mm to 0.3 mm (0.004 to 0.012 inch) built up by spraying in thicknesses of 0.025 mm (0.001 inch) at a time. Its chemical resistance is not so good as that of PTFE but being non-porous it is stronger and more useful for resisting corrosion. Great care is needed in preparing the surface of the metal to be protected; corners must be radiused, welds must be ground down and pores filled with metal. The expense of the surface preparation limits its use to applications where high corrosion resistance is essential.

Fluidised sintering and flame spraying

Apart from the usual methods of applying paint, by spray, brush or roller, there are other ways of applying plastic linings, using fluidised sintering and flame spraying.

In fluidised sintering, the hot object is dipped in a fluidised bed of cool powder of the plastic coating or lining. The object is heated to a temperature above the softening point of the plastic and the dipping thus produces a fairly uniform coating which is later stoved to fuse it smooth. A fluidized bed is a layer of powder that is blown upwards at a rate high enough to keep it "boiling" but not so high that powder is blown away. It is used because its resistance to the entry of an object to be dipped is low. A disadvantage of the method is that the thickness of the coating depends on the heat capacity of the metal and therefore on its thickness. Thicker metal receives more plastic than thin metal.

Flame spraying is a job at which at least two men must work together. It is a little more risky than fluidized sintering, so far as the burning of the plastic is concerned, but it can be used for lining objects that are too large for fluidised sintering. The first man preheats the metal surface with a gas flame and the second man follows, applying the plastic by flame spraying. A final heating by flame is needed to fuse the plastic into a homogeneous lining.

Mortars, screeds or toppings

The latex or synthetic resin or synthetic rubber screeds or toppings over floors are known as monolithic surfacings and were first used in the USA in the early 1950s. These synthetic resin cements are used to form mortars in somewhat the same way as Portland cement with the important exception that the mix cannot be made sloppier and weaker by adding water. The cements include epoxide, furane, phenolic, polyester resins and cashew-nut shell liquid (CNSL). Usually there are two main components, the resin, a syrupy fluid to which the accelerator (hardener or catalyst) a watery fluid, is added when the cement is to be used. A third component, a filler is also provided, that fulfils the function of the sand in a cement mortar. This filler may be contained in the accelerator. One difficulty in using these cements is that their hardening rate depends on temperature to a much greater degree than that of Portland cement. It may be that in summer the cement will have to be mixed in small batches that do not harden before they are placed. However, usually in winter large batches can be mixed. As with Portland cement mortars the mix ratio of cement to filler varies from 1:1.5 to 1:4 by weight.

The cements are provided for the market either in two-can or three-can packages, which after mixing form the mortar. The mortar is used for jointing brickwork or for bedding and jointing floor tiles or channel blocks. The cements have good corrosion resistance but the ceramic blocks are even more corrosion resistant, and it is therefore best to make the joints as thin as possible. The chemicals which severely attack ceramic blocks are the strong ones, hydrofluoric acid and strong caustic alkalis. There is no difficulty in explaining to the bricklayer that the joints should be thin but it is not always easy to get him to make thin joints. In good quality work, joints are as thin as possible but this takes more time than with thick joints. Therefore the joint thickness should be worked out beforehand bearing in mind the unevenness of the blocks and it should be stated before work starts. It is usually best for such work to be done by a specialist contractor.

Screeds (horizontal layers of mortar) of synthetic resin cements are made of similar materials to the mortar but with a slightly coarser filler (aggregate) and are applied in thicknesses of 3 to 10 mm. A Portland cement mortar screed is much thicker, at least 50 mm. Such great thicknesses are not possible with synthetic resins because of their high cost. Where extra thickness is required it is provided in the base concrete that is much less expensive. Epoxy resins adhere well to ordinary concrete.

In workshops where the floor is liable to be often flooded with corrosive liquid it is necessary to provide a complete tanking, rising some 15 or 30 cm up the walls all round. The tanking may consist of acid-resisting asphalt or such sheet materials as polyisobutylene, plasticised PVC or a synthetic rubber. The membrane used for tanking must be continuous and the sheets must be either joined by adhesives or welded by hot-gas welding or by some other method.

Cost of corrosion-resisting floors (early 1969 basis)

Conventional red quarry tile floors 18 mm thick with Portland cement mortar joints cost 18 dollars/sq metre and with epoxy-polyamine joints about 22.5 dollars. Engineering brick floors are correspondingly thicker and more expensive.

With chlorinated rubber or epoxy resin or urethane, a floor coating costs from 4 to 12.5 dollars/sq metre, with thicknesses from 0.12 mm for chlorinated rubber to 3 mm for polyurethane. Asphalt flooring 43 mm thick costs around 12.5 dollars/sq metre, latex 6 mm thick about 18.5 dollars, and epoxy-polyamine or polyester with glass reinforcement, 3 mm thick, costs about 22 dollars/sq metre.

7. FASTENERS

In this section we shall discuss some materials for bolts, nuts, screws and so on, as well as appropriate methods of using them. Bolts and nuts, being the commonest engineering fastener, are of the greatest interest. What is true of them is often true of other fasteners, such as rivets, split pins or window latches.

Fasteners cost more in labour to put in than to buy. All those named here are low in first cost but their placing is important for the structure and can be expensive. Unfortunately most bolts are made of easily corrodible steel and they are often placed in situations where they attract water by capillary action and are more likely to corrode than the rest of the structure. Boatbuilders have recognised these facts for many years. Corrosion-resistant fasteners of every type are therefore in regular use on boats and ships. Other users are only just beginning to understand what boatbuilders have always known.

If fasteners cost more to put in than to buy, it is obviously even more costly to replace them. Therefore where corrosion is likely and the structure is planned to last for a number of years, it is advisable to use corrosion-resistant fasteners.

Relative costs of bolts of different materials

It is interesting to know the relative costs of bolts of the same size, made of different materials. Applied to an uncoated carbon steel bolt, the extra costs of protective coatings are: hot-dip galvanizing 13 per cent, sherardizing 17 per cent, heavy zinc electroplating 30 per cent, cadmium plating 40 per cent. An 18-8 stainless steel bolt costs from three to five times as much as the plain carbon steel. In spite of this heavy extra cost there are many places where stainless steel alone is suitable. An even better steel for specially corrosive situations is the 18-10-3, with 3 per cent molybdenum. Near British power stations burning pulverized coal, where the fine ash falls on the roof, stainless steel hook bolts are now used for holding roofing sheets down to the purlins. Ordinary mild steel bolts were found to corrode too quickly. For bolting precast concrete units together, one material that does not make unsightly rust marks on the concrete is stainless steel. Silicon bronze and aluminium bronze have also been used but they are less readily available than stainless steel.

Austenitic stainless steel self-tapping screws, whether 18-8 or 18-10-3, are usually not hard enough to cut threads in for example, window frames of the same material. It may therefore be necessary first to use a self-tapping screw of the same dimensions but of a different material such as hardened ordinary carbon steel, so as to cut the thread in which the stainless steel screw can be fixed.

Aluminium alloy self-tapping screws also cannot be used in window frames of the same material. Plated hardened carbon steel screws have given satisfactory service, so have screws made of stainless steel.

Those who are not familiar with the various grades of protective coating available on builders' hardware should be warned against copper-plated steel articles that have an excellent appearance in a heated shop but in the damp air will remain rust-free no longer than bare steel.

Cathode/anode size ratio

Even though the electrochemical theory of corrosion may be true there are many situations in which it has had to be disregarded, particularly in the use of fasteners. Corrosion is not inevitable, especially if the metals are kept clean and dry. If the general rule that different metals should not be used together has to be broken, there is a further rule that must be followed. This is that the cross-section of the anode must be large and that of the cathode small. The anode is the part that loses metal, therefore it must be bulky so that it is not excessively weakened.

As an example of this principle, two assemblies were tested in a 5 per cent solution of common salt. This is a rather stronger solution than seawater, which is 3.5 per cent total salts but 3 per cent common salt. Aluminium alloy screws inserted into 18-8 stainless steel sheets were severely corroded after only 7 days testing. The anodic (aluminium) area was too small. But when 18-8 stainless steel screws were inserted into aluminium alloy sheet they were still in good condition after six months' immersion in the same solution. The aluminium alloy sheet was pitted, as would be expected, but was not destroyed.

For similar reasons, ordinary steel bolts should not be used in stainless steel or copper panels, even if the bolts are plated. Stainless steel bolts also should not be used in direct contact with zinc-coated steel of any type, especially in polluted or seaside air, so as to avoid rapid corrosion of the zinc near the bolt.

In case it is unavoidable to use different metals together, it may sometimes be practicable to plate the noble metal so as to reduce the corroding voltage between it and the corroded (anodic) metal. Thus stainless steel bolts, used for fixing aluminium alloy panels on aircraft, can be cadmium plated. Another alternative to insulation, for preventing local attack on aluminium, is to use a chromate (inhibitor) sealing compound on the surfaces in contact, or to use plastic-coated stainless steel bolts.

Protective coatings on bolt threads

The thickness of a coating can seriously affect the fit of a bolt into its nut; looseness and tightness of fit are both undesirable. This does not apply to wood screws or self-tapping screws, which can take any zinc coating thickness up to 0.05 mm (0.002 inch) without difficulty. For use out of doors, such screws are usually passivated with chromate. For bolts and nuts, however, the coating can be only about one tenth of this value, some 5 microns or 0.0002 inch. Being so thin, it is usually put on by electroplating which is more closely controlled than hot dipping.

Zinc is the most widely used protective coating for bolts. Zinc coating is much less costly and therefore much more used than cadmium but cadmium is useful in particular situations of high humidity or for protecting steel in soft water or for reducing the potential between metals in aircraft. The two main disadvantages of cadmium are that it is expensive and its vapour is toxic, so it is ordinarily only used as a thin electroplate. Perhaps the best overall protection for bolts is given by a tin coating over cadmium but this is relatively expensive. It resists acid water well. A 5-micron (0.0002 inch) cadmium coating is adequate to resist neutral or alkaline water.

Other useful coatings for fasteners, though perhaps more costly, are chromium, tin-nickel alloy, or bronze. Compared with zinc, all these metals are hard, chromium extremely so, and they therefore resist both abrasion and corrosion.

Thread friction

Thread friction must always be kept in mind in the choice of the bolt metal or coating metal for the thread. Cadmium coatings usually lubricate the thread but zinc coatings tend to increase the friction, especially if they are uneven, which is likely with galvanizing and possibly sherardizing. In modern steel structures it is important to use a bolt that does not need oiling, for the following reason. A fixing method for steel structures, now being increasingly used is the high-strength (friction-grip) bolt. If the bolt is oiled this should be done only very sparingly because oil should never reach the contact surfaces of the plates or other members gripped by the bolt. The security of the joint depends on the clamping of the plate contact surfaces, and the clamping effect will be reduced by oil between the plates.

Threads which are zinc-coated by sherardizing are usually smoother, with less friction than hot-dipped threads. Electroplated threads are smoother than either, but the coating is thinner. Sherardized thicknesses are from 0.02 mm (0.0008 inch) to 0.04 mm (0.0015 inch) but hot dipping can give even thicker coatings, to 0.075 mm or 0.003 inch though 0.025 mm or 0.001 inch is possible. It is often satisfactory to use nuts tapped after hot-dipping, and to rely for corrosion resistance on the zinc coating over the bolt threads. Sometimes sherardized self-tapping screws may have soft threads which is a disadvantage for this type of screw.

For very corrosive situations where the fastener strength does not have to be so high that a steel bolt is essential, an all-plastic fastener has been produced. It can be used for example in mines with very corrosive water. This three-piece unit is not threaded in the ordinary sense but is quickly inserted into a hole through metal or wood or plastic sheet. A 90-degree turn in one direction or the other will lock or unlock the fastener.

Monel metal bolts

An interesting alloy, Monel K500, with the strength of a high-grade steel (minimum yield strength 55 tons/sq inch) has recently been used for making permanently corrosion-resistant bolts in tall buildings where corrosion could endanger human life. Monel K500 contains 66 per cent nickel, 29 per cent copper, 2.75 per cent aluminium and 0.9 per cent iron approximately. It is therefore expensive but it is also strong and corrosion-resistant. Bolts made of this alloy support armoured-glass panels over a shopping centre in London and over Sydney Opera House they support the precast slabs on the roof. Some of the latter are 2.5 metres long (8 ft) and they are 25 mm in diameter (1 inch). Monel K500 was chosen because it will resist the salty air of Sydney as well as the dilute hydrochloric acid that will periodically be used for washing the outside of the building. The same alloy is being used to replace high-tensile brass fasteners in the movable window-cleaning gantries that are hung outside many tall modern buildings.

8. INSPECTION AND TESTING OF METAL OR PAINT COATINGS

The up-to-date maintenance engineer will have noticed that plastic coatings have been omitted from the title of this section, but this is because they can be regarded as paint and tested in similar ways. Plastic linings and coatings are discussed in Section 6. The four essentials in coatings, whether of paint or metal or plastic, that give long protection to the underlying metal are: thickness, uniformity, adhesion and ductility, which for paint is usually called flexibility. Uniformity here implies the absence of thin patches. Tests for adhesion and ductility can be found in the standards literature, but the first two qualities are of the highest interest to the maintenance engineer because he can control them, and the thickness of course controls the cost. In an industrial environment the combined paint and metal coating (or either if used alone) should not be less than 0.125 mm (0.005 inch).

Visual inspection

Visual inspection of coatings, apart from being essential because it is quick, is usually also reliable, so far as it goes, but it does not indicate thickness. Metal coatings and paint, should be seen to be continuous. Hot-dip galvanizing is liable to have lumps or blisters that usually imply an inclusion of something that will weaken the zinc. The sparkle of new galvanizing, called spangle, though decorative, is of no value for anti-corrosion purposes and attempts are being made to reduce its scale. Sprayed zinc or aluminium coatings are always rougher than hot-dip galvanizing but should in any case never show black spots or blisters. Electroplated surfaces are the smoothest type of metal coating. They are usually also the thinnest because they are the most expensive.

Thickness measurements in general

Coating thicknesses can be determined by destructive or non-destructive methods. Generally speaking, only non-destructive methods will be of interest to the maintenance engineer unless he has a chemical or metallurgical laboratory at his disposal. Some of the destructive tests, that do not involve thickness measurement, measure the resistance of a standard painted or metal-coated panel to the corroding effect of salt spray or kerosene or scratching or impact or bending or some other way of stripping it. These tests are all described in the standards literature but it is worth pointing out that "test panels" in the sense used here are pieces of aluminium or steel sheet, usually measuring 15 by 10 cm, sometimes 10 by 5 cm.

Every manufacturer aims to apply the most uniform protective coating that he can, so as to give the highest protection at the lowest cost. The accurate measurement of thickness can provide the information needed to lower the cost of protection and to improve its quality. Without discussing the mathematical theory of probability it is possible to understand that for every job there is a certain minimum number of thickness measurements to be made so as to achieve an appropriate degree of certainty about the product. In manufacturing, at least one product in ten must be fully inspected, with occasional spot checks of doubtful products. Using an instrument that gives immediate readings, not only the routine measurements, but also the spot checks are easily and quickly made.

Non-destructive measurement of thickness

Thickness-measuring instruments based on four different principles are mentioned here but many others exist. In Great Britain alone there are more than 20 makers of instruments for measuring paint thickness and about the same number who make instruments for measuring the thickness of metal plating. All these instruments give immediate readings but each one has its most suitable field of use. The maintenance engineer should make wide enquiries before deciding to buy an instrument. The four principles of operation mentioned below are: beta-ray back scatter measurement, eddy-current measurement, thermo-electric measurement and magnetic measurement. The last is the oldest method and possibly the most suitable for measuring paint thicknesses on iron or steel.

The beta-ray back-scatter instrument is used mainly for measuring coating thicknesses of precious metals on semi-conductors, electrical contacts, printed circuits, and electronic or watch components. It can measure the thickness of a coating on a wire of only 0.2 mm diameter.

The eddy-current instrument is considered best for measuring insulating films (paint) on non-ferrous metals, and involves a high-frequency alternating field in the instrument. Provided that the coating metal has a smaller conductivity than the basis metal, non-ferrous coating metal thicknesses can also be measured. Anodic coatings on aluminium and its alloys can be measured. In appropriate circumstances, coating thicknesses as small as 0.2 thousandth of a micron can be measured.

The third instrument was developed recently by the British Non Ferrous Metals Research Association (BNF). The

BNF thermo-electric thickness tester measures the thickness of metal plating by the principle of the electrical voltage (thermocouple) produced at a heated contact between two different metals. The point of the meter is heated and brought into contact with the metal coating. An electrical conductor from the point leads to a direct current amplifier. The other connexion to the d.c.amplifier is brought round from the iron or steel basis metal beneath the coating.

The magnetic (or electromagnetic)instrument is well established but can only be used on a basis metal that is magnetic (usually iron or steel), and is only suitable for measuring the thickness of a non-magnetic coating. Nickel is magnetic, though much less so than iron or steel, and the instrument could not be used for measuring the thickness of nickel plating on steel .

Early types of the magnetic instrument had several disadvantages which are now overcome. They could be used only for measurements on a flat surface and away from the edge of the metal. Also it was essential to re-calibrate the instrument after taking it into an electric train or tram or near any other electric motor or generator. At least two calibration surfaces are needed for all these instruments. One of these is an uncoated metal plate to show the zero reading, the other is a metal plate coated with a known uniform thickness of the protective coating, to show the desired reading. Modern designs of the magnetic instrument may have overcome the serious disadvantage that readings had to be taken in the middle of large flat areas, because at least three"pencil" magnetic instruments exist, while on the larger modern instruments a small lightweight probe is used for taking the readings.

The calibration of an instrument is the adjustment of its scale readings so that they give correct values. For example the Celsius thermometer is correctly calibrated when it reads 0° at freezing point and 100° when water boils. Calibration surfaces for thickness-measuring instruments carry known thicknesses of coating (one of which may be zero) to enable the scales of thickness testers to be correctly set.

Inspection of painting

The paint should be chosen after discussion of the job with the paint manufacturer or the painting contractor and should if possible be made according to the standards of the country where it is to be used. Simple tests of the paint's ease of brushing or spraying, drying time and viscosity, as batches come in, can be made by non-specialists and will show whether the paint in the later batches is the same as in the first batch. Flow cups or cup viscometers (BS 1733:1955) are simple instruments for measuring viscosity (also called consistency) and the flash-point test is also not very time-consuming.

Since the value of the paint is only a small fraction of the cost of the structure, it is obviously false economy to buy the cheapest paint but the most expensive also is not necessarily the best. Some trouble should be taken to find out the best coating for the job, whether metal coating is to be used or paint, and the type of surface preparation.

Probably the most expensive single task in applying the protective coating is the surface preparation of the steelwork. It also has more effect on the life of the paint than any other work put into the anti-corrosion scheme. The most important inspection work is therefore the inspection of the surface after preparation. Methods of preparation have been discussed in the section on painting. Here we are concerned with the inspection and approval of the surface by the inspector working for the maintenance engineer, and with its final cleaning before priming.

Standards of surface preparation of steelwork are perhaps the least advanced of all standards in the painting industry but they do exist, however imperfect. The maintenance engineer or his inspector must come to an agreement with the contractor about the quality of the blast-cleaned surface that must be obtained.

Blast cleaning can contaminate the steel surface in several ways and these must be avoided. The compressed air must discharge an air blast without oil or moisture, therefore without mist. It must be dry. This can be verified by opening the compressed air valve and blowing to waste for a few seconds. If water or oil or mist is discharged, blasting must be stopped until the inspector is satisfied that the blast is dry. There should be a drain cock at the lowest point of the blast supply and it should be opened at least twice daily so as to discharge any oil or water that has collected. It is difficult to provide a completely dry air supply from a compressor, but it is possible. The air circuit may have to be re-designed, passing the air through a dryer after the drain cock, and possibly also through a pre-heater. Similarly, oil from the compressor must be kept out of the air line. This can be prevented by the use of good equipment and regular preventive maintenance, without excessive oiling. Such difficulties are unlikely with impeller blasting but this is ordinarily used only at factories. For site work, compressed-air blasting is usual.

If the grit or blasting shot are to be re-used, care must be taken that grease or old paint are removed from the steel before it is blasted, otherwise the grit will become dirty and foul the steelwork when it is re-circulated.

Agreement with the blast-cleaning contractor on the correct standard of finish is usually achieved by a mutually accepted standard of comparison. This is a piece of steel, at least 10 cm square and 6 mm thick that has been blast cleaned to the agreed standard and sealed with a suitable varnish. The standard surface should be one that can be regularly achieved in practice and the surfaces obtained should not be rougher than the standard. It is better for the surface to be too smooth than too rough. Excessive roughness means that peaks may occur that will not be adequately covered with the paint or sprayed metal. stated in another way, the same amount of paint will cover a larger area of smooth surface than of rough surface and will be uniformly thicker over a smooth surface than over a rough one.

To prevent rusting, some immediate treatment must be given to blast-cleaned steel, either a metal coating or a prefabrication or pretreatment primer. If the prepared steel surface becomes rusty it must be blast-cleaned again.

Maintenance painting also needs careful inspection. All dirt, salts, grease and so on must be removed from the surface before painting starts. If small areas are to be painted, surrounding areas of good paint must not be too much damaged by the surface preparation, and the new paint should overlap the edge of the old paint.

Instruments, painting conditions

Instruments required by the painting inspector for any type of painting will include a thermometer, a hygrometer, a thickness gauge for wet paint, and a thickness tester for dry paint or metal coatings. The hygrometer shows what is the relative humidity of the air. At relative humidities above 90 per cent with rising temperature (and above 85 per cent with falling temperature) painting should be stopped.

The same applies to painting at temperatures below 4°C (40°F). These temperatures and relative humidities should be discussed with the painting contractor so as to make sure that he fully understands their meaning, and perhaps slightly modified if he states a good reason. Special care should be taken to watch the temperature and relative humidity after blast cleaning because compressed air cools the steel and may cause dew to fall on it. There should of course never be any painting out of doors during rain, mist or snow. Such conditions can ruin wet paint and correspond to relative humidities of 100 per cent or more.

The electrical continuity testing of plastic coatings or non-conducting paint is briefly discussed in Plastics, p. 65.

9. SOURCES OF INFORMATION

In his search for information, the maintenance engineer will find that the names of the trade associations are particularly worth knowing. They can usually flood the enquirer at short notice with many pages of beautifully illustrated and well produced material that costs him no more than a postage stamp and the trouble of writing a polite, preferably typewritten letter. They exist to promote the interests of their own trade and are therefore supported by the large companies in it. It is also worth remembering that, although they must tell the truth, they are particularly liable to emphasize the advantages of their own products and to say as little as possible of their disadvantages. In spite of this their publications are extremely useful; the staff answer letters promptly and can be helpful in many other ways.

Institutes or institutions, being learned societies, however, are rather different. They are much less wealthy, being supported only by the subscriptions of the men and women qualified to practise their particular trade or profession. Although sometimes understaffed, institutions usually have information that is low in cost, high in quality and impartial. Every institution that has a stable existence possesses its own monthly or at least quarterly journal that reports matters of technical interest to its members. If a letter sent to an institution is not answered, and this may be because of shortage of staff, it is best to write again. The request for information should be re-written in a way that is easier for the institution to respond to, or that will bring the institution a small payment for a publication.

Research associations are a type of organization that is perhaps peculiar to the United Kingdom. They exist like trade associations to help their own particular trade, but by research, not solely by publicity. They also are supported by the subscriptions of their members but they receive Government support, often as much as the sum subscribed by their members. This means that they must conform to certain Government expectations and in particular the information they publish has to be of a high standard. None of the bias possible to a trade association is approved of and their publications must be impartial. One example is the Corrosion Advice Bureau of BISRA, the British steelmakers, which produces excellent publications, many of them free. Usually all information from a research association has to be paid for.

The maintenance engineer who is starting from a point where he knows very little and has to acquire as much absolutely reliable technical knowledge in a short space of time, should approach his country's standards institution. If his own country does not have standards on the matter of inquiry he should investigate the standards of other countries. These foreign standards are usually available for reading at the headquarters of local standards institutions and can sometimes be bought from them.

A very large number of products are involved in the struggle against corrosion: corrosion-resisting steels,other corrosion-resisting alloys or metals, metal-spraying or plating products, hot-dipping, shot blasting, a very large number of paints, primers, undercoats, top coats and all their pigments, binders, thinners, corrosion inhibitors and passivators, quite apart from the building industry and all its techniques of damp-proofing, heating and ventilating and air conditioning that reduce the relative humidity of the air and its dust content and make it less corrosive.

In most countries, almost the only book that covers all these subjects effectively is the standards yearbook. Sometimes in the smaller countries the field is covered the more conveniently because all the material is referred to in one volume. Even if all the material is referred to in one book, however, the standards and codes concerned must still be read, either in a reference library or after purchase. The author of this report knows the UK best and has found that the yearbook of the British Standards Institution (BSI) gives pointers to a very large amount of more or less co-ordinated information, almost all that a beginner to an industrial subject needs. There is certainly a vaster quantity of diverse and useful information in the standards yearbooks of larger countries but the information is not always so conveniently summarized in one book.

In case the previous paragraph should give a wrong impression, it should be pointed out that the standards yearbook merely indicates which are the standards or codes to be referred to and read on any particular subject. Standards generally are accepted rules, sometimes having the force of law, for the dimensions and quality of products. Dimensions are ordinarily defined in one standard, quality in another. Codes of practice are recommendations for good practice. They do not have the force of law but they explain the background and sometimes give a list of articles to read on the subject. For example British Standard Code of Practice 2008:1966, "Protection of iron and steel structures from corrosion", gives a list of 93 literature references, mainly in English, but also in French, German and Russian.

As a matter of interest, in 1969 the BSI had more than 5000 published standards, was undertaking new work or revisions at the rate of 500 standards or codes a year and had some 2400 projects in hand.

Drafts are the early form of codes and standards before they have been approved for publication. They are therefore not printed but written out in typescript and are then known as "Drafts for comment". The process of receiving comments on the draft, discussing them in the appropriate committees and agreeing on the final text takes several years for most publications, therefore there is always a large number of documents in draft form. By tactful inquiry it is occasionally possible to obtain copies of the draft if any copies of it remain. Periodically, when a draft has reached a certain stage, it is reproduced in a limited number of copies that are circulated to those interested, for them to send in their comments. When a draft is ready for comment, this is usually announced in the monthly journal of the standards institution that is producing it.

The special importance of institutes or institutions, in the UK at least, arises from the fact that every individual working in a specialist subject must join his specialist institution as a means of progress in his work. Therefore every important specialist belongs to the institution concerned and can be found by writing to it. The literature of the institutions is useful but their members can be even more so because accepted good practice does not find its way into the literature for some years.

Of the institutions listed below, a few publish journals that are solely concerned with corrosion prevention, as will be seen from their titles. The others publish matter of occasional interest to the maintenance engineer.

A. Selected scientific institutions

American Iron and Steel Institute, 150 East 42nd Street, New York 17

American Welding Society, 345 East 47th Street, New York 17

CEBELCOR (Centre belge d'étude de la corrosion) Avenue Paul Héger,
Grille 2, Brussels, Belgium

Electrochemical Society, 30 East 42nd Street, New York

Institute of Metal Finishing, 178 Goswell Road, London EC1

Institute of Metals, 17 Belgrave Square, London SW1

Institution of Chemical Engineers, 16 Belgrave Square, London SW1

Institution of Civil Engineers, Great George Street, London SW1

Institution of Corrosion Technology, 14 Belgrave square, London SW1

Institution of Mechanical Engineers, Birdcage Walk, London SW1

Institution of Structural Engineers, Upper Belgrave Street, London SW1

Institution of Water Engineers, 11 Pall Mall, London SW1

Iron and Steel Institute, 4 Grosvenor Gardens, London SW1

Metal Finishing Association, Saint Dunstan's House, Carey Lane,
London SW1

National Association of Corrosion Engineers, 2400 West Loop South,
Houston, Texas 77027 USA

Oil and Colour Chemists' Association, Wax Chandlers' Hall,
Gresham Street, London EC2

Royal Institute of Chemistry, 30 Russell Square, London WC1

Society of Chemical Industry, 14 Belgrave Square, London SW1

Steel Structures Painting Council, 4400 Fifth Avenue, Pittsburgh, Pa
USA

Stanford Research Institute, Menlo Park, California 94025 USA

B. Selected research associations

British Welding Research Association, Abington Hall, near Cambridge
England

Building Research Station, near Watford, Herts, England

Corrosion Advice Bureau, British Iron and Steel Research Association
140 Battersea Park Road, London SW11

Forest Products Research Laboratory, Princes Risborough, Bucks,
England

Rubber and Plastics Research Association, Shawbury, Shrewsbury,
Shropshire, England

Water Research Station, Ferry Lane, Medmenham, near Marlow, Bucks
England

C. Selected standards organizations and other national bodies

American Society for Testing and Materials (ASTM), 1916 Race Street,
Philadelphia, Pa, USA

British Standards Institution, 2 Park Street Mayfair, London W1

Comité européen des associations de fabricants de peintures et
d'encres d'imprimerie, 42 avenue Marceau, Paris 8e France

U.S.National Bureau of Standards, 318 Washington DC, 20234 USA

U.S.Atomic Energy Commission, Washington D.C. 20545 USA

U.S.Bureau of Mines, "C" between 18th and 19th Street NW,
Washington D.C. 20545 USA

The publications of U.S.Government organizations can generally be obtained from the US Government Printing Office, Washington DC, 20402 USA. The U.S.National Bureau of Standards publishes three monthly journals and is the main agency of the US Government for basic and applied research in physics, chemistry, mathematics and engineering. It is therefore unlike the standards organisations of most countries, which usually do very little research. The USA Standards Institute (before 1966 known as the American

Standards Association) publishes nothing itself and does not itself initiate or write standards. The ASTM is probably the most interesting of these three organizations to the maintenance engineer.

D. Some trade associations and commercial research stations

Aluminium Federation, 60 Calthorpe Road, Five Ways, Birmingham 15, England

Copper Development Association, 55 South Audley Street, London W1

GKN Fasteners Corrosion Laboratory, Birmingham, England

Tin Research Institute, Fraser Road, Greenford, Middlesex, England

Zinc Development Association, 34 Berkeley Square, London W1

E. Books on corrosion prevention

Anti-corrosion manual, 1964, Scientific Surveys Ltd, 11a Gloucester Road, London SW7

Corrosion, by L.L.Shreir 1963, Newnes, London, 2 volumes

Finishing Handbook and Directory, annually, Sawell Publications Ltd, 4 Ludgate Circus, London EC4

Manual of Maintenance Engineering, Factory Publications, Mercury House, Waterloo Road, London SE1

Packaging code (Temporary protection of metal surfaces against corrosion during transport and storage), BS 1133 Section6 1966, British Standards Institution, London

Painting of Buildings, BSCP 231:1966, British Standards Institution, London

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Protection of Iron and steel structures from corrosion, BSCP2008:196 British Standards Instittion, London

F. Periodicals concerned with corrosion prevention

Anti-corrosion methods and materials, monthly, Sawell Publications Ltd, 4 Ludgate Circus, London EC4

British Corrosion Journal, Institution of Corrosion Engineers, 14 Belgrave Square, London SW1

Corrosion, National Association of Corrosion Engineers, 2400 West Loop South, Houston Texas, 77027 USA

Corrosion Prevention and Control, monthly, Scientific Surveys Ltd, 11a Gloucester Road, London SW7

Materials Protection, National Association of Corrosion Engineers, 2400 West Loop South, Houston Texas 77027 USA

Product Finishing, monthly, Sawell Publications Ltd, 4 Ludgate Circus London EC4

A number of other journals have useful articles from time to time including: Chemistry and Industry, Chemical Processing, Industrial and Engineering Chemistry, Materials and Methods, Metal Industries, Revue Métallique, Sheet Metal Industry. The regular or occasional publications of the bodies listed under A,B,C and D above are also most interesting.

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