by R. A. Cottis*

Corrosion is not a problem – but the cost of corrosion is

Corrosion of metals presents a perpetual problem. Although technology is available to prevent it in many cases, costs *are* involved. The author reviews various aspects of corrosion and methods for its prevention — stressing that such costs should be weighed against those of extensive metal damage. Referenced to specific illustrative examples, the invaluable roles of education, research and the corrosion specailist are outlined, particular emphasis being placed on high temperature oxidation, anodising of aluminium, intergranular damage and corrosion in marine environments.

La corrosion n'est pas un problème — mais son coût en est un

La corrosion des métaux est un problème perpétuel. Bien que la technologie permettant de l'éviter existe dans de nombreux cas, elle coûte cher. L'auteur passe en revue divers aspects de la corrosion et des méthodes préventives et il insiste sur le fait qu'il faut mettre en balance d'une part les frais et d'autre part les dégâts importants causés aux métaux. Illustrés par des exemples particuliers, les rôles inestimables de l'éducation, de la recherche et du spécialiste de la corrosion sont exposés. L'auteur insiste tout particulièrement sur l'oxydation à haute température, l'anodisation de l'aluminium, les dégâts intergranulaires et la corrosion en milieu marin.

Korrosion selbst ist kein Problem — aber die Kosten sind eins

Die Korrosion von Metallen stellt ein ständiges Problem dar. Obwohl heute Techniken verfügbar sind, die sie in vielen Fällen verhindern können, so bringen diese Kosten mit sich. Der Autor befaßt sich mit verschiedenen Aspekten von Korrosion und den Methoden zu ihrer Verhinderung; er betont, daß eventuelle Kosten gegen starke Metallschäden abgewogen werden müssen. Anhand von einzelnen anschaulichen Beispielen werden die bedeutenden Funktionen von Information, Forschung und Korrosionsspezialisten gezeigt. Besonders hervorgehoben werden hierbei Oxidierung unter hohen Temperaturen, Aluminium-Anodisierung, interkristalline Korrosion und Schäden in Meeresumgebungen.

As a subject, the study of corrosion is rather like weather forecasting. Virtually everyone is aware of the more obvious manifestations, and all too often the 'experts' appear to have difficulty in getting it right. After all, everyone knows that cars do rust, but no one seems to be able to prevent this. How then can the title of this article be justified?

The author's justification lies in the nature of the problems resulting from corrosion. To take the example of the rusty car, the experts can offer solutions, one being the use of stainless steel for the construction of bodywork, which has been shown to give at least 20 years service. However, it is doubtful whether many customers would pay the considerably higher price, and it is equally questionable whether the world's supply of chromium could support such a change. More generally there are few corrosion problems which cannot be technically overcome (if in doubt try platinum!), what is much more difficult is to contain corrosion in the most cost effective manner.

Before we examine some of the cost implications of particular corrosion problems, and ways in which these problems are being tackled, it is worth putting the overall national costs of corrosion into perspective. Various studies have examined the costs of a corrosion in the UK, the USA and elsewhere. In general, for developed countries these show costs resulting from corrosion and its control of around 3% of the gross national product. This figure may perhaps take on greater significance when expressed in terms of a corresponding product. Thus the cost of corrosion in South Africa is comparable to its annual production of diamonds, while North Sea oil more or less pays Britain's corrosion bill. It is clear that corrosion offers plenty of scope for saving money. It is estimated that 15-25% of the cost of corrosion could be saved simply by the use of known methods of corrosion control. These cost savings can be achieved in many ways. An obvious example is the use of a more corrosion resistant material to give a longer life and hence a lower annual cost. Equally, however, it will often make economic sense to use a very cheap material accepting the more frequent replacement which becomes necessary.

A familiar example of this balance between cost and corrosion resistance can be seen in the selection of materials for a car exhaust system. Traditionally, these parts have been made in mild steel, which gives a life in the region of 15 months, resulting in frequent, but relatively inexpensive replacements. In an effort to prolong the life of vehicle exhausts two alternatives have been developed. Of these stainless steel is considerably more expensive than mild steel, but offers very long service in excess of five years. A lower cost option is to use aluminium coated steel, which gives more modest improvements in corrosion performance, about two years life, but at a cost which is not very much greater than that of mild steel.

The costs and expected life of these three alternatives are shown in Table 1.

Table 1 Costs and lives of typical exhaust systems for a medium-sized saloon car

	Cost (£)	*Life (months)*
Mild steel	30	15
Aluminised steel	35*	24
Stainless steel	70	60

*The cost of an aluminised system is estimated: few exhaust replacement centres offer these!

In simple terms, this suggests that stainless steel is the most cost-effective choice for an expected life of 10 years, costing a total of £140, compared to £175 for aluminised steel and £240 for mild steel (figure 1).

1 *Even stainless*

involves borrowing from a bank then, in addition to the actual cost of the exhausts, a significant bill for interest will also be accumulated. Because the stainless steel exhaust requires the outlay of large sums of money early in the life of the car, it accumulates a proportionately larger amount of interest. The amount owing to the bank after ten years is shown in Table 2 for a range of interest rates.

Table 2 Total costs of providing exhaust systems for ten years with money borrowed at various rates of interest

	5%	10%	15%	20%
Mild steel	324	440	597	809
Aluminised steel	237	321	437	595
Stainless steel	203	294	424	608

It can be seen that aluminised steel systems become more competitive with stainless steel as interest rates increase, whereas ordinary mild steel systems are always significantly more expensive. One wonders why it is that mild steel systems dominate the replacement market!

Even this analysis is incomplete, since it does not take account of factors such as inflation and the time for which the owner expects to keep the car. Imagine the problems of the corrosion engineer when recommending materials for the construction of a large chemical plant!

In the more complex industrial situation there may often be greater advantage in opting for more expensive *corrosion resistant materials and systems*, since the costs of lost production incurred during replacement of less resistant components may far outweigh actual component costs. Thus a critical valve in a chemical process plant may cost £1000 in an alloy expected to last for one year or £10 000 in an alloy expected to last five years. Clearly, the second option is not a reasonable choice on the basis of components cost alone, but if valve replacement requires a plant shut-down resulting in loss of production worth £2000, the balance swings in favour of the component with the longer life.

This example is clearly oversimplified, and a wise selection would also take account of reliability and maintenance strategy. Thus a component with a known history of reliable operation would be preferred to a less reliable component, or one with no service history. Equally it might be reasonable to use a lower cost, shorter life component if its replacement can be scheduled to coincide with regular maintenance periods, so that replacement does not incur any additional production losses.

Control of corrosion costs

Having seen that corrosion is primarily an economic problem, what can be done to minimise the cost of corrosion? One of the more unfortunate features of UK takes the form of a large number of small losses, such as the failure of millions of car exhaust systems at a cost of a few tens of pounds each, or the gradual deterioration of thousands of tons of structural steelwork exposed to the elements. Three major aspects of methods of corrosion control are education, the work of corrosion specialists and applied corrosion research.

Role of education

Because of the widely dispersed nature of corrosion problems, one of the most powerful weapons in the battle to reduce corrosion losses is education. This can operate at several levels, as examplified by the work of the UMIST Corrosion and Protection Centre. The primary aim of the Centre is the training of corrosion specialists by means of the M.Sc. course in Corrosion Science and Engineering, with more specialised training being given in the form of research programmes for the degrees of M.Sc. (by research) and Ph.D. These courses attract students from a wide range of academic and industrial backgrounds, and may form the basis for a career as a corrosion scientist or engineer. Alternatively the one-year M.Sc. course provides a sound understanding of corrosion and its control for professional metallurgists, chemical engineers and similar disciplines.

While the training of professional corrosion scientists and engineers is an important activity (as is evidenced by the continuing demand from employers, despite the current recession), it has a relatively small immediate impact on the large number of 'minor' corrosion losses which do not merit the attention of a full-time corrosion specialist. This presents a very difficult problem of conveying a relatively limited 'corrosion awareness' to a large number of people. Members of staff of the Corrosion and Protection Centre attempt to play their part in the solution of this problem by the presentation of lectures to non-specialist audiences, by the preparation of articles and publications for the non-specialist and by the presentation of a series of short courses introducing the practical side of corrosion control to engineers and technicians. As far as industrial corrosion problems are concerned it is economically attractive to an organisation for a wide range of personnel to acquire a general understanding of the principles of corrosion. These can range from the more obvious examples of engineers involved in the design and operation of plant and equipment ... course of their everyday work.

Role of the corrosion specialist

There are relatively few specialist corrosion scientists and engineers in the UK — probably numbering a few thousand. Many of these are employed in industrial plant with significant corrosion problems. In this situation it is important that the corrosion specialist is seen as an integral part of the design, operation and maintenance team, so that corrosion problems can be minimised by design, rather than being tackled as a failure investigation after the plant has been constructed.

A second role for the corrosion specialist is in the provision of a research and/or advisory service for suppliers of materials for use in the control of corrosion. These specialists play an important part in the development of new materials, and, as technical service/sales engineers, in the encouragement of corrosion awareness among non-specialists.

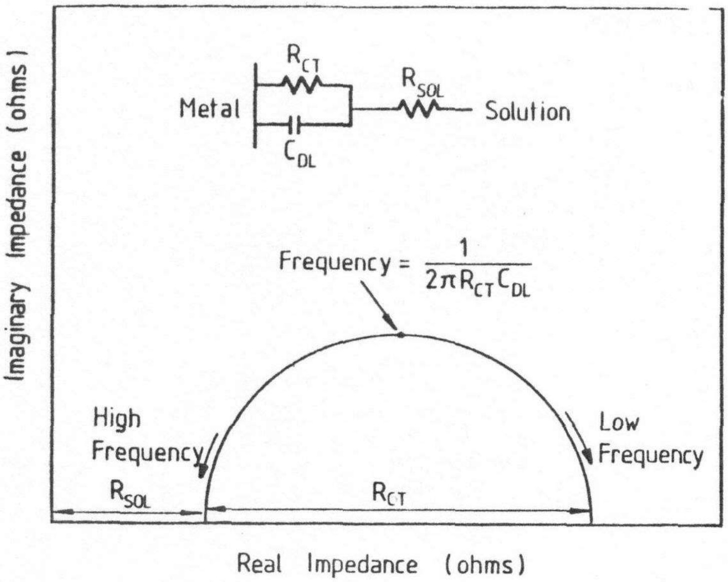
Finally, a number of independent consultants offer a corrosion advice service to smaller organisations who cannot justify the employment of full-time staff to handle corrosion questions. As an example the Corrosion and Protection Centre Industrial Service (CAPCIS) provides a corrosion failure investigation and advice service to industry. All too often however, the consultant is investigating a failure when it would have been far more economical for him to have given advice at the design and installation stage!

Role of research

The more widespread awareness of known principles of corrosion control, and the efforts of specialist corrosion scientists and engineers, can realise significant savings from the application of existing knowledge. The role of applied corrosion research is to extend this knowledge to provide more economical materials and corrosion control systems, and to increase the reliability of corrosion control systems by providing a better understanding of the mechanisms involved.

In common with most university departments, research at the UMIST Corrosion and Protection Centre is a blend of pure and applied work, but the industrial importance of corrosion, and the Centre's many contacts with industry probably results in a greater proportion of studies with direct relevance to practical corrosion problems. Some examples of this class of research which are currently in progress at the Corrosion and Protection Centre are presented here.*

*Interested readers can also obtain a copy, on request, of the Centre's research in progress brochure, which gives brief details of all the 90 or so projects currently in progress



2 A.C. impedance diagram for a typical corroding metal.

Corrosion monitoring

As was indicated previously, corrosion problems are often far more severe if they occur unexpectedly. A known, steady rate of corrosion can be tolerated in a chemical process plant by means of a planned replacement policy. By ordering replacements well in advance of shut down periods the time (and hence production) lost can be kept to a minimum. In contrast an unexpected failure can cause prolonged shut down and large production losses while replacements are being obtained. For this reason the monitoring of corrosion processes plays an important part in ensuring the reliable operation of such plant.

Existing techniques of corrosion monitoring cover a wide range of applications. In particular, the linear polarisation resistance technique offers an accurate direct reading of corrosion rate on a near-continuous basis. However, the accuracy of this technique is restricted in certain circumstances, especially in environments where the electrical resistance of the corrosive fluid is very high. A large research group at UMIST is working on electrochemical aspects of corrosion processes, and techniques developed by this group offer methods of monitoring corrosion in these, more difficult, environments.

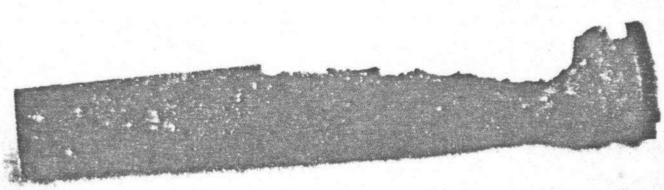
The best-established of these techniques is the measurement of the a.c. impedance of the interface between a metal sample and its environment over a range of frequencies. If the real and imaginary components of the impedance are plotted with frequency as a parameter (figure 2), the resulting complex plant or Nyquist diagram permits the analysis of the thickness of some surface films (by means of the capacitance), the corrosion rate (proportional to $1/R_{CT}$) and the resistance of the solution (R_{SOL}).

More advanced techniques are also being investigated, and offer some promise for the detection and measurement of localised corrosion, such as pitting, crevice corrosion and cavitation.

High temperature/oxidation corrosion

The performance of alloys at high temperatures in industrial environments is often limited by their resistance to oxidation or corrosion by components of the environment. For many thermal processing and energy conversion systems such as boilers and gas turbines, the efficiency of the process is a function of the operating temperature. Hence in this case the economies of the corrosion problem are controlled more by the costs of the operating efficiency than by material costs. Consequently there is a continuing search for alloys capable of operating at higher temperatures and in more hostile environments.

It is well known that the theoretical maximum efficiency of conversion of heat to other forms of energy is controlled by the difference in temperatures of the heat source and sink. The gas turbine can play a useful part in this conversion process, since it can extract energy directly from a hot, pressurised gas stream without the intermediate process of heat transfer in a boiler. Consequently there is considerable interest in materials to withstand coal combustion or gasification products at high temperatures, and the availability of suitable materials could materially influence coal gasification and power generation economics.



3 Severe hot corrosion of a gas turbine stator blade.

These environments are extremely corrosive (figure 3), consequently research work at the Centre is concentrating on the development of coating methods for existing alloys, rather than trying to achieve both good mechanical properties and corrosion resistance in one alloy.

4 Section through a porous anodic film on aluminium.

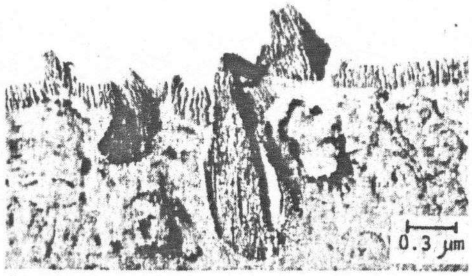
Anodised aluminium

The corrosion resistance of aluminium is well known and plays a large part in its widespread use for architectural metalwork, particularly window frames. What may not be so widely recognised is that untreated aluminium will suffer from fairly rapid pitting corrosion a result of atmospheric pollutants or salt spray from the sea. The good atmospheric corrosion performance of aluminium is obtained by anodising, artificially thickening and reinforcing the natural oxide film which protects aluminium ▶

against corrosion.

Despite its generally good performance, anodised aluminium can suffer from corrosion in the atmosphere, particularly if pollutants are allowed to collect on the surface, and the cleaning of anodised aluminium components can be a significant part of the maintenance costs for modern aluminium clad buildings. The corrosion may take the form of localised pitting attack, and much work has been done at the Centre in order to understand this process, and thereby to develop methods of combatting it. As an example, figure 4 shows a section through the normal anodic oxide film on aluminium. The porous structure which can be seen is subsequently immersed in boiling water to hydrate the oxide, causing it to expand and block the pores. This process is known as sealing, and increases the corrosion resistance of the material.

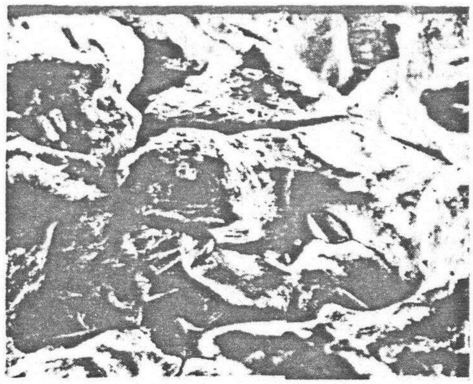
In contrast, figure 5 shows a film formed on an aluminium alloy containing iron, where a particle of intermetallic is present at the surface. This has caused a major change in the nature and thickness of the film, which provides a local point of weakness which is liable to initiate the growth of a corrosion pit.



5 *Anodic film over an aluminium-iron intermetallic.*

Intergranular corrosion of sacrifical anodes

A very cost-effective method of protecting steel against corrosion in moderately aggressive environments such as seawater is to use cathodic protection. In essence this consists of making the steel electrically more negative, thereby slowing down or stopping the normal corrosion process of iron dissolving to give positively charged ferrous ions. This can be done either by means of an external power supply, or by connecting the steel to a more reactive metal such as zinc or aluminium. The latter is known as the sacrificial anode method of cathodic protection, and is particularly convenient to use, since no external power source is required, and, if properly designed, is essentially self-regulating. For these reasons a majority of the steel oil production platforms are protected by sacrificial anodes which are attached to the structure when it is fabricated. In general these perform well, and corrosion of the submerged structure of the platform is not a major problem. However when zinc sacrificial anodes get hot, as is the case near the hot riser, where the hot oil emerges for the well, the problems become rather more severe. Because of the high temperature, corrosion reactions occur more rapidly, and it becomes more important that the cathodic protection system provides sufficient current to protect the structure. Unfortunately it has been found in practice that the zinc alloy sacrificial anodes normally used for the protection of this area fail prematurely because of an intergranular corrosion (see figure 6). Work is in progress at the Corrosion and Protection Centre to determine the cause of the premature failure of the anodes, and thereby to develop solutions to the problem and permit this economically attractive method of corrosion protection to be applied in this particular situation.

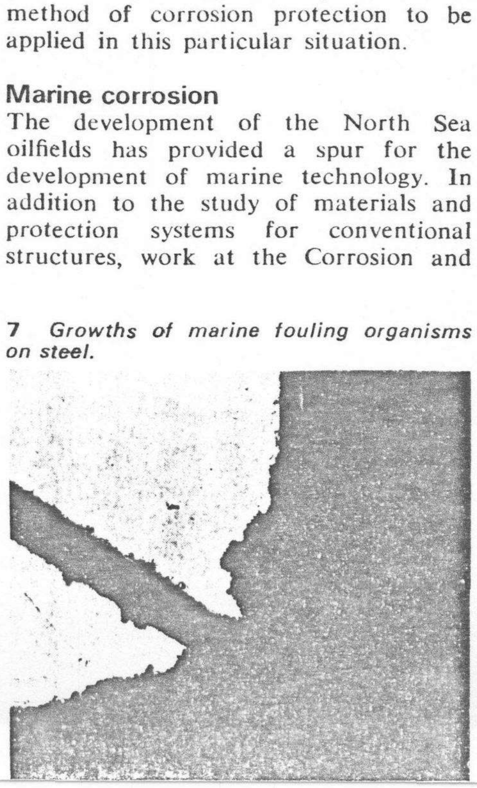


6 *Intergranular corrosion of a zinc sacrificial anode (x 100).*

Marine corrosion

The development of the North Sea oilfields has provided a spur for the development of marine technology. In addition to the study of materials and protection systems for conventional structures, work at the Corrosion and Protection Centre also reflects the demand for higher performance materials which will permit lighter and less expensive structures to be used for oil production platforms, and in the more distant future, for wave energy devices. Thus, as a part of a considered SRC programme investigating the performance of steel wire ropes in the marine environment, workers at the Centre are studying the feasibility of cathodic protection as a means of providing a long service life for large wire ropes used to tether wave energy devices and floating oil production platforms. This is particularly important for the economics of power generation from wave energy, since the cost of rope tethers, and particularly the cost of their replacement, is a major proportion of the cost of the overall system.

7 *Growths of marine fouling organisms on steel.*



The marine environment is also complicated by the inevitable growths of seaweed, algae, barnacles and so on, which can modify the conditions at the steel surface in a variety of ways. In order to clarify the possible influence of such fouling growths, a number of joint programmes are commencing at the Corrosion and Protection Centre, the joint UMIST/University of Manchester Pollution Research Unit and CAPCIS. These are studying the influence of marine fouling growths on possible hydrogen embrittlement problems, on the efficiency of the cathodic protection, and on the performance of sacrificial anodes (figure 7). The results of this work will assist in the design of new structures, allowing the cost of the corrosion protection system to be minimised, and will give operators an indication of the extent to which it is necessary to remove fouling growths for corrosion control purposes.

The UMIST Corrosion and Protection Centre is of course not alone in its efforts to develop improvements in the methods available to control the costs of corrosion, and many other university departments and government and commercial laboratories are also engaged in similar work. However it is only by the continuing and increasing awareness among non-specialist engineers, managers and technicians of the potential costs of corrosion, that this research work can be translated into the maximum possible financial benefit.

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