

CORROSION

Volume 2

Corrosion Control

Edited by

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PREFACE TO 1ST EDITION

The enormous scope of the subject of corrosion follows from the definition which has been adopted in the present work. Corrosion will include all reactions at a metal/environment interface irrespective of whether the reaction is beneficial or detrimental to the metal concerned—no distinction is made between chemical or electropolishing of a metal in an acid and the adventitious deterioration of metal plant by acid attack. It follows, therefore, that a comprehensive work on the subject of corrosion should include an account of batteries, electrorefining, chemical machining, chemical and electrochemical polishing, etc.

The fact remains, nonetheless, that the environmental reaction of a metal used as a construction material is the most important type of corrosion reaction, and the one of most concern to the engineer. The technological and economic consequences of the wastage of metals by corrosion are now fully appreciated, and figures have been published which show the enormous financial losses, both to the individual organisation and to the economy of the country as a whole, resulting from the deterioration of metals. The need for conserving metals has been publicised by Dr U. R. Evans, Dr J. C. Hudson, Mr T. H. Turner, Professor H. H. Uhlig, Dr W. H. J. Vernon, and others, and the 'corrosion consciousness' which prevails today is largely due to their efforts.

In the light of what has been said above, little further explanation of the implications of the title of the present work is required. Its treatment of the subject of corrosion will centre round the *control* of the environmental interactions of metals and alloys used as materials of construction.

The effective control of corrosion reactions must be based on an understanding of the mechanism of such reactions and on the application of this knowledge to practical problems. The work, regarded as a whole, represents an attempt, therefore, to present the subject of corrosion as a synthesis of corrosion science and corrosion engineering. Thus in the planning of the content an attempt has been made to strike a suitable balance between the primarily scientific and the primarily practical aspects, and so the nature of individual sections ranges from the fundamental and theoretical to the essentially practical.

It is hoped that this approach has resulted in a work that will be of some value to the student, the corrosion worker, and the engineer in the field of corrosion.

Corrosion represents the joint effort of over 100 authors, all of whom have been free, within the necessary limitations of length, to express their own views. Grateful acknowledgements are made to the individual authors from Great Britain, the United States, and Canada for their valuable and enthusiastic co-operation.

The task of the editor in finding suitable authors for various topics was considerably lightened by the fact that the majority of corrosion specialists in this country belong either to the Corrosion Group of the Society of Chemical Industry or to the Institute of Metal Finishing, and acknowledgements are made to Mr S. C. Britton (then Secretary, Corrosion Group) and to Dr S. Wernick and Mr I. S. Hallows (Hon. Secretary and Assistant Editor respectively of the I.M.F.). The editor wishes to express his appreciation of the considerable assistance received from Dr E. C. Rhodes and Dr G. L. J. Bailey of INCO (Mond) in providing authors from this organisation.

The editor also acknowledges with pleasure the encouragement and assistance he has received from Mr L. W. Derry (Head of Department of Metallurgy) and Dr D. M. A. Leggett (Principal) of the Battersea College of Technology, and from Dr A. M. Ward (Principal) of Sir John Cass College.

Throughout the course of this work the content and subject matter have been discussed with various workers in the field, and the editor would like to take this opportunity to thank Mr S. C. Britton, Professor C. W. Davies, Dr T. P. Hoar, Dr E. C. Potter, and others for their advice and constructive criticism.

He would also like to take this opportunity to express his appreciation to Dr U. R. Evans and Dr W. H. J. Vernon for assistance given when he first contemplated entering the field of corrosion, and for their encouragement and advice in connection with the present work.

Finally, grateful acknowledgements are made by the editor to Mr T. F. Saunders and Mrs N. E. Orna, M.A., of George Newnes (Technical Books) for their kind co-operation at all stages of the work.

L.L.S.

1963

PREFACE TO 2ND EDITION

Corrosion was first published in 1963 and with the appearance of the 2nd edition it is of interest to look back over the intervening years and to consider the progress that has been made in the science and technology of the corrosion and protection of metals. The word 'corrosion' signifies 'destroy gradually, decay, disease' and over the years attempts have been made to find an alternative that would have a more positive connotation and that would be more attractive to the young student with a leaning towards the applied sciences. Unfortunately, an appropriate word has proved to be elusive, although in this respect other technologies have succeeded where 'the corrosionist' has failed; *tribology* and *terotechnology*, to name but two, have without doubt the imposing sound that *corrosion* lacks. The difficulty is overcome to some extent by using expressions such as 'corrosion control', 'corrosion protection', etc. but the unfortunate word 'corrosion' cannot be dispensed with.

Strangely, and in spite of its name, 'corrosion' continues to flourish and has now become an established academic discipline, and if the quality and quantity of scientific publications and books are criteria of its importance, then the story of corrosion over the past decade or so is one of outstanding success. In the United Kingdom there are now Professors of Corrosion Science at the University of Manchester and Imperial College, London, and there are also a number of others, who although not designated as such have made their reputation by their work in this field. There are now a number of universities and polytechnics with departments that specialise in corrosion and provide courses in the subject for undergraduate and postgraduate students; there are three MSc courses devoted solely to corrosion and protection and a number of others in which it is given some prominence.

The importance of the subject is also reflected in the establishment of a Corrosion and Protection Centre at the University of Manchester Institute of Science and Technology, under the direction of Professor G. C. Wood, the first Professor of Corrosion Science in this country, and more recently a special advisory centre has been established at the National Physical Laboratory.

Progress has also been made in establishing corrosion protection as a reputable professional activity, and the recent merger of the Institute of Corrosion Technology and the Corrosion and Protection Association to

form the Institute of Corrosion Science and Technology represents an important step in that direction. It is hoped that the new Institute will follow in the footsteps of the well established National Association of Corrosion Engineers in stimulating courses, publications, standards and research in the field of metals protection.

This progress, which will undoubtedly continue, stems from a number of factors and due acknowledgement must be made to the early workers in this field who did so much to give corrosion its present status. Of more recent origins is the awareness by government of the cost of corrosion to the economy of the country as a whole, to industry, and to the individual consumer, and it is evident that the technology for the preservation of metals from the ravages of corrosion will become of increasing importance.

The present edition of *Corrosion* represents a complete revision of the 1st edition which was published in 1963, and although the philosophy and structure of the book have remained unchanged (see Preface to 1st edition) several new sections have been added, which should make the work more comprehensive. Over the past 13–14 years the scope of the subject has increased enormously, and this means that a detailed treatment of each aspect of corrosion is not possible even in a work that extends to two volumes, and contains approximately 2300 pages. Nevertheless, it is hoped that *Corrosion* in its revised form will make a valuable contribution to ‘better dissemination of existing knowledge’ in this important field of materials conservation.

L.L.S.

Foreword by J. B. Cotton, Esq.,

Chairman, Department of Industry Corrosion Committee
(1972–75)

The fact that the first edition of this book met with such success demonstrates that its initial publication filled a long standing need. Since its first appearance in 1963, knowledge of corrosion science and technology has increased enormously and several significant developments have occurred that have made it essential to produce a revised, up-dated edition.

An event of the utmost significance was the attempt to survey, comprehensively and quantitatively, the cost of corrosion to the United Kingdom. This task, sponsored by the then Department of Trade and Industry in 1969, was undertaken by a Committee, chaired by Dr T. P. Hoar. The results, contained in the Report of the Committee on Corrosion and Protection, published by HMSO in 1971, put the annual cost of corrosion in the UK at £1365M. More importantly, it was estimated that of this sum, £310M could be saved if the available knowledge on corrosion prevention was fully applied in practice. It is fair to say that the new edition of *Corrosion* sets down the basic knowledge that needs to be applied in recouping this loss.

The selection of the most appropriate system for corrosion prevention and its translation into industrial practice is, however, often a complicated procedure, in which the true economic benefit has to be assessed and appreciated before investment in a protective scheme can be justified. Although the book is sufficiently comprehensive to provide the answer to many corrosion problems, an individual system may often require a level of judgement and expertise that it is not possible to include in any work of reference, however detailed, and for the non-expert this book also indicates areas where it is advisable to seek further advice.

The major finding of the Hoar Report was the need for (a) better dissemination of information on corrosion and protection, (b) more education in corrosion and protection, and (c) an increased awareness of the hazards of corrosion, and it was to pursue these objectives in the economic interests of the nation that the Department of Industry Committee on Corrosion was established in 1973. A comprehensive work of reference, such as this book, is an essential aid to achieving the Committee's objectives and had a book of sufficient scope not existed it would have been necessary to produce one. Fortunately, the up-dating and revision of a book that has already established itself as an authoritative source of information on the subject has been completed so that publication can take place almost coincidentally with the

opening of the National Corrosion Service at Teddington. These developments, together with the expansion of advisory facilities that is also taking place at existing centres, should ensure that industry in the UK is not lacking in the provision of advice upon protection against corrosion.

Corrosion knows no national boundaries, and this book should be of great value, therefore, to countries throughout the world and in particular to those where advisory services are non-existent.

A handwritten signature in black ink, appearing to read "J. B. Cottrell". The signature is written in a cursive, flowing style with a long horizontal stroke at the end.

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15.8 Protective Coatings for Underground Use

Introduction

The general conception of a paint is of a cold-applied material containing thinners which evaporate to leave a higher molecular-weight base protective, of 25–50 μm thickness per coat. For buried or submerged structures, where maintenance is difficult or even impossible and a degree of physical protection is also necessary, such thin protective paint barriers between metal and the corrosive electrolyte environments of soil or water are usually quite inadequate. In relatively non-corrosive soil, thin bituminous coatings on thick cast iron may be satisfactory, but this is the exception rather than the rule. In dealing with underground structures, therefore, the thicker protectives needed are regarded as *coatings* rather than as paint finishes.

The most usual forms of buried metal structures are pipelines, piles, tanks and power and telephone cables. Power cables must usually have some metal protection, covered by expensive continuous factory-applied sheathings of considerable thickness. Since water, gas and petroleum pipelines provide the greatest area of metal surfaces to be protected below ground, a detailed discussion of the protection given to them would appear to be the best means of dealing with coatings for underground use.

Improvements are continually being made in the quality of coating materials and their application, but it is still difficult to produce at economic cost a permanent coating for a buried pipeline. The disruptive effects of handling, construction, penetration by rocks, soil stress, material ageing, etc. inevitably result in areas of bare metal being exposed to corrosive soil electrolyte at isolated locations, with ultimate pitting or holing of the metal. The aim is to supply the best possible coating at economic cost and to provide for any initial or later failures by application of cathodic protection. The combination of coating with cathodic protection shows the greatest economic advantage.

In pipelining, the trend is towards all-welded steel for long lines, and since the wall thickness is less than that of cast iron, protection is the more important. Many types of coating are used, from thick concrete to thin paint films, and each has its own particular suitability, but the majority of pipelines throughout the world today are coated with hot-applied coal tar or petroleum asphalt-base-filled pipeline enamels into which reinforcing wraps, such as glass fibre are applied.

The use of coatings applied in the form of tape is also increasing. Polyethylene and polyvinyl chloride films, either self adhesive or else supporting films of butyl adhesive, petrolatum or butyl mastic are in use as materials applied 'cold' at ambient temperatures. Woven glass fibre or nylon bandage is also used to support films of filled asphalt or coal tar and these are softened by propane gas torches and applied to the steel surface hot, cooling to form a thick conforming adherent layer.

Recently, sheets of high density polyethylene extruded on to the pipe surface over an adhesive have become available and the use of polyethylene or epoxy powders sintered on to the steel surface is becoming more frequent.

Some use has been made in the water industry of loose envelopes of polyethylene sheeting and with the increasing lengths of submarine pipeline requiring heavy concrete coatings for reducing buoyancy, the use of a heavily filled bituminous coating is projected.

In the special case of pipelines operating at relatively high temperatures such as for the transmission of heavy fuel oil at up to 85°C, heat insulation and electrical insulation are provided by up to 50 mm of foam-expanded polyurethane. As a further insurance against penetration of water, and to prevent mechanical damage, outer coatings of polyethylene (5 mm), butyl laminate tape (0.8 mm) or coal-tar enamel reinforced with glass fibre (2.5 mm) have been used.

Properties Required of Buried Coatings

The aim in applying a coating to a buried metal such as a pipeline is to prevent electrical contact with an electrolyte such as soil and/or water. The characteristics required are as follows:

1. *Ease of application.* It must be possible to apply the coating in the factory or in the field at a reasonable rate and to handle the pipe reasonably quickly after the coating has been applied without damaging the coating.
2. *Good adhesion to the metal.* The coating must have an excellent bond to steel. Priming systems are frequently used to assist adhesion.
3. *Resistance to impact.* The coating must be able to resist impacts without cracking.
4. *Flexibility.* The coating must be flexible enough to withstand such deformation as occurs in bending, testing or laying, as well as any expansion or contraction due to changes in temperature. It must not develop cracks during cooling after application or curing.
5. *Resistance to soil stress.* The coatings are often subject to very high stresses, due, for instance, to the contraction of clay soil in dry weather, and they must be able to resist such stresses without damage.
6. *Resistance to flow.* The coating should show no tendency to flow from the pipe under prevailing climatic conditions. It must not melt or sag in the sun and it must have sufficient resistance not to be displaced from the underside of large-diameter pipes.
7. *Water resistance.* Coatings must show a negligible absorption of water and must be highly impermeable to water or water-vapour transmission.

8. *High electrical resistance.* The coating must be an electrical insulator and must not contain any conducting material.
9. *Chemical and physical stability.* The coating must not develop ageing effects, e.g. denaturing due to absorption of the lower-molecular-weight constituents, or hardening with resultant cracking from any cause including oxidation. It should be stable at operating temperatures.
10. *Resistance to bacteria.* The coating must be resistant to the action of soil bacteria.
11. *Resistance to marine organisms.* In the case of submarine lines, the coating should not be easily penetrated by marine life, e.g. mussels, borers, barnacles, etc.

These characteristics cover the general ideal for a pipeline coating, but obviously modified conditions may impose requirements which are more, or less stringent; this of course also applies to other types of buried structures.

Preparation of Metal Surface

Before applying a protective coating it is essential to ensure that the surface is free from rust, millscale, moisture, loose dust, or any other incompatible material which might prevent the electrically non-conducting coating from bonding properly with the metal surface or which might produce defects in the continuous film.

The following cleaning methods are available and each may have a particular advantage in given circumstances:

- (a) *Mechanical cleaning.* Hand or mechanical wire brushing, impacting or abrading are methods suitable for hot applied coatings, for repairs to damaged areas or for relatively small or inaccessible areas. Visual standards to assess the degree of cleanliness are available but are not commonly used.
- (b) *Blast cleaning.* Air-blast or centrifugally-impacted sand, shot or grit are appropriate for thin-film multicoat systems or for continuous factory production. Several visual standards are available. The cost of attaining a very high standard of cleanliness is considerable, and careful consideration should always be given to specifying the correct level of blasting for the particular application.
- (c) *Pickling.* Dipping in inhibited hydrochloric or sulphuric acid is commonly used in factory production, particularly in conjunction with hot phosphoric acid dipping (Footner process). The considerable facilities necessary for this method limit its use to the larger steel producers. Published standards are available for the phosphate surface conversion coating process.
- (d) *Flame cleaning.* This is appropriate only for field repair work where a dry or warm surface can be obtained only by flame application and must be preceded usually by mechanical cleaning.
- (e) *Pipeline travelling machine.* For long runs on continuously-welded pipelines, a machine with rotary wire brushes and/or impact tools and cutting knives may be used to prepare the surface. These machines,

which are self-propelled along the pipe itself, are commonly combined with drip or spray apparatus to apply the primer which is spread over the surface by rugs or brushes so that the prepared surface is immediately primed.

No matter which method of cleaning is adopted, it is desirable to apply the primer or coating immediately after the cleaning operation.

The preparation of the metal surface to receive the protective coating is of prime importance since a coating which is not bonded to the metal surface can allow electrolytes to contact the metal, with resultant corrosion. If water films develop between the metal and the electrically non-conductive coating, cathodic protection becomes ineffective.

Coating Techniques

Dipping, Spraying and Brushing

These methods are generally appropriate for either thin-film solvent-based paints or for coatings up to about 150 μm thickness. The techniques are more usually used for the priming layer of the coating systems.

Factory or Yard Application

Protective coatings applied at a factory have the advantage that the work can be carried out under strictly controlled conditions but suffer from the disadvantage that they may be damaged during transport to the site.

Pipes are frequently shot-blasted or descaled by acid pickling, then phosphated, either sprayed with primer or dipped into a bath of hot asphalt to provide a thin prime coat. The dry primed pipes are then slowly rotated by a lathe head, while hot enamel, mastic or asphalt/micro-asbestos paste is applied from a hopper travelling alongside the pipe. A pipe coating approximately 5 mm thick is produced by use of a heated pallet attached to the hopper feed. Reinforced-glass wrapping materials may also be spirally wound on to the coating according to requirements.

'Rolling Rig', 'Fixed-head' and 'Rotating-head' Coating Machines

The coating equipment under this heading may be used in permanent factories, but is often set up at temporary coating yards close to the location where the pipes are to be laid. The coating produced is usually 2–3 mm per pass.

Rolling rig machines The rolling rig machine rotates the cleaned and primed pipe on mechanically driven 'dollies', while a tank travelling alongside the pipe floods it with hot asphalt or coal-tar-base enamel.

At the same time internal and external reinforcing wraps may be spirally wound into or on to the hot enamel.

Fixed-head machines Fixed-head machines are fed with the cleaned and primed pipe, which mechanically rotates as it passes through the fixed coating head which floods the hot enamel on to the pipe. At the same time reinforcing wraps are pulled on to the rotating pipe.

Rotating-head machines In rotating-head machines the coating head and wrapping spindles rotate as the pipe is fed through the machine.

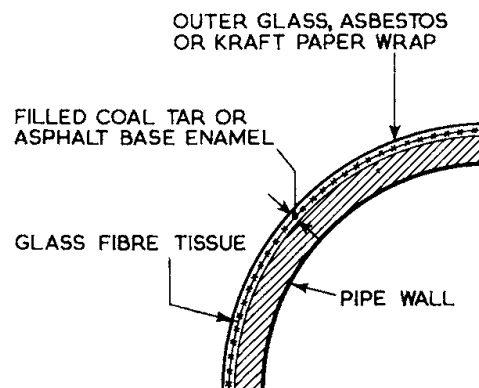
Pipeline Travelling Machines

In the case of long continuously-welded steel pipelines the above pipe-coating methods present the disadvantage that the joints have to be coated in the field after welding. To overcome this difficulty equipment which travels along the welded pipeline has been developed.

A mechanically propelled cleaning machine travels along welded lengths of the pipeline. The machine has counter-rotating cutting knives or brushes, and also applies by rotating swabs, a thin coating (cold application) of primer to the clean metal surface. When the primer is dry, a coating and wrapping machine travels along the pipeline.

The wrapping materials usually consist of staple glass tissue, pulled half-way into the hot enamel, and an outer wrap of glass impregnated with coal-tar or asphalt enamel to produce a coating of approximately 2.5 mm as shown in Fig. 15.7.

Fig. 15.7 Type of coating produced by mechanical flood coat and wrap machine



These machines can coat and wrap up to 5 km of pipeline per day. After the coating has been checked for pin holes by a high-voltage rolling-spring electrode, the pipe may be lowered directly into the trench, so that undue handling is avoided. The line travelling machine is usually used with coal tar or asphalt-base pipeline enamels. Similar line travelling machines are in use for the cold application of tape coatings.

Types of Coating Materials

Plasticised Coal Tar and Petroleum Asphalt Enamels

The majority of pipelines today are coated with hot-applied plasticised coal tar or petroleum asphalt enamels. Both coal-tar pitch and petroleum asphalt have been used as protectives with and without filling materials. When filled

they are termed *enamels* or *mastics*. The term *bitumen* or *bituminous* has always been loosely applied and it is preferable to specify petroleum asphalt base or coal-tar pitch base.

Straight and filled enamels Fillers are normally added up to a maximum of about 30% weight (calculated on the mixture) which is equivalent to about 15 to 20% by volume. A filled coal-tar pitch has a higher softening temperature (as shown by the 'ring and ball' test) than the unfilled material, which results in a reduced tendency to flow. This fact is important in tropical countries or if a pipe is to operate at a somewhat elevated temperature. Resistance to impact and abrasion of a coating is improved by the filler. The viscosity of the pipe coating is also increased; this entails a higher application temperature (193–249°C).

A satisfactory filler must have the following characteristics:

1. Low water absorption. In this respect certain fine clays are unsuitable.
2. Ability to be readily wetted by the enamel.
3. Finely-ground composition, particles preferably of laminar shape to prevent settling when the enamel is molten.
4. Relatively low specific gravity, so that there is the minimum tendency for the filler to settle-out in the melting kettle.

In present-day practice the materials which are commonly used and which satisfy most closely these requirements are talc, pumice powder, micro-asbestos and slate powders.

It must be appreciated that there is an optimum percentage of filler which imparts to a coating the required melting point and toughness; beyond this point application becomes more difficult and watertightness may be impaired.

Petroleum asphalt or coal-tar pitch as coatings The question of whether coal-tar pitch or petroleum asphalt is the more suitable for the coating of underground pipelines has raised a good deal of controversy. Asphalt and pitch are both waterproof materials, and they resemble one another in physical type. In the right circumstances both can be very effective in preventing the access of water to buried or submerged steel surfaces.

Petroleum asphalts are manufactured in two general types: (a) a straight residue from distillation, which can be of the hard, high-melting type, and (b) so-called 'blown' grades which are prepared by partially oxidising the asphalt base by blowing in air. The general difference between the two grades is that 'blown' asphalt has a higher softening point than straight asphalt of the same penetration (i.e. hardness). In assessing a pipeline coating the softening point is of considerable importance, since it determines the tendency to flow, and a certain minimum softening point is therefore necessary. A 'blown' asphalt has the advantage over straight material of the same softening point in that it has a better resistance to impact, since it is of a more rubbery nature. For this reason most petroleum asphalt coatings are based on the 'blown' variety.

So far as coal tar is concerned, it was formerly the custom to use the straight residual pitch, but nowadays shock resistance is improved by a so-called plasticising process.

The differences between asphalt and coal tar in relation to their application as pipeline coatings require comment.

1. It is often claimed that a coal-tar-base coating absorbs less water than an asphalt coating and there is evidence in practice to support this claim, but some asphalt enamels in practice have been as good as the best coal-tar enamels.
2. Coal-tar enamels are claimed to have better adherence than the asphaltic enamels to clean metal, probably because of the presence of polar compounds, but little difference can be noted in practice under proper pipelining conditions.
3. The asphaltic enamels are easier to apply since they do not produce so much obnoxious fume and are usually applied at slightly lower temperatures.

The field performance of the asphalt-base pipeline enamels was, at one time, erratic, probably because the material had been drawn from varying sources, without a close specification being used. The plasticised coal-tar-base enamel to the American Water Works Association Specification C-203 thus gained some favour in major pipelining organisations.

The AWWA C-203 Standard remains a widely used specification suitable not only for the materials, but also for their associated reinforcing wraps and application procedures. The standard has been regularly updated. Hot-applied asphaltic and coal-tar coatings with their priming systems are now well classified, described and specified in BS 4164:1967 (coal tar) and BS 4147:1967 (asphalt), but no guidance is given in these specifications to application procedures.

Reinforcing materials

Internal At one time open-weave hessian cloth was very largely used as an internal reinforcement material, but experience showed that this is subject to rotting in the soil. Even when the material appears to be covered with enamel, some of the fibres must protrude, and thus moisture is absorbed so that after a period of years the hessian is generally found to be in a water-logged condition and forming food for bacteria.

The type of material to be used depends very largely on whether coating is carried out mechanically or by hand. For hand application it is not possible to use comparatively fragile staple tissues made of glass or asbestos and it is necessary to use a strong open-mesh fabric, such as woven asbestos or woven glass. The woven wraps are a great deal more expensive than the staple tissues, which are mechanically applied.

It is not economical to use expensive woven material for long lines, which can be, and normally are, coated by mechanical means. For such lines the most commonly used material nowadays is a glass-fibre tissue of a nominal 0.5 mm thickness, consisting of glass fibres bonded together with a phenolic resin or starch.

The improvement in coating quality achieved by using the internal glass wrap is illustrated by the following results. The tensile strength of a 3.2 mm thickness of 104°C softening-point enamel, 300 mm × 300 mm is virtually nil. A piece of 300 mm × 300 mm glass tissue 0.5 mm in thickness will break at about 50 kg under steadily increasing tensile load, but if it is embedded in

3.2 mm of the enamel a tensile strength of the order of 150 kg is obtainable. These wraps are now longitudinally reinforced to prevent tearing on line-travelling or other coating machines.

Where the pipeline is expected to have to withstand unusual dimensional variation due, perhaps, to temperature changes or near yield point pressure testing, the use of a woven glass or nylon reinforcement in place of the glass tissue is said to increase the flexibility of the coating system considerably.

External wrap The purpose of an external overlapping wrap is to provide a shield against the penetration of the enamel by stones and to prevent the pulling of the enamel away from the pipe by soil stress. It also reduces flow of the enamel owing to the weight of the pipe, and damage to the coating caused by handling can be more easily observed.

The properties required of an external wrap are as follows:

- (a) Compatibility of impregnant to bond with the enamel used.
- (b) Tensile strength to prevent breaking while wrapping.
- (c) Hardness to resist penetration.
- (d) Flexibility to allow wrapping without cracking.
- (e) Free rolling from the reel while wrapping.
- (f) Resistance to soil conditions and bacterial attack.
- (g) Non-absorption or low absorption of water.

These properties apply to a reinforcing outer wrap such as coal tar or asphalt-impregnated glass or asbestos bonded lightly to the outside of the hot-applied enamel. For some conditions kraft paper is adequate to facilitate handling and reduce soil stress. Were it not for its screening effect on cathodic protection with a consequent decrease in the effectiveness of the latter, the external wrap could be loose around the coating. It has become conventional to have the external wrapping lightly bonded to the coating to prevent lamination and water entry.

Armour wrapping In rocky ground it has always been considered good practice to pad the trench for a buried pipeline with clean sand. This procedure can be very expensive if the sand has to be hauled long distances, and an armour wrap has been developed to supplement the normal outer wrap to meet such conditions.

A typical wrap is supplied in sheets about 6 mm thick, consisting of a sandwich of mastic enamel between sheets of asbestos about 1.5 mm thick. It may be longitudinally indented to allow the material to be wrapped around the pipe and secured by steel ribbon straps.

An objection to this form of wrap is that its mode of application renders it extremely difficult to obtain a good uniform bond between the wrap and the enamel. In view of this, water could become trapped under the armour wrap, and because of the non-conducting nature of the wrap itself the effective application of cathodic protection would be difficult.

Cold-applied Tapes

Hot-applied coatings require special melting and handling equipment to be available at the construction site. Clearly, considerable economies are possible if this equipment can be dispensed with, particularly in remote areas

with difficult access. Thus, the availability of cold-applied tapes for use either at the joints between factory-coated pipes or continuously over the pipeline has led to the increased usage of this type of wrapping.

The tapes are usually relatively thin (0.5 mm) and easily damaged. It is, therefore, essential to take elaborate precautions to provide physical protection to the tape once it has been applied both during construction and after burial. Good results have been obtained when the tape is applied by line travelling machine and without further handling, immediately lowered into a sand padded trench and covered over with fine sand before the trench is back filled.

Initial effective electrical resistance of tapes, as evidenced by the cathodic protection current demand, has been outstanding. There have been reports of increasing current demand with time which indicate a need for investigation. The current demand increase has been found, on occasion, to be due to poor construction practice, but not all tapes are affected in this way.

On large diameter pipes having a raised seam weld, difficulty is encountered in covering the weld 'shadow' effectively.

Petrolatum-type tapes Petrolatum has, like lanolin, long been recognised as a means of preventing corrosion. It is easily cold-applied and has a definite place in corrosion engineering, but it is not suitable for buried structures, unless it is screened from soil and water by a woven glass or nylon cloth or an impervious membrane such as p.v.c. The polythenes normally tend to swell in contact with it. Earlier petrolatum coatings were frequently applied with cellulosic backing material; there were several objections to this type of protection, e.g. attack by sulphate-reducing bacteria on the cellulose, absorption of the grease by dry bentonite-type clays, lack of physical strength against stones, and water absorption.

Petrolatum-type tape coatings now incorporate inhibitors against bacteria and with their backing film have high electrical and water resistance and therefore find extensive applications in the UK. A great advantage of the petrolatum-type coatings is ease of application and conformability to irregular surfaces.

Pressure-sensitive tapes Unlike the more recently developed petrolatum tapes which rely on both the petroleum and backing films, the pressure-sensitive tapes offer protection which depends almost entirely upon the prevention of ingress of moisture to the metal surface by the tape itself.

The tapes are cold-applied, either by hand or by mechanically-operated equipment moving along the cleaned pipeline.

The tapes are usually produced from polythene or polyvinylchloride films of 25 μ m to 0.5 mm in thickness and the inner surface is coated with an adhesive, frequently rubber-based. The adhesive is usually between 25 and 100 μ m thick.

Earlier tapes frequently suffered from the migration of plasticiser from the tape to the adhesive with the result that the tape became detached from the metal, to which the adhesive remained attached. This has now been overcome by using a barrier between the tape and adhesive which itself may contain inhibitors against soil bacteria.

Spiral corrosion due to inadequate overlap has been detected with self-adhesive tapes, and a 25 mm (or preferably half-tape-width) overlap is to be advocated. Within normal limits, the thicker the adhesive the better.

The self-adhesive tape coatings are thin and the adhesive itself does not necessarily come into contact with the valleys in the cleaned metal surface. Under these circumstances, the transmission of water vapour through the film to the metal may be possible. Moisture-transmission characteristics and other properties of p.v.c. and polyethylene tapes, as given by major manufacturers, are provided in Table 15.6.

Table 15.6 P.V.C. and polyethylene tapes

<i>Material</i>	<i>Physical property</i>					
	<i>Thickness of film plus adhesive (mm)</i>	<i>Tensile strength (kg/cm width)</i>	<i>Elongation at break (%)</i>	<i>Moisture absorption (%)</i>	<i>Moisture-vapour transmission rate (g/m² per 24 h)</i>	<i>Dielectric strength (V)</i>
P.V.C.	0.229 + 0.025	10	175	0.19	24.0	10 000
Polyethylene	0.203 + 0.100	10	70	0.02	3.1	14 000

Table 15.6 is only indicative of general properties, and the latest developments of specific manufacturers of self-adhesive tapes may show advances on these.

P.V.C. tends to be more conformable to irregularities than polyethylene. Both types have their right and proper application for buried structures.

Laminated tapes In more general use now than pressure sensitive tapes are tapes consisting of polyvinyl chloride or polyethylene films in conjunction with butyl rubber. These tapes are applied with an adhesive butyl rubber primer. Thicknesses of up to 0.75 mm are in use and loose protective outer wraps of p.v.c. or polyethylene sheet are commonly applied. Tape quality control is exercised with reference to ASTM standard test methods and may include water vapour transmission rate and elongation.

Conventional holiday-detection is of little value in the field but great attention should be given to preventing damage to the applied tapes.

Coal-tar Epoxy Coatings

The epoxy resins when mixed with the correct amine produce tough films which adhere closely to metal. The chemistry of these resins is considered in Sections 15.5 and 15.9.

The thickness and water resistance of the normal air-cured film can now be much improved by the incorporation of suitable coal-tar pitch material. A typical coal tar/epoxy coating material would be constituted as follows:

Epoxy resin	30
Coal-tar pitch	25
Filler	25
Solvent	20

and to the above would be added the amine curing mix.

The coating is of the two-pack type, consisting of resin plus curing hardener. In practice the resin and amine may be mixed together and used for application by brush or spray, or by mechanical means at ambient temperature. Sometimes the clean metal is heated, as are the coating components, which are then sprayed separately on to the metal to reduce curing time. Little reaction occurs below 4°C. For pipeline coating the pipes can usually only be handled after a few hours, depending on the mix and temperature, but it takes anything from two to seven days before the best characteristics of the coating develop.

Information to date indicates that the total thickness of the coating should not be less than 0.3 mm and this requires several applications. These coatings are very tough and closely adherent (one pipeline company states that they handle coal tar/epoxy-coated pipe like bare pipe, including bending in the field). The first coal tar/epoxy coatings came into use only in 1953, and although they seemed most promising they have been little used to date compared to other materials. This is undoubtedly due to their relatively slow setting and curing time.

Polyethylene Sheet

The practice has been developed amongst some water undertakings to envelop uncoated spun iron pipes in 0.5 mm thick polyethylene sheet, the ends of which are tied down to the pipe with a substantial overlap by means of adhesive tape. This method has great advantages in cost and simplicity. No long term performance figures have been published but many have grave doubts about the effectiveness of this method since the possibility of aggressive soil water entering at perforations or through overlaps, appears to be very high.

Foam Polyurethane

These materials have been finding extensive use on transmission pipelines supplying heated heavy fuel oils to power stations. To prevent damage to the 50 mm thick coating, a mechanically stronger outer wrap which can also prevent water ingress is usually necessary. In one method of production, the foam is manufactured inside a polythene tube over the steel tube. In other methods where the foam is produced by spraying on to the steel surface, conventional tape or enamel coatings have been used.

Weight Coatings

For pipelines to be placed under water, it is necessary to provide negative buoyancy. This is commonly achieved by placing lightly reinforced concrete up to 150 mm thick over the 3–5 mm hot enamel coating on the steel. Joints at the welded tube ends have to be coated with a minimum of delay due to the high production rate required on the laying barge, and tapes have therefore found application at this point. Where submarine pipelines are ‘pulled’

into position off the land, joint repair is more commonly carried out by means of the same hot enamel used as the pipeline coating. For the final joint between towed 'strings' of up to 300 m, fast setting epoxies have been used.

A composite asphaltic mastic filled with high-density aggregate is now available as a combined insulation and weight coating, and this could be the development area in this field.

Internal Pipeline Coatings

In some instances it is necessary to coat pipelines internally, and materials widely used are red lead, hot-applied enamels, concrete and epoxy resins.

Internal coatings are usually applied at the factory and no difficulty exists in field construction if flanges, screwed, or spigot and socket joints are used, nor is there any difficulty with welded pipes above, say, 750 mm diameter, where patching can be carried out on the joints from the inside. Repair of internal coating on smaller-bore welded pipes presents many problems, which have not yet been satisfactorily overcome for all conditions.

Pipelines in the ground can be mortar lined *in situ* by the use of travelling devices. Epoxy resin paints for long welded pipelines already laid have been applied *in situ* by placing two plugs in the pipeline with the paint between them, and then forcing them to travel through the pipeline by the use of compressed air.

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22.1 Glossary of Terms*

Activation Overpotential: that part of an overpotential (polarisation) that exists across the electrical double layer at an electrode/solution interface and thus directly influences the rate of the electrode process by altering its activation energy.

Active: freely corroding; the antithesis of passive.

Active-passive Metal (alloy): a metal that exhibits a transition from the active (freely corroding) state to the passive state when its potential is raised above the passivation potential (or a transition from the passive to the active state when its potential falls below the Flade potential).

Activity (thermodynamic): the thermodynamic activity of an entity, i , is $a_i = \exp(\Delta G/RT)$ where ΔG is the free energy increase of 1 mol of i when it is converted from a standard state (defined as when $a_i = 1$) to any other activity $a_i = x$.

Addition Agent: a substance added to an electroplating solution to produce a desired change in the physical properties of the electrodeposit.

Adhesion: the attractive force that exists between an electrodeposit and the substrate.

Alclad: a composite in which a thin layer of aluminium, or an aluminium alloy of good corrosion resistance, is bonded metallurgically to a high-strength aluminium alloy (of lower corrosion resistance) to provide a combination of these two properties.

Anion: a negatively charged ion; it migrates to the anode of a galvanic or voltaic cell.

Anode: the electrode of a galvanic or voltaic cell where the positive electrical current flows from the electrode to the solution (for example, transfer of cations from electrode to solution or anions from solution to electrode).

Anode Corrosion Efficiency: the ratio of the actual corrosion rate of the anode to the theoretical rate according to Faraday's law, expressed as a percentage.

Anode Polarisation: difference between the potential of an anode passing current and the equilibrium (or steady-state) potential of the electrode having the same electrode reaction.

Anodic Protection: reduction of the corrosion rate by making the potential

*Terms used in chemical thermodynamics have not been included and reference should be made to Appendix 1.9B. For paint terms, see Section 15.10.

of the metal sufficiently more electropositive by an external source of e.m.f., so that the metal becomes passive.

Anaerobic: air or uncombined oxygen being absent.

Anaerobic Bacteria (anaerobes): group of bacteria that are unable to multiply in any but a minute trace of oxygen.

Angstrom Unit (Å): $1 \text{ Å} = 10^{-8} \text{ cm} = 10^{-4} \mu\text{m} = 10^{-1} \text{ nm}$ (preferred unit).

Anodising: the formation of oxide films on metals by anodic oxidation of the metal in an electrolyte solution. The term can be used for thin dielectric films but is more particularly applied to thick porous films formed on aluminium.

Anolyte: the electrolyte solution adjacent to the anode.

Anti-pitting Agent: an addition agent (*q.v.*) which is used to prevent the formation of pits or large pores in an electrodeposit.

Austenite: the γ -modification of iron, having an f.c.c. lattice, which is stable above about 700°C ; the term is also applicable to solid solutions of carbon, chromium, nickel, etc. in γ -iron.

Bainite: a structure produced in carbon and alloy steels by rapid cooling to a temperature above that at which martensite is formed, followed by slower cooling.

Base Potential: *see under Potential.*

Bimetallic Corrosion: corrosion of two metals in electrical contact, in which one metal stimulates attack on the other and may itself corrode more slowly than when it is not in such contact; *galvanic* is often used in place of *bimetallic*.

Breakaway Corrosion: a sudden increase in corrosion rate, especially in high-temperature 'dry' oxidation, etc.

Breakdown Potential: *see Critical Pitting Potential.*

Bright Plating: electroplating under conditions whereby the electrodeposit has a high degree of specular reflectivity.

Brightener: an addition agent used specifically to produce an electrodeposit of high specular reflectivity.

Brush Plating: a method of electrodeposition in which the plating solution is applied to the article to be plated by means of an absorbent pad or brush which contains the anode.

Buffer: a substance, or mixture of substances, which when present in an electrolyte solution tends to diminish fluctuations in pH.

Burnt Deposit: a rough, poorly coherent, electrodeposit that results from the application of an excessively high current density.

Calcareous Scale: a scale consisting largely of calcium carbonate and magnesium hydroxide which may be precipitated from a hard water.

Cathode: the electrode of a galvanic or voltaic cell where positive current flows from the solution to the electrode (for example, by transfer of cations from solution to electrode).

Cathodic Protection*: reduction of the corrosion rate by making the potential of the metal to be protected more negative, so that the current at any anode is reduced while that at any cathode is increased.

Cathodic Reactant: species which is reduced at a cathode.

Catholyte: the electrolyte solution adjacent to the cathode.

*See also list of underground-corrosion and cathodic-protection terms, p. 22.13.

- Cation:** a positively charged ion; it migrates to the cathode in a galvanic or voltaic cell.
- Caustic Embrittlement:** stress-corrosion cracking of carbon steels caused by the presence of caustic alkali.
- Cavitation Damage:** erosion of a solid surface caused by the collapse of vacuum bubbles formed in a fluid.
- Cementite:** the iron-carbon compound of formula very close to Fe_3C .
- Chemical Conversion Coating:** a protective or decorative coating which is produced deliberately on a metal surface by a chemical environment.
- Chemical Polishing:** improvement in the brightness and levelness of a surface finish of a metal by a chemical dissolution reaction.
- Composite Plate:** an electrodeposit consisting of two or more layers of metals deposited separately.
- Concentration Cell:** a galvanic cell in which the e.m.f. is due to differences in the concentration of one or more electrochemically reactive constituents of the electrolyte solution.
- Concentration (diffusion or transport) Overpotential:** change of potential of an electrode caused by concentration changes near the electrode/solution interface produced by an electrode reaction.
- Corrosion:** the transformation of a metal from the elementary to the combined state by reaction with a non-metal (or liquid metal).
For the purpose of the present work—the transformation of a metal, *used as a material of construction*, from the elementary to the combined state. (See also **Bimetallic Corrosion**, **Breakaway Corrosion**, **Filiform Corrosion**, **Fretting Corrosion**, **Galvanic Corrosion**, **Graphitic Corrosion**, **Intergranular Corrosion**, **Localised Attack**, **Pitting**, **Stress-corrosion Cracking**, **Uniform Corrosion**.)
- Corrosion Control:** control of the corrosion rate and form of attack of a metal of a given metal/environment system at an acceptable level and at an economic cost.
- Corrosion-Erosion (or erosion-corrosion):** conjoint action of corrosion and erosion resulting from the abrasive action of a fluid (solution or gas) moving at a high velocity, resulting in continuous removal of the protective film from the metal surface.
- Corrosion Fatigue:** failure by cracking caused by reversing alternating stress in the presence of a corrosive environment.
- Corrosion Potential (mixed potential, compromise potential):** potential resulting from the mutual polarisation of the interfacial potentials of the partial anodic and cathodic reactions that constitute the overall corrosion reaction.
- Corrosion Product:** metal reaction product resulting from a corrosion reaction; although the term is normally applied to solid compounds it is equally applicable to gases and ions resulting from a corrosion reaction.
- Corrosion Rate:** the rate at which a corrosion reaction proceeds; it may be expressed as a rate of penetration mm y^{-1} (in y^{-1} or i.p.y. are still widely used) or as a weight loss per unit area per unit time, i.e. $\text{gm}^{-2} \text{d}^{-1}$ $\text{mg dm}^{-2} \text{d}^{-1}$ or m.d.d. are still widely used).
- Couple (bimetallic, galvanic):** two dissimilar metals in electrical contact.
- Covering Power:** the ability of a plating solution to produce an electrodeposit (irrespective of thickness) at low current densities on all significant areas.

- Crevice Corrosion:** localised corrosion resulting from a crevice formed between two surfaces—one at least of which is a metal.
- Critical Anode Current Density:** anodic current density that must be exceeded in order to produce an active to passive transition (for a given metal it varies with the nature of the solution, temperature, velocity, etc.).
- Critical Humidity:** the relative humidity (r.h.) at and above which the atmospheric corrosion rate of a metal increases markedly.
- Critical Pitting Potential:** the most negative potential required to initiate pits in the surface of a metal held within the passive region of potentials (it varies with the nature of solution, temperature, time, etc.).
- Current (I):** the rate of transfer of electric charge; unit current is the ampere (A) which is the transfer of 1 coulomb/second (1 C/s).
- Current Density (i):** the current per unit area (geometric) of surface of an electrode (units: $A\ m^{-2}$, $mA\ m^{-2}$, $A\ cm^{-2}$, etc.).
- Current Efficiency:** the ratio of the rate of the actual electrochemical change at the electrode (anode or cathode) to the theoretical rate according to Faraday's law, expressed as a percentage. (*The particular electrode and electrode reaction must be specified.*)
- Deactivation:** prior removal of the constituent (of a liquid) that is active in causing corrosion. The term is usually applied to the removal of oxygen by physical and/or chemical methods.
- Dealloying:** selective removal by corrosion of a constituent of an alloy.
- Delayed Failure:** *see under Sustained Load Failure.*
- Depolarisation:** reduction or elimination (by physical or chemical methods) of the electrode polarisation needed to produce a specified current.
- Deposit Attack:** localised corrosion (a form of crevice corrosion) under and resulting from a deposit on a metal surface.
- Dezincification:** preferential corrosion of zinc from brass resulting in mechanically weak copper-rich areas in the form of plugs or layers; sometimes both zinc and copper corrode, but copper is redeposited.
- Differential Aeration:** the stimulation of corrosion at a localised area by differences in oxygen concentration in the electrolyte solution in contact with the metal surface; the area in contact with the solution of lower oxygen concentration is the anode.
- Diffusion Coating:** a coating produced by diffusion at elevated temperatures.
- Diffusion Layer:** the thin layer of solution adjacent to an electrode through which transport of species to or from the electrode surface occurs by diffusion rather than by convection.
- Electrochemical Cell:** a cell in which chemical energy is transferred into electrical energy.
- Electrolytic Cell:** a cell in which electrical energy is used to bring about electrode reactions and is thus converted into chemical energy. (Note: the term 'electrochemical cell' is frequently used to describe both types of cells.)
- Electrochemical Equivalent:** theoretical number of moles of electrochemical change resulting from the passage of 1 Faraday (1 F) of electrical charge; if M is the molar mass (kg) and z the number of electrons required for one act of the reaction then the electrochemical equivalent is M/z kg.
- Electrode:** an electron conductor by means of which electrons are provided for, or removed from, an electrode reaction.

Electrode Potential (E): the difference in electrical potential between an electrode and the electrolyte with which it is in contact. It is best given with reference to the standard hydrogen electrode (S.H.E.), when it is equal in magnitude to the e.m.f. of a cell consisting of the electrode and the S.H.E. (with any liquid-junction potential eliminated). When in such a cell the electrode is the cathode, its electrode potential is positive; when the electrode is the anode, its electrode potential is negative. When the species undergoing the reaction are in their standard states, $E = E^\ominus$, the *standard electrode potential*.

Electrogalvanising: galvanising by electroplating.

Electroless Plating: formation of a metallic coating by chemical reduction catalysed by the metal deposited.

Electrolysis: decomposition by the passage of electric current.

Electrolyte: a substance which in solution gives rise to ions; the term is also used for a solution of an electrolyte or for a molten ionic salt.

Electrolyte Solution: a solution in which the conduction of electric current occurs by the passage of dissolved ions.

Electrolytic Cleaning: cleaning obtained at cathode or anode of a cell containing a suitable solution.

Electron Acceptor: a species in solution that accepts one or more electrons from a cathode for each act of the cathodic reaction and is thus reduced to a lower valence state.

Electrophoretic Plating: production of a layer or deposit by discharge of colloidal particles in a solution on an electrode.

Electroplating: electrodeposition of a thin adherent layer of a metal or alloy on a substrate of desirable chemical, physical and mechanical properties.

Electropolishing: surface finishing of a metal by making it the anode in an appropriate solution, whereby a bright and level surface showing specular reflectivity is obtained.

e.m.f. Series: a table of the standard equilibrium electrode potentials of systems of the type $M^{z+}(\text{aq.}) + ze = M$, relative to the standard hydrogen electrode, and arranged in order of sign and magnitude.

Epitaxy: the phenomenon whereby a deposit or coating takes up the lattice habit and orientation of the substrate.

Equilibrium Potential: the electrode potential of an unpolarised reversible electrode.

Evans Diagram: diagram in which the E vs. I relationships for the cathodic and anodic reactions of a corrosion reaction are drawn as straight lines intersecting at the corrosion potential, thus indicating the corrosion current associated with the reaction.

Exchange Current Density (i_0): the rate of exchange of electrons (expressed as an electric current per unit area) between the two species concerned in a reversible electrode process at the equilibrium potential.

Exfoliation: loss of material in the form of layers or leaves from a solid metal or alloy.

Faraday: quantity of electric charge required to bring about a change of one electrochemical equivalent ($1 \text{ F} \approx 96\,500 \text{ C}$).

Fatigue: failure of metal under conditions of repeated alternating stress.

Ferrite: the body-centred cubic form of iron (α -iron) and the solid solutions of one or more elements in b.c.c. iron.

Filiform Corrosion: corrosion in the form of hairs or filaments progressing across a metal surface.

Film: a thin coating of material, not necessarily thick enough to be visible.

Flade Potential: the potential at which a metal which is passive becomes active (*see* **Passivation Potential**).

Fogging: reduction of the lustre of a metal by a film or particulate layer of corrosion product, e.g. the dulling of bright nickel surfaces.

Fouling: deposition of flora and fauna on metals exposed to natural waters, e.g. sea-water.

Fretting Corrosion: deterioration resulting from repetitive rubbing at the interface between two surfaces (fretting) in a corrosive environment.

Galvanic Cell: an electrochemical cell having two electronic conductors (commonly dissimilar metals) as electrodes.

Galvanic Corrosion: corrosion associated with a galvanic cell (often used to refer specifically to **Bimetallic Corrosion**).

Galvanostatic Polarisation (intentiostatic): polarisation of an electrode during which the current density is maintained at a predetermined constant value.

Galvanic Series: a list of metals and alloys based on their relative potentials in a given specified environment, usually sea water.

Galvanising (hot dip): coating of iron and steel with zinc using a bath of molten zinc.

Graphitic Corrosion: corrosion of grey cast iron in which the metallic constituents are removed as corrosion products, leaving the graphite.

Green Rot: carburisation and oxidation of certain nickel alloys at around 1000°C resulting in a green corrosion product.

Half-cell: one of the electrodes, and its immediate environment, in an electrochemical or electrolytic cell; particularly, an electrode and environment arranged for the passage of current to another electrode or (especially) for the measurement of its electrode potential.

Hematite: an oxide of iron corresponding closely to Fe_2O_3 produced during the oxidation of iron: it is an n -type semiconductor in which diffusion of O^{2-} ions occurs via anion vacancies.

Hydrogen Electrode: an electrode at which the equilibrium $\text{H}^+(\text{aq.}) + e \rightarrow \frac{1}{2}\text{H}_2$ is established. By definition, at unit activity of hydrogen ions and unit fugacity of hydrogen gas the potential of the standard hydrogen electrode $E_{\text{H}^+/\frac{1}{2}\text{H}_2}^\ominus = 0.00 \text{ V}$.

Hydrogen Embrittlement: embrittlement caused by the entry of hydrogen into a metal.

Hydrogen Overpotential (Overvoltage): the displacement of the equilibrium (or steady-state) electrode potential of a cathode required for the discharge of hydrogen ions at a given rate per unit area of electrode.

Immunity (thermodynamic): a condition whereby the equilibrium activity of metal ions (simple or complexed) in solution is prevented from exceeding some arbitrary value by making the potential of the metal sufficiently negative to that of the solution. Pourbaix has defined this arbitrary activity at 10^{-6} g ion/l .

Impingement Attack: localised corrosion resulting from the action of corrosion and/or erosion (separately or conjoint) when liquids impinge on a surface.

Inhibitor: a substance added to an environment in small concentrations to

reduce the corrosion rate.

Inseparable Anodes and Cathodes: anodes and cathodes which cannot be distinguished experimentally although their existence is postulated by theory.

Interference Films: thin transparent films which exhibit interference colours.

Intergranular Corrosion: preferential corrosion at grain boundaries.

Internal Oxidation (subsurface corrosion, subscale formation): formation of isolated particles of corrosion product (or products) beneath the metal surface, which may be coated with a uniform film of corrosion product.

Ion: an electrically charged atom or complex of atoms.

Isocorrosion Chart: a chart having temperature and concentration of the corrodent as co-ordinates and curves (isocorrosion curves) of various specified constant corrosion rates of the metal.

Knife-line Attack: severe highly localised attack (resembling a sharp cut into the metal) extending only a few grains away from the fusion line of a weld in a stabilised austenitic stainless steel, which occurs when the metal comes into contact with hot nitric acid and is due to the precipitation of chromium carbides.

Leveller: a substance which is added to a plating bath to produce a levelling or smoothing action.

Levelling Action: the ability of a plating bath to produce a surface which is smoother than that of the substrate.

Limiting Current Density: the current density at which change of polarisation produces little or no change of current density.

Linear Polarisation: the linear relationship between overpotential and current density that is considered to prevail at potentials very close to the corrosion potential.

Local Anodes and Cathodes: *see Inseparable Anodes and Cathodes.*

Localised Attack: corrosion in which one area (or areas) of the metal surface is predominantly anodic and another area (or areas) is predominantly cathodic, i.e. anodes and cathodes are *physically separable*.

Matt Surface: a surface of low specular reflectivity.

Metal Distribution Ratio: the ratio of the thicknesses of metal produced during electroplating on two specified parts of the cathode.

Metal Spraying: application of a metal coating to a surface (metallic or non-metallic) by means of a spray of metal particles. The metal particles may be produced by 'atomising' a metal wire in a flame-gun or by introducing metal powder into a similar gun.

Migration of Ions: movement of ions towards the anode and cathode under the influence of an electrical potential gradient.

Mil: one thousandth of an inch (1 mil = 0.001 in = 25.4 μm).

Millscale: thick oxide layer on metals produced during fabrication by hot-rolling; most of the oxidation occurs as the metal passes from one rolling-mill to the next.

Negative Potential: *see under Potential.*

Nernst Equation: the thermodynamic relationship between the reversible potential of a reaction (or half-reaction) and the activities of the species involved in the reaction.

Noble Potential: *see under Potential.*

Normal Electrode Potential: *see under Electrode Potential.*

Occluded Cell: a corrosion cell of a geometry that prevents intermingling of the anodic reaction products (anolyte) with the bulk solution, resulting in a decrease in pH of the anolyte; shielded areas or pits, crevices or cracks in the surface of the metal are examples.

Open-circuit Potential: the potential of an electrode from which no significant current is flowing, as on open circuit.

Overpotential (overvoltage, polarisation): the displacement of the equilibrium (or steady-state) electrode potential required to cause a reaction to proceed at a given rate.

Oxidation: loss of electrons by a species during a chemical or electrochemical reaction; addition of oxygen or removal of hydrogen from a substance.

Oxidising Agent: a substance that causes oxidation of another species.

Oxygen Concentration Cell: *see under Differential Aeration.*

Parabolic Oxidation: an oxidation reaction that conforms kinetically to a parabolic law so that the rate of oxidation decreases with thickness of oxide.

Partial Reactions: anodic reaction (reactions) and cathodic reaction (reactions) constituting a single exchange process or a corrosion reaction.

Partial Current (current densities): the currents (current densities) corresponding with each of the partial reactions.

Parting: selective dissolution of one metal (usually the most electro-reactive) from an alloy leaving a residue of the less reactive constituents.

Passivation Potential: the potential at which a metal in the active state becomes passive.

Passivator: a substance which in solution causes passivity.

Passivity: (difficult to define precisely) a metal or alloy which is thermodynamically unstable in a given electrolyte solution is said to be passive when it remains visibly unchanged for a prolonged period. The following should be noted:

(i) *During passivation* the appearance *may* change if the passivating film is sufficiently thick (e.g. interference films on Ti).

(ii) The electrode potential of a passive metal is always appreciably more noble than its potential in the active state.

(iii) Passivity is an *anodic* phenomenon, and control of corrosion by decreasing cathodic reactivity (e.g. amalgamated zinc in sulphuric acid) or by cathodic protection is not passivity.

An alternative definition: a metal in a given solution is said to become passive when there is a significant decrease in the corrosion rate on raising the potential of the metal (by an external e.m.f. or by adding an oxidant to the solution) above a certain critical value.

Patina: a green coating of corrosion products of copper (basic sulphate, carbonate and chloride) which forms on copper or copper alloys after prolonged atmospheric exposure.

pH: a measure of the hydrogen ion activity defined by $\text{pH} = -\log a_{\text{H}^+}$ where a_{H^+} is the activity of the hydrogen ion.

Pickle, Pickling: a solution (usually acidic) used to remove or loosen corrosion products from the surface of a metal.

Anodic and *cathodic* pickling are forms of *electrolytic* pickling in which the metal is anodically or cathodically polarised in the pickle.

Pitting-Bedworth Ratio: ratio of volume of oxide/volume of metal converted

into oxide during a high-temperature oxidation reaction.

Pits (in electroplating): macroscopic channels in an electrodeposit which may or may not extend to the substrate.

Pitting (corrosion): localised corrosion in which appreciable penetration into the metal occurs resulting in the formation of cavities.

Pitting Potential: potential at which a metal pits (*see also* **Critical Pitting Potential**).

Polarisation (overpotential, overvoltage): difference of the potential of an electrode from its equilibrium or steady-state potential.

Potential-pH Equilibrium Diagram (Pourbaix diagram): diagram with equilibrium potential and pH as co-ordinates that show the phases that are at equilibrium when a metal reacts with water or an aqueous solution of a specified electrolyte.

Pores, Porosity (in coatings): microscopic channels in coatings (metallic or non-metallic) which extend to the substrate.

Positive Potential: *see under* **Potential**.

Potential: potential difference at an electrode defined with reference to another specified electrode.

base potential: a potential towards the negative end of a scale of electrode potentials. The potential of an electrode which is made cathodic is said to become 'more base' or 'more negative' (preferred term).

negative potential: a potential more negative than the potential of the standard hydrogen electrode, e.g. $E_{Zn^{2+}/Zn}^{\ominus} = -0.76 \text{ V}$.

noble potential: a potential towards the positive end of a scale of electrode potentials. The potential of an electrode which is made anodic is said to become 'more noble' or 'more positive' (preferred term).

positive potential: a potential more positive than the potential of the standard hydrogen electrode, e.g. $E_{Cu^{2+}/Cu}^{\ominus} = +0.34 \text{ V}$.

(*See also* **Corrosion Potential, Electrode Potential, Equilibrium Potential, Flade Potential, Open-circuit Potential, Passivation Potential, Protection Potential, Redox Potential**.)

Polarisation Resistance: slope of the 'linear' overpotential *vs.* current density curve at potentials close to $E_{corr.}$ or the tangent of the curve if it is non-linear; $R_p = \Delta E / \Delta i \Omega$.

Potentiostatic Polarisation: polarisation of an electrode during which the potential is maintained at a predetermined constant value by means of a *potentiostat*.

Protection Potential for Pitting: potential below which new pits cannot be initiated nor pre-existing pits continue to propagate.

Rack: a frame for suspending and carrying current to articles during plating and related operations.

Rate-determining Step (r.d.s.): the step in the sequence of steps of a reaction that has the highest activation energy and is thus rate-controlling.

Redox Potential: the electrode potential of a reversible oxidation-reduction system, e.g. Cu^{2+}/Cu , Fe^{3+}/Fe^{2+} , MnO_4^-/Mn^{2+} , Cl_2/Cl^- .

Redox System: a reversible oxidation-reduction system.

Reducing Agent: a substance that causes reduction of another species.

Reduction: a chemical or electrochemical reaction in which a species gains electrons; the removal of oxygen or the addition of hydrogen.

Reference Electrode: a half-cell of reproducible potential by means of which

- an unknown electrode potential can be determined on some arbitrary scale (e.g. hydrogen scale, Cu/CuSO₄ scale, Ag/AgCl scale, etc.).
- Relative Humidity:** the ratio of the amount of water vapour present in the atmosphere at a given temperature to the amount required for saturation at the same temperature, expressed as a percentage.
- Reversible Electrode:** an electrode in which a small increase or decrease in potential can reverse the direction of the electrode reaction.
- Reversible Potential:** *see under Equilibrium Potential.*
- Rusting (rust):** corrosion of iron or ferrous alloys resulting in a corrosion product which consists largely of hydrous ferric oxide.
- Saturation Index:** an index which shows if a water of given composition and pH is at equilibrium, supersaturated or unsaturated with respect to calcium carbonate (or to magnesium hydroxide).
- Scale:** a thick visible oxide film formed during the high-temperature oxidation of a metal (the distinction between a film and a scale cannot be defined precisely).
- Season Cracking:** cracking resulting from the combined effect of corrosion and stress, which is usually confined to the stress-corrosion cracking of brass in ammoniacal environments.
- Selective Leaching:** *see Parting.*
- Sensitisation:** susceptibility to intergranular attack in a corrosive environment resulting from heating a stainless steel at a temperature and time that results in precipitation of chromium carbides at grain boundaries.
- Sherardising:** the coating of iron and steel with zinc by heating in contact with zinc powder at a temperature below the melting point of zinc.
- Shield:** a non-conducting medium which is used for altering the current distribution on a cathode or anode.
- Spalling:** the break-up of a surface through the operation of internal stresses, often caused by differential heating or cooling.
- Standard Electrode Potential:** *see under Electrode Potential.*
- Steady-state Potential:** the potential (not varying with time) of an electrode that is operating under steady-state conditions of zero or constant current density.
- Stoichiometric Number:** number of times the rate-determining step must occur for one act of the overall reaction.
- Stray-current Corrosion:** corrosion caused by stray currents flowing from another source of e.m.f. (usually d.c.).
- Stress Intensity Factor $K_{I_{s.c.c.}}$:** a fracture toughness parameter used for evaluating susceptibility to stress-corrosion cracking (the subscript I signifies a tensile mode of stressing).
- Stress-corrosion Cracking:** cracking produced by the combined action of corrosion and static tensile stress (internal or applied).
- Strike (n.):** an electrolyte solution used to deposit a thin initial film of a metal.
- Strike (vb):** to electroplate for a short time at a higher initial current density than is normally used.
- Stripping:** removal of a metal coating by means of an electrolyte solution (or an electrolyte solution and external e.m.f.).
- Subscale Formation:** *see under Internal Oxidation.*
- Substrate:** the basis metal on which a coating is present.

Subsurface Corrosion: *see under Internal Oxidation.*

Sulphate-reducing Bacteria (S.R.B.): a species of anaerobic bacteria (*devibrio desulphuricans*) that is capable of causing rapid corrosion of iron and steel in near-neutral solutions in the absence of dissolved oxygen.

Sustained Load Failure: delayed failure due to the presence of hydrogen in stressed high-tensile steels.

Symmetry Factor: ratio of distance across the double layer to summit of energy barrier/distance across the whole double layer.

Tafel Equation: the linear relationship between the overpotential and the logarithm of the current density for an electrode reaction in which charge transfer is rate determining.

Tarnish: dulling, staining or discoloration of metals due to the formation of thin films of corrosion products. (The term can also be applied to thin transparent film which may give rise to interference colours.)

Thief: an auxiliary cathode which is placed in a position relative to the article to be electroplated so that the current density on certain areas is reduced.

Throwing Power: a measure of the ability of an electroplating solution to give a uniform plate on an irregularly shaped cathode.

Transfer Coefficient α : the transfer coefficient of a cathodic process is the fraction of the electrical energy difference $zF\Delta\phi$ that assists the transfer of an ion through the double layer towards the electrode and inhibits its transfer in the reverse direction; frequently experimental values of α are approximately 0.5.

Transpassivity: active behaviour of a metal at potentials more positive than those leading to passivity.

Transport (transference): *see under Migration of Ions.* The term 'transport' is frequently used to include diffusion as well as migration of an ion to an electrode.

Transport Number: the proportion of the current carried by a particular ion (transfer number).

Tuberculation: localised attack in which the corrosion products form wart-like mounds over the corroded areas.

Uniform Corrosion (general corrosion): corrosion in which no distinguishable area of the metal surface is solely anodic or cathodic, i.e. anodes and cathodes are *inseparable*, cf. localised corrosion.

Voltaic Cell: a term sometimes used for an electrochemical cell; it is sometimes used to refer to a cell in which chemical changes are caused by the application of an external e.m.f.

Weld Decay: localised attack of austenitic stainless steels at zones near a weld, which results from precipitation of chromium carbides.

Terms used in Cathodic Protection and Underground Corrosion*

Anode Lead: the electrical connection between the anode and the power unit

*These terms are derived from various sources, principally from the *List of Definitions of Essential Telecommunications Terms (Part I, Corrosion)*, International Telecommunications Union, Geneva, 1957, 1st Supplement, 1960, and the B.S.I. Code of Practice for Cathodic Protection, CP1021:1973; terms taken from the Code of Practice are marked with an asterisk.

- in impressed-current schemes; normally a copper-cored plastics-sheathed standard electric cable.
- Anode Shield:** protective covering of insulating material placed on a painted structure in the immediate vicinity of the anode to reduce the cathodic current density in that area, thus preventing the development of excessive alkalinity and stripping of the paint (*see Saponification*).
- Attenuation*:** the decrease in potential and current density along a long buried or immersed structure from the drainage point.
- Attenuation Curves:** a graph of interfacial electrical potentials between the pipe and surrounding soil in cathodic protection schemes *vs.* the length of the pipe.
- Backfill:** the soil replaced over the pipe in the trench (general connotation). In cathodic protection, special backfills are packed around the anodes. These backfills are selected to lower circuit resistance of the anode; for sacrificial anodes a gypsum/bentonite mixture is used, and for impressed-current anodes, coke breeze.
- Bond*:** a conductor, usually of copper, that connects two points on the same structure or on different adjacent structures, and thus prevents significant differences in potential between two points.
- Cantilever Anode:** anode supported as a cantilever.
- Cathode Lead:** the electrical connection from the negative terminal of a d.c. power unit.
- Cathodic Protection Rectifier:** transformer-rectifier arrangement for supplying the direct current which flows between a groundbed and a buried structure which is receiving cathodic protection.
- Continuity Bond:** electrical connection made to connect together adjacent sections of a buried structure in order to ensure its electrical continuity.
- Corrosion Interaction (or interaction):** increase (or decrease) in the rate of corrosion of a buried or immersed structure caused by interception of part of the cathodic protection current applied to another buried or immersed structure.
- Current Drainage Survey:** a survey to determine current requirements for cathodic-protection schemes. A temporary groundbed is installed at a suitable location and an impressed current is applied between it and the pipe or other structure. A survey of potentials along the structure will produce attenuation curves, and permits fairly accurate estimation of initial current requirements.
- Direct Electric Drainage:** a means of electric drainage comprising the employment of permanent metallic connections.
- Drainage Bond*:** bond to effect drainage (*see Drainage*, definition (b)).
- Drainage (electric drainage)*:** (a) flow of positive current through the soil or the electrolyte solution from the cathodically protected structure to the groundbed of the impressed current system, or (b) protection of an immersed structure from electrochemical corrosion by making an electrical connection between the structure and the negative return circuit (rail, feeder, busbar) of a d.c. electric traction system.
- Drainage Point:** the location in a cathodic-protection installation where the cathode lead is attached to the pipe; normally the point of maximum negative potential of the pipe, though this is not always the case when an area of low-resistance soil is adjacent to the drainage point.

- Earth*:** (a) the conducting mass of earth or of any other conductor in direct electrical connection with earth, (b) a connection, intentional or unintentional, between a conductor and earth.
- Electric Drainage:** means of electric protection of an underground system against the corrosive action of stray currents arising from a d.c. electric traction system employing one or more connections (drainage bonds) made between the system to be protected and the return circuit of the traction system (rail, return current feeder, negative busbar of the sub-stations).
- Electro-osmosis:** passage of a liquid through a porous medium (such as a soil) under the influence of a potential difference.
- Flood Coat:** application of coal-tar or bituminous coatings to pipelines by flooding the heated coating materials over the pipe surface; wrappings and slings are used to pull the coat underneath the pipe.
- Forced Drainage*:** form of drainage in which the connection between the protected structure and a traction system includes a source of direct current.
- Groundbed:** in cathodic protection of underground structures, a buried mass of inert material (e.g. carbon), or scrap metal connected to the positive terminal of a source of e.m.f. to a structure.
- Holiday:** a flaw, often in the form of a pinhole, in a protective organic coating.
- Holiday Detector:** a high-voltage low-current output generator with a built-in spark gap used for detecting pinholes (holidays) in pipeline coatings.
- Impressed Current:** cathodic current supplied by a d.c. source to a structure in order to lower the potential to the protective potential for cathodic protection.
- Insulating Flange*:** flanged joint between adjacent lengths of pipe in which the nuts and bolts are electrically insulated from one or both of the flanges and the jointing gasket is non-conducting, so that there is an electrical discontinuity in the pipeline at that point.
- Interaction:** *see Corrosion Interaction.*
- Interaction Testing:** routine investigation carried out when installing cathodic protection schemes on pipelines. The accepted criterion in the UK is that when the secondary structure potential has been moved more than 0.02 V in a positive direction, steps must be taken to eliminate the interaction.
- Line Wrapping:** the technique of wrapping a pipeline over the pipeline trench; applied only to welded steel pipelines. It is carried out by a line-wrapping machine which travels along the pipe, cleaning it, priming it, pulling in the reinforcement, and, if necessary, applying the outer wrap.
- Locating and Bonding:** when cathodic protection is applied to an existing jointed pipeline, all joints must be located without digging up the pipe. On location, each joint is exposed and an electrically conducting bond (usually galvanised steel strip or copper cable) is welded into position.
- Polarised Electric Drainage:** a means of electric drainage comprising the employment of metallic connections between the underground cable system and the traction return circuit, with the insertion of a unidirectional system (rectifier or contactor and relays) in the connections.

Primary Structure*: a buried or immersed structure cathodically protected by a system that may constitute a source of corrosion interaction with another (secondary) structure.

Protection Current: current made to flow into a metallic structure in order to effect cathodic protection.

Protective Potential: an optimum negative potential at which pipe protection is accepted as being sufficient in cathodic-protection schemes. It is a negative potential of the pipe/environment interface, and is applicable to steel when the potential is more negative than -0.85 V *vs.* a Cu/CuSO_4 electrode located as close to the pipe as practicable. When sulphate-reducing bacteria are present in soil the value should be -0.95 V . An alternative criterion for steel is to change the pipe potential 0.3 V in a negative direction. Similar criteria are applicable to steel in natural waters.

Reactive (active, sacrificial) Anode: a mass of metal (Mg , Zn , Al) which, buried or immersed and connected to a metallic structure which is to be protected, forms a cell with that structure and has the effect of making it more negative with respect to the surrounding environment.

Remedial Bond*: a bond established between a primary and secondary structure in order to eliminate or reduce corrosion interaction.

Remote Potentials: in dealing with a pipeline cathodic-protection system, it is often advantageous to refer all measurements to a half-cell located at a distance from the pipe. Such measurements are referred to as *remote potentials*.

Resistance Bond*: a bond either incorporating resistors or of adequate resistance in itself to limit the flow of current.

Sacrificial Anode: *see under Reactive Anode.*

Safety Bond*: a bond connecting the metallic carcase of a piece of electrical apparatus with earth, in order to limit the rise in potential of the carcase above earth caused by the passage of any fault current or excessive leakage current, and so reduce the risk of electric shock to anyone touching the carcase.

Saponification: deterioration by softening of paint film caused by action of aqueous alkali, resulting from cathodic protection at excessively high current densities, on the fatty-acid constituents of the film.

Sensing Electrode*: a permanently installed reference electrode used to measure the structure/electrolyte solution potential and to control the protection current.

Stray Currents: currents flowing in the soil and arising from electric installations parts of which are not insulated from the soil.

Structure/Soil Potential: potential measured between a buried structure and a suitable non-polarisable electrode, placed in the soil or water as near to the structure as possible; when the value is being indicated the type of electrode used should be clearly stated.

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