PRESERVATION OF STRUCTURES

IN A

MARINE ENVIRONMENT

by

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WHERE THE SEA MEETS THE LAND

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ABSTRACT

The effects of the environment on the three principal materials used in marine construction are reviewed, together with means which have been developed to prevent and/or control deterioration of marine structures built from those materials.

For timber, the biology, mode of attack and methods of detection of marine borers and termites are examined, together with techniques for pretreatment and insitu treatment of the timbers.

The nature of the corrosion of various grades of steel in both atmospheric and marine environments are discussed, together with methods of corrosion control and prevention, including cathodic protection and other protection systems.

Concrete technology as it is affected by seawater is reviewed and the corrosion of reinforcement in concrete is discussed, and methods of corrosion control and prevention are evaluated.

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0.1 INTRODUCTION

0.1.1 GENERAL

The interest in marine activities, both by Government and private interests, is growing rapidly. The greatly increased activity on the sea, in the sea, and under the sea involves the use of a variety of equipment and focuses attention on the need for knowledge of the behaviour of materials in each of these environments.

The work involved in the preservation of marine structures cannot be readily carried out by persons trained exclusively in any one of the sciences. While basically, preservation can be considered an Engineering problem, the Engineer concerned with preservation, requires advanced knowledge of zoology, chemistry and metallurgy.

The scope for application of preservation techniques in Australian conditions is vast, as not only do the available construction materials vary in quality and quantity from site to site, but there is an almost complete range of environmental conditions to be countered.

0.1.2 DESIGNING FOR PRESERVATION

It appears anomalous that the designer of an Engineering structure is often the Engineer with the least practical experience. The success of the structure in meeting its design function rests generally with the ability of relatively junior Engineers to understand the physical forces acting to destroy the structure from the outside, as well as being able to proportion the stresses within the structure.

The practical design lifetime of an Engineer is very short, in the order of ten years, as usually by the age of thirty, the successful design Engineer will be on the threshold of a managerial career within his Engineering organisation. This factor, together with the high rate of turn-around of junior Engineers as they seek to find their niche in a chosen profession, acts to inhibit the development of expertise in a field of work requiring a sound knowledge of the on-site conditions affecting a structure.

This general instability and inexperience in the junior levels coupled with generally only nominal supervision applied by senior

Engineers, often results in inferior structures being designed, detailed and built, with a resultant increase in the maintenance effort required to ensure that the structure fulfils its functional requirements, and hence a higher than necessary final cost of structure results.

It is therefore essential that the Design Engineer should be aware of the limitations not only of his analytical design, but of the materials of construction in the environment of the site.

0.1.3 ECONOMIC CONSIDERATIONS

The choice of construction materials in marine applications inevitably involves a cost effectiveness evaluation. In the fiscal sense any marine structure represents a series of payments in return for a service performed. Initially, a sum is expended for the installation. Subsequently, additional money may be spent for maintenance or repair. Finally, when the original structure is no longer able to perform its function a further outlay must be made to replace it. If the functional requirement continues the payments go on indefinitely. On the other hand, the functional requirement may change after a period of years or disappear altogether. The most important estimate, therefore, which can be made concerning a marine structure is its functional lifetime.

In a comparison of structures, the cost of failure of a structure must be considered, i.e. what operations will be disrupted if the structure fails. If this cost of failure is high, additional money must be spent on protection of the structure to reduce the probability of failure.

0.2 SUMMARY

In this thesis, the problems of designing for the functional life of marine structures in Australian conditions are discussed, and traditional and modern preservation techniques for the three basic marine construction materials, viz. timber, steel and concrete, are critically reviewed.

For each of these materials, the factors influencing deterioration of a structure in a marine environment are examined in relation to the natural resistance to attack of each of the materials.

The thesis is divided into three distinct sections, viz.:-

Section 1 - Timber

Section 2 - Steel

Section 3 - Concrete

and detailed recommendations are made on preferred preservation treatments for each material considered.

Section 1

T I M B E R

1.01 TIMBER AS A COMPETITIVE MATERIAL FOR MARINE WORKS

The use of timber for harbour and dock works is of great antiquity. In the last century other materials were developed which have become keenly competitive with the older traditional materials. These include iron, steel and concrete. Such new resources may be used separately or in combination with each other or with timber. The present-day harbour or dock engineer has therefore to assess the relative merits of a variety of alternatives in the choice of materials of construction.

It is thus more necessary than ever that the engineer should know the advantages and disadvantages of the competitive materials in every respect, such as: resistance to environment; suitability for function; economic factors; considerations of construction.

Environment may include wet and dry conditions, marine borer activity and abrasion. Suitability for function involves strength, resilience, weight and fire resistance. Economic factors not only include price but also availability, for although scarcity implies a high price, material may be quoted at an apparently reasonable price but for delivery many weeks or months after it is needed. The necessity of proofing against borers, rot or fire may appreciably increase the cost. The problems of the constructor include ease of working, stability of dimensions, freedom from warping and handling weight.

With so many variables to consider, it is evident that each problem of choice must be dealt with on its own merits. In countries where timber is available in great quantities, it may be used with advantage such as in the closely piled timber wharves found in the American continent and in Australia. In other parts of the world, such as North Africa, its scarcity would justify the use of materials which anywhere else would be uneconomic. Similarly, the incidence of marine borers varies, not only from port to port, but even in many cases, within the port itself. This is often the case where large quantities of fresh water flow into estuaries.

The importance of timber to the harbour engineer in particular, lies in the comparatively simple equipment and processes needed in its conversion to structures of all kinds. The traditional trades of the carpenter and shipwright, with their portable tools, may be utilised without difficulty of transport at sites remote from the central workshops, while the great majority of timbers also are comparatively easy to transport to site. Furthermore, where the application of power tools,is practical, the use of timber for construction can be far more expeditious than other materials. This is exemplified by the great use of timber for temporary works of all kinds, in which speed and economy of execution are of great importance.

Although timber may have to face keener competition with steel and reinforced concrete when works of considerable magnitude are planned by large port authorities, as the size of the undertaking becomes smaller and the works comparatively limited in scope, so timber assumes a greater importance. Timber construction is therefore of particular value for smaller port undertakings and for the smaller works of larger authorities.

With increasing sizes of ships, timber sizes in wharf structures increased. It was therefore fortunate that the discovery of more resistant timbers, for use at first, in the ships themselves and later in wharf structures, came at a time when a great expansion of dock and harbour facilities was under way. The early 19th century in England, brought a great increase in the use of hardwood and softwood timber from overseas sources and during that period much practical experience was gained in its use for wharf construction.

A review of the past and present uses of timber in dock and harbour engineering leads to the inevitable conclusion that, whatever new materials may be introduced and new methods found for applying existing alternatives to timber, the forests of the world will still provide an important source of material for maritime works. The great inroads on these forests necessitate two important requirements; first, that all forest products should be used without waste, and second, that replanting is undertaken on such a scale as will guarantee adequate supplies in the future.

Waste may be avoided by the selection of a timber most suitable for the work, by careful design based on tests and strength classification, and by the use of the rapidly developing art of timber engineering. New methods of protection against fire, rot and insect pests will undoubtedly be found, thus extending the life of timbers already established and enabling varieties, not otherwise suitable, to be utilised.

1.02 HISTORICAL REFERENCES

Throughout history, a ceaseless war has been waged against the ravages on timber of marine borers. The Romans complained of the destruction caused by the Teredo, which ruined their wooden installations in the maritime areas of north-western Europe. Christopher Columbus, having sailed westward and discov ered America, lost four of his ships through Teredo attack in the heavily infested waters along the American coast.

Sir Richard Hawkins wrote in 1593, "These arteres or broma (shipworm) in all hot countries enter into the planks of ships and especially where there are rivers of fresh water, for the common opinion is that they are bred in fresh water and with the current of the rivers are brought into the sea. But experience teacheth me that they are bred in the great seas of all hot climates especially near the Equatorial line. For lying so near under and near the line and towing a shallop at our stern, coming to cleanse her in Brazil, we found that all her underwater covered with these worms as big as the little finger of a man. In a little time if the ships been not sheathed they put all in hazard for they enter in no bigger than a small Spanish needle and little by little their holes become ordinarily greater than a man's finger. The thicker the plank is the greater be groweth yea I have seen many ships so eaten that most of their planks under the water have been like honeycomb especially those betwixt wind and water."

Sir Richard was one of the first seamen to realise that fresh water, contrary to being a breeding ground for marine borer, was in fact a haven where wooden hulled ships could lie up for a period to be cleansed. His observations have since been substantiated by science. In addition to killing any borers in the wooden hulls, this procedure also caused fouling organisms to drop off the sides and bottoms of the vessels. As ships travelled further and further from shore and were away from their harbours for longer periods of time other procedures were adopted.

The presence of Teredo and its depredations in timber has been known for a long time, but serious scientific study was not begun until the eighteenth century. A Dutch naturalist, Godfrey Sellius can be said to have written the earliest treatise on this pest. His "Historia Naturalis Teredinis, sen Xylophagi Marine" was published in 1733 and dealt with the damage to the dykes in Holland. Others took up the task and in the nineteenth century many important papers and treatises were published. The writers tended to concentrate on the biology of the pests and it is interesting to note that it was not until 1923 that during investigations of the nutriment of the Teredo, it was discovered that the pest was able to digest the cellulose and hemicellulose of wood. Until then it was believed that the 'worm' entered timber only for the purpose of sheltering from its enemies and that its food consisted of plankton and other micro-organisms brought into the digestive system by means of its siphons. There is still much being learned concerning the feeding habits and life cycles of teredo.

Another important wood destroyer is the Limnoria or gribble. The damage caused by this pest is far more insidious and prevalent, at least in English waters, than Teredo and only recently has attention been paid to its life cycle. W. T. Calman in his booklet "Marine Boring Animals," Natural History Museum, mentions the fact that Robert Stevenson first drew attention to this pest when the timbers of the Bell Rock lighthouse were destroyed, and that specimens were sent to the

Museum in 1814, but that H. Rathke had already named it prior to this date. In 1834 John Coldstream wrote a paper on this crustacean which was published in "Edinburgh New Philosphical Journal."

It is written of ships sailing on voyages of discovery in the reign of Henry VI : "They cover a piece of the keeles of the shippe with thin sheets of leade, for they had heard that in certain partes of the ocean a kind of wormes is bredde which many times pearceth and eateth through the strongest oak that is."

Treatment of the wood itself to retard marine borer attack is very old. The Phoenicians painted their piles with tar or charred the surface. Only recently in Australia charring has been revived in the patented Carboteredo process, and strong claims are made for it. A surface coating of vaseline is applied and heated with a blow torch until fairly even charring has occurred to a depth of 1/4 to 1/2 inch. Knots and ends are re-impregnated and hammered to consolidate the char at these points.

Treatment on a large scale began with the development of the creosote impregnating process a century ago. The first to propose creosoting was Franz Moll who took out a patent in 1836. Practical adoption of the process followed Bethell's patent in 1838. Over recent years, creosoting has become the common method of poisoning the food supply of fungi, marine borers and termites.

1.03 BALANCE OF NATURE

The deterioration of timber in the sea is part of an essential balance of nature. Timber is dead wood, and like all other dead organic matter, must be returned to the soil.

On land this is accomplished by a multiplicity of wood destroying insects and fungi. Dead wood in the sea is reduced first by marine soft rot and then by marine boring organisms. Eventually the chemicals regained from the reduced wood are returned to land by the normal cycle of weather.

Whilst predators and parasites do exist, they are unfortunately insignificant as an economical control for borers. The most spectacular of the predators is an annelid worm, probably Nereilepas species, which attacks the Teredo when the latter's tunnels become broken by mechanical action. These worms live in the Teredo tunnels after the original occupants have been consumed. They move rapidly in the water and on the surface of the timber; they have been observed to attack and enter exposed tunnels within minutes of the tunnels being broken. The same annelid is able to attack and consume Martesia striata when the latter's bi-valve is open during feeding. Parasites such as Teredicola do exist, but to date, no specific study has been made.

1.04 ENVIRONMENTAL EFFECTS ON MARINE BORERS (1) (2)

Infestation may be due to importing borers in infested shipping or driftwood. Changes in food supply, natural environment and cyclical changes may create conditions favourable to attack. Removal of old untreated timber marine structures, and prevention of the use of harbours as dumping grounds for timber waste are two measures advocated to reduce the borer population.

All forms of marine timber boring organisms are influenced by their environment, and populations may change rapidly with changes of environment.

Salinity, temperature, current action, depth of water, pollution, hydrogen-ion values, dissolved oxygen and sulphuretted hydrogen all have a great bearing on the presence, or possible presence of borers. A variety of such combinations may occur in any one harbour, and wide variations in severity and nature of attack may occur.

1.04.1 SALINITY

Salinity is a general controlling factor; some species are strictly limited in their habitat by salinity, and in certain cases, complete populations of specific species have been cleared from estuarine areas by such things as port works and barrages causing interruptions to tidal flow and changes in salinity. On the other hand, such works can also cause changes which create more hospitable conditions, giving rise to an eventual increase in population density.

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(1) reference 1.2
(2) " 1.5

Salinity variations of ten parts per thousand may have a marked effect on marine borers. Ocean salinity is usually about 30 to 35 parts of salt per 1000, and the danger point for borer activity is usually reached at 15 parts. Limnoria and Bankia usually require 20 parts, Limnoria being killed in 24 hours by 6.5 parts. In freshes, colonies may be exterminated. Teredo activity decreases in salinities of less than 9 parts per 1000. However, by plugging the entrance to the tunnel with its pallets, the borer can greatly defer the effect of fresh water. Six weeks at below 4 parts appear necessary to kill.

Bankia is much less resistant than Teredo to low and changing salinities, and thrives in salinity as low as 7 parts per 1000. Nausitora prefers low salinity in Australian waters and is adversely affected by a rise. Some species occur in tropical fresh waters. Fresh water for a period of 10 days and over, will kill Teredo. This is of considerable importance to owners of wooden vessels, pontoons, etc. where fresh water facilities are available. It also confirms that the action of slipping craft is not sufficient to completely kill Teredo, since they can survive removal from the water for several days or even longer.

1.04.2 <u>WATER TEMPERATURE</u>

Water temperature has considerable bearing on borer activity, and in some places, attacks can occur only during a limited period of the year. Temperature effects are much reduced after the borers have entered the timber. In cooler waters, borer activity may be limited to two months of the year, although the borers continue to burrow after they enter, unless the water temperature falls to just above freezing point, when they lie dormant.

Temperature is mainly of importance in the breeding season. Teredo, for example, must have fairly warm water for egg laying and for the larvae to exist. Limnoria are generally less affected by temperature than Teredo. Where the temperature of harbour water is raised by the introduction of hot water (e.g. from a power station cooling water outfall), there is a tendency for attack to intensify.

1.04.3 POLLUTION

Pollution in industrial port areas offers a valuable control by both killing the free-swimming larvae and maintaining timber in an inhospitable state by accumulations on the surface of the timber. Pollutants include industrial effluents, chemicals, oils and mud in suspension. There is some doubt however about domestic sewage, some authorities stating that it is actually beneficial to Teredo and others that it is the reverse. All are agreed that this form of pollution has no effect on Limnoria.

Removal of pollution from sewage, mill wastes, catch basin overflows and oil has been known to be accompanied by a marked increase in borer activity. It is possible that there may be invasions of certain harbours by borers, as a result of pollution prevention programmes.

Oxygen in the water is necessary for respiration of borers. A small amount of hydrogen sulphide is fatal. Normal sea water has a pH value of 7.5 to 8.5 and any marked change is fatal to borers. (A value of lower than 7.0 is usually an indication of industrial waste or heavy pollution). Heavy silt is a great aid in limiting Limnoria, and it appears that Teredo cannot thrive in muddy or turbid waters.

Clean tropical ports provide the most hospitable environment as the water is usually unpolluted and temperature and salinity remain constant. If considerable volumes of untreated timber are used over long periods in such areas, a population build-up of marine borers can make further use of timber uneconomical.

1.04.4 LIGHT

During their larval stage, Teredo and Limnoria are affected by light intensity. The most favourable conditions exist in an illumination of 160 foot candles (1720 Lumens per sq.in.) deep shade). Tests[1] have shown that at night, Limnoria and ~~Teredo larvae~~ are more

(1) reference 1.5

active at the surface, but remain in deeper water during the day. This aversion to light is illustrated by a simple test of two pieces of identical and perishable timber, both fixed at a constant depth. If one piece is stained white, and the other black, the black piece will be attacked more rapidly than the white. In practical usage, it is again illustrated by the fact that the underside, or shaded side of a wooden structure in the sea will be attacked more severely than the top or front. This is quite obvious in horizontal parts of wharf structures, such as walings and ladder steps. This colour factor is also illustrated with boottopping on wooden craft. White boottopping will cause heavy weed fouling but less marine borer activity at the water line than a craft with black boottopping which will have less weed growth but will be more heavily attacked.

1.04.5 CURRENTS

Some species are able to tolerate conditions of extreme turbulence, and in certain circumstances seem to prefer active water to still water.

Fast flowing tideways, (in excess of 2 knots), are not hospitable to the larvae of marine boring organisms that normally inhabit coastal waters. Other deep sea species however are able to tolerate considerably stronger currents.

1.05 BIOLOGY OF ORGANISMS

The animal organisms responsible for the biological deterioration of wooden marine structures are members of two main groups. The first group is composed of animals from the phylum Mollusca. In their larval stages, they are oyster or clam-like in appearance and metamorphose into worm-like animals as they bore into timber. Members of this phylum are responsible for the rapid destruction of timbers exposed in a marine environment. The particular genera involved are the Teredo and Bankia of the family Teredinidal and the pholad Martesia.

The second group of organisms is comprised mainly of the genus Limnoria and in some harbours by members of the genus Sphaeroma. They are shrimp-like in appearance, about 1/8 inch to 1/4 inch long, and generally burrow just beneath the surface of the wood. These animals have been described as having the body of a shrimp and the head of a termite. They are responsible for the destruction readily visible on surface inspection of timber.

1.05.1 MOLLUSCAN BORERS [1] [2]

The molluscan or teredine borers begin their existence as free-swimming larvae. The teredo is considered to be bi-sexual. Fertilisation, and development of the larvae occurs within the body of the animal, and the mature larvae are ejected into the water through the excurrent siphon of the animal. At this stage, the larvae of the teredo are about 250 microns in diameter. The period of free swimming larval life varies according to the species, but it is during this period that the larvae must come onto an hospitable surface, and escape predators, weather, adverse conditions of salinity, temperature and current. It will be realised that to combat so many adverse factors marine borers generally are exceedingly prolific. From the free swimming stage, the larvae reach the crawling stage, the critical point of the life cycle when an hospitable surface must b e attained. During the process of its metamorphosis, the Teredo will start burrowing. It is during this period of metamorphosis that the Teredo is most eadily controlled, by ensuring that any wooden craft or structure maintains an inhospitable surface.

Should the larvae manage to penetrate an inhospitable surface, for instance through a scar or abrasion, the adult animal will be able to live and thrive in the untreated interior of the wood.

The mature teredo is a greyish, slimy and worm-like creature, varying in length from a few inches to five feet, according to species and local conditions, and from 0.125 to 1 inch across.

The main food has been proved to be the wood itself, supplemented by plankton to provide protein.

In the Bankia genus, adult animals eject sperm and eggs into

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(1) reference 1.2
(2) " 1.6

the sea where fertilisation takes place. Swimming immature larvae are developed within a few hours. The larvae develop for about a month before they are ready to attack timber. After the timber is attacked, the Bankia larvae metamorphose in a manner similar to that of the Teredo.

Martesia differ from the Teredine borers in only one major respect: the metamorphosis into a worm-like structure does not take place. As a result, the animals burrow just below the surface, enlarging the burrows as they grow.

1.05.2 CRUSTACEAN BORERS [1] [2]

The crustacean borers resemble a wood louse in appearance. The most common wood borers in this class are members of the genus Limnoria, also known as the gribble. The body of the animal is from 1/8 inch to 1/4 inch in length and is about one-third as wide. Their seven pairs of legs have sharp, hooked claws which enable the animals to cling to wood and move freely on its surface. They burrow just below the surface of the timber and form a series of tunnels. It has been found that at a low population density there are only two animals in each tunnel, one male and one female, with the female in the blind end of the tunnel.

The female carries the eggs in a brood pouch on the underside of the body between two rows of legs. The number of eggs in a single brood is seldom less than six or more than seventeen. When hatched, the young differ only in size from the adult and are ready to bore at once. They begin to bore near the parent so that Limnoria infestation generally spreads from a centre. Heavily infested wood may contain 300 to 400 animals of all ages per square inch.

It is thought that Sphaeroma burrows mainly for protection, although some nourishment may be obtained from their substrate. Some of their burrows terminate in brood chambers where dozens of young are kept and guarded by an adult which rolls itself into a ball, thus firmly blocking the tunnel. Sphaeroma is related to the terrestial woodlouse which has the same habit of rolling itself into a ball when

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(1) reference 1.2
(2) " 1.6

disturbed. It is this habit that has earned Sphaeroma the colloquial name of "Pillbug".

Research has established that the crustacean borer Sphaeroma is the principal if not the only agent in the destruction of piling in the Port of Sydney, and no natural piling timber is immune to attack.

Limnoria is the most destructive of the Crustaceae borers and the most common and most dangerous, because of its tolerance of creosote and weak solutions of copper. Limnoria are voracious eaters. They attack mainly in the wind and water area, although attack at depths down to 20 feet are known. Some Limnoria are controlled by conditions of illumination, and attack more densely at low light intensity.

1.05.3 BREEDING SEASONS

Borers have definite breeding seasons but this varies among species, so that attack may be nearly continuous. Limnoria adults which are free to move from place to place, seem able to breed throughout the year when temperature and salinity are favourable. Teredo breeds in late summer or early autumn. Bankia breeds from Spring to Summer.

1.06 MECHANISM OF ATTACK

1.06.1 Effects of Soft Rot

Continuous research into the use and protection of timber in marine environments has given a comprehensive knowledge of the action of marine soft rot and marine wood boring fauna. Unfortunately this knowledge is not yet fully utilised by all those concerned with the use of timber in the sea.

The presence of marine bacteria and marine micro-fungi has long been realised as being responsible for the destruction of natural organic matter in the sea, it has also been confirmed as being present in driftwood.

In a paper on "Marine fungi, the taxonomy and biology," (1) published in 1944, Bardhoorn and Linder pointed out the role of

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(1) reference 1.1

microfungi in causing decay of timber submerged in the sea and proved that a number of different marine fungi, which they isolated, caused an attack of the "soft-rot" type.

When "soft rot" occurs in water, the depth of penetration is limited, but if any form of abrasive action occurs the softened surface is more quickly removed and a new surface is exposed to attack. M. R. Deschamps[(1)] in 1952 emphasised the role of fungi and bacteria in aiding attack on wood by marine borers.

Soft rot has been observed in hardwoods and softwoods of all durability classes and it is by no means unusual to find superficial soft rot on very durable hardwoods which have been chosen for a particular use. Soft-rot occurs most frequently between high and low water marks, where timber used in marine defence work is alternatively very wet through submersion and, though drier when the water recedes, yet remains damp. The timber is never dry or wet enough for a period of sufficient length to inhibit spore growth and so preclude the incidence of decay.

The function of the fungi is to soften the surface of submerged timber making it mechanically hospitable to initial boring by the larvae of Teredinidal species of marine borer.

Tunnels of live Teredo are mainly free of soft-rot, but tunnels of dead ones often contain evidence of the fungus.

Hardwoods known to have considerable resistance to waterlogging and Teredo attack, during 6 months exposure in equatorial seas show evidence of tasting marks but little successful burrowing. However, once soft rot has caused surface softening, burrowing can proceed unhindered although it will be mainly as a stenomorphic form.

It is known that Teredo larvae are mechanically ill equipped to burrow into clean sound timber. Their ability to burrow into hard impermeable timbers is therefore dependent on the surface of such timbers being in an hospitable condition. In the case of permeable timbers, an hospitable conditioning may be produced by soft-rot or waterlogging, or both. The latter is probably the ruling one in the case of attack on most softwood timbers.

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(1) Reference 1.1

Softwood timbers are less affected by soft-rot than hardwoods, and this indicates a similar behaviour between marine and terrestial species of the fungus. Attacked timber, when examined at 100 magnifications exhibits a surface deterioration typical of soft-rot -- a softening of 0.02 to 0.04 inches.

It is known that mature Teredo can burrow with no ill effect into timber treated with a very high copper retention, provided they have made initial attack into hospitable timber which is fitted flush to that treated; it is also known that the larvae are inhibited by such treatment. Therefore the conclusions that may be drawn are that it is not the toxic effect of the treatment that is the controlling factor, but that it is a very efficient fungicide that is stable in sea water, which retards action by soft-rot, and consequently maintains the timber in a condition inhospitable to initial burrowing by larvae.

It has been stated that the shells of the free swimming larvae are still uncalcified and have no teeth, hence mechanical penetration by young animals is favoured by the fungial softening of the surface layers of the wood.

Whether this dependence of Teredinidae larvae on marine soft-rot represents true symbiosis is still conjecture, certainly an essential association does exist.

1.06.2 ATTACK BY TYPES OF BORERS

1.06.2(a) TEREDO (1) (2) (3)

The crawling larvae is microscopic, and its original entrance hole into the timber is correspondingly small -- 0.01 to 0.02 inches in diameter. As the animal grows inside the timber its diameter and length increase rapidly under suitable conditions. The tunnel is lined with a calcareous substance which is manufactured by the animal, and this lining gets progressively thicker with age, particularly at the original entrance into the timber. In some species this has been found up to 0.16 inches thick. Even though the host timber may be so badly attacked that it has been partially eroded,

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(1) reference 1.1
(2) " 1.2
(3) " 1.7

exposed tunnels may project up to 6 inches into open water, with the live animal inside. Again some species of Teredo are able to repair broken tunnels (provided parasites and predators do not gain access first). At the entrance to the tunnel the animal manufactures out of the same calcareous substance, extensible siphons and pallets. In some species these siphons project into the open water, and their function is as intake and outlet for respiration, and for feeding. The pallets are hard and are effectively used to close the tunnel.

It has been said that Teredo burrow mainly along the grain, but this is not a hard and fast rule. Rather it appears that in fixed horizontal structures, initially they burrow upwards, and turn along the grain when no further vertical travel is possible; however observations of floating structures show this does not seem to apply to them. In any very heavily attacked and overcrowded structure they will tunnel in any direction to avoid their fellows. Likewise they are most reluctant to cross, or even approach any foreign body; it has been observed that provided there is room to manoeuvre Teredo will always turn away from bolts. In very heavily attached and overcrowded specimens they are sometimes forced nearer, but never near enough to break the surface adjacent to a foreign body. They will cross from one piece of timber to another, provided the two pieces are absolutely flush. They can be prevented from such a crossing by a sandwich of a foreign material, but the efficiency of this will only last whilst the sandwich is dry. Even bitumastic paper can be penetrated when it is waterlogged. Linen, canvas, and cotton treated with a copper napthonate canvas proofer provide a reasonably efficient barrier, but the glue line in plywood does not.

Under certain ideal circumstances Teredo may attack extremely densely, and as a result overcrowded conditions may be encountered that do not allow maximum development of the animals, or they may attack a timber which permits the initial attack but is resistant to their burrowing. In both circumstances a stenomorphic form of the Teredo will result. Destruction of the structure is by steady surface erosion. It is the form of attack that occurs in durable timbers that contain silica or alkaloids.

In a dense attack on thin boat timbers stenomorphic forms of Teredo cause rapid waterlogging and destruction.

Damage by Teredo of wooden craft and structures is spectacular, and eventually completely destructive. However, this bi-valve can be controlled and should not be such an unparalleled menace as it is popularly considered.

1.06.2(b) MARTESIA [1] [2]

Martesia in common with other wood boring molusca probably cannot attack timber in the sea until such timber has been rendered hospitable by the prior action of marine soft-rot as described above. Martesia larvae are delicate, they have chitinous shells and the usual muscular but soft foot similar to Teredo, and once marine soft rot has caused an initial surface softening of the larva, is able to gain access by burrowing into the softened surface. When burrowing has started, the conical adult form occurs. Once initial access has been made the association between the borer and marine soft-rot appears to be less essential. The association between marine soft-rot and Teredinidae has been discussed and a similar association between marine fungi and Limnoria is realised but up to now, no positive work has been conducted to discover the extent of such an association between Martesia and soft-rot. Association does exist, but as Martesia striata is able to tolerate certain preservative treatments that Teredinidae cannot, the form of symbiosis is probably different for these marine boring molusca.

The initial entrance hole of Martesia striata is invisible to the naked eye but as the animal grows the entrance hole becomes enlarged to accommodate the opening and shutting of the bi-valves of the growing animal. In the adult, the entrance hole may be enlarged to 0.16 inches in diameter and be plainly visible. The rate of burrowing and the rate of growth in an hospitable timber is approximately 0.004

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(1) reference 1.2
(2) " 1.7

inches per day and after the animal has reached a penetration of 0.2 inches the characteristic conical shape of the animal and the burrow is reached. The maximum penetration so far observed is 1.9 inches although the largest complete specimen extracted is 1.5 inches long with a diameter of 0.63 inches. Such growth was achieved during an immersion period of 358 days in an even textured softwood timber. The type of timber attacked and/or preservative treatment concerned has a direct relationship on the rate of growth. In hospitable timbers attack is very dense reaching 780 per sq.ft.

1.06.2(d) SPHAEROMA (1) (2)

Adult Sphaeroma will burrow into any timber that is in an hospitable condition, and prerequisite for such hospitality is sufficient waterlogging. The adults explore the surface by crawling and swimming, and usually start burrowing in the lee of some shelter as might be found by joints and fittings. The adults are powerful acrobatic swimmers of limited range and duration, and depend on tide and current to assist in journeys of more than a few yards.

Depth of burrowing seldom exceeds 2 inches and the diameter of the burrows are at their maximum at 0.2 inches. They burrow in all directions irrespective of the direction of the grain of the host timber. Once inside, they seldom meander but maintain the direction of the original entry. They appear to be gregarious, attacking as a colony over a relatively small area, and within such an area attack may be severe. Over a period of about two years, however, such colonies enlarge and eventually join up; thus the whole surface of the host timber becomes weakened.

The actual damage caused by burrowing Sphaeroma is of little consequence, but many close burrows do cause a surface weakness that is completed by a mechanical and tidal erosion. Sphaeroma is most active between the neap tide rise and fall. Piling attacked by Sphaeroma assumes an "hour glass" appearance at this level, leading to eventual failure.

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(1) reference 1.2
(2) " 1.7

1.06.2(d) LIMNORIA(1) (2) (3)

Limnoria prefer timbers that have strongly defined growth rings.

Adult animals burrow into the soft textured early wood, and move mainly along the grain, though transverse burrows will be made. Small holes are made through the surface of the timber to open water, and other holes are burrowed down through the adjacent layer of late wood into the next layer of early wood. The young are hatched and reared in these galleries and eventually assist in the burrowing. As the surface of the timber becomes overpopulated the Limnoria burrow inwards through late wood and into the next layer of early wood. They leave behind them a fragile, perforated layer of wood that is rapidly eroded by tidal action.

In creosoted timber, the creosoted layer is destroyed as described above, thus allowing Teredinidae to attack the untreated interior.

The variation of heartwood resistance is particularly important in respect to Limnoria and in a lesser degree, to Bankia and Teredo.

Where a cross-section of a pile is exposed to Limnoria, attack usually begins most rapidly at the centre and expands in depth and area at a decreasing rate. In some cases, only a shell may be left. Damage of this type varies appreciably in different piles and in different sections of the same tree.

The reasons for this variation are not yet clear. Turpentine has been considered to owe its resistance to the high silica content but there appears to be no significant difference in silica content between Turpentine wood of low and of high resistance. A possible cause is the presence of fungi in the wood of low resistance, and preference of Limnoria for wood affected by fungi being indicated under other conditions. Some aspects of this variation are at present under investigation.

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(1) reference 1.1
(2) " 1.2
(3) " 1.7

1.07 DETECTION OF BORER ATTACK

Consultants and organisations in Canada, U.S.A., and the U.K., are able to provide teams of marine zoologists, divers and timber technologists to undertake an assay of marine soft rot and marine wood boring fauna in a subject area and adjacent waters, to determine to what extent timber should be used in a development scheme, and what preservative treatment should be prescribed.

Such a team could also survey existing port works to determine the extent of marine borer damage and the need for replacement. While a vast amount of timber - piles, fenders, etc. - is replaced annually, often it transpires after extraction, that the old timber would have been capable of further work. A port's maintenance diver may diagnose on external appearance and by removing a section from the surface of the timber. This can be misleading, as frequently marine borers reach only to stenomorphic form, which immediately under the surface of the timber appears to be a very serious attack, but in fact may be only a dense attack of dwarf forms with shallow penetration, and do not cause any serious weakening of the timber. An exact knowledge of the internal condition of any marine timber can be obtained by the use of wood chemistry, wood anatomy and marine zoology coupled with the use of ultra-sonic testing equipment.

Principal point of attack for marine borers is between water level and mud line on submerged timbers. Submergence conceals the action of borers, especially of those which enter by pinpoint holes and grow as they consume the interior wood. Marine borer attack is most destructive to the pile supporting marine structures. Complete failure of the structure may be the first indication of borer activity. For these reasons, discussions in this text of ways of finding and fighting marine borers are centred on piles, but apply equally to other submerged structures.

1.07.1 ULTRA-SONIC DETECTION

During investigations of wooden marine structures for borer damage over a period of more than ten years, the staff of British Columbia Research Council realised the inadequacies of visual underwater inspections. Visual inspection by divers had been the only technique for assessing the condition of marine piling. Limnorial damage usually is easily recognisable as it is visible on the piling exterior. However, instances occur where Limnoria enter small surface defects and then erode away the piling interior. Here, judicious use of a probe by the inspecting diver may help form a qualitative estimate of piling damage.

Where Teredine infestations occur, the only instances where attack can be readily detected is when the animals are alive and undisturbed. Under these circumstances the siphons of large adults may extend over one or two inches beyond the piling surface, and can be recognised by a trained observer. If the animals are disturbed, the siphons are withdrawn and the presence of the borer is difficult to establish.

When the teredos are dead, the only external evidence of attack is the tiny burrow entrances. Even when the tunnel entrances have not been overgrown with fouling, finding the small pinholes on the pile surface is extremely difficult under water. Only in those cases where damage is so severe that the external shell of the piling has crumbled, is infestation readily apparent. Even in these cases where the inspecting diver observes teredo entrances he cannot make a reliable estimate of internal damage.

In 1955, studies were initiated at the British Columbia Research Council to develop a non-destructive method of testing piling, not based on visual examination.[1] After exploring a variety of potential techniques, it was discovered from tests made under water, that the velocity and the strength of sound waves passing through wood varied inversely with borer damage. On this principle, a sonic testing unit was developed in which ultra-sonic waves are pulsed from a magnetostrictive transducer several inches from the wood surface and directed at the heart of the pile. The plane waves which penetrate

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(1) reference 1.14

into the wood initiate transmission of secondary sonic patterns in the direction of the wood grain. As these wave trains transmit along the axis of the pile they produce radial sets of waves which can be picked up by a receiving transducer. Undamaged wood is an excellent transmitter of these waves, whereas damaged wood delays and attenuates them. The velocity and strength of the sonic signal picked up by the receiving transducer can be amplified and measured.

A unique feature of the testing equipment is that fouling need not be removed prior to testing, since neither the transmitting nor receiving transducers are impinged on the piling surface.

The sensing mechanism can pick up as few as four or five teredine burrows in a single pile cross-section. However, to provide information of commercial value the relationship was determined between sonic values, percentage voids in pile cross-sections, and residual compressive strengths of such sections. Because the relationship between residual load-bearing strength and the percentage cross-sectional loss depends to some degree on the eccentricity of the voids within the cross section, strength categorisation is only feasible to the nearest 25%. Nevertheless, this represents a marked improvement over assessments by visual methods.

An experimental unit was first used in the field in February 1961, and its successful performance on piles, with known damage, immediately brought in numerous requests for inspections from operators of waterfront structures. The out-of-water equipment has now been re-designed so that the ultrasonic pulser, the transformer for operating the signal pulser and the oscilloscope for amplification and readout of the sonic signal have been consolidated into one 9"x9"x16" damage indicator box. By transistorising this unit and providing it with a rechargeable battery, a source of alternating current is no longer required for operation. A calibrated meter scale reads piling damage directly in percent.

The out-of-water unit is connected to the underwater unit by a sealed buoyant plastic cable with a diminutive pulser sealed into the end adjacent to the underwater frame. Piling inspection rollers can be quickly exchanged, above water, for corresponding guides suitable for examining flat surfaces such as timbers and cants or the unit can be completely dissembled to facilitate transportation to another wharf. The underwater unit is virtually weightless in water, buoyed with sealed aluminium floats, and has been designed specially to facilitate all manipulations. The arms, which lock around a pile, spring open on a ratchet for removal, which, when placed to the next pile, lock on by the tripping of a switch. The diver's head-set by which he maintains constant communication with the above-water operator, plugs directly into the underwater inspection unit, with connection to the surface being made through the buoyant cable. The circuitry is so designed that when a damaged portion of pile is traversed by the underwater unit, a hum is created on the audio system to attract the attention of the diver and the above-water operator.

The inspection unit is locked onto a pile at the surface, with the two transducers, 42" apart, pointing at the heart of the pile. The diver conducts the unit to the mudline in a spiral fashion so that at sometime in the descent, all points on the pile surface lie between the sending and the receiving transducers. When a damaged zone is reached, as indicated by the hum on the audio system, a more intensive examination is made both sonically and visually. The diver's comments and the depth of damage are referred to the above-water operator for transcription. At the bottom of the pile, the inspection unit is locked open, transferred to an adjacent pile, and conducted to the surface in the reverse spiral manner.

Preliminary to the inspections, individual piles are identified to designate piling in the inspection plans of the structure. Percentage distribution of the piling by strength categories may be calculated, and from this collective data, the general strength of the entire wharf may be determined.

The question paramount in the mind of any client seeking to avail himself of non-destructive piling inspection services is "How reliable are the results?" Apart from the original research and development which indicated the 25% categorisation to be valid, within which the results are presented to the client, documentation of field evidence is continuing to mount. A number of operators have pulled and examined individual piles, whose external appearance suggested no damage, but which have been reported as damaged by sonic inspection. In all cases where this was done, the sonic inspection data have been verified by sectioning the piling at the indicated damaged area.

The main factors which affect the rate of inspection of piles, are the underwater length of the piling and amount of obstructions. Under good conditions an inspection team can average 100 piles per day, although adverse conditions can drop this number as low as 50. The only postponement to the operations of the equipment is when underwater visibility is very restricted.

1.07.2 SIMPLE IDENTIFICATION TEST

Sphaeroma usually attack a wooden structure in company with Martesia striata. As the entrance hole of Martesia enlarges to about 0.16 inches, it is difficult to determine from casual observation which borer is responsible for the main damage. However, at low tide this can be discovered by the simple test of hitting the attacked timber with a hammer. When so disturbed, Martesia striata will eject a stream of water from the tunnel, and Sphaeroma terebrans becomes distinctly audible by squeaking.

1.08 METHODS OF COMBATTING MARINE BORERS

Four methods can be used in combatting marine borers:-

(1) Use of resistant species of timber;

(2) Protection of the wood by treatment with a preservative;

(3) Protection of the wood by covering the surface with sheathing;

(4) Killing the borers by means of insitu treatments of changes in environment.

These methods are developed in the following sections.

1.09 SELECTION OF TIMBER FOR MARINE WORKS

All timber species tested for resistance to marine boring organisms have been damaged by these organisms. The rate of damage, however, varies considerably for different species and in different harbours.

There are a few timbers which have gained reputations for resistance to marine borers. Among these are the South and Central American woods Greenheart and Angelique and the Australian Turpentine.

Although resistant timbers may withstand borer attack for long periods of time in some harbours, they may be readily attacked in other harbours. For example, Greenheart piles rated as being in good condition after 80 years in the harbour of Liverpool, were attacked in four years at Salem (England), and failed in Java, India, in five to ten years.

In addition to the variable resistance to marine borers offered by resistant timbers in various harbours(1), the same species of timber grown on different soils may differ considerably in both composition and resistance. Turpentine (Syncarpia laurifolia) is used extensively as a pile timber in Australia. In exposure tests in Honolulu harbour, Australian grown turpentine wood was lightly attacked by Teredo and showed moderate superficial action by Limnoria after four years.

Blocks of the same species grown in Hawaii were often badly damaged in five months. Chemical analysis showed the Australian grown timber to contain up to 1.25% silica; the maximum silica content of Hawaiian grown timber was 0.17%. The averages of a number of samples were 0.59% and 0.09% respectively.

EFFECTS OF SILICA CONTENT

Some correlation seems to exist between the silica content of wood and its resistance to marine borers. Timbers with a high silica content, with few exdeptions, are more resistant than timbers of low silica content. Silica is efficient because it provides a

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(1) reference 1.4

mechanical deterrent to the burrowing of marine borer. It is also stable and is not leached out of the timber in the sea. It will not prevent surface softening by marine microfungi, and will not necessarily stop initial larvae attack by Teredo. Such attack will, however, be shallow and of stenomorphic form. A high silica content will completely inhibit attack by Martesia, Sphaeroma and Limnoria. To determine the effects of increasing the silica content of wood, southern yellow pine blocks were impregnated with silica. The borer resistance was increased. Untreated blocks were destroyed in three to six months, while panels impregnated to a high silica content were only lightly damaged after two years.

Some resistant timbers do not have a high silica content. Examples of such timbers are Greenheart and Lignum vital. The resistance of some of these timbers has been attributed to their alkaloid content. A 5 per cent content will inhibit Teredo attack, but not Martesia. These alkaloids are leachable in the sea, and when the content is reduced to 2 1/2 per cent, Teredo can sustain attack.

It should be noted, however, that in no case have timbers of high silica content been low in borer resistance although a few timbers of low silica content may be resistant because of their alkaloid content or for other reasons.

The other essential criterion for natural resistance is impermeability to sea water. For example, Vitex has a high silica content, but is not durable because it is very soft and becomes easily waterlogged, and under such circumstances, marine borers are able to sustain attack.

1.09.1 TIMBER SELECTION AND THE ENGINEER

A great number of timbers suitable for different uses in dock and harbour works are available in different parts of the world. Some of these, although economic for local use, have not sufficient advantages to justify the cost of transport to other parts of the world. The omission of such timbers from any general list does not therefore mean that they are not adequate for the purposes to which they are put locally. Other timbers, however, have such outstanding qualities that they are in demand throughout the world, especially some of those which possess special qualities such as greenheart, jarrah, teak, or turpentine.

It is for this reason that it is necessary for the dock and harbour engineer to have a sound general knowledge of the properties and characteristics of the main varieties of timber. This can only be satisfactorily based on a thorough study of the timber. Although many devices have been employed to combat marine boring organisms, they cause enormous damage to structures each year. In addition to the cost of the damage is the inconvenience which occurs when wharves or ships are removed from service during their reconstruction period.

As an example of the rapidity with which timbers can be destroyed it has been reported[(1)] that in the process of laying an outfall sewer off Sand Island in Hawaii, a long trestle was constructed of Oregon. Heavy equipment to handle the concrete pipe was to operate on the trestle. Danger from marine borers was realised, but since the project was to be completed in eight months, the construction company considered the use of treated structural timbers an unnecessary expense. In 70 days, sections of the trestle collapsed due to borer attack, plunging heavy equipment into the sea.

Timber fenders, which suffer considerable mechanical damage, are expendable, and it is expected that they will be replaced periodically. However, to be economical they must have a biological life expectancy equal to that of their designed mechanical life. In tropical waters especially, this may be achievable only by the use of correct wood preservation, designed for the particular environment. For many years the practice has been for engineers to specify the very expensive naturally resistant timbers; but these are not always satisfactory for mechanically they are often exceedingly strong and very hard. Thus they do not provide all the cushioning effect desired.

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(1) reference 1.2

However the use of wood preservation allows the use of cheaper perishable but treatable timbers which are generally described as secondary hardwoods.

1.09.2 IMPORTANCE OF TURPENTINE IN AUSTRALIA[1]

For practical purposes the heartwood is of primary interest in considering the resistance of Turpentine to marine borer attack. This may be highly resistant to some borer species and of low resistance to others; the wood also varies in resistance to particular borers resulting from variation from tree to tree and within each tree.

Unprotected Turpentine should not be used for marine piling in estuarine areas where the normal salinity is usually or even occasionally in the range from near fresh to about ten parts per thousand, in view of probable Nausitoria damage.

Where salinity is above 20 parts per thousand, a very long life may be obtained providing intertidal protection is given where Sphaeroma is common and providing Martesia is not prevalent in the area. Special precautions are also advisable where Limnoria are common.

In a small percentage of piles, the wood under the sapwood is low in resistance to Limnoria, and general attack may proceed over the whole surface from about mid-tide to silt line. Further information on causes of variations may assist in eliminating such piles from Limnoria areas although it might be noted that the rate of attack is fairly slow and fair service is obtained. Where such piles are located in a structure it is considered advisable to apply a full-length casing at an early stage.

Generally in order to minimise the effects of corewood, piles of not less than 14 inch diameter at the silt line should be used.

Severe attack usually occurs at the ends of heavy sections used for fendering and similar purposes. Previously, muntz or copper sheeting was used for end protection, but fibreglass reinforced

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(1) reference 1.9

plastic attached by waterproof adhesive and copper fastening appears to be more durable.

Where the corewood is directly exposed to attack, as in sawn sections, the effective life may be very limited. Some preservative treated softwoods will provide a longer life in such areas and are considered preferable to sawn Turpentine sections.

The bark of Turpentine shows a high resistance to damage by the high salinity teredinid borers but only limited resistance to Sphaeroma and Limnoria.

The temporary nature of bark protection in Limnoria areas does not warrant additional expense if this is necessary to retain bark intact during transport and driving. A more definite advantage is gained where piles are exposed in Limnoria free areas, particularly where a method such as the floating collar (See Section 1.11.1) is used for intertidal control. The absorption of creosote by the bark assists in Sphaeroma control and the bark provides sub-tidal protection of the sapwood against high salinity shipworms.

The sapwood of Turpentine has some resistance compared with standard controls such as Oregon Pine but is inevitably destroyed by both Limnoria and high salinity shipworms where these borers are present. For this reason, the column strength of such piles is based on the heartwood section only. In view of this also, the economic value of bark protection is somewhat reduced.

Turpentine well deserves its reputation for marine borer resistance, but care is necessary to ascertain the biological conditions of exposure as a basis for its proper utilisation. In most locations a long life is obtained by early attention to possible sources of failure. A variety of economic methods are available to suit the wide range of conditions experienced by harbour engineers.

There is no doubt that they can be much improved and extended with economic benefit.

1.10 PRETREATMENT OF TIMBER[1] [2]

1.10.1 PRESERVATIVE TREATMENT

Thorough treatment with a suitable preservative is effective against all types of marine borers. Coal tar creosote is most commonly used and has been found the most generally satisfactory preservative. Experiments have shown that a proprietary acid copper chrome preservative (Alcure) gives promise of being equally efficient.

The method of applying the preservative is extremely important and pressure treatment by the full-cell or Bethel method is best. With resistant timbers such as Douglas fir, incising and long pressure periods are also necessary. Hot and cold open tank treatment can sometimes be used with very permeable species where the sapwood is thick. Surface brushing is useless. At bolt holes or other cuts in the timber, the timber must be thoroughly treated. Holes and cuts in the timber should be made before the timber has been pressure treated.

1.10.2 CREOSOTE TREATMENT

The life of piles is lengthened by creosoting, provided oil of the correct composition is used. All oils passing under the name of creosote are not equally effective. Borer attacks will progress in creosoted piles, but at a slower rate.

Creosote treatments do not protect the entire wood of the pile. The penetration forms a rather fragile shell, with the interior of the pile as subject to attack as before. Any abrasion or puncturing of the shell invalidates the protection. In a report[3] in 1927, it was reported in America that 80% of all holes in creosoted piles through which borers had entered were caused by "dogging" the piles without plugging the holes. Once borers have gained access to the interior of a pile, destruction takes place rapidly. The effect of Limnoria attack is to honeycomb the surface, which permits loss of creosote and facilitates the entrance of borers.

Creosote treatment may not always stop damage by Limnoria,

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(1) reference 1.7
(2) " 1.8
(3) " 1.2

Martesia and Sphaeroma, which sometimes bore heavily into treated wood. If these are present they may damage the creosoted shell sufficiently to permit entrance of species of borers that would otherwise have been stopped.

The first point of borer damage is generally where the impregnation is thinnest, or where damage has occurred. Loss of creosote by flow similar to leaching is most severe in thin spots. Thus, uniformity of treatment is important. The use of cant hooks, rafting dogs, dogs on shoes, or chain slings which may crush the fibres should be prevented on the part of the pile from a few feet below mud line to two feet above high water. Even a point of minute damage may permit entrance of a borer, which can then work in the pile without difficulty.

Framing or boring should be done prior to treatment as far as possible. Treated piles should not be cut for bracing, but treated filler blocks should be used. Bolt holes drilled in the field should be fitted by pouring hot creosote through a funnel, or preferably by pressure equipment made for this purpose. Cuts should be well painted with two coats of hot creosote. Dipping bolts in sealing compound before driving, and coating the heads with sealing compound after driving, are good practices.

Where corewood is exposed to Limnoria access at limb scars, knot-holes and holes left in construction, this condition may determine the effective life of the piling. In areas of high Limnoria activity, the effective life may be as low as ten years. Fortunately, most knot holes and limb scars are at the top of the trees and being driven into the soil are not exposed to damage.

Where such defects would be normally exposed to attack some form of protection over the defect is warranted and should be designed to give a long life.

1.10.3 RESISTANCE OF TREATED TIMBERS

Observations indicate that firstly, water resistance of timber is of value, and, secondly, that copper preservatives that are effective in the control of Teredo, Limnoria and Martesia attack, are of little value in preventing Sphaeroma attack. Results of tests showed that Sphaeroma is able to tolerate copper in quantities that completely prevented attack by Teredo and Martesia. Creosote, on the other hand generally prevented attack by Sphaeroma but this preservative did not prevent attack by Martesia.

In addition, the fact that Sphaeroma is able to burrow into timber containing high concentrations of copper indicates that this marine borer is probably independent of any prior conditioning of the timbers by marine micro-fungi.

Treatment is complicated by the inevitable fact that the Teredinidae borers and Limnoria will be present also. A further complication is that if the Limnoria is the creosote tolerant species, Tripuncta, any treatment must be one that will provide protection against all forms of borer, that is, sufficient copper to combat Teredo species, Martesia and Limnoria, and sufficient water resistance to combat Sphaeroma.

1.10.4 TREATMENT PROCESSES [1]

For proper treatment, timbers should be impregnated by vacuum pressure in treatment plants, by the following methods:

(a) Full Cell (Bethel) Process.

A vacuum/pressure/vacuum process designed to retain the maximum concentration of preservative in the timber, and consisting of the following treatment:-

Initial vacuum.

Injection of preservative (heated if required), without breaking vacuum.

Final vacuum to assist surface drying.

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(1) reference 1.7

(b) Double Treatment.

A full cell process, applied twice, the first with water solution copper chrome - arsenate and the second with creosote furnace oil after the timber has had time to re-dry after the first treatment. There are some plants able to provide this treatment as one integrated process without having to remove the timber from the plant for intermediate re-drying.

(c) Oscillating Process.

A rapidly alternating pressure/moderate-vacuum process designed to treat timbers which are normally difficult to impregnate. Special plant is required.

(d) High Pressure Process.

A Full Cell Process but carried out in special plant designed to take pressures of up to 1.000 lb/sq.in. - a process designed principally for the treatment of very hard refractory timbers.

The Oscillating Process can only be used on timbers above 30% moisture content, the remaining processes can only be used on partially seasoned timbers below 30% moisture content.

The efficiency of any pressure treatment is to a large extent dependent on the type and condition of the timber to be treated. Ideally, permeable timbers should be used as they permit maximum protection to be achieved.

If treated timber is to be used economically and efficiently for harbour works, pretreatment, grading and conditioning are essential.

Because different species of marine borer are able to tolerate different preservative treatments, the treatment of timber to provide maximum protection becomes complex.

If it is known what borers are present, then a specific treatment can be decided on. To find out exactly what borers exist within an area of envisaged port construction means a special survey and examination of collected material by a competent laboratory.

Such a survey may not be possible. It is then prudent to use a preservative treatment to provide protection against all expected forms of borer, and the following treatment schedules will provide such treatment in permeable softwoods or hardwoods.

PROCESS DOUBLE TREATMENT

1st Part: 5% solution of copper-chromarsenate.

Initial vacuum: 25 in. for 60 min.

Pressure: 200 lb/sq.in. for 360 minutes.

Final vacuum: 20 in. for 10 minutes.

2nd Part: (after re-drying of the 1st part down to 30% moisture content). 70% creosote/30% furnace oil.

Initial vacuum: 20 in. for 30 minutes.

Pressure: 180 lb./sq.in. at 180°F for 60 minutes.

Final vacuum: 20 in. for 10 minutes.

Should weathering be unexpectedly heavy, or should Sphaeroma attack be expected to be heavy, the Second Part may be increased as follows:

Initial vacuum: 25 in. for 60 minutes.

Pressure: 200 lb./sq.in. at 180°F for 480 minutes

Final Vacuum: 20 in. for 30 minutes.

An additional advantage of the heavy treatment with creosote/furnace oil is that should a timber get damaged so that untreated timber becomes exposed, the preservative remains, to some extent, mobile in the timber and would tend to creep and partially cover the exposed section. These circumstances do not occur in timber treated with water solution copperchromarsenate alone as the salts are completely fixed within the timber and cannot be leached out.

1.10.5(a) METAL SHEATHING

Use of metal sheathing applied tightly to the timber was the earliest of protective measures if temporary coatings, such as charring the surface or smearing with tar, used by the ancients are excluded.

Sheet metal sheathing requires preparation of piles before driving. Knots and projections must be removed and the surface made as smooth as possible, then an even coating of asphalt-saturated felt is applied, over which the metal is tightly nailed.

Metal sheathing is effective but the cost of application of corrosion resistant metal is invariably higher than concrete casings.

Considerable variation has been found in the service life of copper and copper alloy sheet under these conditions. Muntz metal sheet has been effective for up to 60 years but usually the life is much lower especially where subject to abrasion. Muntz metal must be homogeneous or electrolytic ac tion may be set up. Nails must be of the same metal as the sheathing metal. The sheathing is fixed before the pile is driven. The approximate cost of muntz metal sheathing protection for a pile is $6 per linear foot of pile. Copper and copper alloys appear to be corroded to a greater degree by Turpentine than by many other timbers.

Aluminium sheet has also been proposed for sheathing purposes.

Scupper nailing with iron or steel nails has some merit where labour is cheap. It was used in ancient times, and is still used in isolated instances in Denmark and Germany. Copper nails have not been found to give much protection. Protection is given both by the nail heads and rust encrustation. Borers seem to have an aversion for the iron compounds formed in the wood. Scupper nailing resists Limnoria better than Teredo, for Limnoria bores only about 1/2 inch and in any spot damage is local, but if Teredo gains entrance it penetrates deeply.

Metal armour is not much used now. In some cases sheet metal shells slipped over the pile and footed in the mud have been used, the space between pile and shell being filled with sand or concrete. Metal armouring has given way to encasement with concrete.

1.10.5(b) FIBREGLASS SHEATHING

Fibreglass/polyester sheathing is also a suitable protection for piling which has not yet found general acceptance. The approximate cost of this form of protection is $2.50 per linear foot of pile.

1.10.6 PILE JACKETS (1) (2)

Comparatively recently, a new system has been developed to extend the useful life of creosoted marine piling. This consists of jacketing wooden piles in wet areas with plastic sheeting. The barrier creates an oxygen-deficient environment around the piling that is lethal to marine borers. These sheetings are resistant to abrasion by floating debris and compare favourably with the cost of concrete jacketing. The approximate cost of this jacket is $2 per linear foot of pile.

CONCRETE ENCASEMENT (3) (4)

Invention has been active in devising methods of concrete protection for timber piles. Records of good service have been rare. The failures can be traced mostly to poor material or to poor workmanship. It has required experience to show how insiduous borer attack can be. Recent use of denser material and of pneumatically applied or pressure concrete should give better and more uniform results.

The history of concrete protection is long and only the outstanding developments are possible of mention. As long ago as 1895 cylinders of concrete to enclose cluster piles were used and are still in service. They were formed by driving three timber piles, lowering a steel plate form over them, seating it in the mud, pumping it dry and filling with concrete. In 1900, Holmes concrete cylinders, a similar construction, was developed. Wood stave forms bound with steel hoops were used and left in place to be destroyed by borers. The results were not good due to poor concrete; mud and sand pockets due to failure to seal the bottom; arching of concrete; laitance

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(1) reference 1.3
(2) " 1.13
(3) " 1.2
(4) " 1.5

pockets; excessive water in the concrete; non-continuous pours; failure to carry the encasement far enough below the mud line to allow for scour, and lack of adequate reinforcement to prevent separation of parts where rupture occurred.

Succeeding practice has led to single pile encasement, using forms, precast shells and concrete applied directly to the wood. Black's patent, used from 1908 to 1913, is notable as the forerunner of later removable sectional forms. The concrete was poured above water level in successively added sectional metal forms, each form being secured to the preceding, and all left in place. This was slower than the later type of hinged wooden forms. Results were not good.

The Newsome-Squire process, introduced in 1921, consisted of placing forms around a wood pile and pouring the concrete while driving the pile, thus securing vibration of the concrete.

Precast casings of special design for pile protection are few but the precasting of concrete pipe is so common that a product for pile casing offers no difficulties. A suitable gasket to seal the casing at the bottom and attention to jointing the sections are the only special details.

A patented form of precast casing first used in 1908 was the Koetitz. The patent covered a special design of sectional jacket with a minimum thickness of 2 1/2 to 3 inches. The piles were driven butt end down, and the casings slipped over the top after driving. The space inside was pumped out and grouted. If the pile penetration can be predetermined, lugs can be bolted to the pile to support the bottom of the jacket. Care is needed in handling to avoid cracks which allow rusting of the reinforcement. The cost is relatively high, but the method has given excellent service.

Recently gunite or shotcrete, shot directly on wood piles before or after driving has been used frequently and very successfully.

The approximate cost of a 1" gunite casing for a pile is

$2.50 per linear foot.

During the Second World War, inability to obtain treated piles of sufficient length resulted in the use of large numbers of untreated wood piles 100 to 125 ft. long with shotcrete coatings in the upper 15 to 50 ft., designed to protect the upper portions and extend a few feet into the mud. The coatings were 1 1/2 inches thick, reinforced with No. 12 or 14 gauge galvanised 2"x2" wire mesh, with the top and bottom 6" having additional wrappings of 6 courses of No. 9 wire. It was found advisable to wet the piles before coating, to keep the shotcrete as dry as possible, and to lap the joints in the mesh 6". To prevent slipping of the coatings it was found necessary to notch the piles 1 inch deep by axe cuts having a 4"x4" area, spaced 18" apart in three or four rows.

The piles withstood much harder driving than creosoted piles. As a test, over 5,000 blows on a pile driven to practical refusal, with a 15,000 ft. lb. hammer, failed to cause any damage other than cracking in the top 2 ft. of coating. The coated piles could be handled after curing three days when using standard cement.

This type of pile provided stiffer wharves than did uncoated piles, and had the added advantage of being fireproof. Costs compared very favourably with precast concrete, concrete-jacketted untreated wood, and treated wood piles.

Experiments in Sweden to find a method of decreasing the solubility of portland cement in sea water let in 1935 to the use of a cement gun to apply to wood piles, before driving, a coating of concrete with an admixture of arsenious oxide (As_2O_3). The resulting solubility was claimed to be 1/40 of that of concrete without the admixture. The piles were water-soaked before coating, unless coated just after cutting. Initial set took place in 1 to 5 minutes.

Excellent results were obtained in driving piles 39 ft. long, coated for 15 feet.

Pressure-jacketted concrete encasements can be applied to wood piles before driving, by use of pneumatic pressures of 5000 to 8000 lb./sq.ft. in air-tight metal forms equipped with pressure heads for air and concrete connections. Reinforcement may be used. This method is controlled by the Presscrete Co.Inc.

A review of armouring and jacketting methods of pile protection shows metal armouring gradually fading out of the picture. Concrete jacketting in turn has shifted from underwater construction to applying the protection before the pile is driven. With better understanding of borer aggressiveness modern processes of increasing concrete density and resistance to sea water, and jacketting open to inspection before driving, concrete offers increased service for pile protection.

1.10.7 PRETREATMENT OF AUSTRALIAN TIMBERS [(1)]

Preservative impregnated timber for marine piling and marine construction generally, has been well established for many years particularly in North America but has not been developed in Australia due to the abundance of timbers of relatively high natural resistance and the absence of treatment plants.

The installation of commercial plants in recent years and the present availability of treated timber now requires further examination of the potentialities and competitive position with alternative materials and methods of construction.

Unfortunately, information on the performance of treated wood in maritime installations under Australian conditions is very limited.

The potential use of preservative impregnated timber can be considered in three groups related to commercial treating practice.

1.10.7)a) MARINE PILING

The impregnation of the sapwood of commercial hardwood round timbers will permit the use of woods of relatively low natural resistance, for marine piling. While the truewood of such timbers

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(1) reference 1.8

cannot be treated by normal methods, the sapwood of approximately one inch thickness can be impregnated by both oil-base and water soluble type preservatives.

It is desirable that the service life of marine piling should be of the order of the functional life of the structure. On this basis, it is considered that the objective for treated timber should be a service life of 40 years or more under the particular conditions of exposure.

This period appears to be a practicable attainment but further research would be necessary to enable the estimation of the probable service of present preservatives.

A cost comparison of impregnated commercial hardwood and turpentine pile sections shows that a turpentine pile costs approximately $1.12 per linear foot, while impregnated commercial hardwood piles cost approximately $1.35 per linear foot, a cost differential of $0.23 per linear foot or approximately $14 for a 60 ft. piling length. Thus it is essential that a service life advantage must be gained from the use of the treated hardwood piling before it can be considered an economic proposition given equal availability of both timbers.

1.10.7(b) SAWN STRUCTURAL TIMBER

The treatment of Radiata Pine, Coachwood, Sassafras and other absorbent woods will permit the use of these timbers for bracing, landing steps, pontoons, floating fenders, swimming pool grids, slipways, small jetty construction and similar uses.

While high pressure techniques may extend the range of treated species available, present commercial treatment is restricted to the more absorbent timbers. Turpentine which is largely used for these purposes is not entirely satisfactory as a sawn timber since the less resistant core wood has a limited life where exposed to Limnorid and Teredinid borers, and treatment of sawn structural timbers is expected to fulfil a need for improved performance in conditions where sawn Turpentine sections are used at present.

If an 8"x4" sheathing timber is considered for comparison purposes, the costs of the various materials per 100 super feet are:-

(a) Turpentine - $40.

(b) Commercial hardwood treated with Tanalith C - $28.

(c) Radiata pine treated with Tanalith C - $45.

The relative merits of the various materials as economic forms of marine construction, depends on the service life obtained under the prevailing conditions.

1.10.7(c) IMPREGNATED PLYWOOD

Some plywood manufacturers in N.S.W. are now producing preservative impregnated marine plywood. Such treated plywood can be considered substantially as a different material to the usual marine plywood, which is normally constructed of wood of low natural resistance to both marine borer attack and fungal decay. The use of normal anti-fouling paint coatings on this plywood should give extended life to plywood boats and punts.

1.10.8 TYPES OF PRESERVATIVE IN USE

The service life is affectdd appreciably by the type of preservative used, initial retention of preservative after treatment, the distribution of preservative, the rate of leaching after immersion and the intensity and type of marine borers.

These factors require consideration in evaluation of the economic efficácy of the preservatives.

The preservatives now available cover a comparatively wide range and can be considered in the following groups:-

(a) Creosote and Coal-tar creosote mixtures.

(b) Water borne metallic compounds fixed in the wood by chemical action. (Chromatdd copper arsenate, acid copper chromate, etc.)

(c) Oil soluble toxins.

(i) Organo-metallic salts (copper naphthenate, copper pentachlorphenate, etc.).

(ii) Organic biocides (D.D.T., chlordane, pentachlorphenol, etc.)

The effectiveness of impregnation treatments can be improved by additional surface coatings and other treatments to retard loss of preservatives but the cost of some effective coatings of this type is appreciable. Cost considerations at present limit such coatings to thick coal-tar or bituminous coatings of short life, but the possible use of polythene and similar wraps may prove reasonably economic.

Creosote and creosote/coal-tar solutions have been used very extensively for impregnation of softwood species for marine construction, particularly in North America.

The present position is that these are the only preservatives recommended for marine construction by the American Wood Preservers' Association. Exposure tests in the U.S.A. have shown superiority of creosote and coal-tar creosotes over alternative preservatives and indicate generally that a creosote coal-tar solution is the most reliable preservative developed to date.

Tests by the Institution of Civil Engineers 1947 indicate that "Within the range of experiments, no process for the preservation of timber was found more satisfactory than that of impregnation with creosote;" but recent reports suggest that a proprietary acid copper chromate solution may prove equal or superior to creosote.

The efficacy of creosote oil from different sources varies to some extent with respect to toxicity and to differential leaching rates but the optimum requirements for Australian creosotes is not known. Variation in resistance by different marine borers also affects the performance.

Extraction tests have been carried out on treated sapwood to indicate the minimum creosote content at which attack occurs by the high salinity teredinid borers in Sydney Harbour. The creosote content of wood found subject to general attack was 3 to 4 pounds per cubic foot (Spotted Gum) and 2 1/2 to 4 pounds per cubic foot (Wollybutt).

It is usually observed that Limnoria attack precedes that of Bankia or Teredo where these borers are present, the minimum creosote content for Limnoria resistance being higher.

Tests indicate that creosote - coal-tar solutions in 70/30 proportion gave a superior result to straight creosotes in resistance to Limnoria.

Consideration has been given to the use of specific additives to creosote to increase the resistance to Limnoria. Preliminary tests have indicated that D.D.T., Chlordane and other insecticides are effective in preventing Limnoria attack.

In tests at Bantry Bay (Sydney), Martesia did not initially attack samples heavily impregnated with creosote (25 pounds per cubic foot); but after three years exposure, attack commenced at localised areas of apparently lower concentration. Martesia attack occurred at such areas without any associated teredinid or limnorid attack.

Atwood and Johnson state that "Martesia seems to be less affected by creosote than other molluscan borers, as is shown by its having sunk a barge built of heavily creosoted timber (24 pounds per cubic foot) in a few months."

The use of creosote impregnated timber in areas where Martesia occurs is not recommended.

The low salinity teredinid, Nausitora has been observed to attack pine with a high creosote content but quantitative information is not available at present.

Until further information is available, the use of creosote impregnated timber is not recommended in areas where Nausitora are prevalent.

1.10.8(a) RESULTS OF TESTS ON POLE SIZE TREATED TIMBERS

A series of pole size samples of commercial hardwoods were impregnated with creosote by the "hot and cold" bath process, and were exposed in Sydney Harbour. Sapwood penetration was generally good, with creosote contents ranging from 12 to 29 lbs. per cubic foot, based on sapwood volume. Standard K55 creosote was used. The behaviour of the treated samples was:-

(i) Spotted Gum (Eucalyptus maculata). All samples with 12.4 to 23 lbs. per cubic foot net retention failed within five years as a result of general attack by teredinid and limnorid borers in the treated section. It was apparent by visual observation that the creosote had leached very rapidly.

(ii) Blackbutt (Eucalyptus pilularis). One sample at 12.7 lbs. per cubic foot showed failure in patches at 5 years and general failure of treated sapwood at 15 years. A further sample at 18.0 lbs. per cubic foot showed variable teredinid attack of treated sapwood rated at 10-20% failure.

(iii) Bloodwood (Eucalyptus corymbosa). All three samples with 15.2 to 20.0 lbs. per cubic foot net retention showed 2-3% of surface attacked in patches at 10 years but general failure occurred at 15 years.

(iv) White Stringybark (Eucalyptus eugenioides). One sample with 25.8 lbs. per cubic foot showed negligible attack at 10 years but general failure of treated sapwood occurred at 15 years.

(v) Yellow Stringybark (Eucalyptus muelleriama). One sample with 16 lbs. per cubic foot showed 1-2% of surface attacked in patches at 15 years, the general condition being good.

(vi) Silvertop Ash (Eucalyptus sieberiana). One sample with 26.6 lbs. per cubic foot showed 1-2% of surface attacked in patches at 15 years, the general condition being good.

The variation in performance shown, even though based on relatively few specimens, is a warning against indiscriminate acceptance of timber species and indicates a need to evaluate each species individually. The occurrence of patches or pockets of low resistance suggests a lack of uniformity which might be overcome by pressure treatment.

A further interesting result was obtained with similar pole size samples of pressure impregnated Turpentine. Net retention was 25 lbs./cu.ft. After 14 years' exposure, these samples were without any attack of the treated wood by teredinid or limnorid borers. At this location, untreated sapwood of Turpentine is usually effectively destroyed in about 2 years.

Although excellent results are indicated with Turpentine, treatment of this species may not be warranted. Under conditions where the truewood is resistant to attack, the only advantage of the creosote impregnation is to retain the sapwood intact. Providing that the truewood section is structurally adequate, the retention of the sapwood is not essential.

In areas where Sphaeroma are prevalent, treatment may be warranted but the use of the Floating Collar is generally more economic where Sphaeroma control only is to be considered. Treatment of Turpentine piles of small diameter should be considered not only to retain a greater section but also on account of the generally lower resistance experienced in small diameter piles.

A source of failure of Turpentine piles resulting from attack of truewood of low resistance exposed at knot holes and limb scars is not eliminated by creosote impregnation. The exposed truewood does not absorb the creosote.

Protection of limb scars and knot holes is also important with any form of impregnation treatment. Piles should be selected free of such defects over the exposed portion of the pile or other methods should be adopted for protection.

1.10.8(b) TREATED PILE SECTIONS UNDER TEST

Some pile size sections of commercial hardwoods having bark intact before treatment were observed over a period of 15 years.

Creosote absorption occurred both in bark and in the sapwood with a relatively high overall retention, but it was not practicable to differentiate between the content absorbed by bark and sapwood.

With all the three species observed, Eucalyptus muelleriana, eucalyptus goniocalyx, eucalyptus botryoides, no attack occurred in any sample over the 15 year period where the bark was retained intact. Where part of the bark was stripped by mechanical damage after treatment, moderately heavy attack by Bankia species occurred in some cases. Some surface attack of the treated bark by Limnoria occurred.

In view of the practical difficulty in maintaining bark intact and the difficulty of adequate treatment of the sapwood, the retention and treatment of the bark is not recommended at present. However, further investigation of treatment procedure and means of bark retention may provide an improved treatment.

1.10.8(c) RESULTS OF TESTS ON SAWN TIMBERS

Information on the marine borer resistance of creosote impregnated truewood in sawn sizes when exposed under Australian conditions, is limited mainly to test samples.

(i) Oregon pine (Pseudotsuga taxifolia) is difficult to impregnate but finds a special use for floating fenders and similar applications where buoyancy is required.

The American Wood Preservers' Association recommends a net retention of 12 lbs. per cubic foot of creosote or of creosote/coal-tar solution. It is essential to incise the surface before impregnation to ensure adequate treatment.

The restricted penetration limits the potential service life of the treated timber of this species and generally other more absorbent timbers would give superior results.

Some impregnated Oregon Pine was produced in Sydney in 1945 for use as fenders for the Captain Cook Graving Dock. The timber (12"x12" and similar sections) was incised before pressure treatment at 90 lbs. per sq. inch. At this pressure the penetration was variable and inadequate to provide marine borer restance. The fenders exposed in sea water suffered progressive attack and were condemned after 10 years.

Where the size or construction of floating fenders and similar components is suitable, retreatment of the timber before appreciable damage occurs should be considered. With Oregon Pine in particular, but generally with all sawn timber, all cutting should be done before treatment in order to avoid exposure of any untreated wood subsequently.

(ii) Sassafras (Doryphora Sassafras) is not regarded as a constructional timber and is typical of the more absorbent N.S.W. timbers suitable for impregnation and test purposes.

Tests were carried out in Sydney Harbour covering a range of three types of creosote with different distillation ranges and with additions of 0.5 and 2.0 per cent of D.D.T. in the creosote. Net retention of creosote ranged from 16 to 26 lbs. per cubic foot.

Only two of the thirty-six treated samples show light but significant attack by Limnoria. After 5 years' exposure, no sample containing D.D.T. was attacked by Limnoria.

It was observed that the frames of sawn 4"x1" Turpentine to which the samples are attached had shown greater deterioration than any of the impregnated samples. In some cases, up to 50% of the cross section was lost in 5 years, destroyed by Limnoria.

(iii) Radiata or Monterey Pine (Pinus radiata) is readily available and should find extensive use in marine construction. No local data on resistance of creosote impregnated Radiata Pine appears to be available, but good performance is reported with this species in New Zealand and with similar species in the United States.

It appears to be comparable with Sassafras in absorption and leaching characteristics. Initial retentions of up to 30 lbs. per cubic foot are obtainable but it is not known whether the service life is proportional to the initial creosote retention.

1.10.9 CHEMICAL PRESERVATIVES

Study of the use of metallic compounds against marine borers have included observation on the toxicity of solutions in which larvae or infested wood is exposed and on the performance of wood impregnated with such toxic salts.

Soluble salts impregnated in wood provide limited protection even though the salts are very toxic to animals immersed in the solution. On the other hand, it has been indicated that compounds of toxic elements impregnated in wood are non-toxic if the solubility is so low as to overcome leaching. If it is necessary that such salts should have a low but definite solubility, then this factor must limit the potential service life of treated timber.

A similar type of action occurs with anti-fouling paints. If the paint is such that leaching occurs rapidly, then the useful life is limited. On the other hand, if the toxic compound cannot be leached from the paint film in excess of the minimum rate required for protection, then marine surface growth becomes attached.

In practice, it is required that the metallic compound impregnated in the timber should be relatively insoluble in order to obtain a reasonable service life.

In tests[(1)] of impregnated wood blocks, it has been found that the decreasing order of effectiveness of "insoluble" compounds against Teredo was:-

Copper
Silver
Nickel
Lead
Mercury
Iron

Zinc and Cadmium were ineffective.

The decreasing order of effectiveness against Limnoria was:-

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(1) reference 1.8

Copper

Nickel

Mercury

Lead, Zinc, Cadmium, Iron and Silver were practically ineffective.

Arsenic compounds have also been shown to be effective but further comparative tests are necessary to establish the relative value. The minimum copper content required to prevent attack by Teredo appears to be about 0.06 lbs./cubic ft.

Impregnation of sapwood of Eucalypt piles has occurred unintentionally where piles have been sheathed with muntz metal and copper sheet. The diffusion of copper salts from the corroding metal has resulted in a skin of effective impregnation of about one quarter inch thickness which has provided effective protection to the otherwise non-resistant wood where the metal sheet was removed. This action is in part responsible for an effective life of 70 years obtained for about 70 per cent of the muntz metal sheathed Ironbark piles in the berth at No. 4-5 Circular Quay, Sydney.

1.10.10 AVAILABLE COMMERCIAL TREATMENTS

At present, commercial treatments include several water soluble inorganic salts "fixed" in the wodd by treatment. These are mainly mixtures of copper, arsenic and chrome salts known under various trade names and widely used as preservatives against fungal decay and insect pests.

These chemicals are not established as standard preservatives for marine timbers. As stated previously, recommended standards in the United States for piles and timber in coastal waters cover the use of creosote and creosote coal-tar solutions only.

However in view of the limitations of creosote, particularly in areas where Nausitora and Martesia are prevalent, the use of preservatives of this type appear to be promising for the treatment of round hardwood piles and of sawn timbers.

The formulation of some of the proprietary preservatives have varied since first introduced and some confusion in evaluation has resulted. Some information on preservatives of this type is set out below:-

1.10.10(a) CELCURE (ACID COPPER CHROMATE) [1]

This preservative was invented in Scotland in 1926 and progressive improvements have been made since then. The composition consists of potassium dichromate, copper sulphate and chromium acetate with or without acetic acid. Boric acid may be used instead of acetic acid, and sodium arsenate may also be incorporated in the mixture.

The acidic conditions retain the salts in solution during impregnation but the toxic compounds are made relatively insoluble by treatment. The variation in composition may be responsible for some inconsistencies reported in tests of this material.

Hunt and Garratt (1938) state that "Contrary to patent claims, it appears to be ineffective against marine borers."

Tests reported by Blew (1949) have shown that wood thoroughly impregnated with at least one pound of Celcure per cubic foot has some resistance to marine borer attack. The protection provided is rated as much less than that provided by standard creosote treatment.

Tests by the U.S. Forest Products Laboratory reported by MacLean (1941) showed occasional slight attack in some of the Celcure treated samples after exposure for one year at Pensacola. Net dry salt retention varied from 0.41 to 1.42 lbs./cu.foot.

Exposure at Panama of Celcure treated test blocks with 0.66 to 4.0 lbs. per cubic foot were reported by Richards. After 12 months exposure, moderate Teredo attack occurred in the lowest concentrations with slight to very slight attack at 2.0 lbs. per cubic foot.

Bryan has reported on tests of Douglas Fir treated with creosote and with Celcure, exposed at Singapore. The composition of the Celcure solution was given as:-

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(1) reference 1.8

Potassium dichromate	5.6%
Copper sulphate	5.0%
Chromium acetate	0.53%
Water	Remainder

Both plain and incised planks (12"x6") were treated with Celcure at 2.6 and 4.8 lbs. of solution per cubic foot respectively on a gross retention basis.

After exposure for 7 years, although none of the samples was absolutely immune from attack, the benefit of incising was obvious and the celcurised samples were considered superior to the creosoted ones. Three of the twelve uncised celcure specimens showed signs of attack by Martesia, while all the incised celcurised specimens were sound.

On the basis of these tests, the Institution of Civil Engineers state that Celcure "might be equally as effective" as ordinary coal-tar creosote.

In view of the difficulty in obtaining adequate penetration in Douglas Fir and improvement in treating practice since the samples were treated, the results appear promising.

1.10.10(b) TANALITH C (CHROMATED COPPER ARSENATE)

This preservative is stated to consist of potassium dichromate (45%), copper sulphate (35%) and arsenic pentoxide (20%) and is impregnated in the wood as an aqueous solution by vacuum/pressure methods. The toxic compounds "fixed" in the wood by treatment are relatively insoluble and have a high resistance to leaching.

It is similar to the preservatives "Ascu" and "Greensalt K", which consist of potassium dichromate (56%) copper sulphate (33%) and arsenic pentoxide (11%).

Radiata pine samples impregnated with Tanalith C were exposed in Sydney Harbour for a period of two years. The treatments range from 0.5 to 3.0 lbs. of dry salts/cubic foot. Under conditions of moderately severe attack by Bankia, Teredo and Limnoria, no attack occurred in any of the treated samples. Untreated controls immersed between October and March were destroyed in two to three months.

This treatment is also considered to have good potential.

1.11 INSITU TREATMENT OF TIMBER

1.11.1 FLOATING COLLAR FOR PILES (1)

A method of protecting piles involving the use of a floating collar, was invented in Australia. The method is suited to the treatment of piles insitu, for attack by Sphaeroma or Limnoria. The method has only been applied to round piles, which are widely used in America and Australia. British Engineers prefer to use squared timbers with its easy and neat joints.

Both Sphaeroma and Limnoria are surface borers and can be eradicated by surface application of toxins either by spraying or by the use of a method such as the floating collar. The floating collar method is more efficient than spraying in securing better penetration and having the advantage of treatment for the full intertidal zone.

The floating collar method has been in use in the Port of Sydney for about 30 years and has proved to be very effective and economic under these conditions. While prior to the advent of this method, the average life of Turpentine piles from Sphaeroma attack with Limnoria had been determined as 32 years, it is now evident that the effective life will reach more than 70 years and is generally better than the functional life of the structure.

The floating collar consists of a hinged cylinder supported by floats, and such that the collar may be moved from pile to pile. Approximately one gallon of special grade creosote is placed in the collar, and the creosote floats on the water surface and is confined by the collar. Over a period of 24 hours during which the collar is left on the pile, the creosote covers the whole intertidal zone and kills Sphaeroma on the pile surface.

In time, further lodgement of Sphaeroma occurs and the procedure is repeated. The period between retreatments varies with

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(1) reference 1.6

the intensity of Sphaeroma in the area and the degree to which control has been obtained. Where the program is designed to eradicate Sphaeroma over a wharfage area rather than for isolated piles, the period between retreatment can be progressively increased. In the Port of Sydney, some areas which were initially treated at 9 monthly intervals now only require treatment at 3 or 4 yearly intervals and have been altered from areas of heavy infestation to mildly active areas.

The collars are now made of fibreglass reinforced plastic instead of the original steel construction, as this is less expensive, has a longer life, requires less maintenance and is more easily handled.

The use of this method is restricted to piles which permit free movement of the collar and are not encumbered with bracing and fendering. Larger floating booms may be used for groups of piles or small structures.

The major disadvantage of the system is the need for periodic retreatment and the fact that some cumulative damage, however small, will occur. Some further investigation is required for areas of very heavy Sphaeroma concentration to introduce toxins having a more prolonged residual effect than the simple creosote immersion.

A prerequisite for this method of treatment is that the wharf design should permit ready access to the piling so that floating collars can move freely with the tide.

The use of this method of treatment is restricted, and it is not a universal remedy for preventing destruction of piling by all marine organisms. Many piles on which inter-tidal destruction has been arrested by the floating collar treatment, continued to deteriorate below the effective reach of this system.

The approximate annual cost of this form of treatment is from $0.30 to $1.20 per pile, depending on the stage of control of the infestation which has been attained by the treatment.

1.11.2 PILE ENCASEMENTS

In areas of high marine borer concentration where frequent treatment may be necessary, the use of a more permanent casing or sheathing may prove more economic. The cost of placing such casings is appreciably influenced by the limitations of working with the tides, working under a wharf and working from a scow or platform.

A further important aspect is the need to ensure good protection at the lower end. Casings placed over the sapwood permit attack by teredinid borers and by Limnoria which leaves the casing as a weak shell. As a general rule, it is necessary to remove the sapwood and expose the truewood before placing any intertidal casing.

This aspect also applies where the wood of low resistance is covered by casing in Limnoria areas; in such cases, as indicated by the general condition at the intertidal level, it is advisable to apply a full length collar to silt level rather than protect the intertidal level only. Otherwise, progressive Limnoria attack proceeds under the concrete shell.

It is also advisable to remove any surface marine growth before placing the casing. The eradication of Sphaeroma or other marine borers before placing of the sheathing is not considered necessary but usually a floating collar or a scrape and spray of creosote is adopted to clean piles or other timber preparatory to casing.

Concrete casings are most commonly used for intertidal protection and these may be applied in a wide variety of ways. Steel reinforced casings may be adopted to strengthen the pile and light wire mesh may be used to ensure adhesion. Usually corrosion of the reinforcing is not appreciable for this condition. Plain concrete or mortar has proved sufficiently strong to withstand minor pile vibration and movement but should be of good quality.

Such casings include retained cylindrical forming such as precast concrete, earthenware pipe, fibro-cement and "Armco" sections, the annular space being filled with cement mortar, tar-cement compounds, etc. Usually where durable formwork is retained, the cost of protection is higher than desirable.

In order to apply economic intertidal casings it appears necessary to be able to work effectively from a floating raft or a scow rather than any fixed platform, to work at all stages of the tide and without assistance of a diver, and to place concrete underwater without segregation and to use recoverable or low cost formwork. A sulphate resisting cement is preferred for durability. Recoverable fibre glass plastic forming may be used for casings, and this method can be excluded for sub-tidal treatment.

The use of fibreglass reinforced cement mortar[(1)] has proven effective and economic for parts of structures which are not suitable for chemical treatments or casings and which are above low tide level, such as stair and slipway sections. In this method, after cleaning, the surface is coated with neat cement paste and then wrapped with fibreglass bandage. The surface is then plastered with quick setting cement mortar. A plastic bandage is then used for temporary protection.

1.11.3 KNOCKER-BLOCK SYSTEM

The "Knocker Block" method of Sphaeroma control is understood to have been first used in Brisbane at Birt's Wharf, Newstead. The method consists of three or four treated oregon blocks about 3"x3"x3" which are nailed to a galvanised hoop iron circle around the pile. As the wood floats up and down with the tide, the blocks knock off any Sphaeroma lodging on the surface of the pile.

The method, although primitive, is basically effective, particularly with new piles, but lodgement of Sphaeroma in fissures, checks and irregularities results in ultimate damage.

1.11.4 OTHER METHODS OF TREATMENT

Electrolysis of the water around the pile to free chlorine

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(1) reference 1.8

has been proposed but experiments indicate that the chlorine was removed by water currents and that Teredo merely ceased feeding while the concentration was high. Frequent repetition of treatment would be needed to kill the swarm of new larvae coming with each tide.

Reduction of salinity by barriers to keep salt water out of estuaries, rivers and portions of bays has been suggested, to create conditions under which the borers cannot live.

Toxic treatment of water is a possibility, using slowly soluble toxics near piles, by attaching tubes to the pile. There are a number of toxics which would kill both larvae and adult borers of both types in the immediate vicinity of the infested structure. It would be necessary to repeat the treatment every 2 to 4 weeks during the breeding seasons. But the toxics would also kill other marine life there, as well as in other regions where washed by tides, currents and winds, so that environmental complications would ensue.

Most of the other wood preservatives in use are salts that leach and are not suitable for submerged piles. Many arsenic, copper and other highly toxic salts in soluble and insoluble form have been used experimentally, but have failed to protect marine piles. Salts insoluble in water and soluble in the digestive juices of higher forms of life have been found ineffective, possibly because the digestive apparatus of borers does not produce chemical substances to make the salts toxic.

It is possible that the plastics industry will develop some method of providing an economic resistant coating.

The use of depth charges or underwater dynamite explosions near wooden structures affected have proved successful, although here again, other marine life suffers and the kill is only in the immediate vicinity of the explosion. It is, however, one of the most successful methods of eradication.

1.12 TERMITE ATTACK IN MARINE STRUCTURES [(1)]

1.12.1 OCCURRENCE OF TERMITES

The types of structures, and the areas with which harbour authorities are concerned, often provide ideal conditions for termite infestation. The typical large masses of heavy timber, abundance of moisture, high humidity, limited ventilation and difficulty of access permit extensive damage in areas where termites are prevalent.

Termites occur in all the states of Australia - mainly in tropical and sub-tropical areas - but with important species in the warmer temperate areas. Only a limited number of these cause damage to wharf structures.

The Darwin termite, Mastotermes darwiniensis, is the most destructive Australian species and commonly occurs in tropical areas extending from North Queensland to North-west Australia.

Coptotermes acinaciformes is the most important economic wood-eating species and occurs in nearly every port in Australia in which termites are found. The life history and habits of this species are typical of most termites likely to be found in wharf structures.

1.12.2 BIOLOGY OF TERMITES

The familiar swarm of flying ants which are often seen in early summer are the winged mature males and females which have left the nest in a colonising flight. These reproductive forms settle on the ground, shed their wings and pair off with the opposite sex. When a suitable nesting place is located, the pair start a nest and become king and queen of a new colony.

All known species form colonies which may develop to include up to millions of individuals. These are mainly workers which build the nest and galleries, tend eggs and young, gather food and feed other castes which cannot feed themselves. The workers are responsible for damage to wood. Soldiers represent about 2 or 3 per cent of the colony and guard it against other insects, particularly

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(1) reference 1.10

ants. In addition to juvenile workers and soldiers, the reproductive caste is also present, either as the immature nymphs or as the winged reproductives (alates) prior to the colonising flight.

Most species can produce supplementary reproductives when the queen dies or when a part of the colony is severed from the nest. Selected nymphs develop functional reproductive organs without growing wings or leaving the colony. A colony which is broken up by repair operations may thus form a number of separate colonies.

In view of the formation of supplementary reproductives, there appears no reason why termite colonies should not last for possibly some hundreds of years providing that food is available.

Moisture is one of the most important items regulating termite behaviour. Most species must have access to sufficient moisture and usually live in the ground or otherwise maintain a ground connection. These are referred to as subterranean termites or soil dwellers. Coptotermes acinaciformis does not require soil contact and in wharf structures usually obtains moisture from rainwater or washing water, sea water, leaking pipes, drains, condensation water, etc. Large termite colonies of this species have been found in isolated mooring piles, in floating timber pontoons and other floating craft.

Dry-wood termites which are reported to live normally in timber with a low moisture content also occur in Australia. One such species, Cryptotermes primus has been recorded as causing damage to construction timber in the Queensland coastal area.

Galleries of mature colonies may extend over several acres and in the case of Mastotermes, galleries have been observed to extend up to 100 yards. Observation of termites in part of a structure thus warrants an extensive search in other parts of the structure and in adjacent areas.

Termites prefer warm conditions and are more active in summer than in winter.

Only a few of the wood eating termites habitually attack sound seasoned timber. The majority feed on living trees, rotten wood or on weathered wood surfaces. It appears that even these species which usually attack seasoned wood prefer decayed wood or wood with some fungal growth present.

Termites eat dead or superfluous members of the colony and this habit has been regarded as an important means of distributing poison throughout a colony. Another notable habit is the grooming of the bodies by licking one another: poison dust particles adhering to the surface are thus distributed through the colony.

1.12.3 DETECTION OF TERMITES

Many timber wharf structures are termite prone and the main task is to detect and eradicate the infestation before any significant damage occurs. The first step is to trace the extent of the colony, the location of the galleries and, if possible, the location of the nest.

The nest is usually small and inaccessible but the presence of termites is shown by mud galleries over the surface of the structure or as tunnels in the timber members. These should be traced back as far as practicable without undue disturbance. Where activity is suspected, the surface of the tube or wood can be carefully opened with a knife, or the wood can be bored to connect a tunnel. If a small section of a large gallery is broken, termites (usually soldiers) will appear at the break and repairs are effected in a short time.

A clicking noise made by soldiers can be heard where a good number of these are present. If greatly disturbed, a large colony will make a noise something like an electric motor.

Much of the success in detection depends on the personal skill and experience of the termite control operator.

1.12.4 METHODS OF ERADICATION

The most successful method of eradication of termite colonies involves the injection of white arsenic powder into termite galleries in such a manner that the normal activities of the termites are not disturbed. The fine dust is usually carried back to the nest and distributed through the colony by the habit of grooming of termites and also as a result of cannibalism. The success of this technique depends on a number of factors:-

(a) Material. White arsenic powder (Arsenic trioxide) pulverised and screened to pass B.S.mesh 200 is used either directly or as a mixture with about 10 per cent of screened Paris Green (Copper aceto-arsenate). Paris Green is used primarily to provide a distinctive green colour for identification and other materials may be used for this purpose. The powder should be dry and free-flowing.

(b) Blower. A robust metal air blower which can be operated with one hand is preferred for injection of the dust. Flexible polythene oil cans or wash bottles or powder blowers are also used. It is desirable that the blower should permit small quantities to be floated into the galleries as a fine dust.

(c) Application. Only a small quantity of powder is necessary providing this is carefully applied, the rate being about 20 to 30 injections per quarter ounce. The largest galleries are selected and injected with the dust. If the nest is located this can be treated directly or by several galleries close to the nest. The gallery is opened, small amounts are blown gently along the tube and the break is then sealed with paper, clay, wood plugs, etc.

(d) Reinspection. The treated colony should be inspected after a period of atleast 14 days and a careful check made for living termites.

(e) Treatment Period. Treatment by this method is usually most successful during summer months when termites show greatest activity. This period is preferred when only a limited annual period is available for an inspection and treatment programme.

(f) Precautions. Persons using arsenic should be made aware of the extremely poisonous nature of the chemical and should be subject to medical examination where they are regularly employed on this work.

As a preliminary guide under average conditions, inspection of wharf structures is warranted at about twelve monthly intervals. A better guide is obtained by checking the time for detection of an infestation. Termites will become progressively more difficult to find in structures which are regularly inspected and treated. Structures in which proper precautions have been taken will also require less attention than structures in which these have been neglected. The inspection program may then be varied to obtain optimum results on the basis of costs of detection in relation to probable costs of damage if undetected.

In the case of wharf structures, best results have been obtained by systematic inspection with some variation of frequency with the history of the structure and of the area.

1.12.5 USE OF RESISTANT TIMBERS

The ultimate method in prevention of termite damage is the use of some alternative material such as concrete or steel. However, in many cases a satisfactory engineering solution will involve the use of timber, and it is necessary to adopt methods which will minimise possible termite damage.

No timber is immune to attack by termites, but the heartwood of some timbers is highly resistant. The resistance to damage is greatly reduced where some fungal infection has occurred, and at times quite extensive attack will occur in "resistant" wood.

Resistant timbers include:=

Ironbarks Eucalyptus crebra

" paniculata

" siderophloia

" sideroxylon

Jarrah " marginata

Turpentine Syncarpia corymbosa

Grey box Eucalyptus hemiphloia

Yellow box Eucalyptus melliodora

Red gum Eucalyptus rostrata

Where facilities are available, impregnation of timber with coat-tar creosote or with water borne preservatives such as Tanalith C, Celcure and Boliden salts provide a more dependable procedure both for prevention of decay and for termite infestation.

The heartwood of most commercial timbers is not sufficiently absorbent for economical treatment and the availability of treated sawn timbers is limited to species such as Radiata Pine and Sassafras. The increased durability provides a substantial advantage where sawn timber is to be used in termite susceptible positions.

1.12.6 SERVICE LIFE OF TIMBER

Damage to the deck structure of wharves by termites may be very extensive. Where adequate preventive and control measures have not been adopted, extensive general repairs have been required within 30 years of construction. On the other hand, adoption of a regular program of termite control will ensure near immunity for long periods at low cost. If care is taken in design and construction details and necessary preservation techniques are adopted, the typical timber wharf substructure with concrete decking as used in New South Wales, will give service without major repair for as long as it is likely to be required.

Damage of the timber results from fungal decay as well as termites. Both are dependent on the presence of moisture and methods of prevention are usually best considered together.

The extent of damage is particularly affected by the type of decking used and whether or not the deck area is covered by a shed structure. Concrete decking usually provides better protection to the deck sub-structure.

Brush box (Tristania conferta) was adopted for general timber decking of wharves in the Port of Sydney in about 1910. This species was selected in view of its resistance to wear and splintering compared with other commercial timber species. This practice continued until about 1945, when reinforced concrete decking was adopted generally for reasons of wearing properties, durability and cost.

In an open wharf apron where no preservative treatment is carried out, an average service life of 12 years (varying from 10 to 15 years) is normal, the usual life being limited primarily by fungal decay at butt joints and to a lesser degree by fungal decay at seatings on girders. Where decking is laid on old girders, from which previous decking had been removed owing to fungal decay, subsequent replacement has been necessary after about 10 years.

1.12.7 PRESERVATIVE TREATMENTS

In the Port of Sydney, regular creosote spray treatment of Brush box decking has been carried out with the object of saturating seatings, butts and other fungi susceptible positions with a wood preservative. Complementary to this application, regular inspection and eradication of termites has also been carried out.

Brush box decking replaced over old girders and treated in this way at about 18 months intervals remained in sound condition with negligible replacement for 23 years, however the surface wear at this stage was appreciable and necessitated replacement.

The normal treatment involves periodic spraying of the seatings of the decking on the girder from the underside of the deck. The topside is sprayed similarly by using a needle-spray between deck planks over the girders and particularly at the butt ends. Deck planks are preferably laid with a gap of not less than one-eighth inch between butt ends to permit penetration and debris which may be left between planks is saturated with a preservative.

During this procedure all other seatings, heads of piles, facing timbers and kerbs are similarly sprayed with coal tar creosote. Where termite activity is appreciable, the use of a creosote/chlordane or creosote/dieldrin mixture is an advantage.

The value of preservative treatment of this type was illustrated by two wharf redecking jobs carried out in 1955. One privately maintained structure with typical timber headstocks, bearers and Brush box decking was repaired as necessary and redecked with standard concrete decking after 33 years of service. This structure had not been subject to any preservative treatment and termites were active in 37 out of 51 bays. The cost of repair and redecking was $[illegible]72 per square.

A second structure which had been under preservative treatment for some 20 years was similarly redecked with concrete after 42 years service at $110 per square. Only two minor termite infestations were located and only a limited amount of the deck substructure required renewal.

The difference in renewal costs ($142 per square) is regarded as a typical illustration of the value of preservative treatment.

Brush box decking was originally laid over a malthoid covering of the timber girder. Subsequent experience has shown that this type of covering does not prevent fungal decay of the girders. As a result of perforation by fastenings and by wear from movement of the timber decking under traffic, moisture penetrates the covering and is retained on top of the girder. This procedure accentuates conditions favourable to fungal decay and to termites and has resulted in extensive damage of durability class I timbers in 25-30 years.

The use of the malthoid also increases the difficulty of applying preservative to the tops of the girder and to the seating of the decking. It is regarded as more of a hindrance than a help when preservative solutions are regularly applied. However, it is not uncommon to find unblemished surfaces under the malthoid where initial and periodic creosote application has penetrated under the covering and where traffic has not been severe.

Methods tested for the protection of the girders and decking have included the following:-

(a) Sheet lead (2 lb). Over a period of 20 years, sheet lead laid on the girders showed extensive corrosion and mechanical wear and did not provide a waterproof covering. The effective life was only 10-15 years.

(b) Creosote impregnated felt. This material was not satisfactory. After a period of 20 years only shreds of the felt remained and no benefit was observed.

(c) Creosote impregnated wood shims. Sassafras shims 3/8" thick, impregnated with coal tar creosote to about 20 lbs. per cubic foot have given a partial success for protection of girders over a 20 year period. The shims were in generally good condition except for some splitting from deck fastenings. The shim provided protection for the girder surface but at grooves or gaps between shims the girder often had appreciable decay extending into the girder and under the shim protected area. Decking surfaces in contact with the shims were also in good condition.

The use of creosote impregnated wood shims is very beneficial but it is desirable that they should cover the whole of the girder face and should not be split by action of the fastenings.

It is thought that strips of resin bonded waterproof plywood of suitable absorbent timber, impregnated with coal tar creosote, would be preferable to solid wood shims. Such plywood would be in long lengths or with splayed ends for butt joints and extend for one inch over the sides of the girders.

1.12.8 FUNGAL DECAY

Provided that concrete decking over the timber substructure is entire and without shrinkage cracks or permeable construction joints, the supporting timbers will remain free from fungal decay for an indefinitely long time. This type of structure usually has good sub-deck ventilation and for conditions in New South Wales, condensation of water on the timber does not provide sufficient moisture for fungal decay.

In practice however, serious fungal decay is not infrequent in the substructure as a result of moisture traps.

The reduction of moisture and of fungal decay as a result of the use of concrete decking assists also in eliminating termite infestations. However, it is normal experience that if an infestation does occur, the protection provided by the concrete slab and the generally warmer conditions under the slab are very favourable to termite activity. The damage may then be extensive and repairs will certainly be more expensive than with timber decking.

1.12.9 DESIGN DETAILS

The following aspects require particular attention to control termite infestation or fungal decay or both:-

(a) Expansion Joints.

The provision of expansion joints over a supporting girder invariably permits penetration and retention of moisture on the top surface of the girder.

The use of bituminous or similar expansion joint filling has proved ineffective in preventing water penetration and cannot be relied on for this purpose. Appreciable decay has been observed with durability class 1 timbers within 30 years.

The use of a waterproof membrane or capping appears to be the most satisfactory solution where these joints cannot be avoided. Generally a waterproof membrane would be placed on the surface of the timber before placing of concrete formwork for decking.

This need applies more particularly to exposed decks. In view of the practice of hosing down shed floors for cleaning, protection would also be an advantage inside sheds, but a less durable membrane would be sufficient. Similar protection should be provided where precast deck slabs are used on supporting timber.

In view of the long service life required, copper, muntz or similar alloy sheet (24 guage), P.V.C., reinforced polyester, or polythene plastic sheet are suggested. Lead sheet, aluminium sheet or bituminous sheet are not recommended for use under these conditions. Glass fibre reinforced polyester resin has been used satisfactorily for specially formed waterproof membranes including door stops, floor grates, etc.

(b) Construction joints.

The seepage of water through deck construction joints, shrinkage and other tension cracks gives a similar condition to that with expansion joints. A membrane protection is warranted for girders under constuuction joints on exposed wharf decking, but under normal conditions can be neglected where it is under wharf shed protection.

(c) Concrete deck outer edge.

In some past practice, the edge of the concrete deck has been finished flush with the face girder or even partly covering it. Under these conditions, appreciable fungal decay will occur although reasonable control is usually maintained by regular creosote spray treatment.

Variation of design is desirable by extending the concrete slab beyond the timber face, by chamfering the outer edge of the timber member to assist drainage or by providing a deflecting shield or membrane.

(d) Support of Timber at Seawall face.

Where the headstocks or girders are supported at the seawall face, direct access of termites is permitted from the soil through the ends of the structural timber. Protection may be provided by placing the ends of the girders or headstocks in a concrete recess which excludes moisture, provides a waterproof base and has a sufficient gap to the walls of the recess to permit inspection and the application of preservative if necessary.

If a special recess cannot be provided, means of injection and saturation of the soil adjacent to the ends of the timbers should be provided.

(e) Waste drains and discharge pipes.

Care is required in the detail of slots placed in the shed doorways which are intended to prevent rainwater from entering sheds and to drain water used in hosing shed floors. Definite means of deflecting such wastes from any supporting timber is advisable.

Care is also required in locating and maintaining waste discharge pipes. Infestation of termites from this source of moisture is not unusual.

(f) Railway and Crane tracks.

Rail tracks laid directly on timber girders in recesses of concrete decking have necessitated extensive repairs or renewal in 15-20 years. The general conditions are very favourable to retention of debris and of moisture and the construction does not permit reasonable access for preservative surface applications. Methods which provide protection of the timber such as laying rails in specially formed concrete recesses are recommended.

The filling of the space between rail and concrete over the timber girder with a bituminous mix is not effective in preventing moisture penetration.

(g) Concrete paving of timber decking.

The use of lightly reinforced concrete paving over old decking has been proposed as a means of improvement of the wearing surface for mobile handling equipment.

Serious fungal decay and termite infestation has occurred under such decking as a result of moisture penetration of cracks and of moisture accumulation at the edges of paving and near shed plates. It is thought that these difficulties could be reduced by attention to detail and with the use of a waterproof barrier such as a polythene sheet on the timber.

(h) Creosote grooves.

The extent of termite and fungal decay in some of the older concrete decked timber structures has led to the use of creosote grooves for control of termite damage in supporting girders. In this method, a groove is cut along the top of the girder with partial cross grooves at about 4 foot intervals. The groove is about 3/8 inch deep by 3/8 inch wide. The grooves provide a means of flooding the top of the girder with a preservative as required to control termites and fungal decay.

This method has proved successful, particularly where details of design and construction have not been adequate in eliminating moisture penetration. It would be preferable to use waterproof barriers or shields in preference to creosote grooves, but in areas where termites are very common this method would be advisable.

Termite nests may be located in the heads of timber piles and have occurred in offshore piles where necessary moisture is derived from seawater and rainwater rather than by contact with the soil.

The number of piles attacked in this way is not very great and does not present any difficulty in control. Such piles usually have a pipe and some fungal decay in the corewood. Periodic spray application with a creosote/chlordane or creosote/dieldrin mixture at the head of a pile, preferably through a bored hole to the pipe, is adequate for control.

Termites also occur in the interior of timber punts and pontoons and can be controlled with normal eradication treatment and spray if necessary.

The timbering used for fendering of the "round corners" of jetties is prone to termite damage. Usually this consists of a considerable quantity of timber to which it is difficult to gain access for inspection and treatment, and tends to collect dust and debris. Provision for inspection and spray treatment for fungal decay has proved adequate for control.

Hollow cast iron bollards fixed to timber decking provide suitable conditions of protection and warmth for termite nests. The frequency of this occurrence has led to the use of a small hole left in the bollard to permit the injection of a preservative mixture into the hollow core of the bollard.

1.13 CONCLUSIONS.

The importance of timber as a marine construction material lies in its general availability and its simple adaptation from its natural state to structures of all types using simple tools of conversion.

In a marine environment, timber is subject to attack by several different forms of marine borers,and while various methods have been devised for protecting the timber from attack the best results have been obtained from systems which cut off the supply of oxygen to the timb er. Thus the preferred method of treatment of timber is by shielding the timber using sheathing or wrappings which are applied before the timbers are placed in the water to ensure that efficient protection is obtained. The most recent advance in this field being the use of plastic jacketting over the timber.

Although some timbers exhibit a degree of natural resistance to attack by marine organisms, which has been attributed to the silica and alkaloid contents of the timber, no timber is immune to attack. In Australian conditions, Turpentine (Syncarpia laurifola) has proved to be a most satisfactory timber, exhibiting a high degree of natural resistance. This has led to the wide abuse of the material for all types of structures, to such an extent that the availability of the timber for long piles is now extremely restricted.

It is therefore essential for the optimum utilisation of resources that this timber be used only where essential, and that Engineers should be made aware of the existence of alternative timbers for works of minor importance. In this regard an important recent development in Australia has been the establishment of commercial plants for the pretreatment of softwoods and selected hardwoods, thereby enlarging the field of economically suitable timbers for marine works.

An important factor in the economic use of timber resources is that it is essential that timbers are used for the full duration of time during which they are of adequate strength to carry the applied loads. For this to be achieved, it is necessary to employ a more positive system of underwater inspection than that of a probe inspection by diver attempting to assess the internal condition of a timber by its external conditions. The ultrasonic detector recently developed in Canada appears to provide a long awaited answer to this problem, and it is difficult to comprehend why such a development is not more widely accepted than it has been to date in Australia.

For best results from a timber design in both the marine and atmospheric environments, it is essential that the design Engineer is fully aware of the characteristics of the timbers available and of the environmental conditions existing at the site, as well as the methods of preservative pretreatment which are economically suitable. Only in this way can a satisfactory design be made using the available resources in a manner most economical to the whole community.

SECTION 2

S T E E L

2. STEEL CORROSION

2.01 INTRODUCTION

The subject of the durability of metal structures exposed to atmospheric and aqueous agencies is one of vital importance in docks and harbours. Until the commencement in recent years of systematic research, the evidence on metal durability was scanty, incomplete and inconclusive. It is only within the past century that iron began to usurp the pre-eminence previously enjoyed by timber and stone in maritime construction, and steel was an intrusion of still later date. Consequently there has only just elapsed sufficient time in which to acquire reliable data, for the determination of the actual life of metallic structures, more particularly steel, under various conditions and, moreover, experiments were not carried out from the earliest possible time.

2.02 HISTORICAL DEVELOPMENT

In 1824 and 1825 Sir Humphrey Davy[(1)] published the results of his work for the Commissioners of the Navy Board, who were concerned about the corrosion of the copper sheathing on wooden ships. He prevented the corrosion by attaching to the copper either iron or zinc blocks which themselves corroded sacrificially as anodes to provide direct electrical current, which flowed through the water to the copper and so gave cathodic protection. By adjusting the area of iron to copper to about 1% it was possible to prevent serious corrosion, but to allow just sufficient corrosion to occur to maintain a clean metal and prevent attachment of marine growths. Over-protection resulted in calcium and magnesium carbonate films on the copper, to which marine growths became attached.

Over the last hundred years wooden ships have been replaced by steel ships and for marine structures, such as jetties, timber has largely given way to the use of steel for piles. Zinc continued to be used for protecting the propeller and stern gear of

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(1) reference 2.11

of steel ships and also boilers, but only with partial success, because those using it tended to carry on a tradition without having a sound knowledge of the electro-chemical mechanism of corrosion. In fact, a common phrase in ship yards was that a zinc was a "good zinc" if it did not corrode, which illustrates how little its correct function was appreciated in practice.

Since about 1920, much work has been carried out and the state of knowledge has so advanced that submerged steel can now be given complete protection under conditions where maintenance was previously considered impossible, such as for steel jetty piles, submarine pipelines, etc. Magnesium and aluminium have joined zinc as available sacrificial anode materials, and cathodic protection using direct current together with iron or inert materials for the anodes has found increasing favour.

2.03 THE CORROSION PHENOMENON

There is nothing unnatural about corrosion. Most of the heavy metals used in engineering occur on the earth in the form of ores. These are in the main, oxides or hydroxides of the metals. For example, two of the most important iron ores are haematite and magnetite, both of which are oxides of iron. When the ores are smelted in the blast furnace with coke and limestone, the oxygen is forcibly removed from them, and the iron is set free. Throughout its subsequent existence, this iron strives to recombine with the oxygen from which it has been separated. Plenty of air is at hand in the atmosphere for the purpose. Consequently, when the iron or steel billet is heated at the rolling mill, it combines with the oxygen of the air to form iron oxides, or millscale, which is one cause of corrosion troubles. Later in its life, as a manufactured article, the iron continues the process of reversion to the ore by rusting at the slightest provocation. The ore and not the metal is the stable body, and rusting represents the natural tendency for the iron to revert from the unstable to the stable condition.

The chemical changes involved have been studied by

FIGURE 2.0

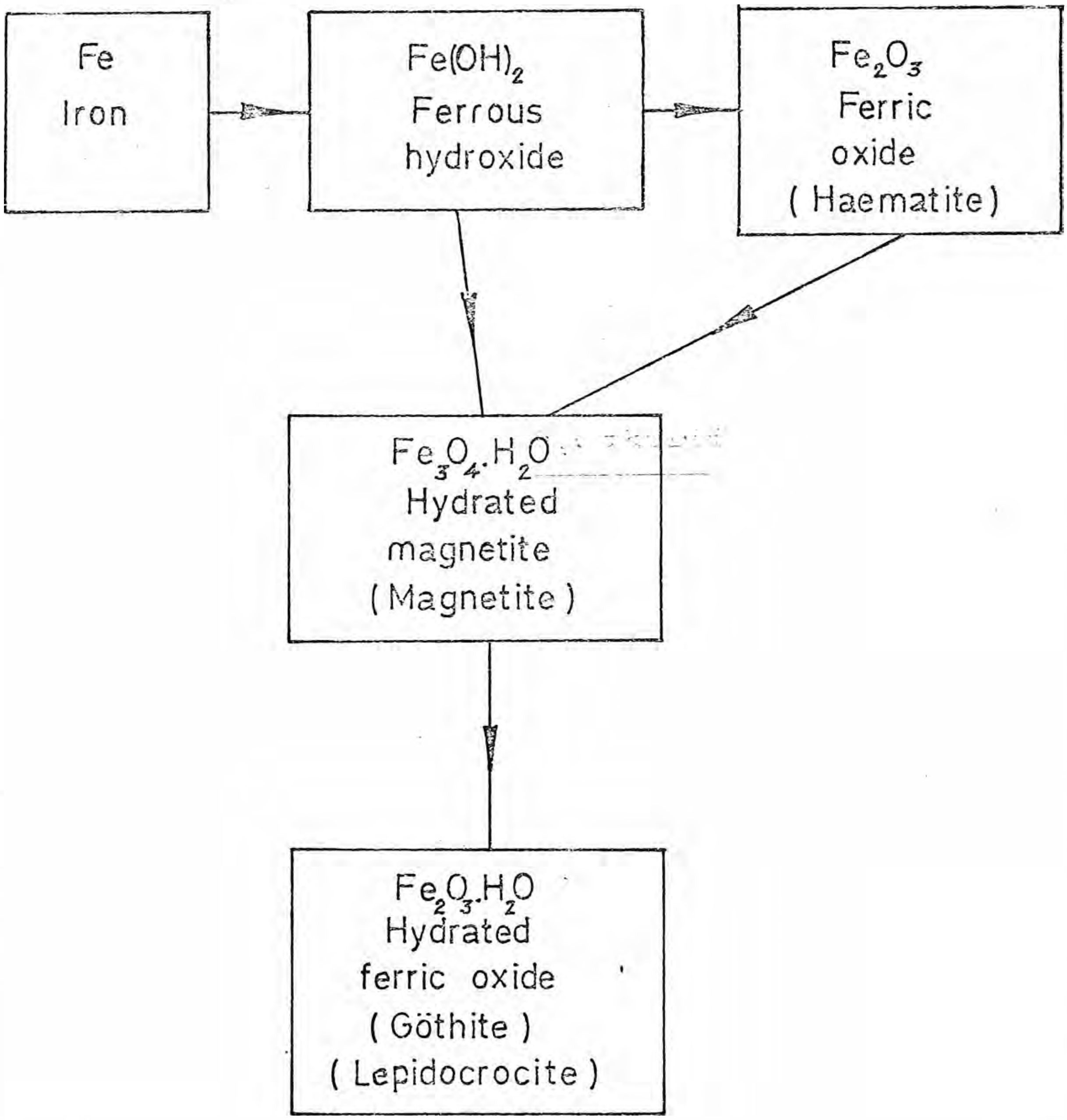
Fe
Iron
$Fe(OH)_2$
Ferrous
hydroxide
Fe_2O_3
Ferric
oxide
(Haematite)
$Fe_3O_4.H_2O$
Hydrated
magnetite
(Magnetite)
$Fe_2O_3.H_2O$
Hydrated
ferric oxide
(Göthite)
(Lepidocrocite)

FIGURE 2.0

many investigators[1] and, although some details remain to be settled, they are adequately represented by the reactions given in Fig. 2.0.

The rusting process is thus essentially one of oxidation and the transition from each stage to the succeeding one is brought about by the intervention of oxygen and/or water. Natural iron ores corresponding to the corrosion products are shown in brackets; some of these, e.g. gothite, occur in atmospheric rust. The primary reaction is the decomposition of water by iron to form ferrous hydroxide and hydrogen; this can proceed directly under certain special circumstances in the laboratory, but as a general rule it is also necessary for oxygen to be present, so that the hydrogen liberated can be oxidised to water at the instant it is formed.

2.04 ELECTRO-CHEMICAL SERIES OF METALS

The nature of corrosion of metals may be stated as their constant effort to revert to the stable condition of the mineral. The reduction of a metal from its natural state of combination with other elements is achieved by the expenditure of energy, and it follows that only in the so-called "noble" metals, headed by gold, is the metallic state naturally stable. The tendency of a metal to corrode may be expressed numerically by the amount of energy liberated in the change from the metallic to the oxidised state; or in electro-chemical terms, by the standard electrode potential of the metal.

The so-called Hydrogen Scale of Potential is that in which the potential between blackened platinium saturated with hydrogen under one atmosphere pressure and an acid solution of normal hydrion concentration is taken as zero, just as the temperature of freezing water is taken as zero on the Celcius thermometer.

By arranging the metals in the order of their normal electrode potentials, the Electro-Chemical Series is obtained.

This series does not give either the rate or the mode of corrosion in a given environment, otherwise the corrosion problem

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(1) reference 2.6

FIGURE 2.2

CORROSION MECHANISM

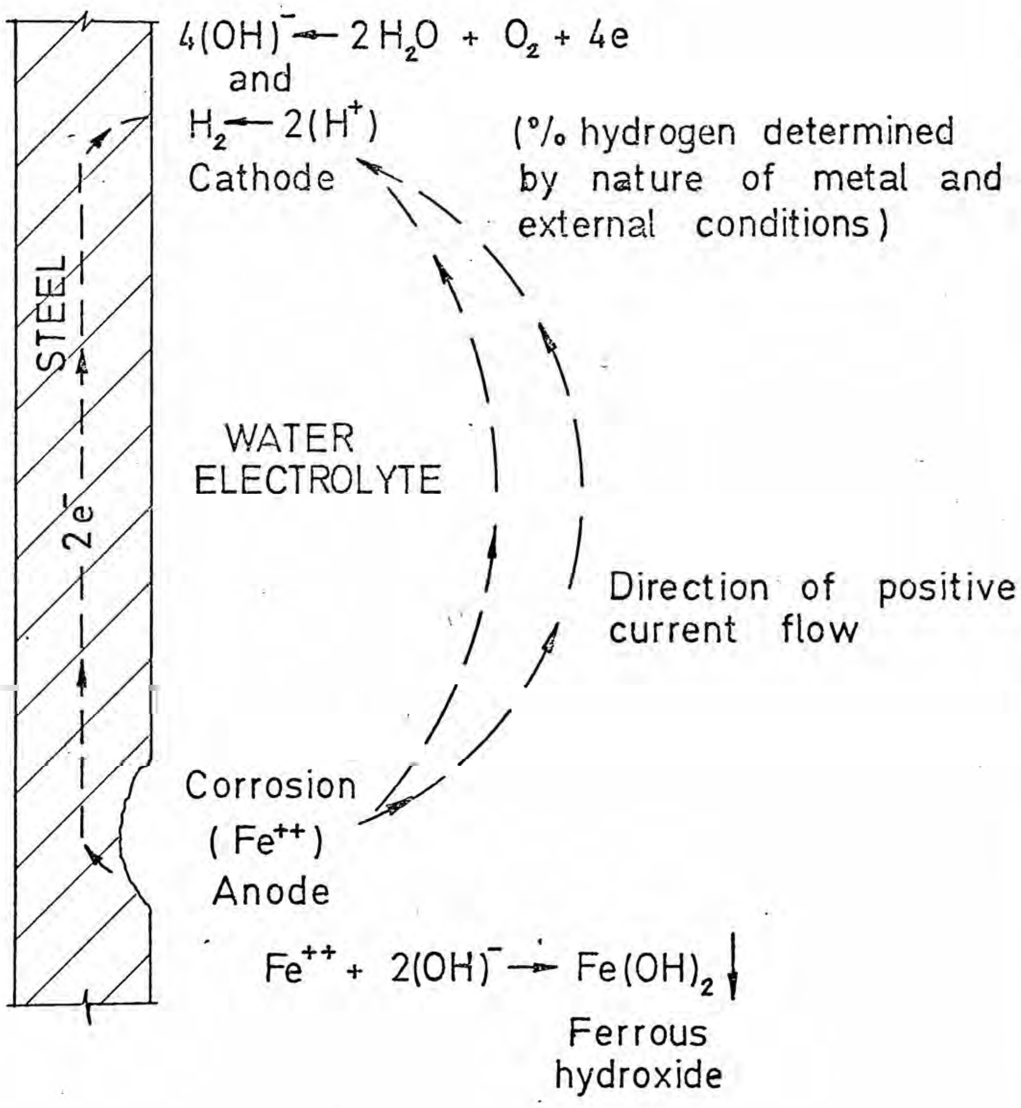


FIGURE 2.2

would be simpler than it is. It is necessary to consider other factors superimposed upon the initial corrosion tendency. For example, the extreme reactiveness of aluminium under normal conditions leads to the formation of a film of oxide (alumina) which effectively suppresses continued attack upon the metal beneath it. The same action occurs to some extent with all metals.

A practical list of the electro-chemical series in which a metal in the list will preferentially corrode and protect a metal below it follows:-

<u>ANODIC</u>

Magnesium

Aluminium

Zinc

Carbon Steel

Cast Iron

Stainless Steel (active)

Lead

Tin

Brasses

Copper

Bronzes

Monel

Stainless Steel (passive)

Silver

Graphite

Platinium

<u>CATHODIC</u>

2.05 MECHANISM OF IMMERSED CORROSION

The liberation of energy which occurs when corrosion of immersed metals takes place, is accompanied by a redistribution of electrons which, if conditions are favourable, may produce recognisable electric currents. These can be visualised by considering a simple voltaic cell, (Fig.2.2) all the features of which have their counterpart in ordinary immersed corrosion, even though separate anodes, and cathodes cannot always be visually distinguished. The corrosion process may be regarded, in view of the evidence, to be made up of anodic and cathodic components which can be influenced respectively by appropriate means.

The voltaic cell (the electrolyte being a dilute acid solution), represents the hydrogen evolution type of corrosion, in which corrosion is a function of the amount of hydrogen evolved. Here the cathodic reactions may be represented as follows:

$$2e + 2H^+ \rightarrow 2H \rightarrow H_2$$

Hydrogen evolution corrosion is normally associated with acid industrial waters. In neutral salt solutions, however, the accumulation of electrons in the cathode is prevented (except in very reactive metals) only by the intervention of oxygen, which becomes reduced according to the equation:

$$2e + O + H_2O \rightarrow 2(OH)^-$$

This constitutes the oxygen absorption type of corrosion. In the more general case in which alkaline salts are present, the formation of hydroxyl ions at the cathode must accord with the formation of free alkali.

Experiments[(1)] have shown that the mechanism of corrosion of metals is electro-chemical in character, and that the four main parts of the process can be demonstrated to be:-

(1) The production of an electrical current;
(2) The production of a soluble metallic salt (chloride) at the anodic (unaerated) places;
(3) The production of alkali (hydroxide) at the cathodic (aerated) places; and
(4) The precipitation of an insoluble hydroxide where the products from the cathodic and anodic areas meet.

For example, with iron immersed in a solution of sodium chloride, the primary anodic product is a soluble iron chloride and the cathodic product sodium hydroxide. By precipitation we get white ferrous hydroxide, but in the presence of oxygen it rapidly oxidises

---

(1) reference 2.4

and becomes green in the lower surface (ferroso-ferric hydroxide) and brown on the upper surface (ferric hydroxide), this mixture of iron hydroxides being what we know as "rust."

2.06 FACTORS INFLUENCING CORROSION

The agents by which the course of corrosion may be influenced are of many kinds and may be conveniently classified as promoting and controlling factors, or those associated with the metal and those connected with the environment. The former include electrode potential, surface condition and internal stresses. The actual amount of corrosion almost invariably fails to reach the value of the calculated amount and it can be recognised, therefore, that there are controlling factors which have some influence in restricting the corrosion attack on the metal. In immersed corrosion they may be either the complex phenomenon associated with hydrogen over potential in hydrogen evolution types of corrosion, or in the oxygen absorption types; the rate at which dissolved oxygen can reach the metal surface, actually the cathodes of the corrosion system. The sensitivity of the cathodes to oxygen supply is seen in the influence of depth of immersion under normal atmospheric conditions.

It is clear in stagnant water conditons, assuming acid activating agents to be absent, that the replenishment of oxygen to the surface of the metal will be more effected the less the depth of water between the metal and the air, until the layer of water becoming progressively thinner, the condition of the air formed film of oxide is reached, which always forms upon a metal surface exposed to air. In the case of atmospheric exposure, humidity provides the electrolyte, and in industrial atmospheres this is invariably acid in character.

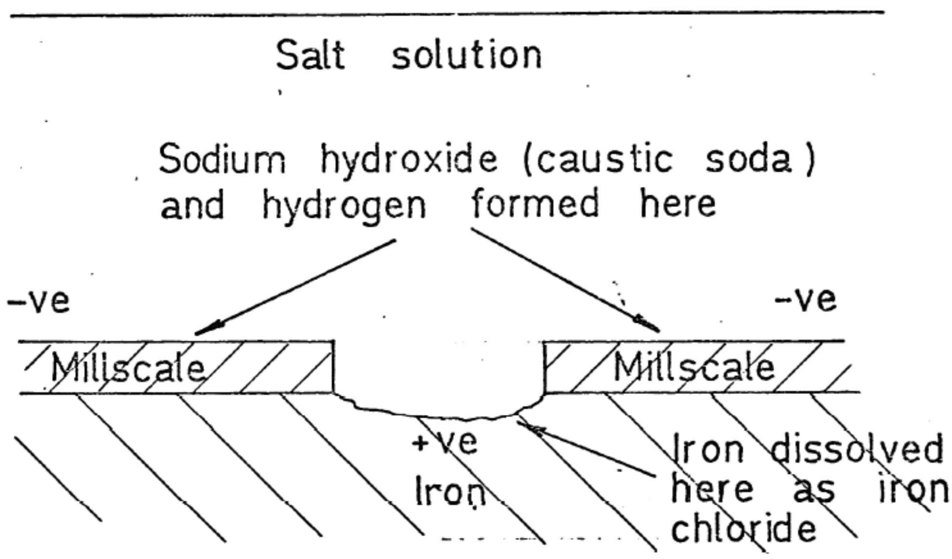
Experiments[1] have established the link between immersed corrosion and atmospheric oxidation. By progressively increasing the speed of movement of aerated water over steel it has been found that the rate of corrosion likewise increased, but that where a critical speed of movement was reached the increase in corrosion gave place to falling values. Increasing the speed still further it was found that

(1) reference 2.4

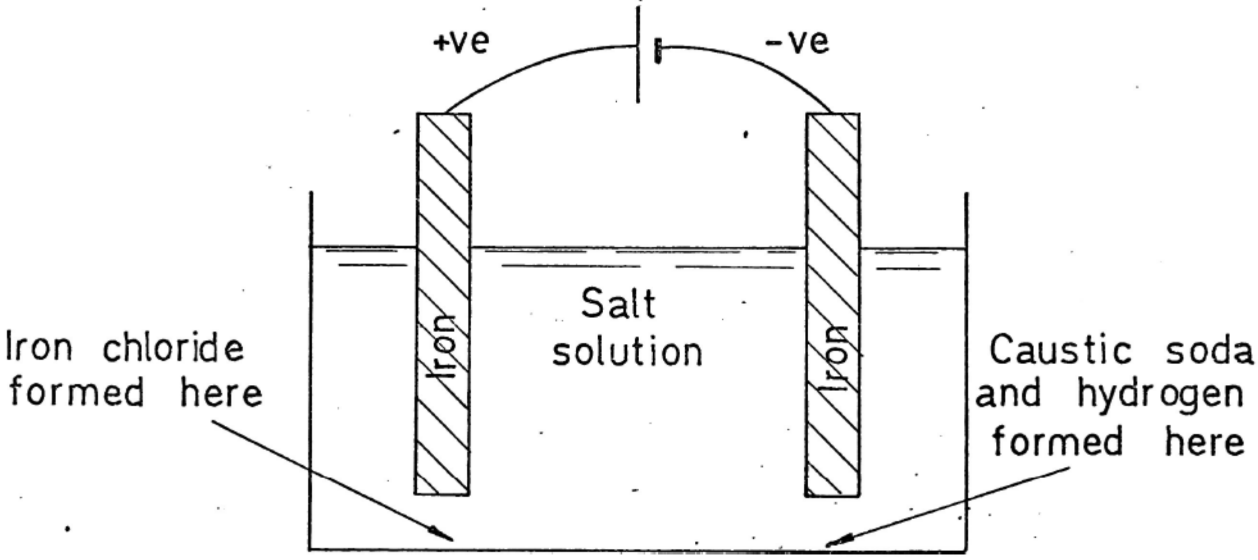
FIGURE 2.3

ELECTROCHEMICAL CORROSION

IRON WITH MILLSCALE



Electrochemical corrosion of iron in the presence of millscale



Equivalent cell with external source of current (two iron electrodes)

FIGURE 2·3

complete inhibition of corrosion occurred, the specimens remaining quite bright and rustless.

In practice, many factors associated with either the metal or the environment determine the rate of corrosion.

2.06.1 FACTORS ASSOCIATED WITH THE METAL

2.06.1(i) Contact with different metals (Galvanic Cells)

Metals have different solution pressures, and if two dissimilar metals in sea water are electrically connected, current will flow through the water from the corroding metal or the more noble metal.

The electro-chemical series is indicative only, and the position of the various metals may be modified by their physical state and the nature of the electrolyte.

The classical marine example of corrosion due to bi-metallic contacts is the corrosion of the steel of a ship's stern plates in which the current naturally flows through the water to a non-ferrous propeller.

The corrosion of aluminium is much greater in contact with copper than in contact with steel. Corrosion of aluminium pipes can be caused by small amounts of dissolved copper from copper pipes being deposited onto the aluminium. Even condensation dripping from copper pipes onto aluminium decks has produced severe corrosion.

2.06.1(ii) Millscale

Millscale is cathodic to steel and if both are exposed to sea water or a marine atmosphere, the millscale will cause accelerated corrosion of the adjacent steel. It is strongly recommended that all millscale be removed from steel to be used for ships or marine structures. (See Fig. 2.3)

2.06.1(iii) Welding and permanent stresses in metal

Metals which are held in a state of stress have energy stored in them, and have a slightly more negative electrolytic solution potential than similar unstressed metal. This phenomenon may arise at a weld or rivet, which on cooling, retains remnant stress.

A weld or the metal adjacent to it often acts as an anode and tends to corrode. Research work has tended to show,[1] however, that this effect is small compared with potential changes due to variation in composition of the metals.

2.06.2 FACTORS ASSOCIATED WITH ENVIRONMENT

Apart from factors associated with the metal, the conditions in the water electrolyte affect corrosion phenomena.

2.06.2(a) Below low water level

In estuaries, variations in salt content or temperature of the water at different depths can create corrosion cells. However, most submerged steel corrosion is attributable to either contact with more noble metals or differential aeration cells.

Under isolated barnacles, pitting corrosion frequently occurs due to differential aeration, but if the whole of the steel is completely screened from the water by a continuous coating of barnacles the corrosion rate may be greatly reduced and be of a fairly uniform nature.

A bare steel pile jetty in Jamaica,[2] which had been designed on the basis of a uniform corrosion rate of 0.003 in. per year, when inspected less than two years after its construction, was found to have pits up to 0.17 inches depth under barnacles.

On Southend Pier, England, at the mouth of the River Thames, the barnacle growth is so dense that corrosion rates are low. Higher up the river at Thameshaven, barnacles are present but more limited in number. At Dagenham (15 miles further up the river), the water is still saline, but barnacles are no longer present, and sulphate-reducing bacteria are very active, so corrosion rates are extremely high. This illustrates the variations which can occur within one estuary.

2.06.2(b) Above the high water line

Above high water level, steel in marine atmospheres receives spray, which evaporates and leaves behind a mixture of salts,

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(1) reference 2.2
(2) " 2.11

FIGURE 2.4

CORROSION MECHANISM WITHIN A DROP OF SALT WATER

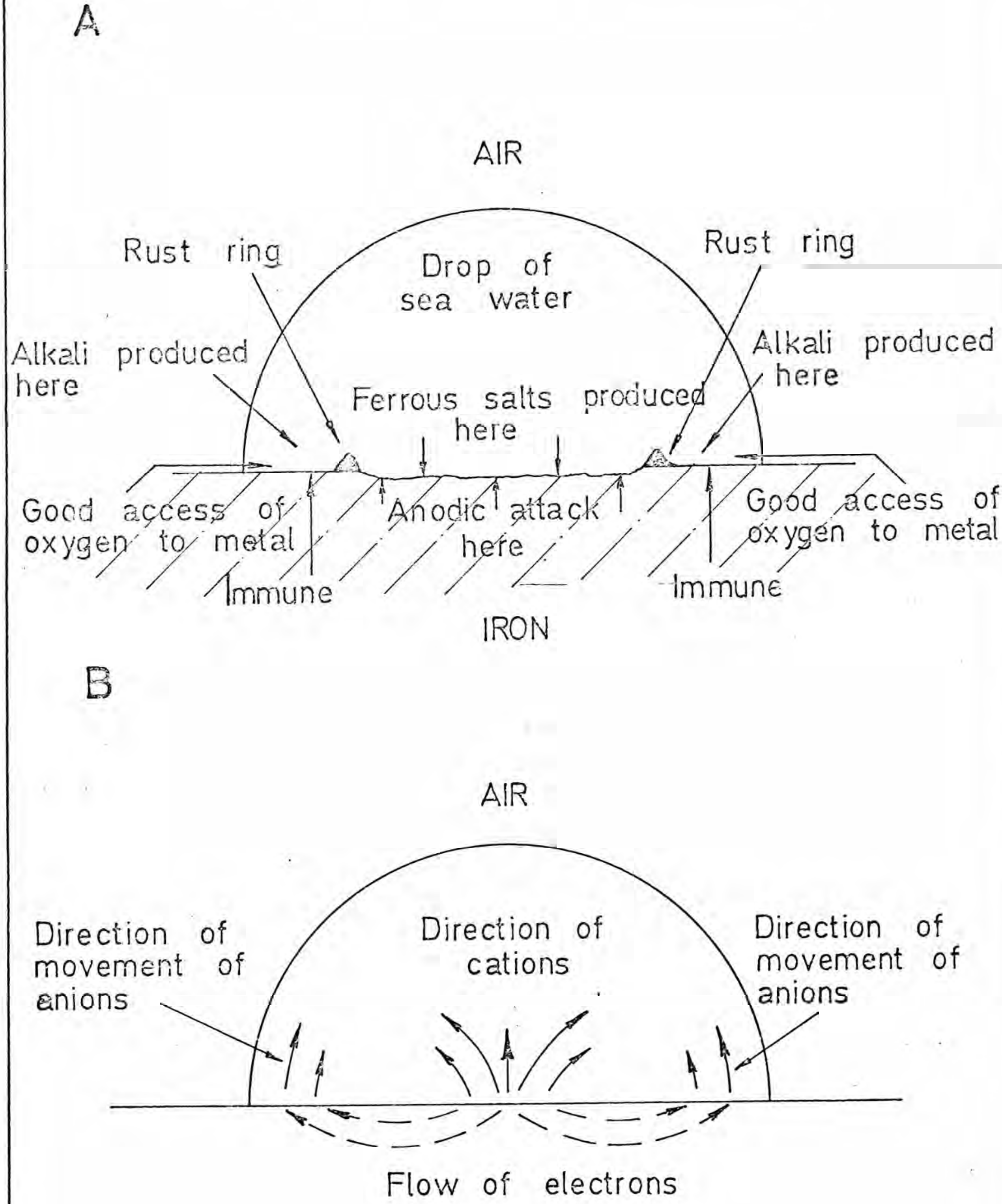

FIGURE 2.4

of which the principle component is sodium chloride. It has been shown that as the drop evaporates, a corrosion cell is produced as shown in Fig. 2.4.

With increase of humidity solutions are again formed, or further spray occurs, with the result that by the above mechanism, multitudinous small anodes and cathodes are formed over the surface of the metal. The position of cells continually changes, resulting in very active corrosion of a relatively uniform nature.

2.06.2(c) Tidal zone

The type of corrosion experienced on the tidal portion of a jetty or similar structure is intermediate in character between submerged and atmospheric corrosion. The main factors tending to increase the rate in this area are the mechanical action of the waves removing rust scale, differential aeration effects at the air-water interfaces and finally salt concentration cells arising from evaporation.

2.06.2(d) In the mud zone

Corrosion rates underground are usually of the order of 1 mil./year. It is generally true therefore that steel piling which is heavy enough to withstand tidal and splash zone corrosion will be little affected by corrosion beneath the sea bed. The near face of a piling wall is in permanent contact with the fill, but if clean sand can be used, the silica unites with the surface rust as it forms, producing a hard protective coating which limits further corrosion.

2.07 ATMOSPHERIC CORROSION

For practical purposes, both the tendency to rust and the rate at which rusting proceeds once it has begun, are of great importance. It has long been known that the severity of rusting varies considerably for the same material when exposed in different climates and various reasons were advanced for this. For example, it was once thought - wrongly - that rusting was caused by the carbon dioxide content of the air. It was subsequently demonstrated, from

FIGURE 2.5

EFFECT OF SULPHUR DIOXIDE AND SOLID IMPURITIES ON THE ATMOSPHERIC CORROSION OF IRON

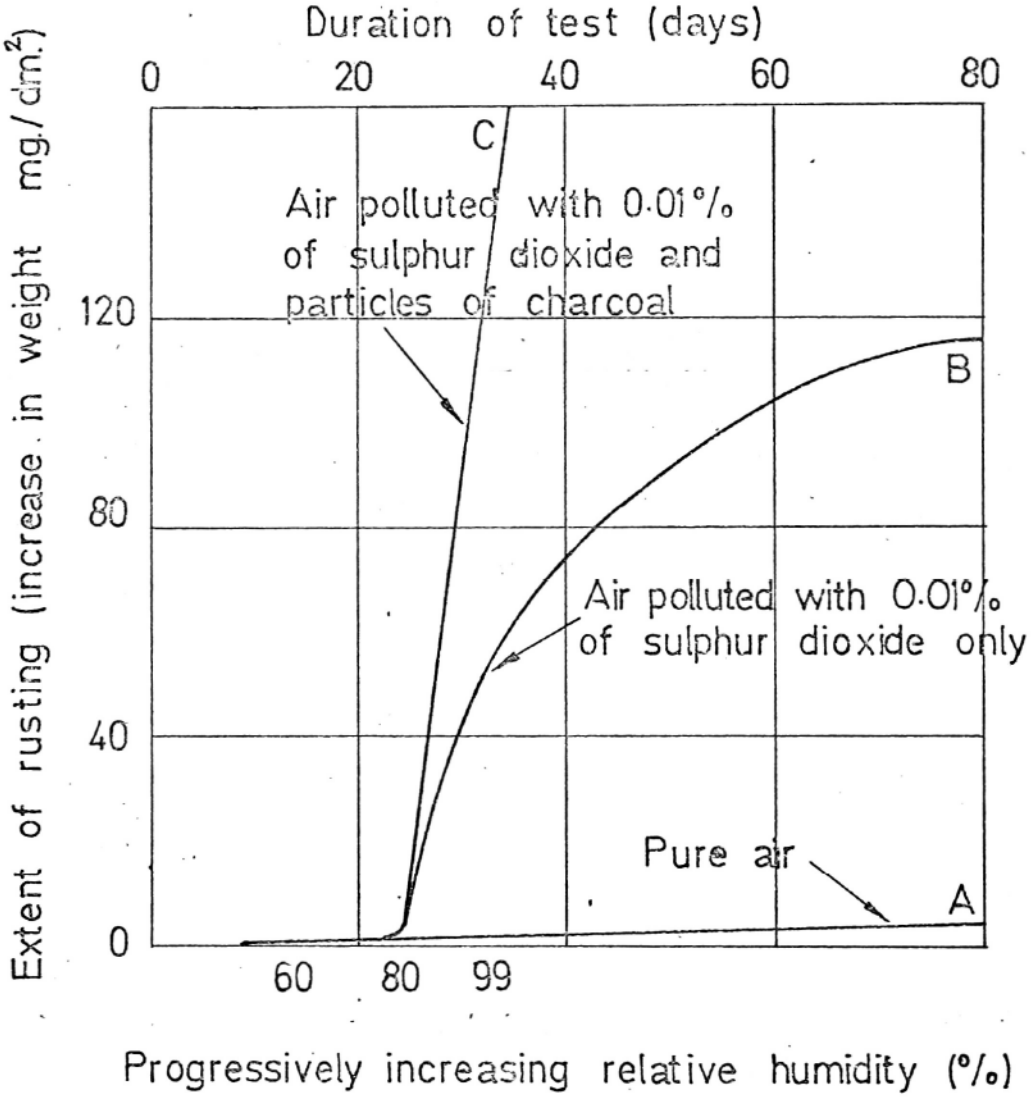

FIGURE 2·5

1930 onwards[(1)], that the relative humidity of the atmosphere, controls the tendency to rust and that the speed of rusting is determined by the degree of pollution of the atmosphere, notably by oxides of sulphur, derived from the combustion of fuel, and solid particles, such as dust.

The essential result of these experiments are depicted in Fig. 2.5. Speciments of bright steel were exposed to the air inside large glass vessels. Starting with dry air and progressively increasing the humidity of the air at appropriate intervals, the amount of rusting of the steel was determined by measuring its increase in weight. Three series of experiments were made:

A. In pure air;

B. In air containing 0.01% of sulphur dioxide; and

C. In the same atmosphere as (B) but using specimens whose surfaces had been partially covered with small particles of charcoal or other substances before exposure, so as to imitate the effects of the grime and dust present in most outdoor atmospheres.

If the air was pure, little rusting took place, even when the humidity approached saturation. In impure air containing sulphur dioxide, the attack on the steel was negligible at low humidities, but, when a threshold humidity of about 70% was reached, rusting became perceptible and when the humidity rose above 80%, it became severe. The presence of solid particles on the surfact of the steel in addition to the sulphur dioxide contamination of the air made corrosion even more intense, here again only when the humidity exceeded the threshold value.

The two main conclusions to be drawn from this investigation were therefore:-

(1) Iron or steel does not rust appreciably in pure air, whether dry or humid.

(2) When the air is polluted with sulphur dioxide, which may be regarded as representing the sulphur compounds

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(1) reference 2.6

discharged into the atmosphere from chimneys, the relative humidity of the air determines whether pronounced rusting will occur or not. The dividing line between severe rusting and comparative immunity from it may be shown at 70-80% relative humidity.

These theoretical deducations have been fully confirmed by the results of practical corrosion tests in numerous parts of the world. The conception of a critical humidity which determines whether corrosion occurs or not, has proved a valuable addition to corrosion theory. It is probable that the value of critical humidity is not the same for all metals. For example, in tests in which twelve different non-ferrous metals were exposed under sheltered conditions outdoors[(1)], the condensation of moisture from the atmosphere was observed to occur more readily on some metals than on others. Under these conditions of exposure, when the metal is sheltered from the rain and the corrosion products remain in contact with it, the humidity at which condensation takes place is probably determined by the deliquescence of the corrosion products. Condensation may, therefore, be expected to occur at different relative humidities for different metals. Experiments made with corrosion products scraped from corroded specimens showed that these products varied considerably in their capacity to absorb water. For example, the following increases in weight were observed when they were exposed for 48 hours to an atmosphere of 90% relative humidity:

COPPER	8%
ALUMINIUM	9%
NICKEL	32%
ZINC	36%
BRASS	68%

It might be concluded from these results that copper and aluminium were likely to be more resistant to corrosion under enclosed humid conditions than the other metals and this in fact proved to be the case.

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(1) Reference 2.6

2.07.1 DATA ON ATMOSPHERIC CORROSION OF BARE STEEL

The available data on atmospheric corrosion of bare steel can be grouped under three headings:

(1) effect of climate;

(2) effect of duration of exposure;

(3) effect of the composition of the iron or steel.

2.07.1(a) Effect of Climate[(1)]

The effect of climatic differences on the corrosion rate of bare unalloyed structural irons and steels is well represented by the Table 2.A. These are the observed average corrosion rates for small plates of ingot iron (a steel) with a very low carbon content) exposed at the places mentioned for several periods of one year each.

TABLE 2.A

AVERAGE CORROSION RATES

Type of Atmosphere	Locality	Rate of Rusting Mils. per Year
GREAT BRITAIN		
RURAL	Llanwrtyd Wells	2.5
MARINE	Brixham Calshot	2.1 3.1
URBAN	Birmingham	4.1
INDUSTRIAL	Sheffield Derby	5.4 6.8
DRY TROPICAL	Khartoum	0.1
SUB-POLAR	Abisko (Sweden)	0.2
DRY SUB-TROPICAL	Basrah	0.6
MARINE TROPICAL	Singapore	0.6
TEMPERATE INDUSTRIAL	Durban	4.5
SURF-BEACH TROPICAL	Lighthouse Beach (Lagos)	24.4
MARINE TEMPERATE	Sydney	3

The practical significance of these results may be illustrated by considering what might be expected to happen to an ordinary wire link fence of 17G (0.056 inch) galvanised steel wire.

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(1) reference 2.6

FIGURE 2.6

VARIATION IN ATMOSPHERIC HUMIDITY

The average humidity for the 24 hours of the day is plotted for each month of the year. Above 70% relative humidity, marked rusting can occur.

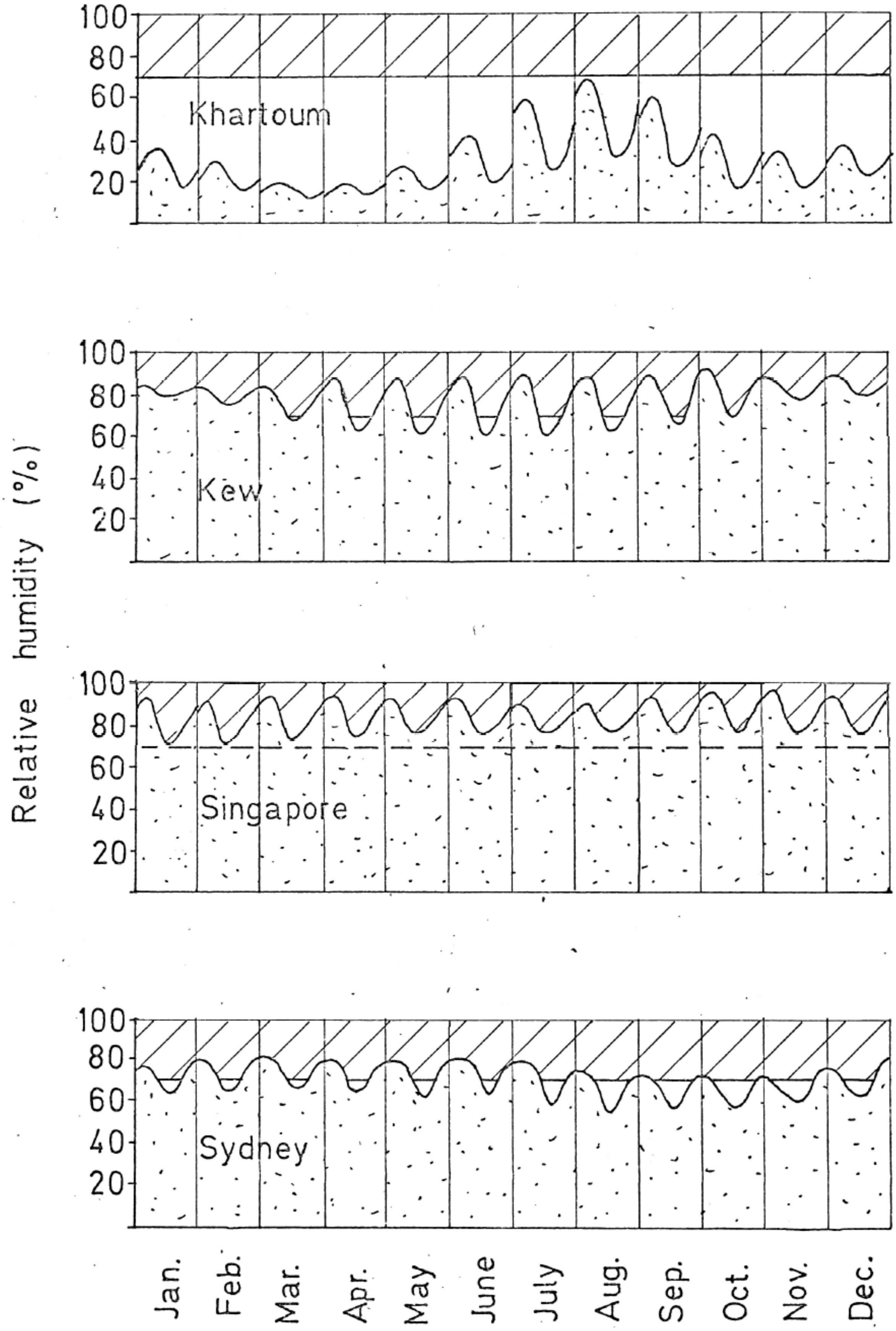

FIGURE 2.6

In the Hope Valley district near Sheffield, because of the smoky atmosphere, such a fence will only last for about 3 years, unless steps are taken to protect it by painting with tar. Its life at Brixham might be estimated as about 8 years. At Khartoum it should still be serviceable after 100 years, but on Lighthouse Beach, Lagos, it would disintegrate within a year. Something like 25 years service should be obtained at Singapore.

These figures are given only by way of illustration, as major differences in the corrosiveness of the atmosphere may occur within narrow limits in any given locality. The results illustrate that there are great differences in the corrosion rates of steel in different parts of the earth.

The low corrosion rate at some stations is primarily due to the relative dryness of their atmosphere. At Khartoum the average value of the maximum relative humidity at any time of the year, is 67%. The differences in the local atmospheric humidity at several stations is illustrated in Fig. 2.6, which shows the variation in relative humidity throughout the year at Kew, Khartoum, Singapore and Sydney.

It is clear from these curves that in Great Britain, the relative humidity lies above the lower limit of the critical value, 70% for approximately 80% of the year. During this period, corrosion can proceed if the other conditions are favourable. On the other hand, at Khartoum this level is never reached. At Singapore the lower limit is exceeded for 90% of the time. Yet often serious corrosion does not occur at these places because of the absence of the second factor needed for severe rusting, appreciable atmosphere pollution.

When the humidity conditions favour corrosion, the rate at which rusting occurs is controlled by the degree of pollution of the atmosphere. It is the lack of sulphur pollution which accounts for the low rates of corrosion observed at places in the tropics, like Singapore, where the relative humidity of the atmosphere is high and

FIGURE 2.7

CORROSION - TIME CURVES FOR MILD STEEL AT SHEFFIELD AND LLANWRTYD WELLS

(The results relate to $\frac{1}{8}$ in. thick plates of ordinary mild steel exposed vertically in the open air.)

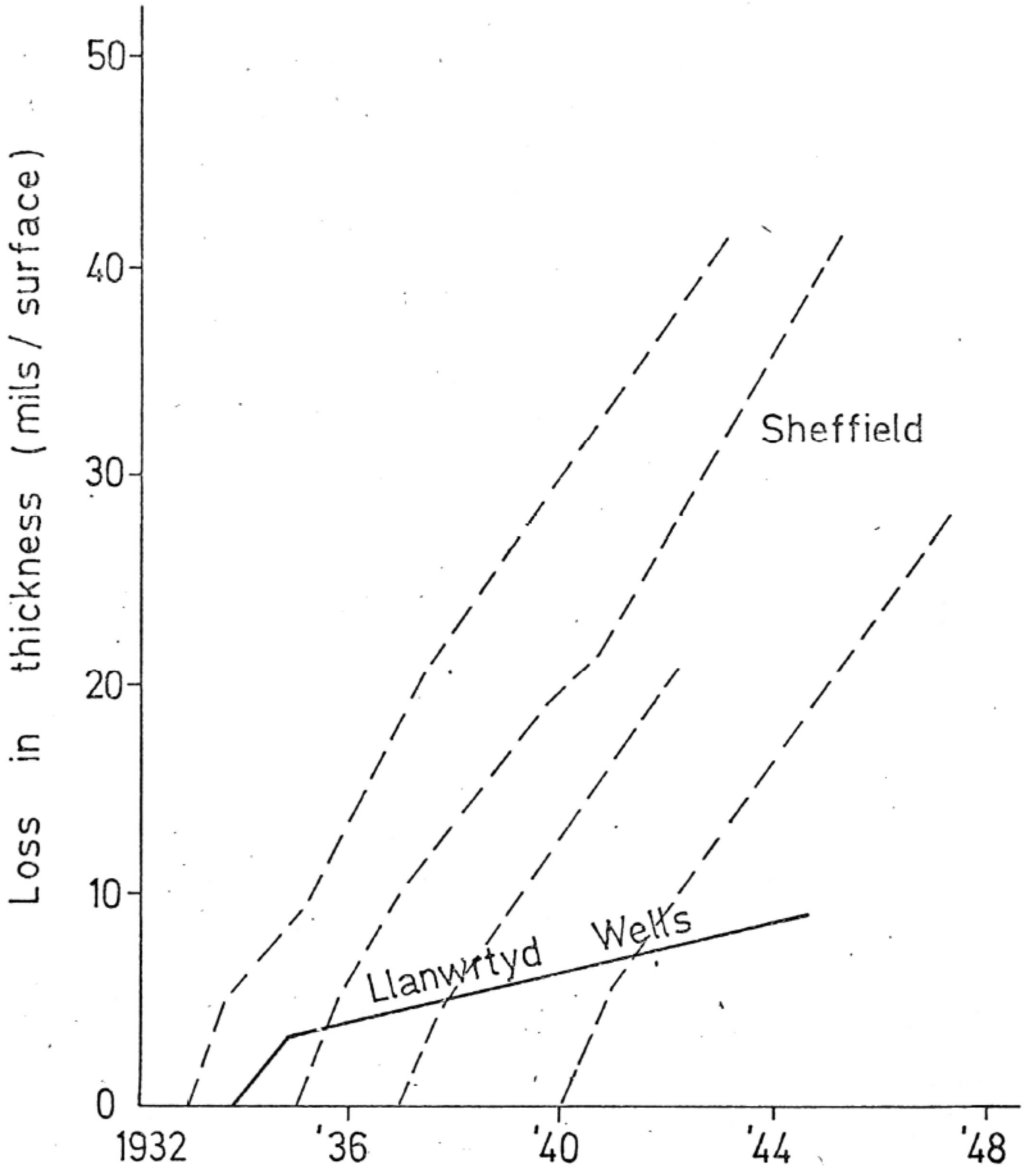

FIGURE 2·7

conducive to rusting. However, on tropical shores, rusting can occur at a devastating speed, as is shown by the figure of 24.4 mils. per year for ingot iron exposed on Lighthouse Beach, Lagos. This extreme rate of rusting results from the steel being continually enveloped in a mist of salt spray from the sea. The amount of salt in the air decreases rapidly on moving inland and there is a corresponding diminution in the degree of corrosion. This is shown by the following figures for Lighthouse Beach, Lagos:

Distance From Surf Yds.	Salt Content of Air *	Corrosion Rate Mils per Year Ingot Iron	Zinc
50	11.1	37.7	1.51
200	3.1	14.9	0.57
400	0.8	2.2	0.11

* Mg. of sodium chloride per 100 sq. cm. per day.

2.07.1(b) Effect of duration of exposure

The rate of rusting of steel in the open atmosphere is not constant throughout the year. There is also evidence that the influence of conditions prevailing during the early stages of exposure may persist for an appreciable time after these conditions have ceased to exist. e.g. a specimen first exposed to corrosion when the conditions are but mildly aggressive may continue to corrode at a low rate when it passes into a more aggressive period and vice-versa. The main concern is with the corrosion that takes place over a number of years. Then the position is much simpler, for the short-period fluctuations in the meteorological conditions tend to average themselves out. The shape of the corrosion/time curve[(1)] for ordinary structural steels exposed in the open air for a number of years has been observed by several investigators in different countries, and is now well established. (See Fig. 2.7)

It is evident from these curves that the relationship between the corrosion of mild steel and duration of exposure was to all intents a linear one from after the first year's exposure. This

(1) reference 2.6

exception during the early stages is due to the specimens being exposed in the as rolled condition, i.e. with the millscale on them. The loss of weight recorded over the first year is augmented by the weight of the millscale shed during that period. It is probable too, that the progressive formation of a continuous layer of rust on the steel surface plays a part in reducing the corrosion rate.

It may be concluded, that for practical purposes, the degree of rusting caused by atmospheric exposure may be taken to be proportional to the duration of exposure, so that figures observed for the rates of rusting over a few years at different localities may be used to predict with reasonable accuracy the lives of bare steel sections exposed to the atmospheres concerned.

2.03 AQUEOUS CORROSION

It has been demonstrated beyond doubt that the great majority of corrosion processes are electrochemical in character. This certainly applies when the corrosive agent is water or an aqueous solution capable of conducting electricity. In such cases the corroding metal or metal system becomes divided into areas of two different types: the anodes, at which the metal corrodes, and the cathodes, at which it does not. These areas together with the solution in contact with them constitute an electric cell. This state of affairs exists, for example, when a piece of steel carrying broken millscale is immersed in sea-water. (See Fig.2.3) A current, flows between the bare steel and the millscale, and as a result iron is dissolved at the bare areas, which act as anodes. The millscale covered areas act as cathodes, where the initial products of the corrosion reaction are sodium hydroxide and hydrogen. The same results would be obtained if an electric current were passed through the solution by connecting the bare areas to the positive pole of a battery and the millscale-covered areas to the negative pole. This view of the mechanism of aqueous corrosion is no longer a vague theory, but rests upon a solid foundation of experimental fact.

The corrosion currents have ben detected and mapped and it has been demonstrated that these currents correspond in magnitude to the weight of metal corroded.

Any heterogeneity in the structure or surface of the metal itself, or in a combined metal system of which it may form a part, or in the external conditions to which it is exposed, will under appropriate conditions set up a corrosion cell. The effect of broken millscale on steel, mentioned above, is an example of the first factor; the accelerated corrosion of the steel parts of a ship's hull adjacent to fittings of non-ferrous metals is an example of the second, and the third is illustrated by the corrosion of steel dock gates exposed to waters of differing salinities, as when fresh river water flows out as a smooth layer over sea water.

In Fig. 2.3 the cathodic products are sodium hydroxide and hydrogen. Unless the hydrogen is removed from the surface of the cathodes, it acts as a blanket, slowing down and ultimately stifling the cathodic reaction, thus stopping the corrosion process. In acid solutions, such as mine waters, the hydrogen is evolved as gas and corrosion can proceed apace; corrosion is then said to be of the hydrogen evolution type. More generally, however, particularly in solutions of neutral salts, such as sea-water, evolution of hydrogen cannot occur to an appreciable extent and the presence of oxygen is necessary to promote the cathodic reaction. In popular terms, the function of the oxygen is to remove the hydrogen at the moment it is formed by oxidising it to water. This is the type of corrosion known as the oxygen absorption type, and where this mechanism occurs, the rate of attack on the metal will often be controlled by the rate at which oxygen can reach the surface. In conformity with this, the rate of corrosion of steel immersed in sea-water has been found to decrease with the depth of immersion, as shown below:

Depth of Immersion Ft.	Loss in Weight oz./sq.ft/year
1	9.6
2.5	8.4
4	7.8

FIGURE 2.1

CORROSION - TIME CURVES FOR CARBON STEEL IN IMMERSED SEA - WATER CONDITIONS

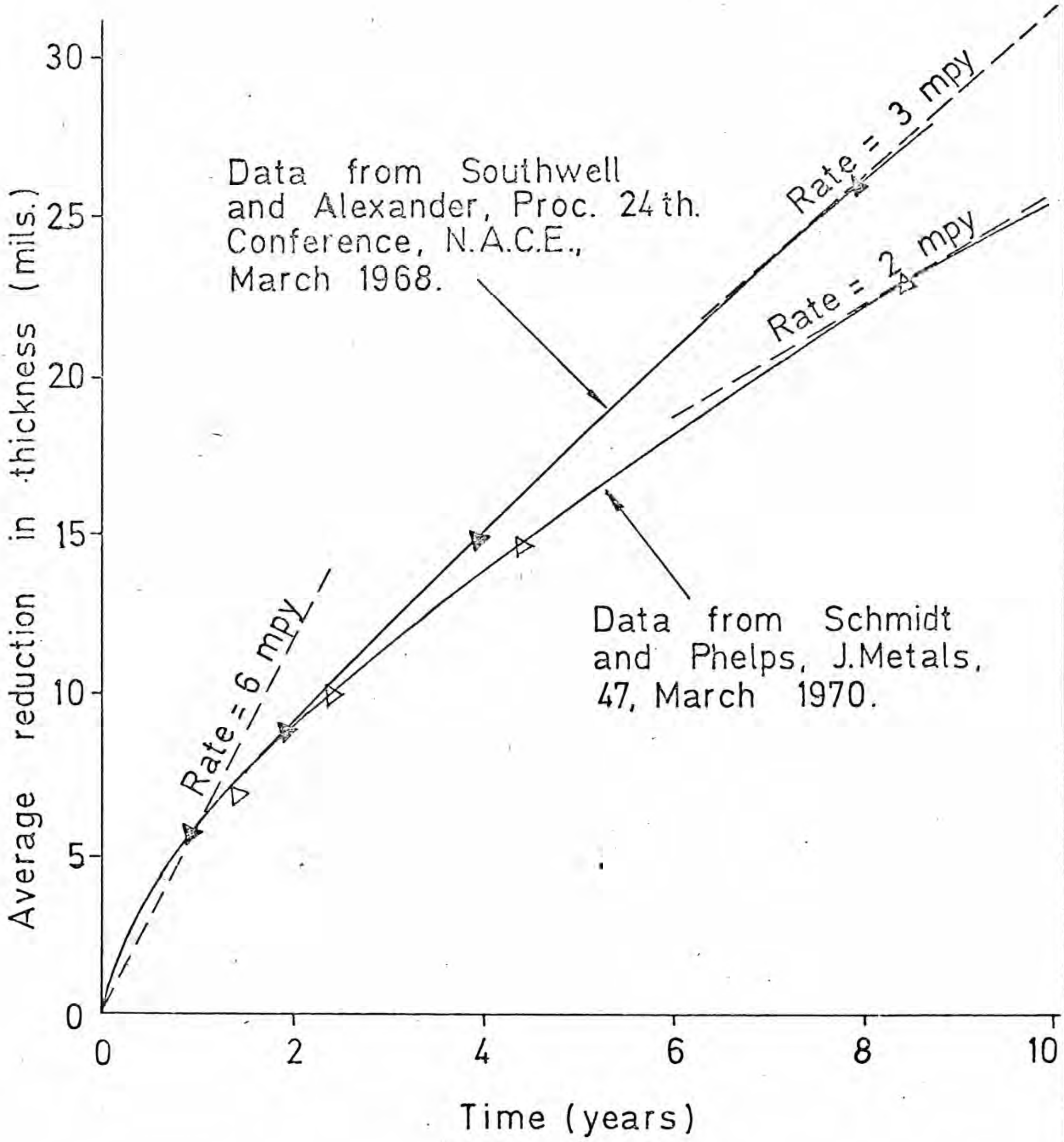

FIGURE 2·1

It is probable that this decrease continues with increasing depth and that little corrosion of the oxygen absorption type is possible at great depths, judging by the relative freedom from corrosion of ships salvaged after long immersion in deep water. Experimental evidence will be forthcoming on this point in several years' time, as the British Post Office Research Station proposes to keep under observation a number of deep-sea telephone repeaters encased in steel, which have been sunk on the bed of the Atlantic Ocean.

In many cases of corrosion, the final product may result from the reaction of the primary products produced at the anodes and cathodes and thus be formed at an appreciable distance from either area,e.g. in Fig 2.3. rust is produced at the places where the soluble iron chloride formed at the anodes meets the sodium hydroxide formed at the cathodes, after these primary products have diffused away from the metal through the solution. The first is the precipitation of ferrous hydroxide, $Fe(OH)_z$, which then changes gradually to the familiar yellow-brown rust by a sequence of reactions similar to those depicted in Fig. 2.0.

2.08.1 CORROSION RATE

The usually quoted linear corrosion rate of 5 mils/year for steel in immersed marine conditions is true only for the first 1 - 2 years of exposure, longer exposures usually giving rise to much lower rate of e.g. 2 - 3 mils/year at 8 years exposure. These rates have been confirmed for a marine pier which shows an average corrosion rate of 2 mils/year for the first 20 years, then about 1/mil/year as the subsequent rate. See fig. 2.1.

2.09 MICROBIOLOGICAL CORROSION

For a long time, corrosion workers were puzzled by the fact that some of the worst cases of corrosion of buried iron pipes were found in water-logged anaerobic soils, i.e. in soils which in their very nature contained no available oxygen for the corrosion process. This seemed to rule out corrosion of the oxygen abeorption.type and it was also clear that corrosion of the hydrogen evolution type did not occur. The explanation was provided by some Dutch investigators[1], who proved that certain bacteria which flourish in anaerobic soils can decompose sulphates when iron is present, converting them into sulphides. The oxygen originally present in the sulphates becomes available for removing the hydrygen formed at the cathodes of the corrosion cells in much the same way as atmospheric oxygen. The chemical reactions involved are not fully understood, but for practical purposes, may be represented as follows:

$$CaSO_4 \rightarrow CaS + 4O$$

$$4\,Fe + 4O + 4H_2O \rightarrow 4\,Fe(OH)_2$$

$$Fe(OH)_2 + CaS \rightarrow FeS + Ca(OH)_2$$

The final result of the whole sequence is:

$$4\,Fe + CaSO_4 + 4H_2O \rightarrow FeS + 3Fe(OH)_2 + Ca(OH)_2$$

The corrosion product contains iron sulphide, and this is why buried iron pipes which have suffered corrosion in heavy clay soils through the intervention of sulphate-reducing bacteria are usually found to be surrounded by a thick black crust of earth and corrosion product, which gives off the characteristic smell of sulphuretted hydrogen when it is wetted with hydrochloric acid.

Extensive research on microbiological corrosion[2] has been conducted at the Chemical Research Laboratory, Teddington, England. In investigations of service failures made in collaboration with the Institution of Water Engineers, no fewer than 44 out of 53 cases of serious external corrosion of buried water pipes were found to be due to the action of sulphate-reducing bacteria. Of the remainder, six came from soils containing ashes and clinker and three from mixtures of clay and clinker.

Sulphate-reducing bacteria are also found in the sea and in natural waters. For instance, they can flourish in the silt and mud of the sea bed. Some cases of marine corrosion are undoubtedly attributable to them. A case has been described in which a new

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(1) reference 2.6
(2) " 2.6

FIGURE 2.8

SEAWATER CORROSION OF MARINE PILES

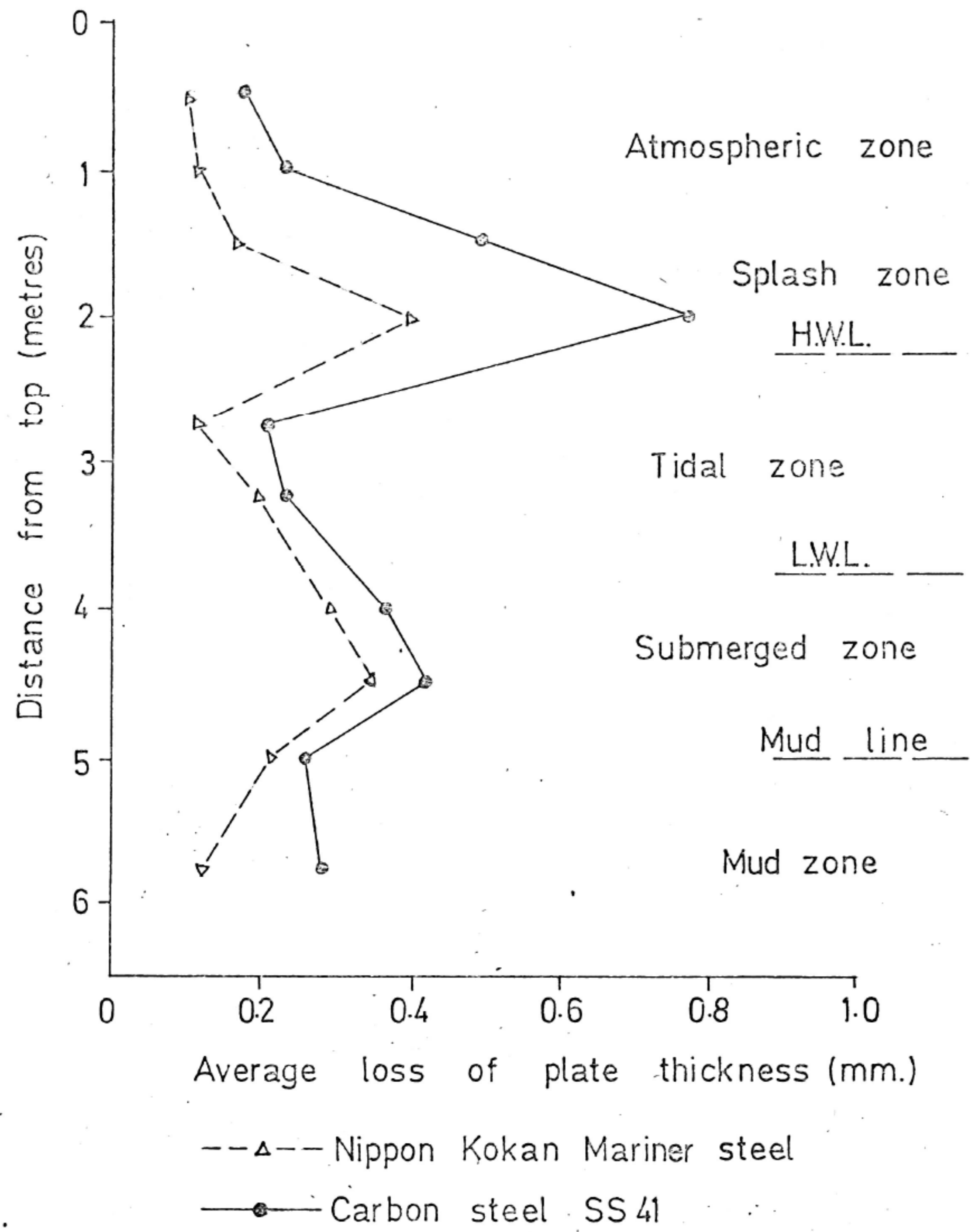

FIGURE 2·8

ship was moored in a river estuary during fitting-out in such a way that for appreciable periods between tides, her bottom rested on mud banks.[1] These mudbanks consist of deposited clay and silt, polluted with organic matter from sewage discharged into the river, so that they constitute an ideal breeding ground for anaerobic bacteria. When the ship was dry-docked five months after launching, her bottom plates and rivets were found to have suffered severe corrosion of the pitting type. It was concluded that sulphate-reducing bacteria were mainly responsible for the attack on the steel. This was demonstrated by tests conducted on pieces of mild steel plunged into samples of mud taken from the banks and held at 37°C for 42 days. Half the tests were made in fresh mud and the others in the same mud after it had been sterilised. The average losses in weight through rusting of three specimens under each set of conditions were:

IN UNSTERILISED MUD -	1.56 gm. per dm^2
IN STERILISED MUD -	0.07 gm. per dm^2

Although sulphate-reducing bacteria permit the corrosion of steel to take place under conditions in which it would not otherwise occur, the rate of corrosion is not necessarily any greater than would result from straight-forward corrosion of the oxygen-absorption type. Thus in the laboratory experiment quoted above, the loss in weight of the steel plates in the unsterilised mud is equivalent to corrosion at the rate of about 6.8 mils. per year. The normal rate of corrosion of steel immersed in sea-water is approximately 5 mils. per year.

2.10 CORROSION TESTING

Fig. 2.8 shows the thickness loss profile obtained by a number of workers at different locations. This profile is quite reproducible, and shows the five main areas of corrosion on a steel pile, viz. atmospheric (subject to moist salt air and spray), splash zone (wave action and spray), tidal (intermittent wet and dry), submerged (continuously wet), and mud zones.

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(1) reference 2.6

Localised pitting corrosion predominates in the atmospheric, splash and mud zones, where small corrosion cells are set up due to droplets of spray condensing (atmospheric zone), removal and general mechanical damage of the protective rust by wave action (splash zone), or possible bacterial action (mud zone).

The long-line effect controls the corrosion in the tidal and submerged zones. This long line effect is brought about by a differential aeration cell being set up along the pile, with the cathode of the cell in the highly oxygenated surface waters, and the anode in the water layers below this which contain lower levels of oxygen. Thus the tidal zone becomes the cathode at which oxygen is reduced and the submerged zone becomes the anode at which the steel corrodes.

Because the anode zone is relatively very large in area with respect to the cathode zone, the overall corrosion loss in the anode zone per unit area is quite low.

The usual methods of determining corrosion data for steel in marine environments is by placing pre-weighed coupons (small specimens) in the desired locations or by driving piles such that they reach from below the mud line to above wave action in the atmospheric zone. After given time intervals, these coupons or piles are withdrawn, and the amount of corrosion determined, by measuring the weight loss or by gauging the thickness reduction.

Examination of the methods of measuring corrosion rates of steel has revealed that individual coupons in the different zones give rise to higher corrosion rates particularly in the tidal zone than those experienced by continuous steel piling which passes through several of these zones. This phenomenon has been attributed to a self generating cathodic protection system which significantly reduces the corrosion rates in the severe tidal and splash zones. Researchers have concluded that piling data have a practical significance with respect to the corrosion and protection of piling and other steel structures partially immersed in sea water and that they are also important in disclosing that the practice of studying corrosion

FIGURE 2.9

EFFECT OF COPPER CONTENT ON THE RESISTANCE OF STEEL TO ATMOSPHERIC CORROSION

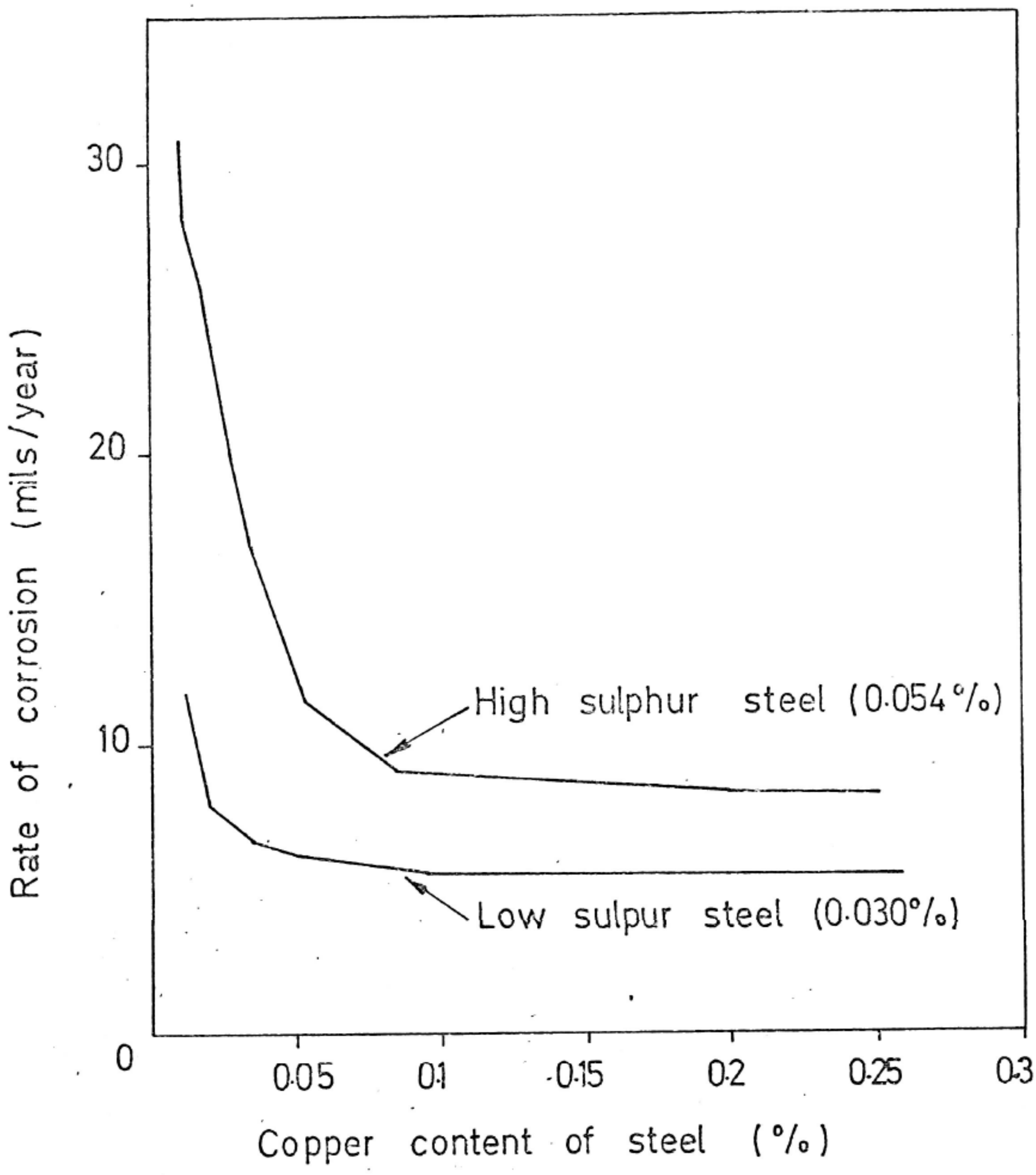

FIGURE 2.9

in the different zones by exposing isolated specimens in each zone will not provide reliable data applicable to the behaviour of structures of components which extend through several zones.

2.11 EFFECT OF THE COMPOSITION OF IRON AND STEEL

The resistance of iron or steel to atmospheric corrosion can be greatly increased by the addition of alloying metals. Steels with increased resistance to corrosion fall into two groups: the rust resisting steels proper which are virtually immune to attack, and the low-alloy steels which undergo rusting but are more resistant than ordinary unalloyed steel.

Variations within accepted commercial limits of the carbon, manganese, silicon, phosphorus and sulphur contents of unalloyed steel do not produce any marked changes in its corrosion resistance. A high sulphur content may increase corrosion under certain conditions; for example, it is undesirable to use high sulphur steels for the manufacture of tinplate subsequently used in the canning industry. Killed steels containing 0.2% of silicon are less corrodible than the balanced steels with a lower silicon content commonly used for the production of plates and sections for structural purposes, but the difference is only of the order of 10%, and has no practical significance. In general, there is no evidence that common structural steels produced by the normal processes, differ appreciably in their resistance to atmospheric corrosion.

2.11.1 Low-Alloy Steels

Of far greater importance are the effects of small quantities of alloying elements deliberately added to the steel. One of the first to be added in this way was copper. Steel containing about 0.2% copper is 50% more resistant to atmospheric corrosion than unalloyed steel. The pioneer in the development of the copper-steels was the American metallurgist D. M. Buck.[1] Some early results obtained by him are shown in Figure 2.9; they are related to steel sheets exposed in the open air in an industrial atmosphere. Buck's conclusions have been fully confirmed by subsequent investigators. These researches paved the way for intensive investigations of a whole range of alloy additions. As a result, several so-called low alloy steels have been put on the market. These are low or medium carbon steels, chiefly used for structural purposes. They combine increased tensile strength with greater resistance to atmospheric corrosion.

2.11.2 Rust-resisting steels

The rust resisting steels proper, which are characterised by a high chromium content, generally combined with an appreciable percentage of nickel, rank among the aristocrats of the anti-corrosion world. Under straightforward conditions of atmospheric corrosion, the best of them are virtually incorrodible, as is shown in Table 2.8, in which they are compared with some non-ferrous metals and with an ordinary and two low-alloy steels. The data relate to complete exposure outdoors in an industrial atmosphere.

The rust resisting steels proper owe their immunity from

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(1) reference 2.6

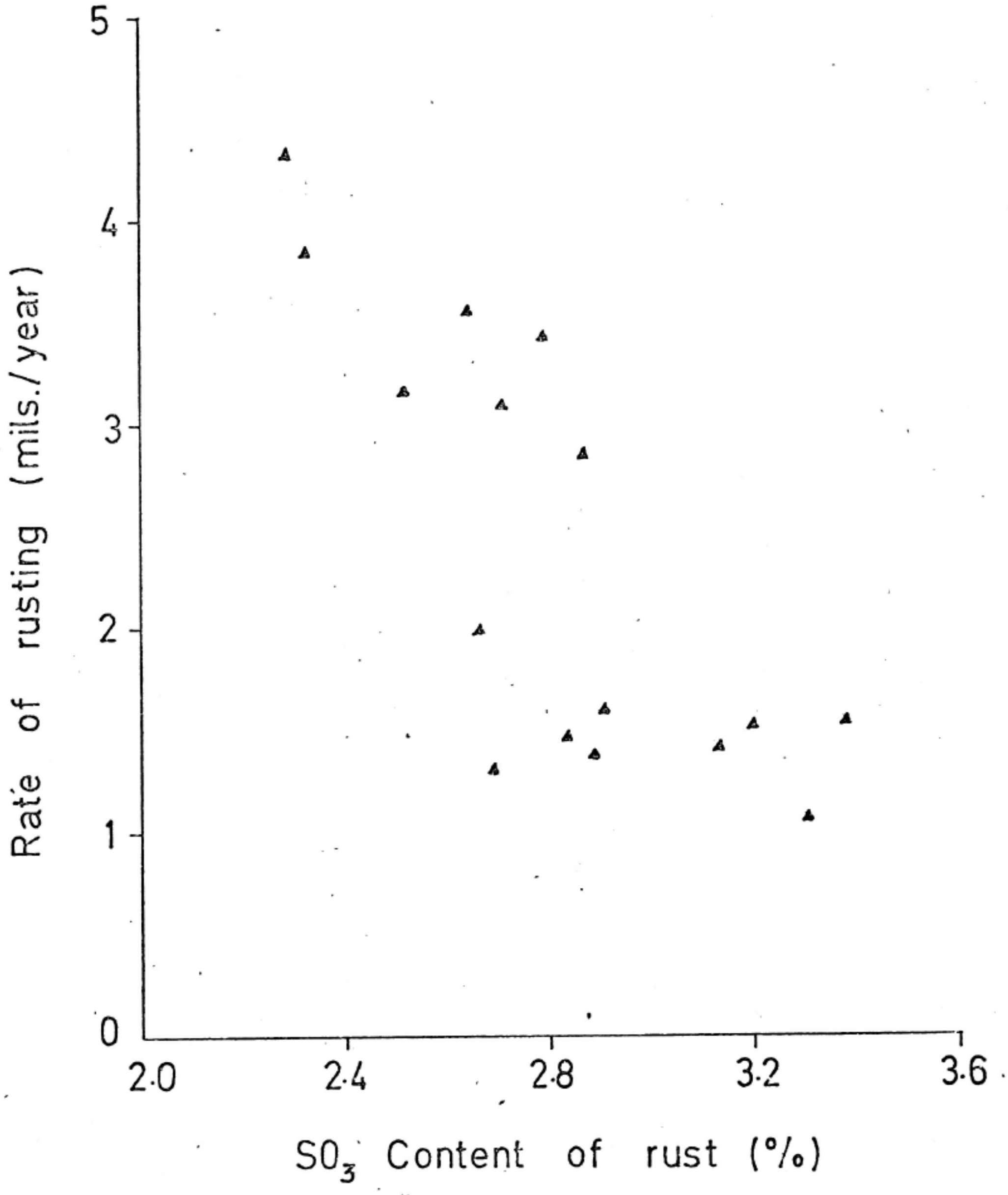
corrosion to the innate rapidity with which they corrode. Their surface is normally covered with a tough and resistant film of oxide. If this is removed by damage, the metal below corrodes so rapidly that the film heals immediately and further attack ceases. If rust-resisting steel is immersed in a solution of iodine in anhydrous methyl alcohol, the metal is dissolved and the oxide film remains behind. This method has been used to isolate the film. It was found that the film consisted of oxides of iron, chromium and nickel. In general, the percentage of chromium oxide present in the film increased as the surface of the steel was made smoother before being exposed to oxidation. The films on the most highly polished specimens contained 90% of chromium oxide. This observation agrees with the fact that the corrosion resistance of rust resisting steels is improved by polishing. The thickness of the film was of the order of one quarter of one millionth of an inch.

Low-alloy steels also depend for their increased resistance to corrosion on the formation of a protective surface layer. Whereas however, on the rust-resisting steels, the layer is a thin film of oxide, on the low-alloy steels it consists of rust. It was noticed in the early days of the use of copper-steels, that the rust formed on them was more compact and darker in colour than the rust on ordinary steel. The same holds true generally for the low-alloy steels which have followed copper-steel : they corrode even more slowly than ordinary steel, because they give rise to a rust that is less permeable to air and moisture than on ordinary steel.

This physical difference in the rusts on ordinary and low-alloy steels is associated in some way with differences in their chemical constitutions. Independent researches by Copson in the United States and by the British Iron and Steel Research Association agreed in showing that the rusts on low-alloy steels have a higher sulphate content than those on unalloyed steels and that enrichment in the alloying elements takes place in the former, e.g. the ratio of copper to iron in the rust on a copper-steel is greater than the corresponding ratio in the steel itself. It is believed that insoluble

FIGURE 2.10

CORRELATION BETWEEN RESISTANCE TO ATMOSPHERIC CORROSION AND SULPHATE CONTENT OF RUST



These results relate to 16 ordinary and low-alloy steels exposed outdoors at Sheffield for six years.

FIGURE 2.10

basic sulphates of the alloying elements, copper, nickel, etc. accumulate in the rust on the low-alloy steels and contribute to its relative impermeability. There is certainly a direct correlation between rust-resistance and the sulphate content of the rust. This is shown by the results depicted in Fig.2.10 for 16 low alloy steels tested at Sheffield.

As low-alloy steels depend for their superior resistance to corrosion on the protective properties of their rust, they lose their advantage under conditions where either rusting does not take place when rust resistance is immaterial, or where rust forms in such a way that it does not adhere to the steel. Consequently, low-alloy steels are at their best when exposed to outdoor atmospheres and do not show to advantage when immersed in the sea or when buried in the soil.

2.12 EFFECTS OF STEEL COMPOSITION IN A MARINE ENVIRONMENT

The effects of the different alloying elements on the corrosion rate of steels in marine environments has not been studied to the same extent as has been done for atmospheric corrosion.

A number of commercially available atmospheric weathering grade steels have been compared with structural carbon steels under totally immersed and tidal zone conditions.[1] Virtually no difference in corrosion could be detected between the structural carbon and these low alloy steels despite the fact that low alloy steels contained total alloying contents of 2 - 4%. On the other hand, it was found that increasing resistance to corrosion in the immersed zone was effected with increasing amounts of chromium up to 2.5% and the addition of a further 1.4% aluminium to this steel gave an average corrosion rate of 1 mil./year. These results are summarised in Fig.2.11. It must be emphasised however, that in both these investigations, individual coupons were used to collect data.

Tables have been published on the effects of the various elements on the sea-water corrosion of steels. Such a table is shown in Table 2.C[2] and much of this data is still in dispute. While one

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(1) reference 2.2
(2) " 2.2

FIGURE 2.11

EFFECT OF Cr CONTENT ON CORROSION RESISTANCE OF STEELS TO SEAWATER

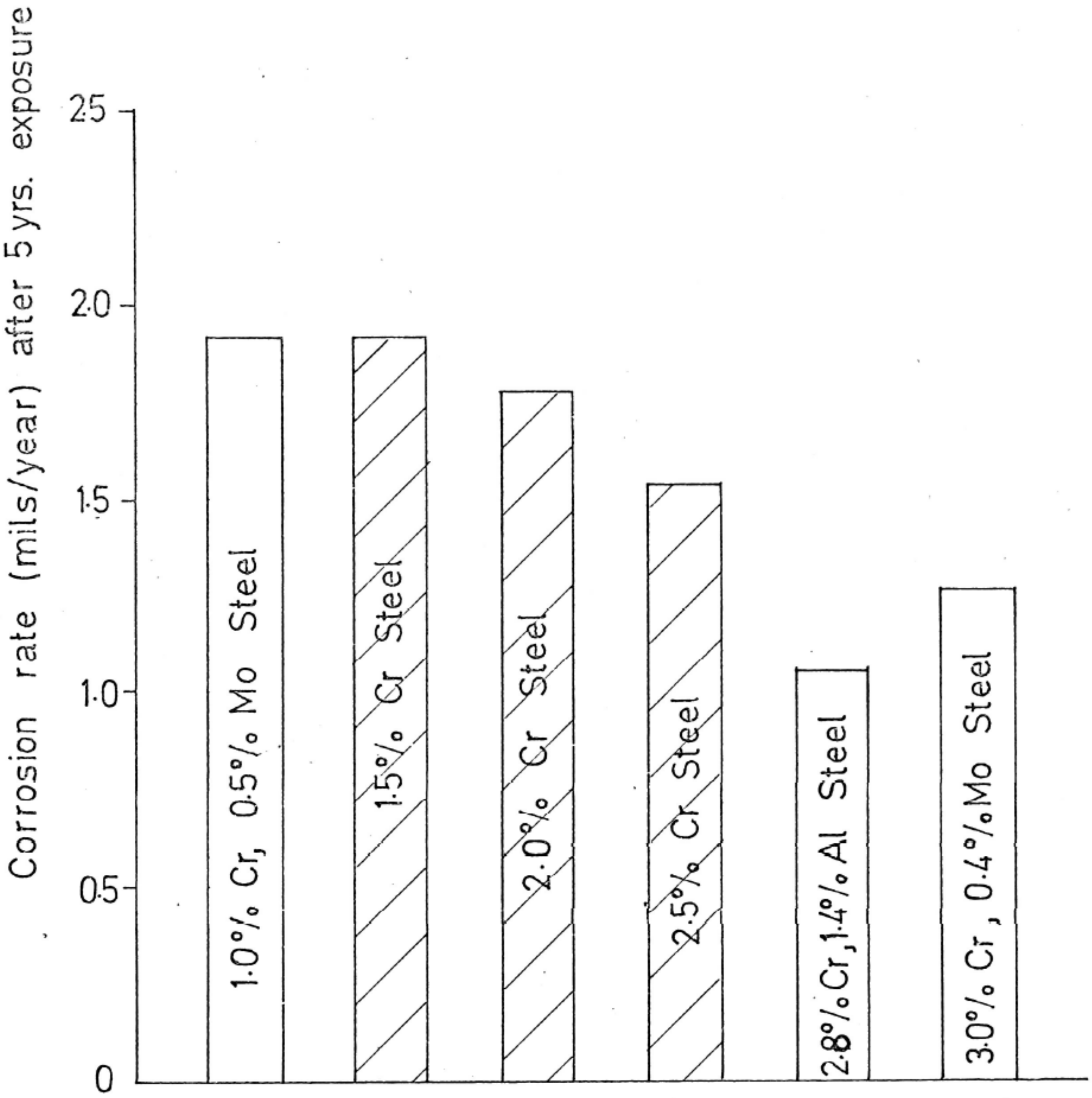

FIGURE 2.11

FIGURE 2.12

COMPARISON OF STEELS AFTER CORROSION IN SEAWATER FOR 5 YEARS

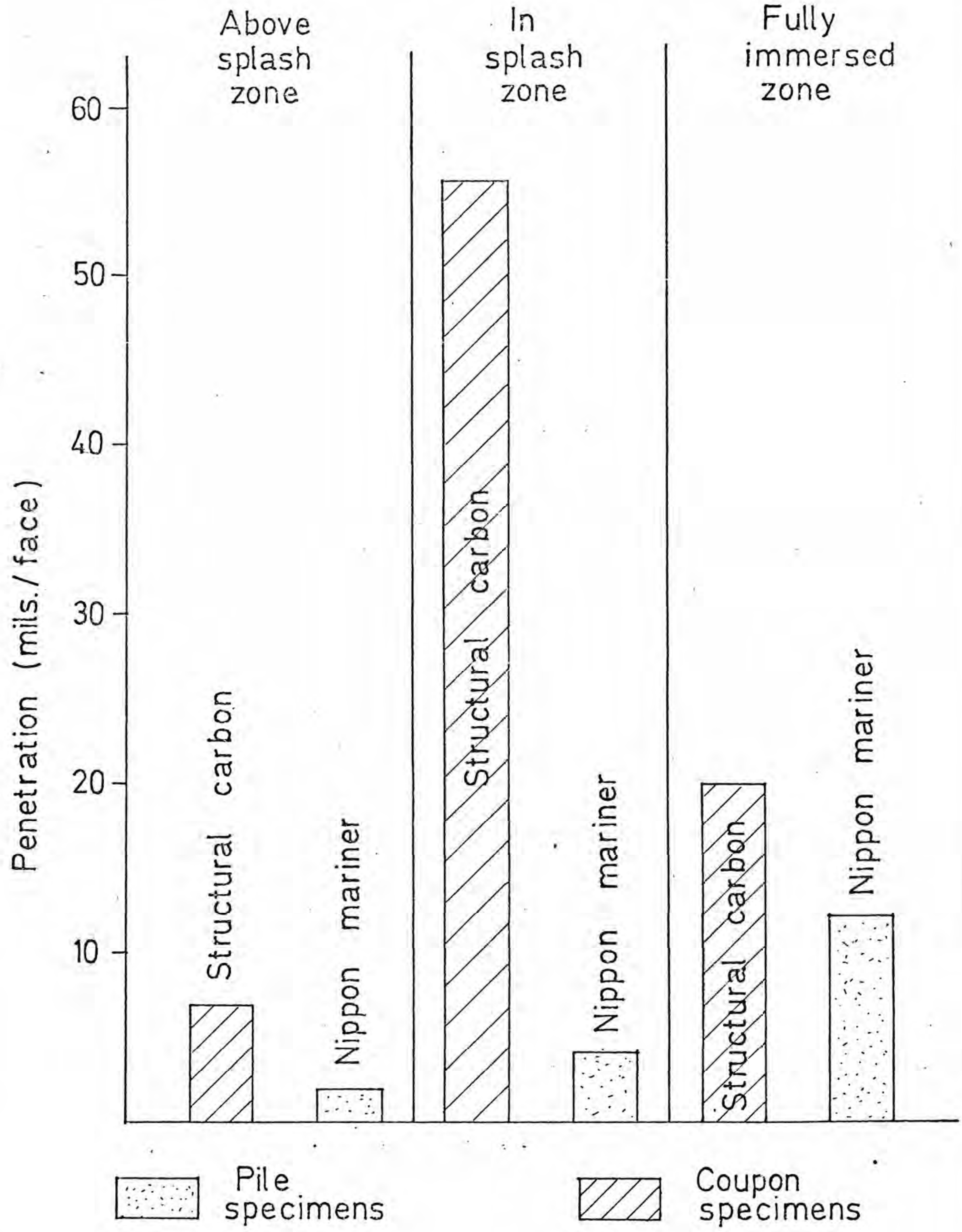

FIGURE 2·12

investigator's work tends to agree with some of these findings, another holds that the addition of 3% Cr significantly decreases the marine corrosion of steels. Others show quite the reverse as regards the effects of chromium using individual test coupons, finding that 2% and 5% nickel steels were no better than ordinary mild steel on an average corrosion basis, and were even more susceptible to pitting attacks.

Despite the unsettled nature of the problem, there are two main proprietry marine-grade steels currently available. These are of the low alloy (2 - 4% total alloying content) type and are intended for use in the uncoated condition. It has been shown[(1)] that these types of steels have virtually no corrosion advantage over structural carbon steels, when exposed in coupon form. The manufacturers of these materials, however, have published corrosion data obtained from piles, which show a marked increase in the corrosion resistance of these steels particularly in the tidal and very severe splash zones. The compositions of these steels are given in table 2.0 and the test data are shown in Fig.2.12. Virtually no difference is apparent between these marine grade steels and the structural carbon and commercial weathering steels, in the fully submerged zones (Fig. 2.12) regardless of method of measuring the corrosion loss; coupons or piles.

2.12.1 SUMMARY OF LITERATURE SURVEY

The literature has shown that the corrosion of steel piling under marine conditions is very similar throughout the world, the only factors which give significant variations between different locations are degree of pollution, water velocity, and severity of wave action. These three factors exert their influences chiefly on the nature, adherence, etc. of the protective rust film developed on the pile. Marine growth has been shown generally to assist in the protection of steel piling over long periods.

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(1) reference 2.2

TABLE 2.C

THE EFFECT OF ELEMENTS ON SEA WATER RESISTANCE

Degree of Effect	Elements	Comments
HIGH DEGREE	P	Effective in submerged and splash zones and at mean-water level. Particularly effective when used with copper.
	Cu	Effective in submerged and splash zones and even in marine atmosphere.
	Cr	Particularly effective when used together with Copper.
	Al	Effective by itself but more effective when combined with Cl
LOW DEGREE	Ni	Good resistance but not very effective in a submerged zone.
	Si	Only a little increase in corrosion resistance.
	Mo	
	Co	
	Be	
ACCELERATION OF CORROSION	C	Accelerating corrosion but having little effect in the C range of practical steels.
	Mn	A little decrease in corrosion resistance.
	S	Accelerating corrosion but harmless when co-existing with copper.

TABLE 2.D

COMPOSITIONS OF PROPRIETARY

MARINE - GRADE STEELS

TYPE	C	Si	Mn	P	S	Ni	Cr	Cu
U.S.S. (FUJI) MARINER	0.22 max.	0.10 max.	0.60 0.90	0.08- 0.15	0.04 max.	0.04- 0.65	-	0.50 min.
NIPPON KOKAN	0.20 max.	0.50 max.	0.90 max.	0.07- 0.15	0.04 max.	-	0.20- 0.80	0.20 0.50

The question of which alloying elements can be used to impart a useful degree of corrosion resistance is at present unresolved. As most of the tests on this subject have been performed on individual coupons, and therefore not directly applicable to a pile situation, one has to rely on the work done by a few steel companies on piles of their own specified compositions. These proprietary marine-grade steels are of the low alloy type with 2 - 4% total alloy content, and according to the company information available, there would appear to be no doubt that the corrosion rate in the splash and atmospheric zones is quite markedly reduced. This alone would represent a significant gain in performance since it is in these zones that cathodic protection is ineffective. As far as the submerged zones are concerned, the only question remaining for the design engineer is to what extent he is prepared to accept the presently attainable reduction in thickness arising from corrosion.

2.13 THE POTENTIAL IMPORTANCE OF MARINE GRADE STEELS

An indication of the economic significance of marine grade steel in relation to plain carbon steel may be obtained from a recent U.S. Navy survey(1) of a sheet piling wall with sufficient depth of water to permit shipping to dock.

The cost comparisons of marine steel with plain carbon steel and of plain carbon steel with and without initial protection are shown in tables 2.E and 2.F respectively. The annual cost shown in the last column of the table represents the initial outlay plus interest amortised over the lifetime to failure.

It is significant that while marine grade steels may cost from 20 to 40% more than standard carbon steels, when transportation, driving and installation costs are included, the cost disadvantage narrows to about 10% or less. If the additional strength of the marine-grade steel permits the use of a thinner section, the marine steel installation may be made at a lower total cost. If, however, the same piling footweight is used, the marine steel is

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(1) reference 2.2

TABLE 2.E

COST COMPARISON OF CARBON AND

MARINER STEEL BULKHEADS.

	Mariner Steel	Carbon Steel
Pile length (ft)	52	52
Wt/sq.ft. of wall (lbs.)	27.0	32.0
Cost/lin.ft. ($)	375	373
Estimated life (yrs)	35+	20-30
Annual cost ($)	22.90	24.3-29.9

TABLE 2.F

COST COMPARISON OF CARBON STEEL BULKHEAD

WITH AND WITHOUT INITIAL PROTECTION

	Protected area/lin.ft. (sq.ft.)	Protection cost/lin.ft. $	Total Cost $	Estimated life (yrs.)	Annual Cost $
Steel uncoated	-	-	354	20-30	23-28.4
Steel + coating	41.5	31.0	385	22-35	23.5-29.3
Steel + cathodic protection		12	366	25-40	21.3-26.0
Combined coating + cathodic protection		43.0	397	25-40	23.2-28.2

economically justifiable by virtue of its claimed additional lifetime to failure.

When the cost of failure is high, when the accessibility for maintenance is limited or when repair costs are high, the advantages gained with marine-grade steel is emphasised. When the function lifetime is certain to be long, marine-grade steels are also desirable.

2.13.1 RESEARCH IN MARINE GRADE STEELS

Knowledge of marine grade steels is largely empirical, and therefore not well advanced. This is due to the long term nature of the testing involved. The complexity of natural conditions has so far prevented their simulation in the laboratory, with the result that no truly accelerated test has been devised.

B.H.P. are currently constructing apparatus in their laboratories in which test coupons are subject to intermittent immersion. It has been found that by this method, it is possible to distinguish between good and bad weathering properties by differences in their corrosion potential behaviour. It is planned to compare the results obtained with exposure tests which have been in progress on the Marlin Oil Rig in Bass Strait.

This work is not aimed to produce a radically new alloy steel, but rather to provide a better understanding of the relative merits of currently used compositions in order that a cost effective marine grade steel can be marketed in Australia.

The weldability of currently available overseas marine-grade steel is a dubious quantity, and one of the questions to be answered is whether a sacrifice in corrosion resistance must be made to produce improved welding properties.

2.14 STEEL PROPERTIES AND PILING DESIGN

Design stresses in steel piles appear unjustifiably low and add significantly and somewhat pointlessly to the cost of steel foundations.

2.14.1 DESIGN STRESSES

If it is accepted that the yield strength provides a reasonable basis for design, it becomes necessary to apply some load factor to this stress in order to give a design value. A load factor of 1.70 is used in steel design codes for tension and compression members. There appears to be no reason for using other factors for the foundation of the same structure, unless special conditions would suggest greater uncertainties in the strength of the material in the foundation. This is rarely the situation and most of the commonly quoted cases of uncertainty (e.g. bearing capacity, soil properties) are not related to the steel but to the surrounding conditions. Hence the load factors employed should be distributed accordingly and low design stresses in the steel should not be used to cover other uncertainties as this will lead to irrational design conditions and the frequent unjustifiable carrying over of uncertainties from one job to another totally unrelated one. It has been suggested that the axial design stress be Fa where

$$Fa + \frac{Fy}{1.70}$$

For structural steel with Fy = 36 Ksi, this leads to a design stress of 21.2 Ksi. This is much higher than the currently used values of between 9 Ksi and 12 Ksi.

Much of this large difference, appears to be an attempt to provide a corrosion allowance. This is a difficult approach to defend, as if corrosion occurs, its direct influence will b e on areas rather than on stresses.

2.14.2 CORROSION ALLOWANCES

A more rational approach would be to design for some applied load P on the basis that the initial area of the pile, A, is reduced by A over the pile life. This would give

$$P = Fa(A-\Delta A) = (A-\Delta A)\ \frac{Fy}{1.70}$$

Then the maximum permissible design stress for the pile is

$$Fa' = \left(1 - \frac{\Delta A}{A}\right) \frac{Fy}{1.70}$$

A logical design approach would be to

(i) assess structure life,

(ii) Assess corrosion rate

(iii) calculate $\frac{\Delta A}{A}$ and hence Fa'

(iv) calculate load capacity as $Fa' A$.

In addition to producing general economies this approach would upgrade the relative load capacities of the heavier pile sections. This is an important point to appreciate : - corrosion rate is independent of cross-sectional area and thus heavy footweight piles will have a distinct advantage over the lighter pile section. Unfortunately, the current blanket use of 12 Ksi for design does not permit use to be made of either the general load benefit or the relative properties of the various pile sections.

2.15 CORROSION PREVENTION

There is ignorance on the part of some engineers of the most effective methods of preventing corrosion. Even when methods of preventing corrosion are known, there is sometimes a reluctance to use them, because of their apparently greater cost. If true economies are to be achieved, it is essential to think not solely in terms of initial expenditure, but to budget for the most efficient and cheapest method of protecting the steelwork during the whole of its desired service life.

The Golden Gate Bridge at San Francisco(1) is an example of where a more liberal outlay on the initial protective scheme would have been amply recouped by material reductions in the subsequent maintenance costs. Sandblasting was proposed as the method of preparing the steelwork for painting, but was rejected on the grounds of economy. The steel was prepared by solvent-cleaning and wire brushing and painted with up to three coats of paint in the shop. By the time the steel had been shipped through

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(1) reference 2.2

the Panama Canal and reached its destination, this shop paint had deteriorated badly, because of the loosening of the millscale underneath it. In many places, repriming was necessary. Failure of the paint through this cause continued during the erection of the bridge and long after it had been opened to traffic in 1937.

Eventually a decision was made to remove most of the paint previously applied and to build up a new paint scheme. To carry out this plan, it was necessary to erect four permanent movable scaffolds. If practical effect had been given to what was already known scientifically at the time, much of the heavy expenditure incurred on maintenance painting could have been avoided.

2.15.1 DOMINANT CORROSION FORM

While long-line corrosion in steel piles usually predominates between tidal and submerged zones, localised corrosion can still operate to some extent in these areas, and may even prevail over long-line effects under some circumstances.

If it is considered desirable to use a protection system on a pile, it is important to know the predominant form of corrosion which is occurring in the areas under consideration, before assessing the appropriate protection system to be employed.

2.16 METHODS OF PREVENTING CORROSION

The prevention of corrosion should first be considered in the design stages of a project.

The practical methods available for preventing corrosion can be classed under four headings:-

1. Treatment of the corrosive medium, so as to render it non-aggressive.
2. Use of corrosion-resistant materials.
3. Cathodic protection.
4. Use of protective coatings.

2.16.1 TREATMENT OF THE CORROSIVE MEDIUM

The prevention of corrosion by treatment of the corrosive medium involves air-conditioning in the case of atmospheric corrosion and the use of inhibitors in that of aqueous corrosion.

2.16.2 THE USE OF CORROSION-RESISTANT MATERIALS

It is improbable that the highly-alloyed rust-resisting steels will ever find wide application for general purposes in marine works, as these steels are expensive and are produced in limited quantities.

The use of low alloy steels offers much more practicable possibilities, as these contain at most, two or three percent of alloying elements, and their potential output is not so limited by the availability of materials, nor are they unduly expensive.

2.16.3 OTHER METHODS OF PREVENTING CORROSION

The prevention of corrosion by cathodic protection and the use of protective coatings is covered in detail in the following sections.

FIGURE 2.13

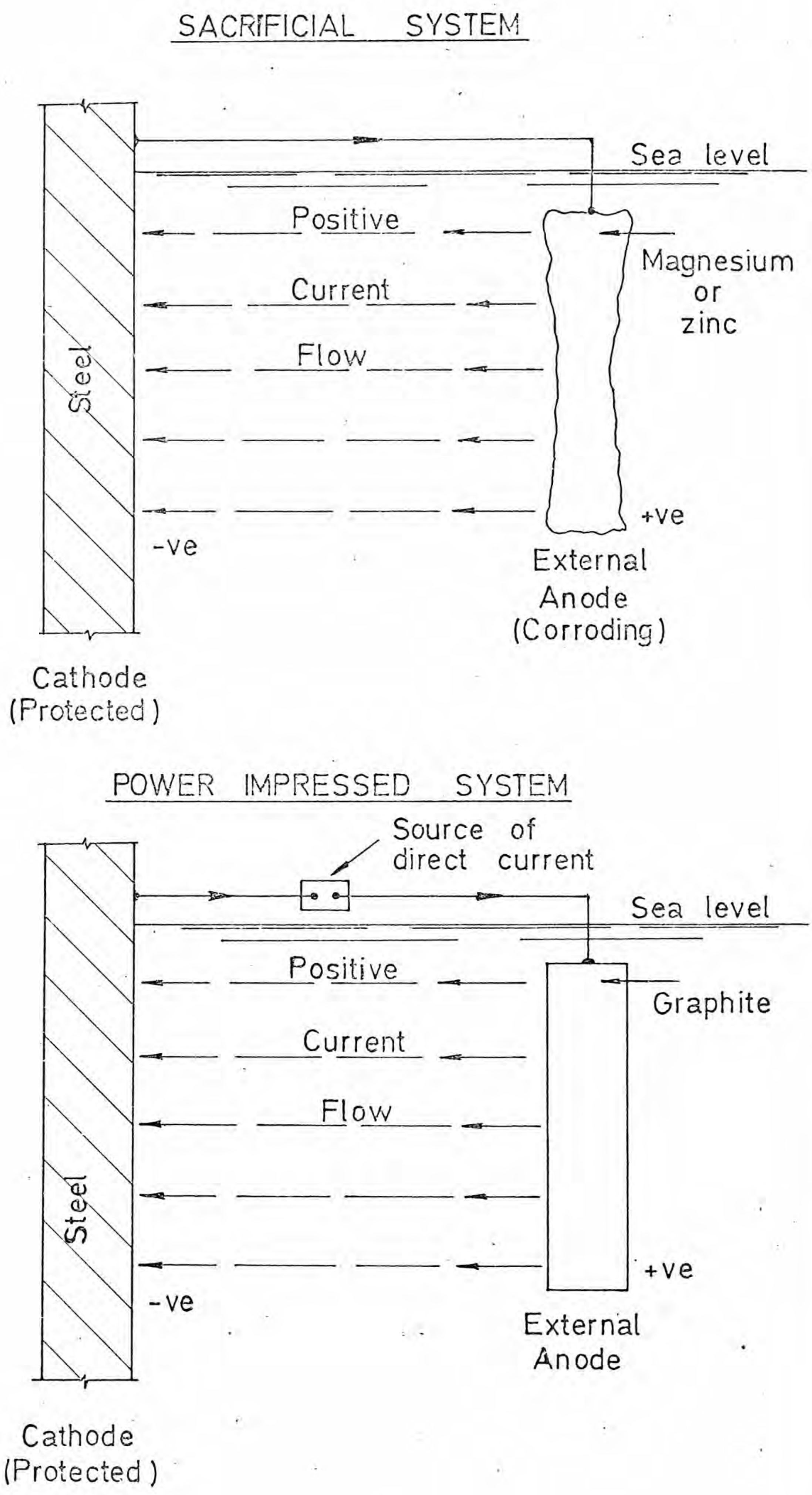
SACRIFICIAL SYSTEM
Sea level
Positive
Current
Flow
Magnesium
or
zinc
Steel
+ve
-ve
External
Anode
(Corroding)
Cathode
(Protected)
POWER IMPRESSED SYSTEM
Source of
direct current
Sea level
Positive
Current
Flow
Graphite
Steel
+ve
-ve
External
Anode
Cathode
(Protected)

FIGURE 2.13

(1) (2)

2.17 CATHODIC PROTECTION

2.17.1 Theory of Protection

The presence of anodes and cathodes in a marine structure can be caused by micoo or macro influences. On the micro scale, they are due to heterogeneities in alloy structure, oxide layers, metal crystals, etc. On the macro scale, anodes and cathodes may be caused by variations in oxygen availability, water composition, bi-metallic couples, presence or otherwise of protective coatings, etc.

Corrosion is associated with the flow of direct current from metal anodes into an electrolyte. It follows that if the potential of the electrolyte is raised and direct current flows from the electrolyte into the metal, the metal ions will oot be able to emerge and corrosion will be arrested. This is the simple concept of cathodic protection, where the whole metal surface is made the cathode to an external anode as shown in Fig. 2.13.

At the cathodically protected metal surface, provided sufficient electrical current is flowing, hydrogen ions will be released to form molecules of hydrogen gas, and when this film of gas covers the metal surface, it is said to be polarised and fully protected. With the spread of polarisation, the current required for protection is reduced, because the hydrogen separates the metal from the electrolyte with a high electrical resistance gas film.

Since hydrogen can be removed mechanically or by oxygen dissolved in the water, more current will be required to maintain the film in rapidly moving aerated water than in stagnant water of low oxygen content. Thus active ships require more current than inactive ships for cathodic protection.

Higher current densities are also needed to maintain polarisation when no oxygen is available but sulphate-reducing bacteria are present, since they also have the ability to remove cathodic hydrogen.

At a cathodically protected metal surface there is an

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(1) reference 2.2
(2) " 2.11

increase in concentration of hydroxyl ions $(OH)^-$ which raises its alkalinity or pH value. In sea water, which contains carbon dioxide as well as calcium and magnesium ions, the increase in alkalinity causes the formation of complex carbonate deposits on the metal. These deposits screen the cathodic hydrogen from oxygen in water, and because of this and their high electrical resistance, they cause the current to flow to the more remote metal areas, so improving the spread of the cathodic protection.

A greater current density will be required to obtain polarisation than is necessary to maintain it, and when calcareous deposits have been formed current requirements for protection decrease. In the case of metal with a protective electrically insulating coating such as paint, the current required for cathodic protection will be a direct function of the area of exposed metal at failures in the coating.

Anodes for cathodic protection may or may not corrode, depending upon their composition, the nature of the electrolyte, and the current density upon the anode. Depending upon conditions anions such as chlorine or oxygen may be released at the anodes.

As illustrated in Fig. 2.13 cathodic protection of steel may be obtained by the electrical connection of a metal of sufficiently high electrolytic solution pressure. This type of protection is usually referred to as the sacrificial anode system. It is also possible to apply cathodic protection by connecting the negative terminal of a direct current source to the steel to be protected, and the positive to a metal or inert conducting material which forms an anode. This method is known as the power impressed system.

2.17.2 Protection Criteria and Testing Methods.

Protection is obtained if the interfacial potential of the whole metal surface is depressed below a critical value, which depends on the metal in question. This potential is measured by placing a standard half-cell in the electrolyte close to the protected

FIGURE 2.14

POTENTIAL MEASURING TECHNIQUE WITH SILVER / SILVER CHLORIDE HALF CELL

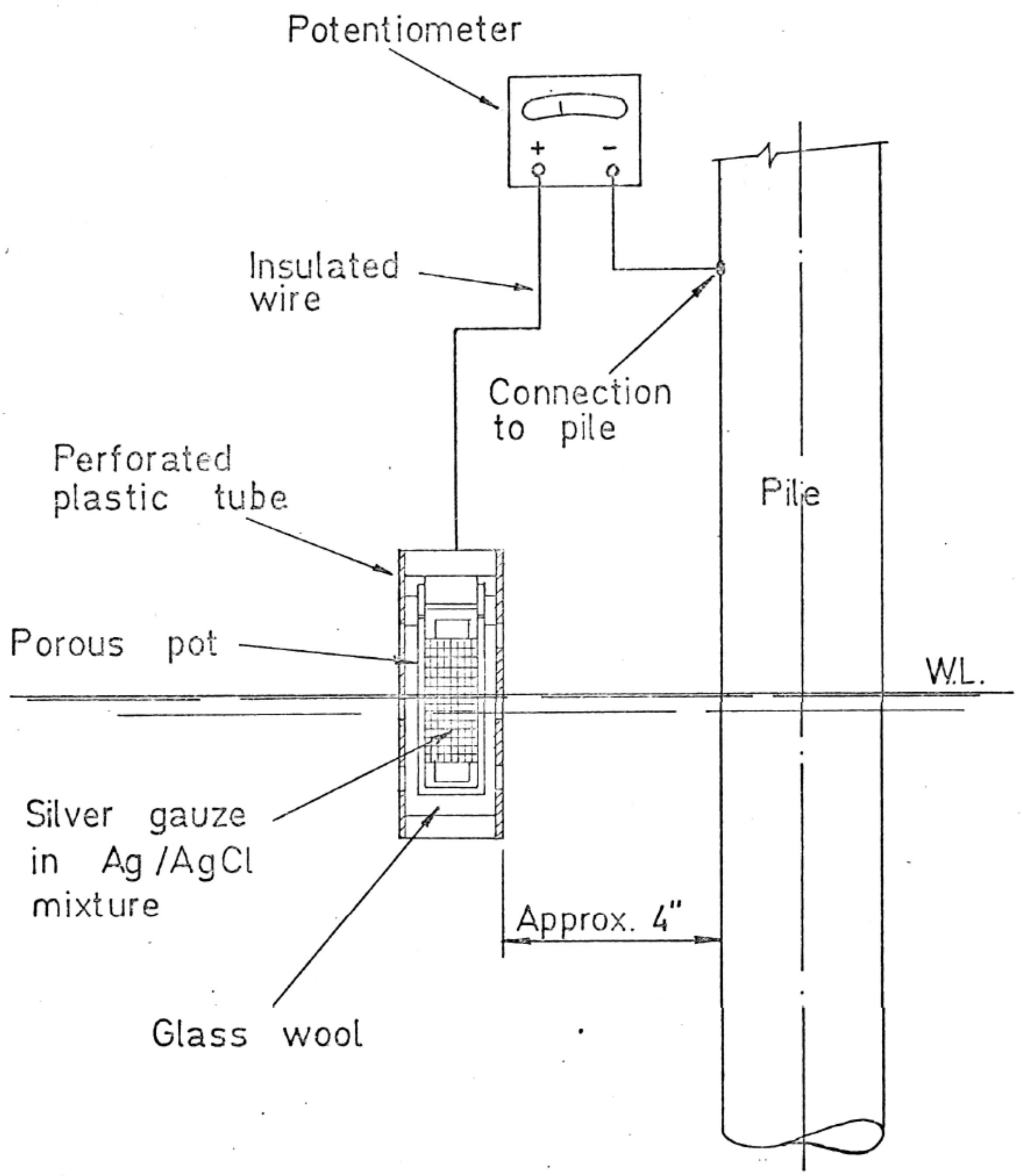


FIGURE 2.14

metal surface and connecting it through a potentiometer or high resistance voltmeter, to the metal, which forms the other electrode of the cell. Fig 2.14 illustrates this technique and shows the simplified construction of the silver/silver chloride half-cell which is normally used for marine applications. Another type is the copper/copper sulphate half=cell, which gives readings about 0.06 volts higher than the silver/silver chloride half=cell when used in sea water. For marine use the silver/silver chloride half-cell is to be preferred.

The natural potential measured by the silver/silver chloride half-cell for steel immersed in the sea may be between -0.500 and -0.700 volts and it is generally agreed that the potential should be made at least -0.800 volts by the flow of direct current through the water to the metal in order to provide protection. The amount of current required to obtain the necessary depression of potential depends on a number of factors such as the oxygen content, and speed of water flow over the surface, temperature, etc.

2.17.3 Protective Current Sources.

The protective current may originate from galvanic anodes or it may be generated by conventional electrical generation methods. In the latter case the cathodic protection is said to be of the impressed current type. In either case, the mechanism of protection is the same and both methods are equally effective.

2.17.4 PRACTICAL CATHODIC PROTECTION METHODS

2.17.4(a) Sacrificial Anodes

The principal sacrificial metals used are magnesium, aluminium and zinc in their pure or alloyed form. Each metal has its own electro-chemical characteristic as shown in table 2G.

TABLE 2.G

ANODE CHARACTERISTICS

Metal Anodes	Potential Difference From Iron (Volts)	Ampere hours per pound of metal at 100% electrode efficiency
MAGNESIUM	1.1	997
ALUMINIUM (ACTIVE)	0.9	1352
ZINC	0.2-0.3	372

These potentials correspond to open circuit potentials with no polarisation of the anode metal or of the steel. The actual values obtained in practice will always be less than those given above.

(A) MAGNESIUM

Of the common metals, magnesium has the highest open circuit potential from iron with which to force current through the electrolyte, and because it provides a relatively large amount of current per pound weight of metal during its corrosion, it is the most popular of the sacrificial anode materials.

Although magnesium at 100% electrode efficiency is capable of supplying almost 1,000 ampere hours per pound, in actual practice local corrosion cells exist on the metal surface, resulting in a lower electrode output. To obtain uniform corrosion of the anodes and the highest possible electrode efficiency, magnesium is usually alloyed with aluminium and zinc.

A typical cathodic protection alloy composition is:-

Aluminium	5.3-6.7% weight	
Zinc	2.3-3.5%	"
Manganese	0.15%min.	"
Silicon	0.30%max.	"
Copper	0.05%	"
Nickel	0.003%	"
Iron	0.003%	"
Other impurities	0.30%	"
Magnesium	Remainder	

A magnesium alloy of the above composition will usually have an electrode efficiency of 20% to 50% in water and give 200 to 500 ampere hours per pound of metal sacrificially corroded, in providing protection to iron and steel.

Magnesium ribbon anode has economic importance when used in conjunction with the heavier permanent type magnesium anodes. If the steel surface to be protected is prepolarised with the short-lived magnesium ribbon, the current density for maintaining protective potentials can be reduced to 3 mA/sq.ft. or less, in stead of 6-7 mA/sq.ft. needed in cases without pretreatment, with a corresponding extension of the life of the anode.

(B) ALUMINIUM

Aluminium has a lower forcing potential than magnesium, but offers a higher theoretical current output per pound of metal corroded. Aluminium in corroding forms a closely adherent oxide film and easily becomes anodically polarised thus preventing current flow to the iron or steel being protected.

Many alloys of aluminium have been made to overcome the problem of anodic polarisation, and the metal has also been used immersed in depolarising backfill materials, but not with sufficient success as yet, to allow aluminium to compete seriously with magnesium.

(C) ZINC

Zinc was used by Sir Humphrey Davy, and until the development of magnesium, was widely used as a sacrificial anode metal. Like aluminium, zinc in corroding forms adherent corrosion films which stop the current from flowing to the iron or steel being protected.

Tests with low aluminium and cadmium zinc alloys have given results comparable with those obtained from super purity zinc.

The characteristics of a typical marine zinc anode are:-

Aluminium	0.10 - 0.50	% weight
Cadmium	0.025 - 0.15	% "
Lead	0.006 (max.)	% "
Silicon	0.125 (max.)	% "
Copper	0.005 (max.)	% "
Iron	0.005 (max.)	% "
Zinc	Balance	

2.17.4(a)(i) Comparison of sacrificial anodes

The following table 2.H sets out properties of anodes of the more common metals.

TABLE 2.H

Property	Metal Anode		
	Manganese	Zinc	Aluminium
ELECTROCHEMICAL EQUIVALENT AMP-HR/LB.	1000	375	1350
DRIVING POTENTIAL	0.85	0.25	0.25
CURRENT EFFICIENCY	49	90	39
THEORETICAL AMP HR/LB	1000	372	1300
ACTUAL AMP HR/LB.	490	335	500
THEORETICAL LB/AMP YR.	8.7	23.5	6.5
ACTUAL LB/AMP YR.	18	26	17

2.17.4(a)(ii) Current requirements for protection

The amount of current required to protect a surface depends on a large number of factors, viz. resistivity of the structure and environment, location, size and type of structure, other structures in vicinity, etc.

The following table 2.I gives representative values of current requirements for various environments.

TABLE 2.I

PROTECTIVE CURRENTS REQUIRED BY STEEL IN DIFFERENT ENVIRONMENTS

ENVIRONMENT	CURRENT (AMP/FT^2)
MOVING FRESH WATER	0.0056
MOVING SEA WATER	0.014
ANAEROBIC NEUTRAL SOIL WITH ACTIVE SULPHATE REDUCING BACTERIA	0.042
WELL CURED CONCRETE	0.000065

The magnitude of current i.e. amp-hr required, is decided by the surface area to be protected in water, the salinity, temperature and the velocity and depth of the aqueous environment. This relationship may be represented as:

$$I_t = \frac{AI_z}{1000}$$

where I_t = current required

A = total submerged area in sq. ft.

I_z = cathode current density required for protection in mA/sq.ft.

Experience has shown that for steel structures in water depth < 50 ft. requires current density of 3 mA/sq.ft. The break at 50 ± 15 ft. is due to the different degrees to which oxygen is available at the steel surface to cause depolarisation.

Table 2.J gives data on the protective current requirements for steel in sea water.

TABLE 2.J

POLARISATION OF BARE STEEL IN SEAWATER

Initial Current Density (mA/Sq.ft.)	Duration (Days)	Film	Current Density for Continued Protection (mA/sq.ft.)
200	1	Soft	2-3
100	2-3	Fairly Hard	2-3
50	5-6	Fairly Hard	2-3
20	20-30	Medium Thickness, Hard	4
10	2-3 Months	Medium Thickness, Hard	4
6	up to 6 months if at all	Light to Hard	4-5

2.17.4(b) Galvanic Anode Cathodic Protection

A galvanic anode system is virtually maintenance free, exeept for annual inspection and potential measurement and replacement of anodes. Anodes are available with a life of up to 10 years.

2.17.4(c) Power Impressed Systems

In the power impressed system of cathodic protection, the flow of current from the electrolyte to the cathodically protected metal is brought about by connecting the metal to the negative terminal of a direct current source of electrical power and connecting the positive terminal to some other conductor or anode, also immersed in the electrolyte, which may or may not corrode.

The required characteristics of the power sources will depend upon the resistance of the electrical circuit, and the current required to give the protective electrolyte/metal potential. To protect a certain area of bare steel in sea water of 50 ohm cms. resistivity, a lower voltage would be required than for the same area of steel in fresh water of 2,000 ohmscms resistivity. Many factors influence the voltage and current output required in a power impressed system and in all cathodic protection design work varied practical experience supported by theoretical knowledge is necessary for complete success.

2.174(d) SOURCES OF DIRECT POWER

2.17.4(d)(i) Batteries

An accumulator or battery can supply direct electrical current for cathodic protection purposes, but it must be recharged from some other source of power at periodical intervals of time. This method can only be used when small currents at low voltages are required. Such conditions would occur if the structure was extremely well protected by a now-conducting coating so that the current required would be small. In most cases, it has been found that batteries as a source of electrical current are inadequate for marine cathodic protection.

2.17.4(d)(ii) Direct Current Generators

In ships the electrical power is frequently direct current. Occasionally this can be used for cathodic protection purposes, but it is usually at too high a voltage. For marine work the voltage required is generally between 5 and 50 volts, which can be obtained by using a D.C. converter.

It may be economical to use direct current generators for jetties, etc. at isolated locations, but in view of maintenance problems they are not popular.

2.17.4(d)(iii) Transformer-Rectifiers

For fixed marine structures such as jetties, dolphins and submarine lines at locations where electric power is available the usual method of obtaining D.C. power is to transform the A.C. mains power and then rectify to give D.C. power.

2.17.5 ANODES AND GROUNDBEDS

Important requirements for an anode in impressed current work are:-

1. Low rate of consumption.
2. Low initial cost.
3. Low volume of consumption.
4. Good mechanical properties.
5. Sufficient bulk.
6. Non-acceleration of corrosion by dissolution products of consumable anodes.

In the case of ships, the anodes for both internal and external protection are usually distributed to give as uniform a current spread as possible to the steel. For such structures as jetties, etc., a large anode or combination of anodes located at a distance from the structure may be used. These large or grouped anodes are known as groundbeds.

The electrical cables and connections to the anodes or groundbeds must be very well insulated from moisture to prevent corrosion.

2.17.5(a) CAST IRON AND STEEL

Scrap steel or cast iron is usually readily available for use as groundbed material for cathodic protection schemes. One ampere of current flowing for one year from steel immersed in water will consume 15 to 20 pounds weight of the metal. In the case of cast iron the corrosion per ampere year, might however be as low as 2 pounds, because as corrosion proceeds, a film of graphite can become exposed. Under these conditions the transfer of current to the electrolyte involves the discharge of oxygen and chloride ions.

2.17.5(b) CARBON AND GRAPHITE

Carbon anodes are used, but graphite which is a better electrical conductor is more popular. They are usually supplied as rods up to 6 feet long and up to 6 inches diameter. Special types are produced for ships. The graphite anodes are usually impregnated under pressure with paraffin wax or resin to fill up any small interstices.

The values recommended for a graphite anode current output vary between 0.25 and 1.00 amperes per sq.ft. according to conditions. Theoretically, carbon or graphite has an electro-chemical equivalent of 4,042 ampere-hours per pound weight in acting as anode and forming carbon dioxide, but usually electrolysis of water occurs with the result that up to 80,000 ampere hours per pound have been obtained.

Chlorine and oxygen are formed at the anode and it is important that the gas may escape freely from the anode surface. If the gas cannot be freely dispersed it will increase the electrical resistance of the circuit. Should the current density on the anode be too high or impregnation unsatisfactory, it is possible that the graphite will disintegrate due to the pressure of gas formed below the anode surface.

The difference in electrode potentials between iron and graphite necessitates the application of about 2 volts from the direct current source before current commences to flow through water to the structure.

Practical disadvantages of graphite are its brittle nature and the difficulty of making a good permanent electrical connection to it for immersed conditions. It is however, a widely used and popular material for anodes for jetties, floating docks, or similar installations.

2.17.5(c) LEAD ANODES

Lead and its alloys are relatively new materials for use as anodes in the power impressed type of protection. They form protective films and tests indicate that they may be very successful. They are easily cast for ships, and being malleable are not liable to fracture like graphite. They have longer lives than steel or cast iron. For marine structures, such as jetties, they can be used in the form of extruded copper cored cables which makes their installation cheap.

2.17.6 COMPARISON OF SACRIFICIAL AND POWER IMPRESSED METHODS

The two most important factors to be considered when deciding whether cathodic protection is to be achieved by sacrificial anodes or power impressed system are:-

(a) The resistance of the electrolyte.

(b) The availability and cost of A.C. power.

If the electrolyte has a resistance of greater than about 2,500 ohm. cms, the use of sacrificial anodes can usually be ruled out because the relatively low driving voltage will enable the anode to deliver only a very small current. However if the structure to be protected is very well coated so that the current requirement for protection is extremely low, as for example on a well coated submerged surface, magnesium anodes may be used in higher resistivity conditions. If the total current demand is greater than about 10 amperes and mains electric power is available then the power impressed system is usually preferable.

If both systems of protectionare possible then a detailed costing is required to decide which system will be most economic during a life of say 25 years. It is usually found that the first cost of a power impressed method is higher than one employing sacrificial anodes, but providing that the cost of making A.C. main's power available at the required location is reasonable, the overall cost of a power impressed system is less after 5-10 years when the anodes may have been replaced two or three times.

2.17.7 APPLICATION OF CATHODIC PROTECTION

2.17.7(a) SHIPS

(A) HULL EXTERIOR

(i) Ships in Reserve.

When ships are laid up, their hull exteriors may be protected by the use of cathodic protection. Since the vessels are moored, the anodes can be placed at such a distance from the hulls that relatively uniform current density over the surface is obtained.

If the vessels are alongside jetties where electrical power is available, the most satisfactory method is to use the power-impressed system with transformer-rectifiers supplying current to scrap metal or graphite anodes. The control of protection is obtained by adjustment of the transformer-rectifier output.

For ships which are lying dormant in more open water attached to mooring buoys where no power is available, the cathodic protection is preferably carried out by the use of magnesium anodes.

The sacrificial anodes are generally of hemispherical form suitable for resting evenly on the sea bed, or of cylindrical form for suspending around the vessels out from the sides. The actual design of the system will depend on the depth and electrical resistance of the water as well as the quality of the coating on the hull exterior.

(ii) Active Ships.

For active ships, the anodes have to be firmly attached to the hull of the ship, but electrically insulated from it. The most convenient location for their installation is usually the bilge keel. The cables from the anodes pass through the hull of the ship via water-tight glands to a control panel where the anode current may be adjusted.

The better the quality of the anti-corrosion paint on a hull and the fewer the holes or holidays in the coating, the less will be the cathodic protection current necessary. Fewer anodes will be required and the throwing power of protective current will be greater, i.e. protection will be achieved at greater distance from the anode locations. Each vessel requires individual study, and results may be greatly affected by paint coating quality.

(B) HULL INTERIORS

Cathodic protection cannot be effective unless continuous electrolyte is present, so nothing can be done to prevent corrosion by sweating inside the hull by this technique. At the bottom of the ship, if water exists in the bilges, magnesium anodes may be helpful, but warning must be given against evolution of hydrogen gas.

2.17.7(b) FLOATING DOCKS

Much that has been said about laid-up ships applies to floating docks. The case for applying cathodic protection is far stronger since docking of a large floating dock for inspection and repainting is governed by the availability of an even larger dry dock.

FIGURE 2.15

COMPARISON BETWEEN PROTECTION OF STEEL HAWSERS AND CHAINS ON MOORED BUOYS

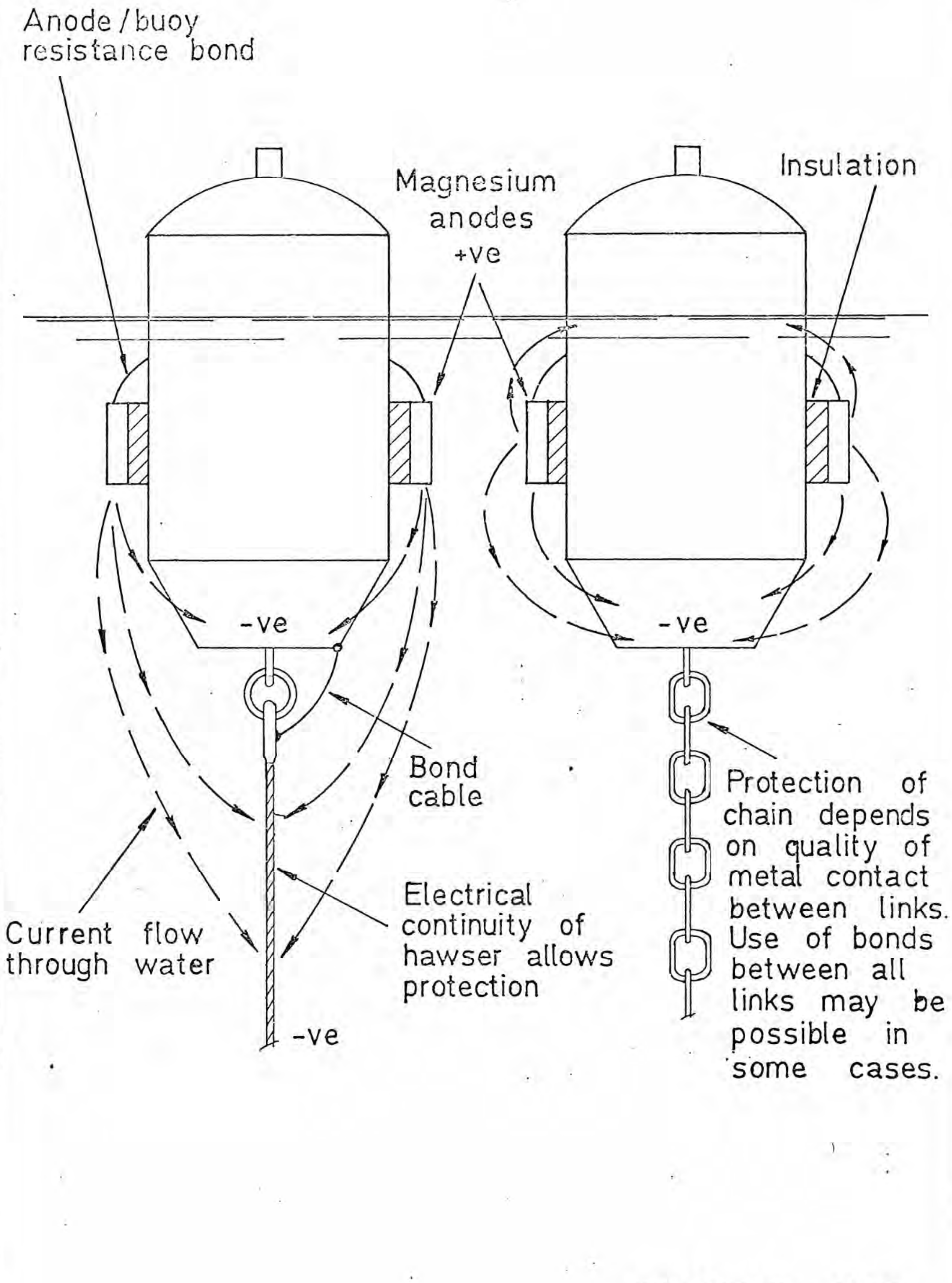


FIGURE 2·15

Furthermore, routine docking for anti-fouling is unnecessary. Generally a power supply is available on floating docks and hence the usually cheaper power supplied ystem of cathodic protection is preferred. Since the dock is generally stationary the anodes should be placed at a minimum of 100 feet away from the structure to ensure a relatively uniform current distribution to the immersed surface of the metal.

2.17.7(c) BUOYS AND PONTOONS

The use of heavy link chain for the mooring of buoys and pontoons, etc. has found favour for many years, as these methods have proved most satisfactory mechanically.

By using cathodic protection as shown in Fig. 2.15 indefinitely long life for steel cable to buoys can be ensured, but in the use of chain, much depends on the electrical continuity between the links and there can be no guarantee against corrosion.

Due to the constant rubbing of the links of the buoy anchor chain, reasonable electrical continuity is achieved. If the buoy potential is reduced to a fairly low value, then it is sometimes possible to protect the whole chain as well. Alternatively, small anodes may be attached to some of the links near the sea bed. The upper links receiving current from the buoy itself.

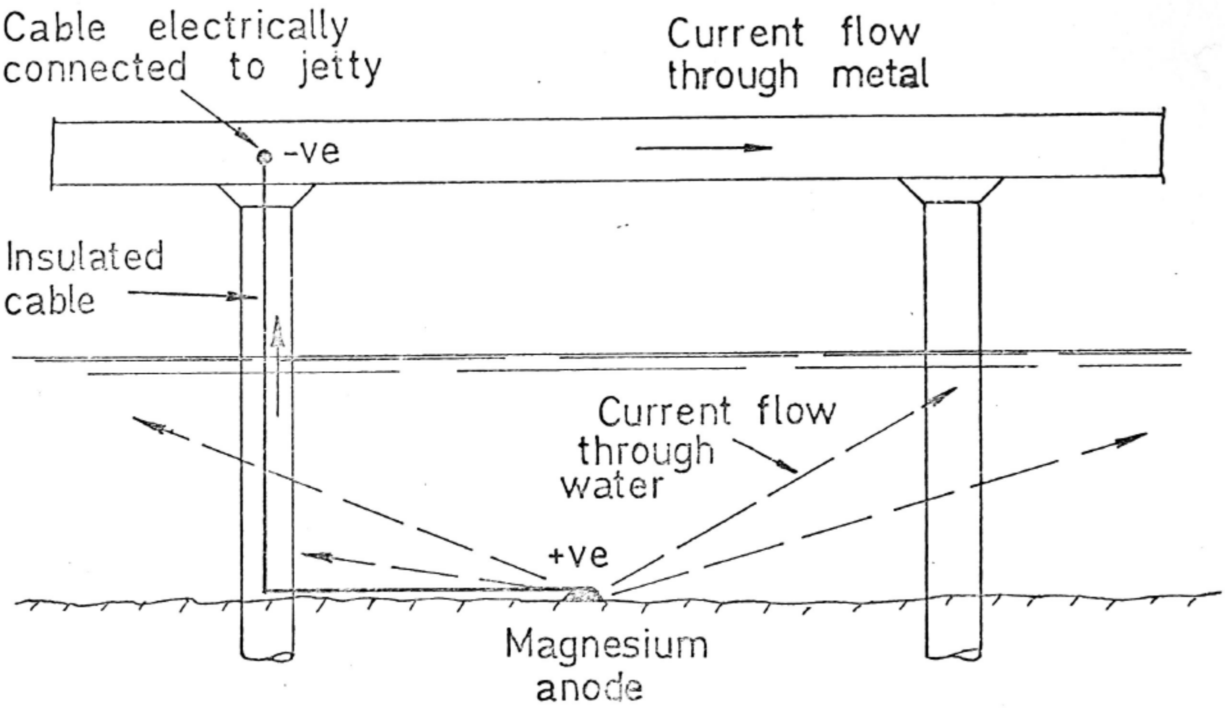
2.17.7(d) JETTIES

The corrosion of steel piles below low water mark, where coating maintenance cannot be effected, has long been a cause of major concern to designers of such structures. Cathodic protection can now give complete protection. Many highly successful installations exist which provide protection where none could be given previously. Good protection is often obtained for part of the intertidal zone, owing to the build-up of calcium deposits which retain a polarising hydrogen film.

Cathodic protection will provide full protection from the toe of the pile to approximately the half-tide level, the degree of protection tapers off between half tide and high tide. It is usually recommended that coatings be applied to piles before driving, covering

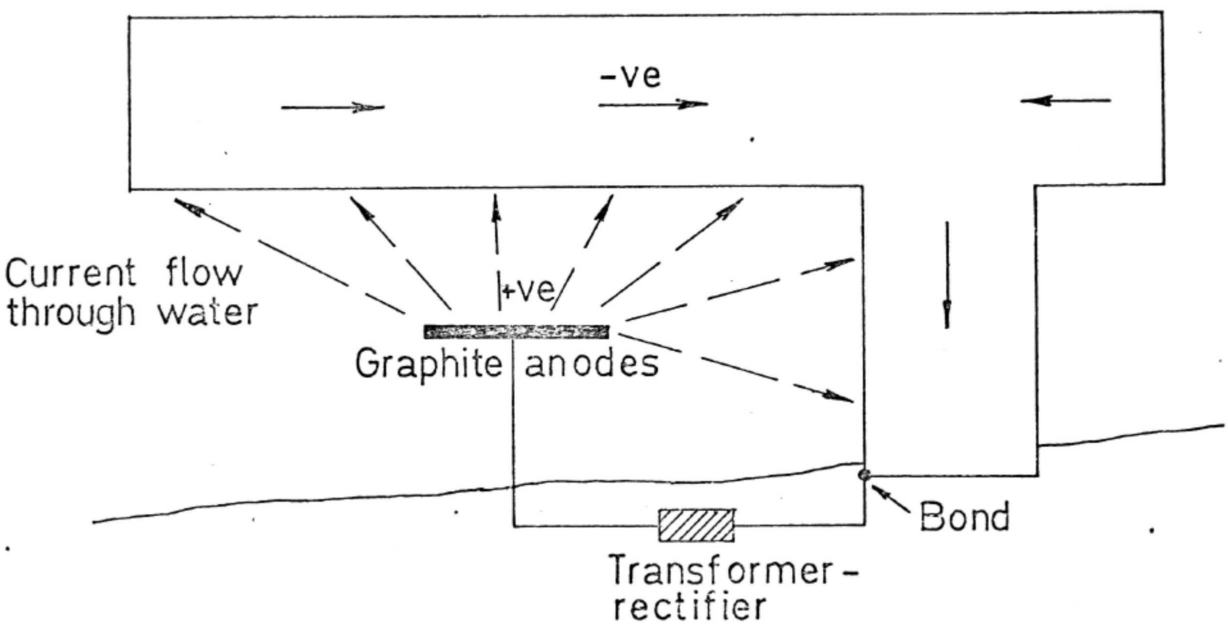
FIGURE 2.16

JETTY PROTECTION BY MAGNESIUM ANODE



ELEVATION

JETTY PROTECTION BY POWER IMPRESSED SYSTEM



PLAN

FIGURE 2.16

the area down to several feet below low tide level. This allows for some piles not being driven fully to the intended depth. Below low water, it is normal to apply no coatings and to use cathodic protection as the sole protective system.

Fig. 2.16 illustrates typical jetty installations using sacrificial anodes and also transformer-rectifiers with graphite anodes.

Both cathodic protection systems are fully satisfactory, and choice depends on local conditions. If power is available the use of transformer-rectifiers is generally much more economical and is more easily controlled, apart from avoiding multiple small works on the jetty structure itself.

A requirement to counter static electricity at oil jetties which are cathodically protected is that an electrical bond must be made between the jetty and its pipelines and oil-carrying vessels before hoses are connected and this bond must not be broken until the hoses have been discounnected. The best type of bonding system to adopt at present, uses a cable clamped to the ship, then plugged into a flame-proof switch, which when closed, completes the circuit to the pipes and jetty before the hoses are connected.

Wharves constructed with steel piles and concrete superstructures, as distinct from steel superstructures, require metallic bonding between piles. Reinforcing steelwork may be used if of sufficient cross-section, but on long runs of wharf, additional conducturs may be required to prevent excessive voltage drops in the structure and consequently wide potential variations.

All joints between structural members required to carry protective current, should be welded or brazed to ensure long term low resistance electrical contact.

2.17.7(e) STEEL SHEET PILING

The comments applied to jetty piling are equally applicable to sheet piling, and the question of coating is again important. It must not be assumed that because sheet piles are of the interlocking type, electrical continuity is complete, however, it is advisable to ensure this continuity by a short fillet weld between all piles when cathodic protection is to be applied.

In the case of land-backed sheet piling wharves, anodes are located on both the land and water sides of the piling.

2.17.7(f) SUBMARINE PIPELINES

Submarine pipelines are an ideal situation for the use of cathodic protection. Care is necessary to ensure complete electrical continuity before laying the line, as a discontinuity can lead to failure of the pipe at this point.

2.17.8 CO-ORDINATION WITH CIVIL DESIGN

It is most desirable in the interests of economy and simplicity, for the cathodic protection design to be co-ordinated with the civil design, rather than to build the structure and then start to think about cathodic protection. This particularly applies to a wharf with a reinforced concrete superstructure. For example, at the design stage it is possible to incorporate for almost no cost, the appropriate bonding between piles and cast-in cable ducts and anode attachment lugs.

2.17.9 EFFECTIVENESS OF CATHODIC PROTECTION

As cathodic protection can readily be renewed or added to during the life of the structure, the maintenance of the desired potential is readily achievable. The ability to obtain complete protection and to make simple measurements to indicate the degree of protection, are extremely valuable features of this method. Because of this assurance of complete effectiveness, it becomes unnecessary to add a corrosion allowance when designing pile thickness, if cathodic protection is to be installed.

2.17.10 ECONOMICS

Cathodic protection is almost an economic necessity on a marine structure where the steel is continually immersed and cannot be readily replaced, such as on jetties and piling. If the structure can readily be painted, the economic advantages are less.

There is no doubt that cathodic protection can do much to prevent corrosion in the sphere of marine work. It does not replace coatings, but used in conjunction with them, can offer economic benefits previously unobtainable.

An appreciation of the costs of using bare steel with cathodic protection below water, compared with coatings, is detailed in table 2.K.

TABLE 2.K

ITEM	COATINGS - NO CATHODIC PROTECTION	IMPRESSED CURRENT CATHODIC PROTECTION AND BARE STEEL
TYPICAL COST PER SQ. FT.	\$0.50 - Applied cost for sand blasting and 15 mils. of coat tar epoxy.	\$0.01/sq.ft./annum based on amortisation over 20 years. Annual power cost included.
EFFECTIVENESS	General coating life is 5-10 years. Some coating is damaged in pile driving and hence no protection from start. Increasingly no protection over 5-10 years.	100%
ANNUAL COST	\$0.05-\$0.10/sq.ft/ annum.	\$0.01/sq.ft./annum as above
ACTION AFTER 5-10 years	Install Cathodic Protection. The coating cannot be maintained.	NIL

2.18 PROTECTION SYSTEMS[1] [2] [3]

Steelwork in a marine environment may be subject to several different conditions of exposure, each of which have different characteristics in relation to corrosion of the steel, as detailed in Section 2.06.2.

Rates of corrosion of steel piling have been established by various investigators[4] in many different parts of the world. The range and approximate average corrosion rates for the various exposure zones are shown in Table 2.L.

TABLE 2.L

Zone	Corrosion Rate Mils per Year	
	Range	Approx. Average
Splash	2.0 - 10.0	5.0
Tidal	1.0 - 8.0	4.0
1'- 2' Below M.L.T.	3.0 - 10.0	7.5
Mid-Immersed	1.0 - 7.0	3.7
Buried in Sea Bed	0 - 12.0	3.0

Consideration of these corrosion rates indicate that the necessity for protection of steel should be firmly established for the particular location in which the steel will be exposed. In some instances, it may be more economic to use slightly heavier sections, than to specify protection systems.

2.18.1 PLANNING AND DESIGN FOR COATING SYSTEMS

2.18.1(a) Planning

The following factors must be considered in planning the protection of structures:

(i) The protection system must be an integral part of the project plan, in order that adequate funds can be allocated for that section of the work.

(ii) The need to ensure a working specification so that the protection system is carried out in the correct manner

(1) reference 2.1
(2) " 2.2
(3) " 2.12
(4) " 2.2

by a competent contractor using the correct materials and the work is well supervised.

(iii) At the planning stage the possibility of corrosion should be considered as an important factor governing the choice of structure and details. The choice of building frame type has a large effect on the cost of initial protection and subsequent maintenance. Column and truss type buildings may be lighter than rigid frames but the surface area is usually slightly larger and the truss details contain areas e.g. crevices and pockets around joints, which are difficult to clean and coat. The use of box or tubular sections in place of open sections is desirable in severe environments as they have a smaller exposed area and are easier to coat uniformly. Closed sections should be completely sealed by continuous welding.

All structures should be provided with equipment to assist in access for maintenance e.g. painters monorails, lifting hooks and access platforms, so that surface maintenance can be carried out without resort to special scaffolding, etc.

(iv) With the wide range of protective systems available today it is possible to select a system which will meet the life requirement of a structure to a reasonable degree of accuracy. For permanent structures the main considerations are length of maintenance-free life and ease of maintenance when necessary, whereas for structures of limited life the most economic system to give the required life should be selected.

(v) The protective system should be designed according to the construction procedure to be followed. The stage at which welding is to be carried out may influence the type of primer and finishing coat to be used. If coatings are to be applied before erection, precautions must be taken to avoid damage during transport and erection.

(vi) Climatic conditions may dictate the time of year when coating can be effectively carried out.

Adequate time must be allowed in the construction programme for a thorough protective scheme to be undertaken, including allowances for drying or curing times.

2.18.1(b) Design

As poor design is a major cause of corrosion it is essential that design features be examined closely in order to minimize the cost of corrosion and to simplify application, maintenance and inspection. By reviewing designs before construction takes place changes can be made for small cost compared with the major expense of alterations after the structure is built.

A good design incorporates features which allow good drainage of all sections and avoids crevices where the accumulation of foreign matter in the presence of moisture may cause rapid corrosion of the underlying surface.

Crevices are often hidden and may be impossible to clean or to reach with a paint brush or spray gun and may be inaccessible for inspection, making it virtually impossible to apply a continuous film. In addition, coatings in narrow crevices do not dry properly or completely, because the solvents cannot escape from the dried film, and with spray application bridging of crevices may also occur. Where crevices cannot be avoided they should be filled by welding or with a suitable mastic.

Structural members such as angles, channels and H and I beams should be arranged to avoid trapping water. Where this is not possible suitably sited drainage holes should be provided, and care must be taken that these drainage holes do not become blocked or do not continually run drainage water on to members lower down.

In general it is desirable to decrease the area exposed to the environment and avoid sharp corners and rough surfaces.

Rounded corners and contours should be used wherever possible, and rough areas such as welds should be ground smooth. A structure with circular instead of square characteristics can be cleaned more easily, gives better continuity of surface, will hold and maintain a more even coating thickness, and has more resistance to corrosion.

Welding is preferable for jointing, as it affords clean uninterrupted lines thereby preventing the collection of dirt and moisture, and affording ease of maintenance.

As labour and scaffolding are the main cost factors in coating and maintenance, steps should be taken to avoid features which make it difficult or physically impossible to carry out effective protection e.g. angles or channels back-to-back with insufficient space to reach the whole surface.

2.18.2 Surface Preparation

Corrosion of a structure can be prevented by suitable protective coatings, the effectiveness of which depends on the type of surface preparation given, and other factors.

Structural steel carries on its surface such detrimental matter as mill scale, rust, grease, oil, dust, weld flux, and spatter, etc. In addition chemical fumes, sea water spray, etc. may contaminate a structure before it is painted.

For best results all of these contaminants should be completely removed prior to the application of a coating system. Poor surface preparation will defeat the function of any paint.

It has been demonstrated that maximum paint life is obtained on completely descaled steel. However the cost of such descaling is significant and the increase in paint life must be evaluated against this extra cost.

Many comparison tests have been made to evaluate the performance of paint on rusted steel, mill scaled steel and descaled steel. Typical examples are shown in Tables 2.M and 2.N. These tests were carried out in an industrial atmosphere at Sheffield, U.K.

TABLE 2.M

EFFECT OF SURFACE PREPARATION ON THE DURABILITY OF PAINTING SYSTEMS FOR STRUCTURAL STEEL

Surface Preparation for Painting	Duration of Protection (Years)	
	Red Lead (2 Coats) + Red Iron Oxide Paint (2 Coats)	Red Iron Oxide Paint (2 Coats)
Weathering and wire brushing	2.5	1.0
Degreasing only: paint applied over intact mill scale *	8.0	3.0
Pickling	9.5	4.5
Blast Cleaning	10.5	6.5

*While these results apply to steel with intact mill scale it should be noted that this condition is only obtained on freshly rolled steel and is rarely encountered at the point of use of the steel.

These examples clearly show the advantage of sandblasting or acid descaling.

TABLE 2.N

EFFECT OF SURFACE PREPARATION ON UNDERWATER DURABILITY OF COATING

Coating System	Test Duration to Failure (Years)	
	Wire Brush	Sandblasted Surface
Two coats of Phenolic Red Lead System - 5 mils.	2.5	5.0
Two coats of thin - coal tar cutback - 5 mils.	5.0	9.0
Vinyl Copolymer - 6 mils.	2.0	10.0

2.18.3 Site Conditions

Where the site environments are unfavourable for surface preparation and painting it is good practice to apply the full protective system away from the site.

The modern trend is to apply coatings before erection wherever possible, and some overseas companies provide this facility at the steelworks. In this way, full advantage is taken of the protective qualities of the coating, and it is possible to thoroughly inspect the quality of the work.

2.18.4 Methods of Surface Preparation

Various preparation methods are available for steel surfaces and these can be classified into five categories, viz.:-

(a) abrasive blast cleaning

(b) acid descaling

(c) flame cleaning

(d) hand tool cleaning

(e) solvent cleaning

Recommended procedures for each method are contained in Australian Standard A.S. C.K.9 "Australian Standard Code of Recommended Practice for the Preparation and Pretreatment of Metal Surfaces prior to Protective Coating".

2.18.4(a) Preliminary Cleaning

Surface contaminants such as weld spatter, slag, heavy rust and chemicals, which are not effectively removed by subsequent surface treatment, must be removed before such treatment commences. This is essential to ensure maximum paint film adhesion.

2.18.4(b) Abrasive Blast Cleaning

Abrasive blast cleaning is the most effective and important method of preparing a metal surface. The choice of blasting conditions is most important as it directly governs the surface roughness. The type and sizing of the abrasive, blasting process, abrasive velocity, distance of the nozzle or wheel from the work, angle of nozzle to the surface and the steel hardness are all factors influencing the surface roughness.

For grit blasted steel, the average surface roughness is less than one tenth of the grit particle diameters. It is advisable to avoid excessive roughening of the surface, as coarse abrasive blasting increases the exposed surface area, and also the profile volume. Tests have shown that adhesion of the paint film is improved by using finer abrasives, resulting in corresponding finer profiles and using less paint.

The order of cost of abrasive blast cleaning of steelwork is $3.25 per sq. yd.

2.18.4(c) Acid Descaling (Pickling)

Acid descaling of steel is the complete removal of mill scale, welding scale, rust and other foreign materials by chemical reaction by the immersion of the steel in an acid solution. It is necessary to add a corrosion inhibitor to the bath to prevent excessive attack on the metal and to limit hydrogen absorption. Welding slag is not removed by this process and should be removed beforehand by mechanical means.

Freshly descaled steel will commence to rust very quickly unless oxidation is delayed by chemical treatment of the surface. Considerable use is made of the duplex type of pickling where the rust and scale are removed with sulphuric acid and then the steel is given a weak phosphoric acid dip to delay rusting until the steel can be primed. This produces an inhibitive iron phosphate coating on the work. Such a surface should always be overcoated with a suitable primer within 48 hours. Some primers, such as epoxy based zinc rich primers, are not fully compatible with phosphate coatings, and this aspect should always be investigated before the primer is selected.

Suitable precautions are necessary to remove residues of unreacted acids and salts from the steel. The design of fabricated steel may require special consideration to eliminate pockets or crevices which trap acid during descaling.

Attention should also be given to the dangers of hydrogen embrittlement associated with acid descaling high tensile steels and welded low alloy structural steels.

The order of cost of the acid descaling process is $1.60 per sq. yd.

2.18.4(d) Flame Cleaning

Flame cleaning is carried out by passing a high temperature, high velocity, oxy-fuel gas flame over the steel surface to be treated.

The elevated temperature at the steel surface removes some of the mill scale and rust, either by differences in the rate of expansion between the metal and mill scale or by the explosive action of water vapour generated underneath the scale and rust or by a combination of these. Tightly adherent mill scale and rust is not removed. It is a slow and expensive method, and should only be used in special circumstances.

The principal advantage of flame cleaning is that moisture is temporarily driven from the surface and the paint can be applied while the steel is still warm.

2.18.4(e) Power Tool Cleaning

Metal surfaces can be prepared by removing loose mill scale, loose rust, and paint with power tools, The tools used for cleaning include air or power driven impact tools, grinders, sanders, rotary wire brushes or a combination of each. Both power and hand tool methods of cleaning provide a lower standard of finish and can be uneconomical compared with abrasive blast cleaning. However power tool cleaning is preferred to hand toolcleaning.

2.18.4(f) Hand Tool Cleaning

Hand tool cleaning is the oldest and most inefficient method used for surface preparation. Unskilled labour is normally employed and usually only loose mill scale, rust and paint will be removed. Very close supervision is required to obtain a satisfactory result.

Hand cleaning is often preceded by a period of weathering of the steel. However there is evidence that this practice has an adverse effect on paint performance. Usually pitting of the steel will develop before the mill scale has been completely removed by weathering and it is difficult to remove the tightly adherent rust in the bottom of the pits.

The tools needed for this type of surface preparation are wire brushes, scrapers, chisels, knives, chipping hammers and in some instances abrasive papers. Special non-sparking tools must be used when cleaning in areas where there may be a concentration of flammable vapours.

2.18.4(g) Cleaning of Welds

Welding procedures leave the metal surface contaminated with weld metal spatter, weld flux scale, flux fume and oxides formed by the heat generated. All of these contaminants may adversely affect paint performance.

The coating thickness over weld metal spatter will be very thin due to the beady nature of the spatter.

Weld flux scale and fume are strongly alkaline and will react with many coatings, particularly in humid environments. Weld heat oxide forms directly adjacent to the weld seam. It forms a rough surface and may become detached from the parent metal after a period of exposure, disrupting the paint film.

Because weld spatter is very difficult to remove even by abrasive blast cleaning, it should be chipped off or sanded. The weld areas should then be abrasive blast cleaned to effectively remove the other weld contaminants.

2.18.5 PROTECTIVE COATING SYSTEMS

Modern coating technology has greatly extended the range of coatings available for marine conditions and sufficient long term experience with the more recent types has confirmed their superior properties. The properties of the main groups of coatings used for marine work are given below:

2.18.6 Conventional Primers:

2.18.6(a) Red Lead Primer

These are available in linseed oil, alkyd resin or phenolic vehicles, the latter two being faster drying than the linseed oil type. They are good primers for poorly cleaned surfaces, penetrating and binding rust and scale. Their slow drying characteristics are a disadvantage and they are toxic, making them unsuitable for coating surfaces subsequently to be welded.

2.18.6(b) Lead Chromate-Red Lead Primer

In this type of primer other pigments are included to improve their rust inhibitive properties. Faster drying vehicles are generally used and they are able to withstand longer weathering periods prior to overcoating than red lead primers.

2.18.6(c) Red Iron Oxide - Zinc Chromate Primer

These primers are compounded with modified synthetic resins or vegetable oils to give faster drying times than the previous types. Their inhibitive properties are due to the formation of a continuous film of insoluble oxide on the metal surface, which is self repairing. They do not present a toxicity problem.

2.18.7 Preweld or Prefabrication Primers

These primers were developed to allow full advantage to be taken of off site abrasive blast cleaning. The primers are required to be fast drying, abrasion resistant, flexible and compatible with welding operations. They should provide protection from corrosion under exposed conditions for at least six months.

The main types of preweld primer available, are:-

(i) Iron Oxide Pigmented Primer

(ii) Zinc Dust Pigmented Epoxy Primer

(iii) Aluminium Pigmented Epoxy Primer

(iv) Iron Oxide and Aluminium Pigmented Polyvinyl Butyral.

Application of the primers is normally by spray and maximum dry film thicknesses of 0.5 to 1.5 mils. are achieved.

Primers containing metallic zinc pigments may cause trouble with blistering when used in immersed conditions and the coating manufacturers recommendations regarding their use should be strictly adhered to.

2.18.8 Wash Primers

Wash or etch primers are pretreatment or conditioning agents used to provide a very adherent rust preventative base, and are especially suited to marine conditions. A two pack basic zinc chromate - vinyl butyral resin primer is widely used, although single pack types are also available.

2.18.9 Conventional Finish Coatings

2.18.9(a) Bituminous Coatings

These coatings are based on coal tar and bitumen. They are low in cost and do not require a primer. As a group they are fairly soft and have poor abrasion and impact resistance. They are affected by oils and may show premature failure near the water line because of this. When subject to severe exposure conditions and temperature change checking, cracking and loss of adhesion may result. Overcoating with other types of coating is difficult due to their poor resistance to solvents. The epoxy resin combinations have overcome this problem.

Bituminous coatings do not require a high degree of surface preparation and the hot applied type made from specially processed coal tar pitch and mineral fillers have a very low permeability to water. This type is usually applied to achieve a D.F.T. of 25 to 30 mils.

As a group these paints are characterised by ease of application, relatively quick drying, toughness and flexibility. They are widely used for the protection of steel over conventional primers. They have good weathering properties and reasonable durability but are readily attacked by alkali and are not suitable for immersed conditions.

Micaceous iron oxide is often used as a pigment in oleoresinous or alkyd finish paints. This pigment is relatively inert and imparts extra stability to the coating.

Aluminium pigments are also widely used, the pigment being in flake form. The flakes overlap thus providing a reflective barrier to sunlight and moisture.

2.18.10 Specialized Coating Systems

A number of special coatings have been developed with improved protective properties for marine environments. These are normally applied as a complete primer, intermediate finish coat system. They often contain inhibitive pigments, aluminium flake or micaceous iron oxide, the vehicle imparting superior properties.

Special coating systems generally require a high standard of surface preparation and are more difficult to apply than conventional paints.

2.18.10(a) Catalyzed Epoxy Coatings

Epoxy coatings are formed by the reaction of curing agents such as amines, amine adducts or polyamides with epoxy resins, the curing agents being added immediately prior to application. They require surface preparation by abrasive blast cleaning.

Formulations are varied to suit the end use, however in general the coatings are strongly adherent, abrasion, solvent and chemical resistant and are highly impermeable. Gloss retention is not godd.

Because epoxy coatings harden by chemical reaction they have a limited pot life. They must be applied above a minimum ambient temperature (usually 50°F) although formulations are available for application below this temperature. The Manufacturer's instructions regarding application and over-coating procedures must be strictly adhered to or poor results will be obtained. Coatings which have cured must be abraded to provide a satisfactory key for the subsequent coat.

2.18.10(b) Catalyzed Tar Epoxy Coatings

Tar epoxy coatings are a modification of the straight epoxies, containing a specially prepared coal tar pitch. The pitch improves the water resistance of the coating and lowers the cost. Aluminium flake pigments are sometimes added to further improve water resistance.

2.18.10(c) Chlorinated Rubber Coatings

Chlorinated rubber is made by chlorinating degraded crepe rubber in carbon tetrachloride. The product is used as a major component of special paints or as a modifying resin. Chlorinated rubber paints depend upon the evaporation of solvent for hardening. They will tolerate a poor standard of surface preparation and application is usually be spray. They are fast drying.

Chlorinated rubber paints have a wide range of chemical resistance and low permeability to moisture. They have a low resistance to solvents, moderate abrasion resistance and can be readily overcoated.

2.18.10(d) Vinyl Coatings

Vinyl resins are usually polymers or co-polymers of vinyl chloride, vinyl acetate or vinylidene chloride. They are non-convertible, drying solely by the evaporation of solvents. Because of their poor adhesive properties, abrasive blast cleaning surface preparation is required. Wash primers are used to improve adhesion. Vinyl coatings have a high degree of impermeability to water and are chemical resistant.

2.18.10(c) Other Coatings

There are numerous coatings which, without having a wide application, are useful for certain special purposes. For example, the use of wrapping tapes and greases containing inhibitors to encase steel. Extruded or sprayed plastic coatings are also available.

2.18.11 Metallic Coatings

2.18.11(a) Hot Dip Galvanizing

In the hot dip galvanize process the steel is given a preliminary cleaning treatment, followed by acid pickling and is then immersed in a bath of molten zinc. A heavy uniform coating of from 3 to 5 mil. thickness is obtained, representing apppoximately 2 oz. of zinc per sq.ft. of steel. Attention must be given to design details to ensure satisfactory results.

The life of metallic zinc coatings in a particular environment is directly related to the thickness of zinc applied. The estimated life of a 2 oz. per sq. ft. coating in marine environments is given in Table 2.P.

TABLE 2.P

APPROXIMATE LIFE OF A 2 OZ./SQ.FT.ZINC COATING IN A MARINE ENVIRONMENT

	Years
Immersed Zone	4-6
Tidal Zone	3-5
Splash Zone	3-5
Atmospheric Zone	10-20

Zinc being anodic to steel, will sacrificially protect areas wheee the coating has been damaged.

2.18.11(b) Sprayed Metal Coatings

The two metals most commonly applied by flame spraying are zinc and aluminium.

Lead coatings are also serviceable for special purposes. They protect steel well in indústrial atmospheres, where an insoluble film of lead sulphate forms on them. When lead and iron are joined in an electrolytic cell, iron is the corroded member of the couple. Consequently, lead coatings are unsuitable for steel to be immersed in water, because the corrosive attack is concentrated at pores in the coating, where intense pitting may occur. The polarities of zinc and aluminium are on the right side of the iron, i.e. coatings of both these metals tend to protect steel cathodically. For surface preparation abrasive blast cleaning is required and the surface roughness must be carefully controlled to ensure optimum adhesion of the sprayed metal. Coating thicknesses vary from 4 mils minimum for either metal to a maximum of 8 mils of zinc and 6 mils of aluminium. In the case of zinc 8 mils represents approximately 4 ozs. per sq.ft. thus it is possible to apply greater thicknesses of zinc using metal spray techniques compared with hot dip galvanizing.

Sprayed aluminium coatings have been shown to give superior results in marine environments compared with zinc but the latter metal is often preferred because of its ease of application. The corrosion products of aluminium are less voluminous than those of zinc, hence serious disruption of paint coatings is less likely to occur.

2.18.11(c) Painting Metallic Zinc and Aluminium Coatings

Metallic zinc and aluminium coatings are often painted to increase their service life. Hot dip galvanized coatings are often allowed to weather prior to painting, this being reasonable practice provided contamination of the surface with pollutants does not occur. The weathering period should not be long enough to allow the formation of excessive amounts of zinc corrosion products. Primers are selected according to the type of finish paint to be used.

Preferred practice with both fresh galvanized and sprayed zinc coatings is to use either a two pack etch primer specially formulated for zinc, a zinc dust/zinc oxide primer, or a calcium plumbate primer. Acrylic water borne primers and epoxy polyamide primers have also been developed for fresh zinc surfaces and have given good results.

The use of pre-treatment primer for sprayed aluminium is not as necessary as it is in the case of zinc. However the application of a primer prevents the occurrence of brown staining resulting from porosity in the deposit allowing slight rusting to occur. Suitable primers for sprayed aluminium are zinc chromate or a simple red oxide zinc chromate type. Finishing direct with aluminium in alkyd or vinyl resins has given good results.

2.18.12 Metallic Zinc Paints

Metallic zinc paints or zinc rich paints as they are more commonly known, are paints pigmented with zinc dust. Organic and inorganic vehicles are used.

Zinc rich paints are essentially primers initially dependent upon galvanic action between the steel and zinc for their protective properties. As the exposure period increases an impermeable layer of complex zinc salts is formed in the paint film which then becomes a barrier type coating. This cycle is repeated at damaged areas.

Abrasive blast cleaning of the steel is necessary for good performance of zinc rich coatings. Excellent results have been obtained with those paints formulated in catalyzed epoxy or polyurethane vehicles.

Although zinc rich paints are sometimes used for continuous underwater service, problems have been encountered with blistering of the primer and poor adhesion of finish coats.

2.18.13 Recommended Protective Schemes

The following remarks are made with reference to the Standards Association of Australia publication MAI.5 1967 "Steel Structures - Part 5 - Protection of Steel from Corrosion"[1]. Table 5.6 of this publication lists coating schemes for Coastal and Tropical Environments and Sea Water Immersion. (Film thicknesses in brackets are suggested values).

2.18.13(a) Marine Atmospheric Environment

The preferred systems for coastal and tropical atmospheric environments are:-

(a) Galvanizing or sprayed metal (6-8 mils.)
Wash or etch primer (0.5 mils.)
Aluminium or micaceous iron oxide (4 mils.)
Total dry film thickness (TDFT) 10-12 mils.

(1) reference 2.12

(b) Coal tar epoxy TDFT 16 mils.

(c) Hot applied coal tar enamel TDFT 60 mils.

(d) Zinc rich or zinc silicate primer (3 mils.)
Vinyl (6 mils.) or coal tar epoxy (8 mils.)
TDFT 8-10 mils.

All of the above systems to be applied to abrasive blast cleaned or pickled surfaces.

For severe atmospheric marine environments this list may be extended to include:-

(e) Chlorinated rubber - full system TDFT 8 mils.

(f) Amine cured epoxy red lead primer (3 mils.)
Catalyzed Epoxy enamel pigmented with micaceous iron oxide (5 mils.)
TDFT 8 mils.

The abovementioned coating systems should be used on all steelwork subjected to occasional sea spray or wind blown salts, e.g. Jetty fittings, cranes, buildings in close proximity to the sea front, etc. Systems (b) and (c) may be used where appearance is unimportant.

For moderate atmospheric marine exposure the following systems will give satisfactory results on property cleaned steel:-

(a) Galvanizing or sprayed metal TDFT 6-8 mils.

(b) Zinc rich or inorganic zinc silicate TDFT 5 mils.

(c) Chlorinated rubber TDFT 5 mils.

(d) Vinyl TDFT 5 mils.

(e) Coal tar epoxy TDFT 8 mils.

(f) Conventional Red Lead or red oxide/zinc chromate primer (2 mils.)
Conventional micaceous iron oxide (4 mils.)
TDFT 6 mils.

Systems (a) and (b) may be applied in one coat thus reducing application costs.

2.18.13(b) Splash and Tidal Zones

The splash and tidal zones of marine structures present the greatest problem both from the corrosion and protection view-point. This comment applies particularly to structures exposed to wave action or heavy winds, e.g. outer harbours, unprotected jetties, offshore oil rigs, etc. Cathodic protection is ineffective above half tide level, coatings may be damaged by shipping or floating debris or in some cases softened by oil or diesel fuel.

Systems which have shown promise for this environment are:-

(a) Zinc rich or zinc silicate primer (3-4 mils.)
Coat tar epoxy (16 mils.)
TDFT 20 mils.

(b) Zinc rich or zinc silicate primer (3 mils.)
Vinyl primer (2 mils.)
Vinyl high build or mastic (10 mils.)
TDFT 15 mils.

(c) Vinyl - multicoat or highbuild
TDFT 10 mils.

(d) Chlorinated rubber multicoat
TDFT 10 mils.

Systems (c) and (d) are somewhat easier to repair than (a) or (b).

18 gauge Monel sheating has been used for protection of the splash and tidal zone in offshore structures, and also fibre glass reinforced epoxy or polyester. Increasing the wall thickness may be more economical in some cases than applying sheathing.

2.18.13(c) Immersed Zone

When protection of the immersed zone is necessary, cathodic protection is the most satisfactory method. Application of a coating is not required as the cathodic currents deposit calcium and magnesium carbonates on the surface of the steel which reduce current requirements to a minimum.

Abrasion of immersed structures by sand in locations where rapid water currents are experienced can be a problem. The effect of this abrasion can be minimized by the use of high build coatings as described in 2(a), (b) or (c). The incorporation of a mineral grit, e.g. alundum, in some coatings improves their resistance to abrasion.

2.18.13(d) Embedded Zone

Protection is not normally required in this zone. If it is required, cathodic protection will normally be used.

2.19 CONCLUSIONS

The corrosion of steel under marine conditions is very similar throughout the world. The factors which give rise to significant variations between different locations are:-

1. Degree of pollution;
2. Water velocity;
3. Wave action.

These factors influence mainly the nature and adherence of the rust film developed on the steel. The rate of corrosion of steel varies also with the location in the structure, due to the presence of different zones of corrosion influenced by different exposure conditions. Marine growth has been found to generally assist in the protection of immersed steel over long periods of time.

Examination of the methods of measuring corrosion rates of steel has shown that individual test coupons in the different zones gives rise to higher corrosion rates than those experienced by continuous steel piling which passes through several of these zones. This is attributed to a self generating cathodic protection system, which significantly reduces the corrosion rates in the tidal and splash zones. The availability of adequate test data on corrosion rates in various locations and exposure conditions is lamentably poor, and a vigorous campaign of testing is required in Australia to ensure efficient use of materials.

The use of alloying elements in steel to produce a degree of corrosion resistance in the so called marine grade steels, is probably the most significant development in recent years in corrosion prevention of steel. This facet requires further investigation, as most of the tests to date on these steels have been performed on individual coupons, and the data cannot be directly related to piles.

Some work has been done by steel companies on their own proprietary marine-grade steels (2-4% alloy content), and these tests indicate that the corrosion rates in the splash and atmospheric zones are significantly reduced. This is important, as these are the zones in which cathodic protection is ineffective.

Protection methods are now available such that steel under all conditions of exposure can be adequately protected, at a price, by either protective coatings or cathodic protection. Cathodic protection will provide full protection from the toe of a pile to approximately the mid-tidal level. The power impressed system is most favoured for marine structures. Coatings, if used in conjunction with cathodic protection, should be applied to the piles before driving, covering the surface to several feet below low water level, to allow for variations in the depth of the finished pile foundation.

The choice of protection methods is an economic one, and must be carefully weighed against the alternative proposition however unacceptable to the purist, of a corrosion allowance of say an additional 0.125 inches of metal, over all sections, as a provision for wastage, with no protection system. This corrosion allowance has been favoured in large modern European port development projects, and there appears to be a significant trend towards this solution of corrosion problems with steel structures.

SECTION 3

C O N C R E T E

3. CONCRETE

3.01 INTRODUCTION

Concrete is very widely used in the construction of harbours, docks, breakwaters and other structures exposed to the action of seawater, and its permanence in maritime works is of great importance. It is favoured as a construction material for many reasons, viz:-

(i) It is composed of readily available materials, which can be used with a minimum of technical skill as compared with other building materials.

(ii) It is fire resistant, it may be used in the air, underground and underwater.

(iii) Construction units may be cast-in-place or precast.

(iv) The density can be varied between 90 and 230 lb./cu.ft.

Most concrete, by virtue of its quality, its environment, or both, never suffers from chemical attack. Good quality concrete is resistant to attack in many exposures; in some instances where attack is anticipated, concrete can be made resistant by proper proportioning, placing and curing to yield adequate strength and low permeability. Most of the main factors involved and methods of producing quality concrete may be found in the following reports and standards:-

Choice of aggregate	ASTM	C33
	ASTM	C330
Selecting proportions	ACI	211
	ACI	613
	ACI	613A
Measuring, mixing and placing	ACI	614
Finishing	ACI	302
Curing	ACI	306
	ACI	605
	ACI	Committee 612 report

3.02 NATURE OF ATTACK ON CONCRETE BY SEAWATER

The destructive action of seawater on concretes has attracted attention in most countries. Concrete in seawater may suffer attack due to:- the chemical action of the dissolved salts; crystallisation of salts within the concrete under conditions of alternate wetting and drying; mechanical attrition and impact of waves; corrosion of reinforcement embedded in it and frost action. Attack in any one of these ways renders the material more susceptible to the action of the remaining potential agents of destruction.

The approximate amounts of the more important constitutents in seawater are:

Constituent	Content (gms/litre)
Na	11.00
K	0.40
Mg	1.33
Ca	0.43
Cl	19.80
Br	0.06
SO_4	2.76

The chemical action of seawater on concrete is mainly due to the presence of magnesium sulphate in the water. This was first realised by Vicat[(1)], the founder of much of the present knowledge of concretes. Vicat began his experiments in 1812 when there was a chaos of opinion on the subject, and the first results of his investigations were published in 1818.

3.03 DETERIORATION OF CONCRETE IN SEAWATER

Magnesium sulphate reacts with the free calcium hydroxide in set cement to form calcium sulphate, at the same time precipitating magnesium hydroxide; it also reacts with hydrated calcium aluminate to form calcium sulphoaluminate. These have often been assumed to be the actions primarily responsible for the chemical attack of concretes by seawater.

The deterioration of concrete in seawater is often not characterised by the expansion found in concretes exposed to sulphate solutions, but takes the form of an erosion or loss of constituents from the mass. The presence of chlorides apparently retard the swelling of concrete in sulphate solutions. Concretes which have suffered deter-

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(1) reference 3.10

ioration lose part of their lime content. Both calcium hydroxide and calcium sulphate are considerably more soluble in seawater than in fresh water, and this, when combined with the conditions produced by wave motion, must lead to an increased leaching action. Calcium sulphoaluminate, though one of the initial products of reaction of set cement with magnesium sulphate, is unstable in the resulting solution, and eventually decomposes again to form hydrated alumina, gypsum and magnesium hydroxide. The hydrated calcium silicates in set cement are also decomposed by magnesium sulphate to give hydrated silica, gypsum and magnesium hydroxide, though some of the latter can combine again to give an hydrated magnesium silicate.

The beneficial action of pozzolanas in concrete in seawater is that they increase the amount of the silica gel which remains, and which itself can form a bonding agent. This is illustrated by the firm condition of some of the old Roman lime-pozzolana concretes which, after nearly 2000 years exposure to seawater, have a very low lime content.

Analyses of concrete progressively attacked by seawater show a progressive rise in the magnesium hydroxide content and a fall in that of lime, but the sulphate content tends first to increase and then to decrease.

The chemical action of seawater is several reactions proceeding concurrently. Leaching actions remove lime and calcium sulphate while reaction with magnesium sulphate leads to the formation of calcium sulphoaluminate which may cause expansion, rendering the concrete more open for further attack and leaching. The deposition of magnesium hydroxide blocking the pores of the concrete probably tends to slow up the action on dense concretes though on more permeable materials it may be without much effect. The relative contributions to deterioration of expansion and leaching will depend on the conditions of exposure and construction. Examples of both are to be found. The rate of chemical attack is increased by temperature, and both the rate and its effects are influenced by the type of cement.

In normal seawater, only small amounts of carbonate and bi-carbonate are present, about 10 and 80 parts per million respectively, and a small amount of free dissolved carbon dioxide. The pH varies between about 7.5 and 8.4, an average value for seawater in equilibrium with the carbon dioxide in the atmosphere being 8.2. In normal seawater some gradual carbonation of set cement occurs, and may help by the formation of a protective surface skin, but it is doubtful if the free carbon dioxide content plays more than a minor part in the leaching of lime from a concrete. Under exceptional conditions, seawater can contain abnormal amounts of dissolved carbon dioxide, and then become much more aggressive, for carbonic acid behaves as a much stronger acid in seawater than in fresh water. These conditions can arise in sheltered bays and estuaries if the sea - bed is covered by organic matter which in its decay produces carbon dioxide. Unless this is accompanied by a corresponding rise in the calcium bicarbonate concentration, aggressive carbon dioxide will be available to attack concrete.

A dissolved carbon dioxide content of from 0.9 to 3 parts per million is considered to be an aggressive level for attack on concrete.

When the pH of seawater is above 7.5 there is little likelihood of leaching by carbon dioxide. Below a pH value of 7, the content is almost certain to be excessive and cause damage even to well made Portland cement concrete.

Apart from these chemical actions, deterioration of concrete in seawater arises also from frost action, and in the case of reinforced concrete from corrosion of the reinforcement.

Corrosion of reinforcement which is a major source of deterioration becomes progressively a more serious risk as the temperature rises, as does also chemical attack on the cement. Corrosion has been found with particular frequency on the underside of deck slabs which are subject to deflection from live loads and cracking which facilitates access of the seawater to the reinforcement.

Experience has shown that the most severe attack of seawater on concretes occurs just above the level of high water, that the portion between low and high water marks is less affected, and that the parts below the low - water level which are continuously immersed are rarely damaged. Concrete is not attacked by seawater unless it can penetrate into the mass. Although no concrete is strictly impermeable, a good concrete is so dense that the rate of penetration of seawater into it is negligible when it is completely immersed and not subjected to an excess hydrostatic water pressure on one side. In concrete which is just above the water level, however, the seawater tends to rise in the material by capillary action and, by evaporation of its upper surface, to draw more water continuously through the mass. Under these circumstances the seawater may very slowly attack the cement chemically while the crystallisation of the salts in the concrete probably tends also to have a disruptive action. The alternate wetting and drying of the surface accentuates the disintegration. It is also the concrete above water level which is subject to the action of frost and is most often to wave action and attrition.

3.04 PROTECTION OF CONCRETE

The rate of attack on a concrete depends on temperature, pressure, cyclic moisture changes and quality of the concrete.

The degree of protection required in any given exposure depends on:

(1) Nature of the aggressive agent.

(2) Temperature.

(3) Concentration

(4) Volume of the agent per unit of concrete surface area.

(5) Whether the agent is stationary or flowing.

(6) Whether the exposure is continuous or intermittent.

The available methods of protecting a plain concrete from an aggressive environment are detailed in section 3.07.9.

3.05 GENERAL REQUIREMENTS FOR CONCRETE IN SEAWATER

Extensive testing has been conducted over many years in countries throughout the world, on the effect of seawater on concretes.

The general conclusions that have been drawn are summarised below:

The prime essential for all seawater concrete is that a dense product of low porosity be obtained. The use of too wet mixes is dangerous, but mixes that are so dry that they cannot be adequately compacted must also be avoided. Vibration compaction is to be recommended. For precast Portland cement concrete products the resistance to deterioration is increased by a long period of hardening in air subsequent to the usual periods of wet curing. For concretes permanently under water a minimum cement content of 500 lb./cu.yd. is desirable. Portland cements, pozzolanic or slag-containing cements, are to be preferred particularly for work in tropical or semi-tropical regions. Concrete between tide levels, or immediately above high water level, is subject to rapid freezing as the tide recedes in cold water climates, and to rapid evaporation in hot climates. A minimum cement content of 600 lb./cu.yd. is necessary. There is not universal agreement as to the relative merits of different types of cements. For cold or temperate, but not semi-tropical or tropical climates, well made high-alumina cement concrete, is probably the most immune to attack, but it is more costly and is more susceptible to the effects of lack of care in making. The water-cement ratio should not exceed 0.5.

In warm climates where chemical attack is a dominant factor, the slag-containing and pozzolanic cements, or sulphate-resisting Portland cement, are to be preferred. In this case, experience indicates that the pozzolana can be treated as a substitution for up to 30 per cent of the Portland cement.(1) The mildest conditions of exposure are those found in temperate waters, where much well-made Portland cement concrete has shown a good record, but advantage is still to be gained from the use of more resistant cements.

3.05.1 SLAG CEMENTS

For many years after the first introduction of the Portland blastfurnace type of cement in Germany in 1892, their use was restricted to seawater work, foundations and other structures in which the concrete was not in contact with air, due to the uncertainty of strength development

(1) reference 3.10

in air.

It is claimed that Portland blastfurnace cement is more resistant to attack by seawater and other chemical agencies than Portland cement, but this applies to the comparison with normal Portland cement rather than the modern sulphate-resisting Portland cement.

Tests have shown[1] that the protection against corrosion afforded to embedded steel by blastfurnace cement was as good as that given by Portland cement and that it is therefore suitable for reinforced concrete structures.

3.06 FAILURE OF A CONCRETE STRUCTURE IN A MARINE ENVIRONMENT

The recent failure of the concrete of the resurfacing slab of the Inner Dock floor at Captain Cook Dock, Garden Island, Sydney, illustrates many of the points put forward in the preceding pages.

Within four years of construction of a new surfacing slab on the dock floor, the concrete had deteriorated and failed to such an extent that the design function could no longer be attained, and the Dockyard Management was forced to resort to inefficient methods of servicing docked vessels while extensive and costly repairs were executed.

Several factors combined to compound the failure. All these factors could have been anticipated in the investigation and design phases of the work. These factors were:-

(1) Inducement of settlement and shrinkage cracking in the concrete due to a major reduction in section of the concrete slab by the poor positioning of a non-structural component within the slab.

(2) Failure to investigate the aggressive nature of the seawater and groundwater at the site.

(3) Selection of a non-resistant cement for use in an aggressive environment.

The following account details the nature of the problem, the subsequent investigation aimed at establishing the root cause of the concrete failure, and the steps taken to repair the damage.

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(1) reference 3.10

FIGURE 3.1

TYPICAL SECTION OF DOCK

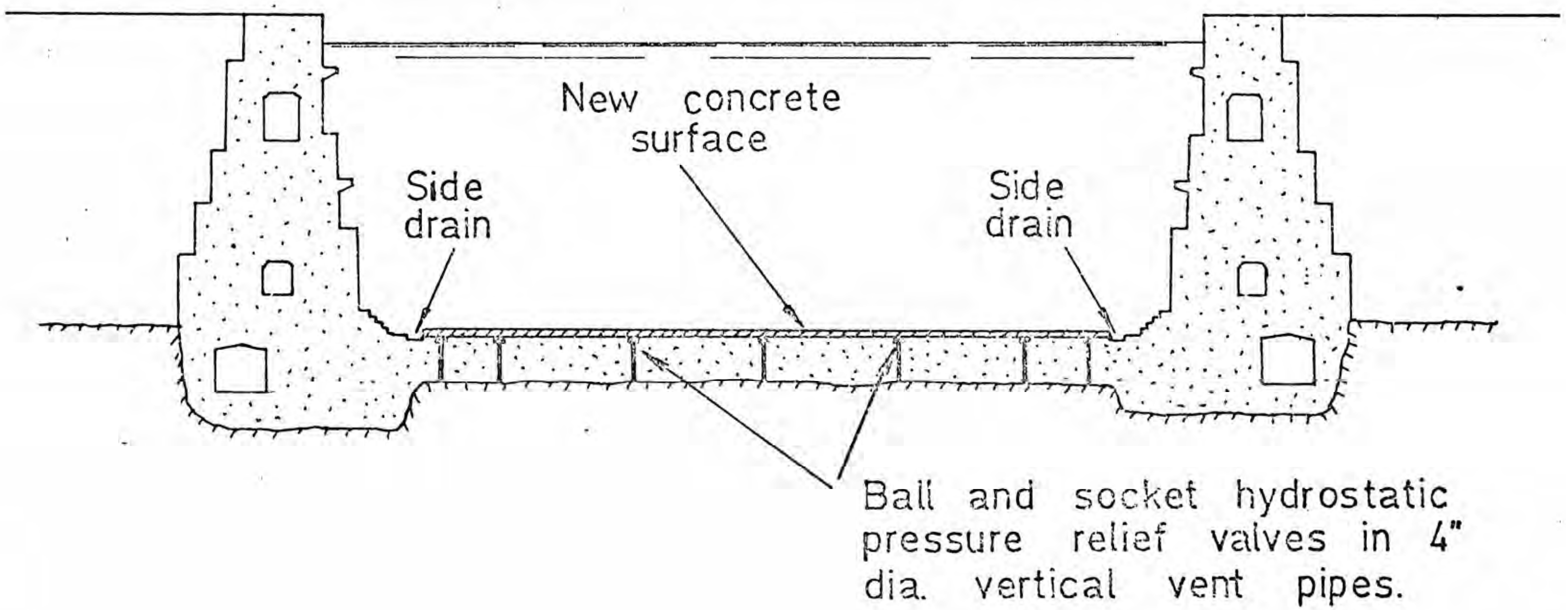
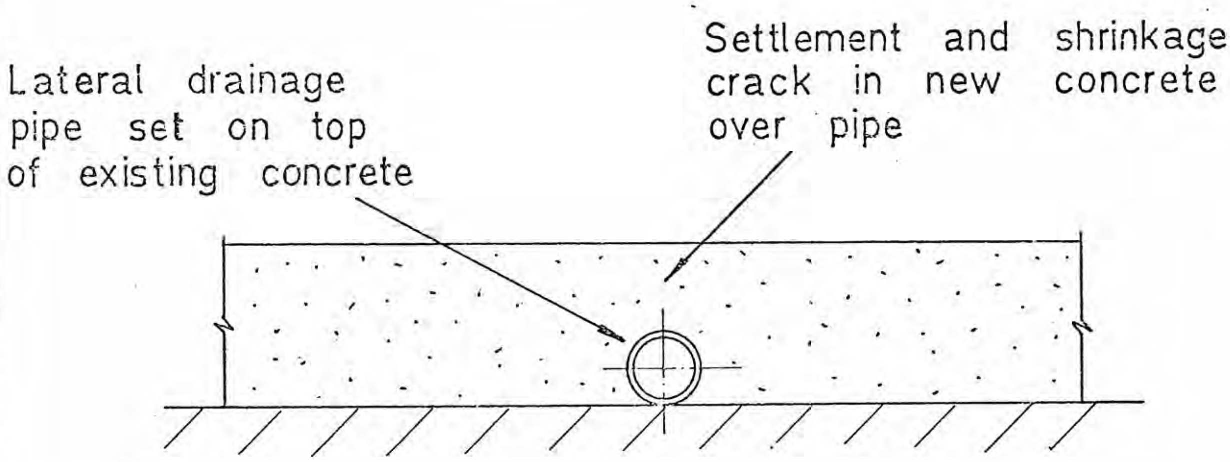


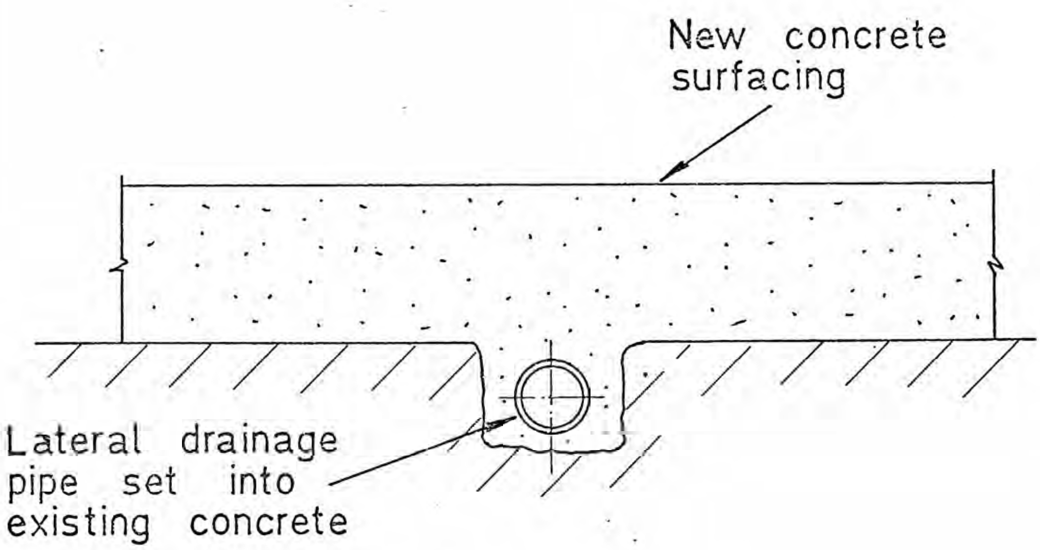
FIGURE 3.1

FIGURE 3.2

DETAIL OF FLOOR AT LATERAL DRAIN



ORIGINAL DETAIL



NEW DETAIL

FIGURE 3·2

3.06.1 DETAILS OF WORK

To meet the docking requirements of a new class of naval vessel, new concrete keel and bilge blocks were designed and built for use in the dock. To accommodate these new blocks, the floor of the dock was resurfaced in 1965 with approximately 7" thickness of concrete laid to fine tolerances in level. The drainage system for groundwater flowing from beneath the dock structure via pressure relief valves, was redesigned to carry the water to the dock side drains by pipe whereas previously this water had spilled over the surface of the dock floor and found its way to the side drains. A typical section of the dock is shown in figure 3.1.

Preparatory to concreting, the surface of the existing floor of the dock was machine scabbled. The concrete slab, varying in thickness from 6 1/4" to 7 3/4" was cast, forming pits above the pressure relief valves and these pits were drained by 3" bore P.V.C. pipe discharging into the side drains of the dock. The P.V.C. drainage lines were positioned directly on the existing dock floor and the concrete slab was cast around and over the pipe. A section of the floor slab at the drainage line is shown in figure 3.2.

3.06.2 MODE OF FAILURE

Almost immediately after the concrete slab was cast in 1965, it was noted that the slab cracked in a regular pattern over and along the line of the P.V.C. pipes forming the lateral drains from the pressure relief valves.

In 1969, it was noted that concrete in the vicinity of these lateral drains was expanding and disintegrating, causing the P.V.C. drains to be crushed flat and providing an alternative flow path and temporary storage reservoir for water flowing from the pressure relief valve gully pits.

An investigation was carried out to determine the cause of the concrete failure. This investigation was aimed at a determination of the type and quality of materials used in the work, and an examination of external factors which may have been aggressive towards the concrete.

3.06.3 CONCRETE SPECIFICATION

The concrete for the surfacing slab was specified to be ready-mixed concrete to the following specification:-

(1) 28 day compressive strength 4,000 p.s.i.

(2) Normal Portland cement complying with A.S. No. A2.

(3) Coarse aggregates; crushed river gravel.

(4) Slump; minimum 0", maximum 0.5".

It was subsequently found to be impractical to place and fully compact this slump concrete in the forms, and the slump was increased at the direction of the Construction Supervisor.

The minimum specified cement content was to be 564 lb./cu.yd., and the maximum water-cement ratio was to be 0.43.

3.06.4 INVESTIGATION OF CONCRETE PROPERTIES

3.06.4(a) Compressive Strength

Records of 28 day compressive strength tests of concrete used in the dock floor were examined. In all but two of the groups of tests, the specified 28 day compressive strength of 4000 p.s.i. was attained. Those specimens which failed to reach this standard represented a very minor quantity of concrete cast in the floor. The range of the strength test results was 3,480 to 6,075 p.s.i., with a mean of 5,133 p.s.i.

3.06.4(b) Cement Type

A check of the source of supply of cement for the work revealed that a routine analysis of cement taken at the time of the construction period, showed that the composition of the cement was: -

C_3S	- - - - - - - - - - -	56%
C_2S	- - - - - - - - - - -	17%
C_4AF	- - - - - - - - - - -	10%
C_3A	- - - - - - - - - - -	12%

This high C_3A content is considered to be an important factor in the subsequent failure of the dock floor slab.

3.06.5 EVALUATION OF ATTACK MECHANISM

3.06.5(a) Testing procedure

A series of analyses and non-destructive tests were undertaken to attempt to establish the nature, extent and cause of the concrete failure. These tests included:-

3.06.5(a)(i) Groundwater Analyses

The ball valves were removed from several pressure relief valve pipes in the dock floor, and the pipes were cleansed and allowed to fill with fresh flowing groundwater. This groundwater was sampled and analysed to determine the following properties:-

(i) p^H valve;

(ii) NaCl content;

(iii) SO_3 content;

(iv) CO_2 content bymmeans of phenolphthalein acidity;

(v) Mineral acid content by means of methyl orange test.

The results of tests and average properties determined were:-

p^H	---	6.08
NaCl	---	19,920 p.p.m.
SO_3	---	1,128 p.p.m

The samples contained no methyl orange acidity. The presence of iron and aluminium compounds in the water interfered with the phenolphthalein test due to the precipitation of hydroxides when titrated with standard alkali. Results from these tests were considered to be suspect, and were neglected in the final assessment of results.

3.06.5(a)(ii) Seawater analysis

Samples were taken of seawater from the harbour immediately outside the dock. These, when analysed gave the following results:-

p^H	- - - - -	7.63
NaCl	- - - - -	27,425 p.p.m.
SO_3	- - - - -	1,990 p.p.m.

3.06.5(a)(iii) Concrete core samples

A series of 3" dia. cores, 12" deep, was taken from the dock floor from sections which appeared to be unaffected by concrete deterioration, to determine the extent of the attack on the concrete.

In all cores, the concrete of the surfacing slab was found to be detached from the old floor concrete. There was no evidence of deterioration of the concrete at this interface, although the interface was discoloured brown.

These cores were checked for relative sensitivity to sulphate attack.

3.06.5(a)(iv) Non-destructive testing

The concrete slab was examined for soundness by means of a sclerometer to assess the extent of the deterioration of the concrete. These tests indicated that the concrete to within 2-3 inches of the visible cracks, was sound. It was therefore concluded that a visual assessment of damage was sufficiently accurate to establish zones in which the concrete was considered to have deteriorated to such an extent that the concrete should be replaced.

3.06.5(a)(v) Additional surveys

In addition to the above tests, inquiries were made of other bodies to learn of the incidence of sulphate attack on concrete in the Sydney area.

It was found that the Maritime Services Board of N.S.W. had had no experience with sulphate attack on harbour structures up to 1972, all cement used by that Board was Type C Portland cement[(1)], with a C_3A content limited to less than 5%. In all works since 1972, only type D Portland cement[(2)] had been used in concrete for marine works.

The Metropolitan Water Sewerage and Drainage Board has encountered aggressive groundwaters in the western areas of Sydney, and at the coast where shales occur. In some instances, the sulphate content of the groundwaters was double the content in seawater. The Water Board specifies types C and D Portland cements for their concrete structures in contact with aggressive waters.

In addition, a literature survey was conducted. This unearthed a parallel failure of a dock structure in which normal Portland cement had been used. (Reference 3.16).

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(1) reference 3.17
(2) " 3.17

3.06.6 CONCLUSIONS

3.06.6(a) Mode of Failure

From the investigations the following conclusions were reached on the mode of failure:-

(1) The lateral drains in the surfacing slab reduced the section of the slab locally by 50%. The pipes would obstruct sedimentation of heavy particles in the wet concrete mix prior to the initial set occurring, causing settlement cracking. This factor, coupled with high shrinkage stresses at the discontinuity in the slab caused by the pipe, resulted in cracking of the slab over the lateral drains, soon after the concrete was cast.

(2) The presence of these cracks in the slab afforded an alternative flowpath for water from the pressure relief sumps, and act as reservoirs to hold both groundwater and seawater.

Chemical analyses of the groundwater and more particularly seawater, indicated SO_3 radical concentrations exceeding 1,000 p.p.m which is a reactive level for sulphate attack on hydrated cement, resulting in expansion of the concrete.

(3) The $_pH$ values of the seawater and more particularly the groundwater indicated a high concentration of carbon dioxide in the water. This carbon dioxide would react with the calcium hydroxide of the cement paste to cause softening and disintegration of the concrete.

Both the above reactions would be aided by the high C_3A content of the cement used in the work (12%).

It is significant that the concrete of the original floor of the dock which was made using Type C Portland cement was unaffected by the conditions which caused failure of the Type A normal Portland Cement concrete of the surfacing slab. This factor has a recorded parallel occurrence in the failure of concrete in a shipway reported by Terzaghi (Reference 3.16)

3.06.6(b) Revision of Specified Requirements

To prevent a recurrence of this failure mechanism for concrete in seawater, the following details should be fully considered when detailing and specifying concrete:-

(i) Use only Type D Portland cement.

(ii) Avoid placing inserts or reinforcement near the top surface of concrete to prevent settlement cracking of the concrete before initial set occurs.

(iii) Ensure adequate drainage of the surface of the structure to ensure that aggressive waters cannot remain in contact with the concrete unnecessarily.

(iv) Design against shrinkage cracking in the structure by avoiding sharp discontinuities and reductions in area of structural members.

3.07 REINFORCED CONCRETE

3.07.1 Introduction

A survey in 1916 of numerous concrete structures along the seaboard of the United States of America, disclosed that the majority of all reinforced concrete structures subject to seawater action showed evidences of deterioration or failure due to the corrosion of the embedded reinforcement above the water line. The conclusions of this survey were:

1. The corrosion occurs first followed by the cracking.
2. Corrosion occurs only above the water line, where the concrete is exposed to salt spray.
3. A high concentration of salts was found in concrete with corroded reinforcing bar.
4. The corrosion of the reinforcement was not related to chemical deterioration of the concrete.

The status of the knowledge of the corrosion of reinforcing steel in concrete structures exposed to seawater is much the same today.

It has been shown that the corrosion is galvanic[1] and that macro-galvanic cells exist with the corroded area anodic and separated by as much as several feet from the cathodic area.

3.07.2 Resistance of Concrete to natural destructive agencies.

The functions of the concrete in reinforced concrete are to provide a medium to withstand the compressive stresses to which the reinforced concrete member may be subject, and to protect the steel

(1) reference 3.11

reinforcement against corrosion. Any corrosion of the reinforcement results in the formation of a film of iron oxide over the metal occupying a volume about 2.2 times that of the steel from which it is formed.[(1)] This expansion results in the cracking and flaking off of the concrete overlaying it. The corrosion damages both the steel and the concrete. The degree of protection afforded to the reinforcement depends on the impermeability and thickness of the concrete covering it. A concrete of high quality is essential for reinforced concrete work, to prevent access of moisture and air to the steel. Reinforced concrete which is exposed to seawater, requires a degree of protection.

Reinforced concrete members may show fine cracks arising from deflection under load or from shrinkage of the concrete. If the width of the cracks is sufficiently small they tend to become sealed by autogenous healing.

Reinforced concrete may suffer attack from eletrolysis by stray currents. In structures where the reinforcement serves as an earth conveying current, due to electrical leakages, corrosion of the reinforcement due to direct electrolytic action occurs in damp positions.

3.07.3 Chemistry of Concrete as it affects reinforcement

The disintegration of reinforced concrete is essentially a problem of the corrosion of steel in a specific environment and the chemical nature of concrete as it affects the corrosion of steel is important.

Set concrete made from Portland cement, sand, stone and fresh water will contain the following:

1. The sand and stone which may in general be regarded as inert.
2. Particles of unground cement clinker, also inert.
3. Calcium hydroxide and small quantities of other alkalies.
4. Hydrated cement minerals (calcium silicates, calcium aluminates and calcium alumino ferrites).
5. Varying amounts of uncombined water.
6. Calcium carbonate and calcium sulphate.

(1) reference 3.10

Wherever any moisture is present, concrete can be regarded as an electrolyte containing mainly calcium hydroxide. The only ions present which could influence reactions with steel under conditions normally prevailing in reinforced concrete structures would be the hydroxyl, calcium sodium, potassium, carbonate and sulphate ions.

3.07.3(a) Behaviour of Steel in Hydroxides

Researchers[(1)] have shown the existence of a protective film of ferric acid on the surface of steel in alkaline solutions. Freshly abraded iron becomes passive when immersed in decinormal sodium hydroxide containing dissolved oxygen.

In the presence of sodium chloride, the concentration of hydroxyl ions necessary to stifle attack on the steel rises steadily with the chloride ion concentration. As soon as chloride ions are in excess, the main anodic product of corrosion will be ferrous chloride, and further attack will not be stifled.

If the hydroxyl ion concentration of the solution in contact with the steel should fall, the protective film would be disrupted and corrosion could proceed.

3.07.4 Mode of deterioration of reinforced concrete

It has been frequently observed that reinforced concrete structures exposed to marine atmospheres deteriorate in a relatively short period of time.

The mode of deterioration starts with the appearance of a brown stain on the reinforced concrete surface, with no evidence of cracking. Later a fine crack appears coincident to the steel underneath the surface. The crack widens with time and eventually the concrete over the reinforcement is spalled off and the reinforcing steel is exposed to the atmosphere.

The deterioration does not always exactly follow this pattern, as often, the brown stain is absent, By the time the crack appears, the steel has corroded. When the crack has widened to the point where spalling of the concrete is imminent, the probability is that the reinforcing steel has been appreciably reduced in section with the associated loss of structural strength.

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(1) reference 3.10

3.07.5 Rate of corrosion of reinforcement

From investigations into corrosion in reinforced concrete bridges in South Africa[1], corrosion rates of 0.005 to 0.010 inches per year have been deduced.

This figure is considered to be severe when compared with an atmospheric corrosion rate of 0.007 inches per year for steel in a severely polluted atmosphere. This figure refers to bare steel, whereas the reinforcing steel was covered with concrete.

3.07.6 Corrosion of steel in concrete

Under most conditions, well-made concrete provides good protection against corrosion of reinforcing steel, however, corrosion remains the most common cause of deterioration of reinforced concrete.

The corrosion of steel in concrete has many similarities with corrosion under other circumstances. The presence of an electrolyte and access of oxygen are required. The result of the corrosion process is the formation of a rust layer on the steel, which exerts tensile forces within the concrete to crack and cause spalling of the concrete cover.

In an alkaline solution, such as the calcium hydroxide solution in set cement, a protective oxide film forms over the steel rendering it passive. For corrosion to occur, this protective film must be impaired and there must be access of oxygen. The stability of the film depends on the maintenance of a minimum $_{p}H$ value and under such conditions, access of oxygen will not cause corrosion. The access of carbon dioxide reduces the $_{p}H$ to 10 or lower and the film is then impaired and access of oxygen will cause corrosion. The presence of chloride ions raises the $_{p}H$ required to stabilise the passive film to a value which may exceed that of a saturated calcium hydroxide solution, so stimulating corrosion.

The corrosion of steel is an electrochemical process associated with the presence of anodic and cathodic areas arising from inhomogeneities in the surrounding liquid medium or even in the steel itself.

The reactions involved in the corrosion process are:

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(1) reference 3.11

At the anode,

$$2\,Fe \longrightarrow 2\,Fe^{++} + 4e^-$$

$$2\,Fe^{++} + 4OH^- \longrightarrow 2Fe(OH)_2$$

followed by oxidation of the ferrous ion to the ferric state.

At the cathode,

$$2H_2O + O_2 + 4e^- \longrightarrow 4OH^-$$

The extent to which these reactions proceed depends upon the conductivity of the electrolyte and the difference in potential between anodic and cathodic areas. The supply of oxygen reaching the cathode controls the rate of the anodic reaction. Under the action of the corrosion current, the electrodes are polarised and the actual compromise potential limits the corrosive effects. For steel in concrete, the strong polarisation of the anodic zones raises the potential to a value close to that of the cathode and the surface of the steel is passivated by the formation of an oxide layer. This accounts for the good durability found with reinforcing bars partially covered by millscale in sound well compacted concrete. In permeable concrete in which the oxygen availability is increased and the $_p$H reduced by atmospheric carbon dioxide, the millscale will stimulate corrosion of the uncovered zones at a rate determined by the oxygen access at the cathode.

The cathodic process, requiring a supply of oxygen, is affected by the different oxygen solubilities in solution of differing solid contents and by the extent of water saturation of the concrete. Under marine conditions where variable amounts of chloride are deposited on the surface of reinforced concrete members, differences in the chloride concentration of the pore liquid arise and since the oxygen solubility is a function of the solution concentration, areas of high and low oxygen availability are produced and a differential oxidation cell is formed. The function of the chloride ion in promoting a differential cell of this type offers a tenable explanation of the rapid deterioration of reinforced concrete of inadequate quality under marine conditions. It has been postulated[1] that the driving force for

(1) reference 3.11

corrosion arises from the concentration cell set up by the differences in chloride content of the pore liquid coupled with the low pH and high oxygen availability in the porous (anodic) zones in the concrete. On this basis, there are two opposing cells, one due to differential concentration effects which tend to make the steel in the porous zones more anodic and the differential aeration cell which has the opposite effect.

It has been established[(1)] that where these two cells are in opposition, the differential oxidation cell exerts the greater influence. The other effects of chloride ion should not be overlooked. The strong anodic polarisation observed in chloride free concrete does not occur when chloride is present and the corrosion is no longer controlled by anodic polarisation but depends on the velocity of the cathodic reaction which in turn is governed by the availability of oxygen. At high chloride concentrations, the resistivity of the electrolyte is greatly reduced, permitting greater corrosion currents, the pH of the pore liquid is lowered and the threshold pH required to protect the steel is raised.

The prime factor determining the protection of reinforcing steel from corrosion is the permeability of the concrete to carbon dioxide and oxygen. In various studies[(2)], it has been found that the dividing line between corroded and non-corroded reinforcement is governed by the depth to which carbonation has occurred and the alkalinity of the concrete has thereby been reduced. The severity of the corrosion in the carbonated zone is in turn determined by factors such as the moisture content of the concrete, the nature of the exposure conditions and the presence in the concrete of chlorides or other electrolytes.

3.07.7 Corrosion due to salt spray

Deterioration of reinforced concrete from the effect of seawater salts can occur in structures up to several miles inland from the coast. It arises from corrosion of the reinforcement, not attack on the concrete itself, and is caused by sea spray carried inland by prevailing winds. The salts gradually accumulate in the concrete and by wetting and drying gradually migrate inwards to the steel.

(1) reference 3.8
(2) " 3.10

3.07.8 Factors affecting passivity of steel in concrete

Clean steel is rendered passive by the action of the hydroxyl ions in concrete in the absence of any aggressive ions. In reinforced concrete there are certain factors which will influence the passivity of steel. If conditions change, it is possible for the concrete to act as an electrolyte in which corrosion cells will operate. These conditions are:-

1. Quality of concrete.

   If cracks or honey-combing are present in the concrete, the atmosphere can penetrate to the exposed steel, and normal atmospheric corrosion of steel will proceed at these points.

2. Concrete permeability.

   Concrete is permeable to varying degrees. The permeability depends on such factors as water-cement ratio, aggregate size and grading, richness of mix, method of compaction, curing etc. The permeability of a section of concrete varies with time and history.

   Since the passivating action of concrete on steel, due to its high $_pH$, can be maintained only by its physical protection and durability, i.e. its ability to exclude hostile ions from near the metal surface, the permeability is of utmost importance.

3. Environment of the concrete.

   Reinforced concrete in an industrial marine environment will undergo more severe corrosion of reinforcement than in a dry unpolluted atmosphere. Different areas of the same structure may suffer different corrosion rates due to one section being sheltered.

4. Steel surface.

   Concrete acts as an anodic inhibitor by deposition of a protective film at the anodes. At the same time, by obstructing the diffusion of oxygen to the metal surface, it impedes the normal cathodic reaction for which the presence of oxygen is necessary. However, the amount of hydroxyl ion required to stifle corrosion increases as chloride ion concentration increases. Thus, steel whose surface is contaminated with salt is likely to corrode in concrete sooner than clean steel. Actively rusting steel or steel whose surface retains millscale is likely to have less corrosion resistance than steel which has been cleaned.

5. Cover of concrete over the steel.

This factor must be considered with permeability of the concrete.

3.07.9 Methods of corrosion prevention

Corrosion of reinforcing steel, by whatever mechanism, is primarily due to the penetration of moisture, chlorides and air to the steel surface. Corrosion prevention methods must either prevent the penetration of these materials, or render the reinforcement passive to their action.

3.07.9(a) Methods of corrosion control are:-

Location of structure.

The first step which could be taken to prevent corrosion of reinforcing steel, is to avoid the more aggressive locations where possible. However, there are usually more important factors to be considered when investigating the location for a marine structure.

3.07.9(b) Design.

Engineers can make an important contribution to corrosion prevention by eliminating potentially dangerous features from their designs. Particular attention should be paid to shedding water from a structure, instead of allowing water to flow over concrete surfaces. Salt water flowing under these conditions can make salt available to act as a corrosion agent in the concrete, where design changes could prevent the problem.

The provision of adequate cover of concrete over reinforcement is essential, and unnecessary reinforcement should be eliminated.

3.07.9(c) Concrete.

The most important contribution to the prevention of corrosion can be made by concrete technology, by the production of an impermeable concrete. Research has shown the importance of water-cement ratio, aggregate grading, curing, richness of mix and compaction in the manufacture of high quality concretes, but no matter how well prepared a specification may be, careful supervision and site control are essential to ensure compliance with the specification requirements.

3.07.9(d) Materials.

Care should be taken that materials used in construction of marine works are free from salt. Water for washing aggregate and mixing should be fresh. Additives should be checked for chloride content. Permeable aggregates should also be avoided.

The steel reinforcement should be free from rust or millscale, however this is an impractical recommendation, and as rusty steel reputedly has a greater bond strength than clean steel, the only precautions required are that the steel be protected from marine atmosphere corrosion and well washed with fresh water before concrete is placed.

3.07.9(e) Surface Coatings.

In general, the vulnerability of concrete to chemical attack results from at least three of its significant characteristics:- its permeability, its alkalinity, and the capacity of hydrated cement compounds to undergo undesirable chemical reactions.

In some instances, concrete needs the additional protection against chemical attack which can only be afforded by a barrier of material resistant to the action of the chemical agents encountered.

A protective barrier cannot protect all concrete substrates equally well. If concrete has not been properly made and is not of good quality, its potential resistance to various corrosive agents is greatly reduced. Protection of such concrete by surface coatings is often impossible.

Protective coatings for concrete may be classified in two principal groups, thermoplastic and thermosetting. Thermoplastic materials can be softened by heat and cooled without undergoing chemical change. Thermosetting materials, in the process of setting, undergo a chemical reaction which causes molecular cross-linking.

Barriers to resist seawater attack may be achieved by using materials in a number of forms, viz.,

(a) Coatings and surface treatments,

(b) Thicker barriers,

(c) Mortars.

Examples of these materials are given below together with comments on their suitability.

Coatings and barriers should be applied as soon as possible after the curing of the concrete, as once salt is present in the concrete, the effectiveness of the coating may be reduced.

3.07.9(e)(i) Coatings and surface treatments[1] [2]

(i) Alkali silicate

Aqueous solutions of sodium silicate, reacts with the soluble calcium compounds in Portland cement concrete and converts them to calcium silicate which is insoluble. The action is to plug the pores of the concrete with chemical resistant compounds by chemical reaction to produce less reactive compounds on or near the surface of the concrete. The depth of penetration of liquid and protection of concrete may be relatively shallow if the first application blocks the pores in the concrete and thus limits the penetration of subsequent. coats. For this reason, the first coat is diluted and the subsequent coats progressively more concentrated.

This coating increases resistance to attack, but does not prevent it. The cost of the finished applied coating is approximately $3 per square yard.

(ii) Silicones

These are synthetic chemicals produced by chemical combination of inorganic materials containing the elements silicon and

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(1) reference 3.1
(2) " 3.4

oxygen with one or more organic hydrocarbons. They are used as surface treatments and they do not function as continuous surface films or coatings, producing a surface which is water repellant but not sealed against water penetration.

Silicone treatment only temporarily delays water absorption when concrete is completely immersed.

Other coatings which can be used on concrete are:- Chlorinated rubber, epoxy, hypalon, neoprene, polyester, styrene - butadiene rubber, polysulphide rubber, urethane and vinyl.

3.07.9(e)(ii) Thicker barriers

Examples of thicker barriers are:
Brick, tile, asphalt and coal tar, vinyl and neoprené. Coatings of tar and pitch have often been applied to protect reinforced concrete from deterioration in seawater but the general consensus of opinion is that their effective life is too short and that in some cases they only hide the damage that is taking place. Coatings applied to the underside of concrete decks have however, been found useful. The impregnation of concrete piles with hot bitumen under reduced pressure has been extensively used by the Los Angeles Harbour Board(1) with very effective results in stopping corrosion of reinforcement.

3.07.9(e)(iii) Mortars

Examples of mortars are: - Furan, phenolic, epoxy and polyester.

The final solution on the need for a barrier and the type of barrier to be used to protect concrete in the presence of seawater will depend on the conditions of each specific problem and site, and may be best resolved by counsel with manufacturers and other experts, and may necessitate tests to prove that a barrier is compatible with the surface it is to protect.

These above methods have been aimed primarily at preventing the penetration of aggressive materials into the concrete. There are also several methods available for protecting the reinforcing steel.

3.07.9(f) Metal treatment

In any treatment of the metal, a prime consideration must be its effect on the strength of the bond between reinforcing steel and

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(1) reference 3.15

concrete. Experiments in various countries have yielded conflicting results on the effect of galvanising reinforcement.[1]

3.07.9(g) Cathodic protection

To ensure continuous economic protection, the cathodic metallic circuit should be electrically continuous if interference effects and anodic spots are to be avoided. The electrolytic circuit should have a reasonably uniform resistivity which should not be so high as to necessitate excessively large voltages for providing the minimum current requirements. To achieve these requirements, the following details must be considered:-

(1) Electrical resistivity of dry concrete may exceed 100,000 ohm/cm^3 and when wet with salt water may be as low as 100 ohm/cm^3. Both these extremes could be met in the same structure under different exposure conditions.

(2) Sacrificial anodes are unlikely to be satisfactory for use, due to their limited forcing potentials. As the resistivity of the concrete is so variable, impressed current systems require extensive anode arrangements to facilitate a reasonable current spread under dry conditions. Under wet conditions, with the same voltage setting on an impressed current system, there exists a risk of damage due to hydrogen evolution.

(3) Acids produced at the anode could cause chemical attack on the concrete.

(4) Alkali produced at the steel surfaces may also affect the concrete.

(5) The operations involved in ensuring that all the reinforcing steel in a structure is electrically continuous are generally too extensive to be practicable.

Thus cathodic protection generally can not be applied economically to a new structure, and is not a practical solution to the problem where it arises in existing structures.

3.07.9(h) Inhibitors

The surface of steel reinforcement, coated with gamma Fe_2O_3 film can act as an efficient cathode. If a non-conductive film of other

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(1) reference 3.2

oxides or hydroxides could be deposited by the use of cathodic inhibitors such as calcium carbonate, aluminum oxide or magnesium hydroxide, the cathode efficiency could be markedly reduced. However, adding soluble aluminium, zinc or magnesium compounds results in their hydroxides being precipitated by the alkaline cement substances throughout the concrete mass and not selectively where they are required at the cathodic steel surface.

Anodic inhibitors such as alkalies, phosphates and chromates contain anions which either form sparingly soluble iron sales or form the gamma Fe_2O_3 film on the anodic steel surface, thus preventing ferrous ions from passing through and into solution at the anode. This type of inhibitor is effective only when present in sufficiently high concentrations and is otherwise dangerous, because if added in sufficient quantities to stop attack, the corrosion becomes intensely localised and the attack is stimulated.

The following factors operate against the use of anodic inhibitors:

(a) If added to a concrete, they will be evenly distributed throughout the bulk of the concrete. If sufficiently high concentrations to be effective are used, the properties of the concrete may be adversely affected.

(b) Should they be incorporated as a coating on the steel, the concrete-steel bond may be weakened.

(c) The amount of inhibitor required to be effective increases as the chloride ion concentration increases. This may lead to the effective concentration of inhibitor for high chloride concentrations being inordinately high.

(d) The solubility of the inhibitor should be such that while sufficient inhibitor is in solution to be effective, it is not so great as to allow leaching out to take place.

It is evident that the use of conventional inhibitors is not a practical solution at this stage, and requires a great deal more fundamental research.

3.07.10 Arresting corrosion of reinforcement[1]

Arresting corrosion is difficult to achieve. The existence of corrosion implies that the concrete is porous, has accumulated salts and has a low resistivity. Reduction of access of oxygen to the anodic areas increases the corrosion of those areas. An increase in the oxygen availability may divert the corrosion to areas previously cathodic.

One method to stop corrosion is for the entire structure to be insulated against the diffusion of air. This can be achieved theoretically by covering the structure with an air-impermeable coating or by saturation of the concrete with water.

Cathodic protection of the steelwork is a relatively new method of arresting corrosion.[2] [3] To achieve cathodic protection within concrete, the passivity of the steel must be changed by an appropriate drop in the steel to concrete potential.

3.07.11 Galvanised Reinforcement

Galvanised steel resists exposure to the elements better than ordinary steel, so that when reinforcement will be exposed for lengthy periods before concrete is cast, it may be advantageous to use galvanised steel.

Galvanised steel can tolerate higher chloride ion concentration without film breakdown and loss of passivity. Once passivity is lost, zinc corrodes preferentially and furnishes cathodic protection to the steel.

It is also thought that soluble corrosion products of zinc can diffuse more readily through the concrete than do the corrosion products of steel. Since it is the accumulation of corrosion products at the steel-concrete interface which exerts the disruptive tensile stresses on the concrete, this accounts, in part, for the improved performance of galvanised reinforcement.

Galvanised steel is not a substitute for good concrete and proper placement and proper cover to reinforcement, although it can be a valuable supplement to good concrete construction.

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(1) reference 3.14
(2) " 3.11
(3) " 3.14

When galvanised steel is embedded in concrete, hydrogen is liberated, under certain conditons, at the surface of the galvanised coating, causing the concrete surrounding the reinforcement to become spongy, with resultant loss of bond between it and the reinforcement.

Experiments by Bird[(1)] have shown that the amount of soluble chromate present in cement has a profound effect on the behavious of the cement towards a galvanised surface, by inhibiting the liberation of hydrogen.

A concentration of 70ppm is required for inhibition. Where the concentration of chromates in the cement dissolved in the mixing water is less than 70ppm, chromate may be added to the mixing water to obtain this figure. If for some reason this is impractical pretreatment of the galvanised surfaces with a 20% solution of chromic acid for 10 minutes and subsequent rinsing with fresh water, has a similar effect, and gives rise to increased pull-out bond strengths.

The effects of chromates on the subsequent life of a galvanised coating on reinforcing steel embedded in concrete and exposed to marine atmospheres, has not yet been fully evaluated.

Only structural grade reinforcement should be galvanised, as galvanising of hard grade reinforcing bars can result in failure by brittle fracture at low levels of stress.

The cost of galvanising reinforcement is approximately 80% of the cost of bent reinforcement, i.e. $250 per ton.

3.07.12 Clinker aggregates

In reinforced concrete, clinker aggregates cause accelerated corrosion of the reinforcement. Action of the sulphur compounds is facilitated by the permeable nature of the concrete and by the tendency shown by clinker aggregates to abeorb moisture from the atmosphere and maintain the concrete in a moister condition than the surroundings. Clinker aggregates are banned in Great Britain for reinforced concrete, and their use in any position in contact with steelwork is also prohibited.

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(1) reference 3.3

3.07.13 Stainless steel reinforcement

The use of stainless steel reinforcement is a new development in the construction industry, which has a potentially wide scope for application in a marine environment.

Stainless steel reinforcement has been developed in the United Kingdom and has been used primarily in wall panelling in precast building construction. The bar being used is a warm worked high strength ribbed type 316 stainless steel, with the following composition:-

Carbon	0.07% max.
Silicon	1.0% max.
Manganese	2.0% max.
Chromium	16.5% - 18.5%
Molybdenum	2.25 - 3.0%
Nickel	10.0 - 13.0%
Nitrogen	0.15 - 0.25%

The molybdenum content increases the corrosion resistance of the metal.

The advantages of stainless steel reinforcement over other reinforcing are:-

(i) High Shear strees/Proof stress ratio.

(ii) High limiting fatigue stress.

(iii) High strength and impact at subzero temperatures.

(iv) High resistance to corrosion.

(v) High stress and low cover applications.

(vi) Non magnetic.

The reinforcement is highly ductile and can be bent around a former pin of equal diameter to the bar without signs of fracture. It is readily weldable, although a reduction in the proof and tensile level will occur as a result of welding, and the heat affected zone of the welded reinforcement will corrode preferentially.

This reinforcement was developed for use in areas where corrosion resistance and strength are vital, however in the three years since the material was introduced, many new uses have been found. As yet, no actual marine application has been carried out, although proposals exist for applications for reinforcement for foundation piles, in offshore oil rigs and in pontoon structures.

The cost of the stainless steel reinforcement is approximately eight times the cost of mild steel reinforcement, or $2000 per ton, however this materials cost represents only one part of the cost of construction of a structure, and in building works, this extra cost has been compensated by reductions of weight of panels due to decreased cover requirements to reinforcement (2" down to 0.5"), with a resultant reduction in piling and foundation costs and necessary craneage capacity for erection at the site. It could reasonably be anticipated that similar benefits would accrue for marine applications of the material.

3.08 PRESTRESSED CONCRETE

Prestressed concrete construction utilises high strength carbon steel under high stress. This reinforcement is susceptible to failure by stress corrosion cracking, and this mode of failure has occurred in seawater, in the presence of stress risers.

Where high tensile steel wires are used in prestressed construction, the large surface area relative to the volume of metal, makes surface attack by corrosion very important.

Calcium chloride[(1)] has been demonstrated to have serious corrosive effects on prestressing steel, and is normally forbidden for use in prestressed structures.

Tests with concrete beams prestressed with black steel and galvanised steel wire[(2)] have indicated that performance under cyclic loading and loading to destruction, was similar for the two types of wire.

3.09 CORROSION OF NON-FERROUS METALS [(3)]

Various non-ferrous metals and alloys can be attacked by the alkaline solutions present in damp Portland cement concrete.

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(1) reference 3.14
(2) " 3.5
(3) " 3.10

3.09.1 Lead

Lead exposed to the atmosphere develops a protective film of lead carbonate, but when embedded in cement mortar, this film is not formed and corrosion occurs. It is therefore necessary to protect lead pipes in concrete by bituminous coating or by wrapping in bituminous felt.

3.09.2. Zinc

Zinc is resistant to attack in solution of $_pH$ 7 to 11, but at higher $_pH$ values, attack occurs with evolution of hydrogen. The $_pH$ value of the solution in a wet concrete is between 12 and 13, but despite this, corrosion of zinc in concrete is rare. Galvanised reinforcement generally gives satisfactory results, but in some cases the bond between concrete and steel has been reduced apparently because the hydrogen evolved caused the concrete layer adjacent to the reinforcement to become porous. This variable behaviour is linked with the soluble chromate in the cement. Small amounts of chromate are sufficient to prevent hydrogen evolution. Galvanised reinforcement is often chromised as a precaution.

Attack on zinc is increased by chlorides, and calcium chloride should not be used in the concrete.

3.09.3 Copper

Copper is not corroded in concrete to any significant extent.

3.09.4 Aluminium

Aluminium, like zinc, reacts with alkali hydroxide solutions with evolution of hydrogen. Much more serious corrosion occurs if the concrete contains calcium chloride and particularly in reinforced concrete if there is electrical contact between the steel and the aluminium. The presence of 1 per cent calcium chloride by weight of cement is sufficient to cause galvanic corrosion. Sodium chloride would have the same effect so the use of aluminium in concrete in, or near seawater, should be avoided.

3.10 CONCLUSION

Although concrete is widely used for marine structures and this application in a crude form dates more than 2,000 years, problems remain, associated with the use of concrete in a marine environment.

Normal Portland cement concrete is susceptible to expansive sulphate attack from aggressive seawater and/or groundwater, or leaching of lime, due to dissolved carbon dioxide in the seawater.

The most effective counter to this form of attack is by the full investigation of the site conditions before the structure is specified, and in the exclusive use of Type D Portland cement concrete.

By far the greatest proportion of marine structures in concrete are built with steel reinforcement, and the problem of attack on cement by aggressive waters, is compounded by the corrosive action of seawater on the reinforcement in the concrete. In this case, the attack is of an insidious nature, as, the initiation of attack is not visible, and by the time the effect is visible, the corrosion is deep seated and is difficult to arrest.

In this case, as usual, prevention is better than cure, and most recent successful developments have centred around the passification of the steel reinforcement. These developments have been the use of chromatised-galvanised reinforcement and, very recently the introduction of stainless steel reinforcement. The initial costs of these types of reinforcement are approximately 80 and 700% higher than untreated reinforcement respectively, however, circumstances exist justifying the adoption of one or other of these types of reinforcing bar under marine conditions, depending on the standard of the structure to be protected. The development of this facet of corrosion protection of reinforced concrete is seen as the most rewarding avenue of research into the subject of preservation of concrete structures in a marine environment.

The time honoured criterion of using a good quality concrete of adequate strength and low permeability with adequate cover over reinforcement is fundamental for a successful concrete structure.

Inhibitors may be used to passify the reinforcement. The additional initial cost in the mix design, additional concrete and good supervision, is a small price to pay for the result of added protection against corrosion.

The various methods of arresting corrosion once it has commenced in reinforcement in a structure, have of necessity engaged many investigators, but to date, no satisfactory general solution is available, although in cases, elaborate schemes of cathodic protection or surface insulation have been carried out in the forms of experimental pilot schemes.

The criteria for a successful reinforced concrete structure in a marine environment may be stated as being:-

(1) Full investigation of the site conditions and of the materials to be used in the work.

(2) Use of type D Portland cement concrete only.

(3) Use of passified steel reinforcement.

(4) Strenuous quality control of the concrete.

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