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CORROSION PROTECTION FOR STEEL SURFACES EXPOSED TO MOVING SEA ICE

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ABSTRACT

Corrosion of steel in ice - abraded zones has reduced the operating efficiency of U. S. Coast Guard icebreakers and of offshore oil rigs in Cook Inlet, Alaska. Possible mechanisms of corrosion are described. Preliminary experiences with various methods of corrosion control are reviewed. Other standard control practices are examined for their potential usefulness in the Arctic. It is concluded that some presently available protection methods are suitable as interim solutions, but that optimum methods await further development. Recommendations are made for further investigations of some aspects of the problem.

*The opinions or assertations of this paper are those of the author and do not necessarily reflect the views of the Commandant or the Coast Guard at large.

INTRODUCTION

As this conference indicates, we are witnessing an acceleration in the exploitation of the world's Arctic regions. As man's activity in the Arctic continues to increase, so will his use of steel there. Where this steel is exposed to sea water and moving ice, special corrosion problems will be encountered.

The designer of a steel structure for Arctic use, whether it be a ship, an offshore oil rig, a navigational aid, or a pier, is challenged by several interesting and interrelated problems. Uncertainties in predicting ice forces will induce him to select extra-conservative safety factors for computing the amount of steel to use. He must select a steel resistant to brittle fracture at low temperatures, estimate corrosion allowances, and choose a suitable corrosion protection method on the basis of a relatively small amount of accumulated corrosion experience in ice-infested waters.

Using reported experiences in Arctic waters with two different applications of steel (offshore oil rigs in Cook Inlet, Alaska and U. S. icebreaking ships), this paper endeavors to: review the practical necessity for corrosion control; postulate corrosion mechanisms which thrive in ice-abraded zones; report attempts at corrosion control; and suggest other methods of corrosion prevention.

CORROSION OF ICEBREAKER HULLS

Corrosion History

The U. S. Coast Guard has operated its Wind-class icebreakers in the Arctic since the mid 1940's. The hulls are constructed of special high-tensile steel plates (see Table I) which originally were welded with mild steel rod. Until the early 1950's, icebreaker bottoms were painted after each voyage into the ice. Little paint survived from one drydocking to the next. The practice of yearly painting was deemed uneconomical and was stopped in 1952. Within five years, accelerated corrosion became apparent, with pitting of the welds the predominant form, and with some lesser pitting also noted on the shell plate. Continued wasting of the hull seams led to rewelding, this time using low-hydrogen rods with a 1% nickel content. By the late 1960's all hull seams had been rewelded at least once. After the rewelding, the pitting attack appeared to shift to the hull plates. Concentrated pitting was noticed in the heat affected zones adjacent to the repaired seams and in the way of the builder's clips and brackets which were removed before launching by flame-cutting.

By the late 1960's, reports of pits 1 cm deep were common. Besides exceeding the design allowance for uniform corrosion, which was 65 mm from the original steel thickness of 3.2 to 4.8 cm, this pitting attack is especially worrisome because it increases the likelihood of brittle fracture of the shell plates in a hull which is repeatedly impacted with heavy loads at low temperatures. A number of hull cracks have, in fact, been experienced although it is not clear that they have propagated from pits (see Figure 1). Nevertheless, pits in the shell plates which act as stress risers must be viewed with alarm.

TABLE I

STEELS FOR ARCTIC APPLICATIONS

A. WIND-CLASS ICEBREAKER HULLS (TYPICAL)

Carbon	0.20% (max)	Silicon	0.15-0.35%
Manganese	1.50	Copper	0.35
Phosphorous	0.04	Nickel	0.25
Sulphur	0.05	Titanium	0.005

B. COOK INLET, ALASKA OFFSHORE STRUCTURES (TYPICAL)

Carbon	0.20% (max)	Copper	0.35
Manganese	0.70-1.40	Nickel	0.25
Phosphorous	0.04	Chromium	0.25
Sulfur	0.05	Molybdenum	0.08
Silicon	0.15-0.50		

Weakened hull steel is not the only adverse effect of shell plate corrosion: the roughening of the hull resulting from pitting adds to the static and kinetic hull friction, and this additional friction reduces the dynamic downward force available for breaking ice. A rigorous study by Coast Guard Commander R. M. White (9) of the parameters affecting the dynamic icebreaking force includes calculations of the magnitudes of these friction losses. White shows that an increase in the coefficient of kinetic friction from the normally assumed value of 0.2 to a value of 0.3 will decrease the downward force for icebreaking by approximately 15%.* In addition, increasing the static friction coefficient from the assumed value of 0.8 to a value of 0.9 will cause a 27% increase in the reversing force needed to extract the ship after it has rammed up on the ice at 5 - 8 m/sec. White summarizes by stating that reducing total friction (static and kinetic) is one of only two feasible ways to increase the downward breaking force while simultaneously reducing the extracting thrust requirement. He concludes by recommending an investigation into the use of low friction coatings (eg. Teflon) on icebreaker hulls.

Other Ships

Arctic ice has scraped down the sides of many vessels, including freighters, tankers, tugs and barges, fishermen and even submarines. Although the above discussion of hull corrosion relates chiefly to icebreakers, much of it can be generalized to apply to ships operating in thin ice or in the path cleared by an icebreaker: a loss of hull strength and operating efficiency will result from corrosion-roughening of the ice abraded portions of the vessel's hull.

Corrosion Mechanisms

The rapid loss of the original welds on the icebreakers was undoubtedly due to galvanic corrosion. The mild steel weld metal was anodic to the high-tensile alloy hull plate in an unfavorably low anode-to-cathode area ratio. Slag and porosity in the wartime welds are possible reasons for pitting instead of uniform attack. Velocity effects (erosion-corrosion or cavitation-corrosion) and imperfections in the early paint coatings could also have initiated localized corrosion cells. Rewelding using low-hydrogen, 1% nickel electrodes made the replacement weld metal cathodic to the hull steel, and stopped the loss of welds.

* For wind-class icebreaker ramming at 4.6-7.6 m/sec.

Accelerated corrosion in the heat-affected zones was probably due to localized variations in the grain structure of the steel caused by the heat of welding or flame cutting adjacent to the new welds and at the former sites of the builder's clips and brackets.

Corrosion of the shell plates has been manifested chiefly by pitting. The mechanism by which these pits were initiated is not clear, but it seems likely that spots of mill scale and/or defects in the bottom paints applied during the early life of these ships were at fault. Normal ship practice is to augment the coating system of a vessel by the use of sacrificial anodes (Zn, Mn, or Al). Hull steel exposed by porosity in the coatings or by damage to the coating is then protected by the anodes. Icebreakers, however, lose most of their anodes soon after entering the ice. Any exposed hull steel is then unprotected and localized attack can be initiated while the ship is underway. Later, in the quiet waters of the home port, attack may continue by the mechanism of pitting. The gradual accumulation of corrosion products will slow pit growth, but the subsequent removal of these products by next season's ice abrasion will set the stage for a renewed attack.

Corrosion Control

The unexpectedly severe corrosion of icebreaker hulls after the discontinuation of bottom painting led to a search for improved coating systems which could endure at least 2 years of service. An additional goal of this search was to select or develop a bottom coating system for the Coast Guard's new icebreaker scheduled for construction in 1972-75.

In 1967, tests of various coatings were conducted on the USCG icebreaker WESTWIND's hull. Two types of inorganic zinc silicate were applied to different areas of the bottom, each with two different topcoats. Also, a polyester glass flake coating was applied, both with and without topcoats. Test details and results are summarized in Table II. The most successful system tested was the polyester glass flake, with top-coated inorganic zinc silicate a close second. In assessing these test results, it should be noted that the coatings were applied to a previously corroded surface. Since sandblasting to near-white metal was required prior to the application of each of the tested coatings, adequate surface preparation of the pitted hull steel was difficult to achieve. Also, owing to the sharp variations in surface contour, uniform coating thickness was certainly not attained. These same coating systems should therefore perform better when applied to properly prepared steel on which deep pitting has not occurred.

TABLE II

TEST OF ICEBREAKER COATINGS

COATING SYSTEM	WHERE APPLIED	RESULTS
1. Self-curing Inorganic Zinc Silicate with sealer coat.	Port side, below boot-top, except between Frames 31-46.	Sealcoat: 5% intact Base coat: 60% intact Light rust over 95%
2. Self-curing Inorganic Zinc Silicate with sealer coat, 1 coat pre-wash primer, and 3 coats cold plastic.	Port side, bottop area except between Frames 31-46.	Cold Plastic: 10% intact Base coat: 75% intact Light rust film on bare metal
3. Post-cured Inorganic Zinc Silicate with no topcoat.	Starboard side, below boottop, except between Frames 31-46.	10% intact Heavy rust film: 100%
4. Post-cured Inorganic Zinc Silicate with sealer coat, 1 coat pre-wash primer, and 3 coats cold plastic.	Starboard side, boottop area, except between Frames 31-46.	Cold Plastic: 10% intact Base coat: 75% intact Light rust film on bare metal
5. Polyester Glass Flake with no topcoat.	Port and starboard sides, below boottop, between Frames 31 and 46.	Port side: 40% intact Starboard side: 85% intact Light rust film on bare metal
6. Polyester Glass Flake with 1 sealer coat, 1 coat pre-wash primer, and 3 coats cold plastic.	Port and starboard sides, boottop area, between Frames 31 and 46.	Overcoat gone Base coat: 80% intact Light rust film on bare metal

Source: USCGC WESTWIND Underwater Hull Inspection Report, 7 July 1969.

While the WESTWIND test was progressing, a survey of commercially available coatings was initiated with a view toward cataloging systems with commercial usages related to the icebreaker application. This survey was recently brought up to date by Coast Guard Lieutenant Commander R. A. Yuhas (10). The candidate coating systems which emerged from these efforts are:

a) Polyester glass flake

b) Inorganic zinc silicates (post-cured or self-curing) topcoated for abrasion resistance.

c) Conventional epoxy coatings

d) Copper-nickel cladding on steel

e) Neoprene (Chloroprene)

f) Polyurethane

g) Various thermal-sprayed coatings including aluminum with a clear vinyl top coat, ceramic, titanium, nickel alluminide, tungsten carbide, and zirconium oxide.

A subjective comparison of those coating systems on which adequate information was obtained is presented in Table III. The tentative conclusion drawn from this survey of commercially available systems was that thermal-sprayed aluminum, top-coated with wash primer and a clear vinyl sealer, presents the best choice among the alternatives listed above. It is this author's belief that the nature of the surface to be coated plays an important part in the selection of an abrasion-resistant coating for corrosion protection. While thermal-sprayed aluminum may work well on new steel, it may also be readily abraded from the "peaks" of a previously pitted surface. Such a surface may be better protected by a coating system with sufficient build to smooth out the surface irregularities.

CORROSION OF OFFSHORE STRUCTURES

Background

Most United States offshore structures presently operating in Arctic conditions are in Alaska's Upper Cook Inlet. Between 1964 and 1969, fourteen oil drilling/production platforms were put into operation there. To date, corrosion rates have far exceeded predictions based on previous offshore experience. In the case of the first Cook Inlet structure, corrosion rates were so high that special leg wraps were installed after one year of operation(2). These "corrosion wraps" have also been used on some of the more recent structures.

Cook Inlet conditions are somewhat unique, even in comparison to truly Arctic sea conditions. In the vicinity of the oil rigs for example, the tide range is about 9 m; the surface current runs as fast as 13 km/hr, (currents no less than 3.7 km/hr are found throughout the water column); the water carries a heavy (20,000 ppm) load of dissolved solids and galcial silts (700 ppm) (2); and it is rich in dissolved oxygen (5). The seasonal ice, while not thick by Arctic standards, nevertheless exerts tremendous forces. For example, Peyton, in a comprehensive discussion of ice and marine structures, has shown that lateral ice loads on a typical Cook Inlet structure are on the order of 4.5 million Kg of force (6). Because the local tidal currents are rotary, and because of the extreme tidal range, the structures must withstand these forces when they are applied from any horizontal direction over a 9 m vertical range.

The importance of corrosion under these circumstances cannot be overlooked. The supporting columns for the structures are subjected at low temperatures to severe cyclic bending loads from all horizontal directions. Continuing high rates of uniform attack and/or the propagation of stress-raising corrosion pits could set the stage for catastrophic failure.

Other Structures

Ice abrasion and the resulting marine corrosion can reduce the efficiency of other Arctic structures besides offshore oil rigs. For example, pilings are frequently protected by angled legs called ice breakers which fail an approaching ice sheet by upward bending. Increasing the friction coefficient on the ice breaker will increase the amount of horizontal force required to achieve enough vertical displacement to fail the ice in bending.

Corrosion History

A typical steel used in the weld-fabricated tubular legs of the Cook Inlet structures is ASTM A-537 Grades A and B (5), a heat-treated manganese-silicon steel for pressure vessels and low temperature applications (see Table I). Most of the structures were built with an extra allowance of steel in the tidal zone, where the greatest corrosion attack was expected. For example, Shell's Middle Ground Shoal Platform "C" was provided with 1.8 cm of extra steel in the tidal zone (5). At the expected corrosion rate of 1.03 mm per year, a 17 1/2 year life was predicted for this platform. Corrosion control below the low tide level was expected from cathodic protection using installed, active anodes.

Experience with typical Cook Inlet structures in the first year or two of their operation exposed inadequacies in the initial provisions for corrosion control, as the following excerpts from a published report by Bertness and Blount (1) indicate:

"During the winter....the coating of paint and corrosion products is eroded by the ice and the metal surface [in the tidal zone] appears clean and bright...; ...between May and October...the tidal area becomes covered with a thin layer of soft iron oxide and pitting attack increases in intensity from high tide to the submerged area;...during the first summer of exposure...growth of the depth of the pits was estimated to be about 1 1/2 mm per year;...The platform was equipped originally with an impressed current (cathodic) system designed to supply .25 ma/ 1000 cm^2 at high tide...a dielectric shield....(extended) a minimum distance of 2.4 m from the anodes;..(four months later), a survey...showed that protective potentials extended only a few feet from each anode;...(One year later, after operating an improved, remote anode system for six months,)...Inspection of the platform legs showed that corrosion had been very severe below the water line. The steel was covered with a very thin film of iron oxide and was heavily pitted. The pits were sharp and deep, as if the metal had been hit with a blast of shot. The rust coating could be removed easily with a knife blade."

Since their report, remote anode systems have been improved and a greater degree of success has been reported. However, operation of these systems in the severe environment is not completely dependable, and their installation and operating costs exceed those initially programmed for corrosion control.

Corrosion Mechanisms

In Cook Inlet, in winter, the scouring action of ice prevents the buildup of corrosion products and corrosion rates are probably controlled only by the oxygen content of the water. In summer, although the accumulation of corrosion products will be slowed by the high water velocities, the corrosion rate will be controlled by the degree to which oxygen can penetrate the iron oxide layers. Areas exposed to a high dissolved oxygen content will be cathodic to areas exposed to lower concentrations of dissolved oxygen. On a steel piling the areas closest to the surface, where oxygen is in the greatest supply, will be cathodic to the deeper areas. This may explain the reported increase in corrosion with depth in the tidal zone reported in Cook Inlet. Ice may figure importantly in the corrosion mechanism because it acts to prevent the accumulation of corrosion products which would otherwise slow the reaction rate.

The dual effects of water temperature in this case are probably nearly self-cancelling: colder temperatures normally reduce corrosion reaction rates; but (because oxygen solubility in sea water is inversely proportional to temperature) this effect may be nullified by an increase in the amount of oxygen available for reduction at the cathode.

The cause of the pitting attack on these structures is more difficult to diagnose. Pitting is a localized, self-propagating form of attack which is usually associated with stagnant conditions because the accumulation of reaction products tends to keep the attack confined to the small anode areas. Generally, increased velocity reduces pitting attack. Local variations in the environment give rise to pits; some of the more common causes are pinholes or "holidays" in paint coating, holes in mill scale, (or patches of mill scale) and local dissimilarities in metal structure or composition. It is not difficult to visualize the initiation of pitting on the Cook Inlet structures; however, the mechanism by which these pits have deepened is not too clear. Possibly, pit growth is continued by differential oxygen concentration caused by "sheltering" from the free stream velocity. Even at high velocities, the bottom of a pit must experience lower oxygen concentrations than the steel surfaces fully exposed to the moving water.

Corrosion Protection for Offshore Structures

Many methods of protection for offshore structures have been reported in the literature. Non-metallic coatings which have found application include inorganic zinc, neoprene, various plastics, and concrete. Metallic coatings, including mild and stainless steels, zinc, and various alloys of copper and nickel have been tried. Cathodic protection is probably the most common method. Candidate methods are discussed below in relation to the Cook Inlet problem.

Inorganic zinc. - A coating of this type has been applied each spring to the tidal zone of a Cook Inlet structure, and apparently has arrested pitting during the ensuing summer (1). In the absence of anything better, this is considered to be a worthwhile technique because the more cathodic areas of the structure are coated and pitting in the submerged zone should therefore be reduced.

Neoprene (chloroprene). - This material has had succsssful use on Gulf of Mexico structures; however, it requires careful factory application. While neoprene may be useful at low temperatures and under heavy abrasive and impact loading, the requirement for factory application will probably preclude its use in the Arctic.

Plastics. - Some vinyl coatings on offshore structures have failed due to bonding difficulties (4). Epoxy and polyester resins appear to be feasible for Arctic structures provided a suitable method of field repairs can be developed.

Concrete. - Although extensively used in temperate zones to shield steel from sea water, concrete is probably not suited to this purpose in the Arctic. A properly proportioned air-entrained mix will insure good freeze-thaw durability, but abrasion resistance will probably be unsatisfactory unless the concrete is shielded with steel, which would thwart the original purpose.

Nickel - Copper Alloys. - Success with Monel (70% Ni, 30% Cu) cladding for splash zone protection has been reported for Gulf of Mexico structures. To reduce cost, the metal is applied in thin (1 to 1.5 mm) sheets and protected against mechanical abuse by bumpers (4). Ni-Cu sheathing applied below the mean low tide level can be expected to stimulate galvanic corrosion of steel. Cladding with this method is probably not feasible for Cook Inlet oil rigs because the large legs and extreme tidal range would require large areas of cladding, and because the severe mechanical environment would require greater thicknesses of the metal. However, Ni-Cu may be feasible for protecting smaller piles exposed to lesser tidal ranges.

Copper - Nickel Alloys. - These metals are expected to be less resistant to attack than nickel copper since their resistance to attack is roughly proportional to nickel content (8).

Zinc. - A zinc coating used on the first Cook Inlet platform was quickly removed by ice and corrosion (2), furthermore the corrosion rate of zinc rises rapidly with increased water velocity (7).

Steel. - Protective wraps of steel installed on-site are not considered to be economical owing to the high corrosion rates already experienced and to the difficulty of replacement. When they are installed, precautions must be exercised against crevice corrosion between the wrap and the leg, lest the cure be worse than the disease.

Stainless steels. - Stainless steels (passive) perform well in contact with sea water at high velocities. Their resistance to corrosion depends on a thin oxide film which would probably be lost to ice abrasion, although it should readily rebuild after the ice season. The nature of corrosion attack during the ice season would be the key to the subsequent corrosion resistance of the stainless steel; if pitting got started during the absence of the passive films; it could continue after the ice season. Low alloy steels coupled with stainless steel in sea water will corrode galvanically; therefore stainless steel cladding should not be applied below the mean low tide level.

Cathodic Protection. - Remote - anode, impressed - current cathodic protection has been successfully employed to obtain corrosion protection for the Cook Inlet oil rigs. Installed anodes were tried with little success; although extra large dielectric shields had been installed, satisfactory current distribution could not be obtained. The typical cathodic protection system which eventually evolved for the structures comprises a number of anodes placed on the sea bottom approximately 15 m from the structure. Current densities as high as 75 ma/1000 cm^2 have been required to obtain satisfactory protection potentials (-800 MV silver - silver chloride half cell) on the structure. Obtaining adequate current distribution and protecting the remote anodes from ice damage and underscour have been the major problems in implementing these systems. Hydrogen embrittlement has been of no concern to at least one operator (1), based on laboratory tests of steel used in structure legs. Although the growth of calcareous deposits resulting from the impressed currents was expected to reduce the required current densities, it is doubtful that such deposits could survive ice abrasion, or even the high water velocities; therefore current requirements will probably remain high.

Steel vs. Concrete. - At this point, it is worthwhile to ask, "why use steel at all for Arctic offshore structures - why not use concrete?" In all probability, carefully controlled concrete construction will be extensively used in the Arctic. As we have seen, however, steel may still be required as protection against abrasion, and corrosion will remain as an economic factor to be considered in the design of the structure.

CONCLUSIONS

1. Further testing and perhaps even development remain to be accomplished before a successful bottom coating system for icebreaking ships can be applied. However, for newly-constructed ships which will operate in moderate ice conditions, top-coated inorganic zinc or polyester glass flake coatings should give reasonable protection.

2. The high costs of building, maintaining and operating a steel structure in Arctic waters will make considerations of corrosion more important from an economic viewpoint than before.

3. Impressed-current cathodic protection for fixed structures can be achieved at sites where emplacement of remote anodes is possible.

4. Ice abrasion maintains long-term corrosion for exposed steel at rates nearly as high as short-term rates because the accumulation of oxygen-barrier corrosion products in cathodic areas is prevented.

5. Uncertainties in structure design parameters make considerations of corrosion important from a safety standpoint. Ice abrasion and its corollary corrosion can reduce the strength of steel structures in Arctic waters. Pitting attacks in two typical applications are particularly dangerous because cyclic loading around locations of concentrated stresses can lead to catastrophic failures.

RECOMMENDATIONS

1. Standard methods for testing the abrasion resistance of paint coatings should be correlated to the special case of ice abrasion and should be applied to candidate commercial coating systems.

2. Low friction coatings should be tested for their usefulness on ice-breaker hulls.

3. The effects of static and dynamic friction on the magnitude of ice loading on cylindrical piles, especially at low loading rates, should be investigated.

4. The corrosion mechanism of pitting in low alloy steels in oxygenated, high velocity sea water should be more thoroughly investigated than is indicated by the literature.

5. Where possible, inorganic zinc silicate should be applied immediately after the ice season to the tidal zone of fixed steel structures.

Figure 1: A and B strakes, starboard bow, USCGC NORTHWIND, November 1967. Although intended to show ice damage, this photograph illustrates well the extensive pitting of the shell plate, the corrosion of the original welds, and the concentrated attack in heat-affected zones caused by flame cutting the builder's clips and brackets.

TABLE III

COMPARISON OF SYSTEMS FOR COATING ICEBREAKER BOTTOMS

Coating Type	Abrasion Resistance	Impact Resistance	Corrosion Properties	Application	Relative Cost	Experience/Remarks
Polyester Resin with glass flakes	Claimed Excellent: Barcol 45-50	Good to Excellent	Excellent Dielectric. No undercut after 1000-hr. 5% salt spray	Sand blast to near white metal	Approx. 4 x coal tar epoxy	In 2-year service on windclass icebreaker, 40-85% retained. Can be topcoated with anti-foul. Can be applied over inorg. zinc.
Coal tar epoxy	Good	Fair	Good	Sand blast to near white metal	----------------	Approximately 100% failure in 2-year icebreaker service.
Inorganic polymer of silicon and oxygen (self-curing)	Fair to Good	Good	Excellent	Sand blast to near white metal	Approx. 1.3 x coal tar epoxy	In 2-year service on windclass icebreaker, 60% retained. Easily patched can be topcoated.
Inorganic zinc lead silicate (post-cured)	Good	Good	Very Good.	Sand blast to near white metal	Approx. 2 x coal tar epoxy	In 2-year service on icebreaker 10-20% retained without topcoat. 75% retained where hard sealer topcoat used.
Chloroprene Rubber	Claimed Excellent: 40-50 shore A.	Claimed Excellent	No information	Sand blast to white metal	Unknown	Not ice tested.
Aluminum (99% Min. purity)	Excellent: Approx. 3500 psi shear bond strength	Excellent	Excellent	Sand blast to white metal	Approx. 2.3 x coal tar epoxy	Not ice tested.
Tungsten Carbide (Technical Grade)	Excellent: 5500 psi shear bond strength	Good (for thin coating)	No information	Sand blast to white metal	Approx. 4.7 x coal tar epoxy	Used on aircraft turbine blades - very smooth.

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