FINAL REPORT

COMMERCIAL SHIP DESIGN AND FABRICATION FOR CORROSION CONTROL

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1.0 INTRODUCTION

In the salt water marine environment, corrosion of the steel hull is inevitable. Control of that corrosion so as not to cause structural failures or necessitate major renewals during the economic life of the vessel requires diligence in the design, construction and maintenance of the vessel. For corrosion control to be cost effective, it must be integrated into the ship design and production processes to provide structures that can be properly coated at the outset and are less prone to, and effectively protected from, corrosion during the vessel life. Corrosion control must also be integrated into the maintenance and inspection procedures so that subsequent recoatings and repairs are minimized in terms of both cost and lost operating time. To achieve effective corrosion control, the following factors must be understood, addressed and integrated:

- Corrosion mechanisms and those areas most affected
- Design of structures and details to enhance coating application and corrosion control
- Coatings selection and application
- Cathodic protection as applied to ships' tanks
- Production methods that assure coating quality
- Operations that may cause coating failures and how to prevent them
- Inspection procedures for early detection of coating or structure failures
- Arrangement and access to avoid confined or inaccessible spaces

This study on Commercial Ship Design and Fabrication for Corrosion Control consists of four major elements:

1. Review current corrosion control practices.
2. Develop design recommendations for corrosion control methodologies.
3. Develop recommendations for corrosion control equipment to achieve Naval Sea Systems Command (NAVSEA) requirements.
4. Prepare a draft for an ASTM Standard or Guide.

This report presents the results arrived at upon regarding elements 1, 2 and 4 only. The remaining results of element 3 were presented separately in [1][1].

Section 2 reviews current ship design and fabrication practices within the context of established corrosion control principles. In Section 3, coating materials, methods and failures are addressed, locations and details where coatings typically fail first are discussed, and the impact of various joining techniques on corrosion is presented. Design methods that increase the life expectancy of coatings and designs that avoid confined or inaccessible spaces are considered on their merits in Section 4; current design and construction methods, as well as those that hold promise of preventing early coating failure are included. In Section 5, the cost/benefit consider-

[1]Numbers in brackets denote references in Section 7

ations for these methods are discussed. Detailed design recommendations are made in Section 6 regarding the applicability and practice of corrosion prevention methodologies during the contract design and fabrication phases of the ship acquisition process that would reduce life-cycle costs.

Based on the findings of this study, a proposed draft was developed which could be used as the basis for a standard or guide. This draft is included as Appendix A. Presented in Appendix B of this report is a questionnaire, with resultant answers from the industry, on what were thought to be the more important and promising aspects of coating-corrosion interaction and present practice.

2.0 REVIEW OF CURRENT PRACTICES

2.1 Mechanism of Corrosion

Steel will not start to corrode without the proper thermodynamic conditions. If the steel in a tank is blasted to bare metal and held in an atmosphere of dehumidified pure air, it will hold the blast for many years before even surface oxidation commences. Unfortunately, the marine environment will react with the cleaned steel to form an oxide layer and start corrosion.

The most common causes and mechanisms of hull corrosion are:

- Galvanic corrosion, which occurs when two metals of different electrochemical potential are in metallic contact in an electrolyte such as salt water. The farther apart the metals are in the galvanic series, the greater the rate of corrosion of the anode. The metals need not be different, as in the case of a flanged plate, where the locked-in stress at the flange make that portion anodic to the rest of the plate. Most hull corrosion is galvanic in nature [2].

- Direct chemical attack, wherein certain chemicals containing elements such as chlorine and sulfur attack the steel without the presence of an electrolyte. This is frequently the cause of pitting in cargo tanks, especially when high-sulfur crudes are carried.

- Anaerobic corrosion, which is caused by sulfate-reducing bacteria that are present in many harbors. Pitting in ballast tanks can start through this mechanism and then accelerate through differential aeration, a type of local galvanic attack caused by differences in oxygen levels at the surface of the steel.

Studies have shown that the general corrosion rate for steel in sea water is about 0.1 mm/ year [3]. The corrosion rates in ballast spaces are potentially much greater and can become the controlling factor in determining a ship's life. If a compartment is not protected by coatings or sacrificial anodes, the time in ballast represents the most corrosive condition. As a result, the International Association of Classification Societies (IACS) now requires that all ballast spaces with one or more boundaries on the hull envelope must have a protective coating.

2.2 Current Corrosion Control Practices

2.2.1 During Design Phases

Current rules and regulations governing pollution and vessel protection require the use of double hulls for tanker construction. Many of the design features of these vessels tend also to assist corrosion control efforts. A survey of some recently delivered double-hulled tankers found them to incorporate the following features [4]:

- Water ballast tanks protected against corrosion by two coats of coal tar epoxy and eight-year sacrificial anodes.

- GRP piping used in ballast spaces to mitigate corrosion problems.

- Ballast spaces equipped with forced ventilation and hydrocarbon gas detectors. These spaces can also be inerted in an emergency via an inert gas system.

- Enhanced accessibility to ballast tanks with side stringers and direct access trunks from upper decks to the double bottom.

- Greater double bottom heights and wing tank widths than the 1 m minimum and 2 m maximum dimensions required. For example, the 290,000 dwt tanker AROSA has a 3 m double bottom and 2.44 m wide wing tanks; the E3 tanker has a 3 m double bottom and 4 m wide wing tanks. Oversizing allows for easier access for construction and maintenance while increasing the ship's safety.

- Corrugated bulkheads which allow for easier cleaning, coating, and inspection. A reduced number of stiffeners also reduces corrosion problems by minimizing horizontal surfaces that create standing pools of water.

2.2.1a Basic Structural Design

Unidirectional double hull vessels are unique with regard to hull structure as shown in Figure 2.1. They use the double hull envelope as flanges of longitudinal girders between transverse bulkheads. These girder-plate combinations, in addition to providing longitudinal strength, constitute the structural barrier between the internal and external loads. The longitudinal girders, usually uniformly spaced in a transverse direction, form cells that are long longitudinally and narrow in the transverse and vertical directions. The use of stiffeners is kept to a minimum and the resultant structures provide practically identical longitudinal spaces between transverse bulkheads for the major part of the midportion of the vessel. The width of each cell could be from about 1 to 3 meters depending on the type and size of the vessel. The major advantage, from a coating standpoint, is smooth surfaces. The major disadvantage, from a corrosion standpoint, is the large number of cells to inspect and coat. In addition, and as a plus, there are many horizontal areas to facilitate inspection on the larger vessels. At the same time, these horizontal areas could be a problem from a corrosion standpoint due to trapped water if they are not designed to drain freely.

Unidirectional double hull vessels have their own advantages and disadvantages with regard to coating and corrosion. Some of the advantages are summarized below [5]:

- Completely flush inside surfaces of cargo spaces and ballast tanks for easy and reliable paint application, although there is typically more coating area than a conventional double-hulled vessel.

FIGURE 2.1 Single Skinned Tanker (top). Double Hull Tanker (middle). Uni-directional Double Hull Tanker (bottom) [6]

- Minimizing structural discontinuities by reducing the number of sharp corners which cause coating failure to occur.

- Minimizing stress concentration and crack initiation possibilities and fatigue damage, decreasing the more flexible structures prone to coating cracking.

- Easier production due to smaller number of steel parts, fewer joints and more identical parts, hence more suitable for automatic welding [6].

Some disadvantages are:

- Depending on the type and size of the vessel, the spaces may not be inspector friendly.

- Large and numerous flat surfaces may become a corrosion problem due to accumulation of water from condensation if not designed to drain freely.

2.2.1b Design of Structural Details

Practically every operator can attribute structural failures to poor design of structural details and poor weld workmanship, including fabrication and fit-up. The most significant problems with detail design stem from the early designs in the late 1960s and early 1970s when tank vessels first began to be designed using sophisticated analytical techniques that lead to efficient, optimized structures. In many ways, these efficiencies brought about great advances in the shipbuilding and operating industries and facilitated the rapid growth in tanker size. However, the general effects of structural optimization brought about an overall lightening of scantlings, and problems with structural details have resulted.

Many of the structural details used in larger vessels were designed from experience and fabrication preferences, and without any specific analysis requirements or guidance from classification society rules. It is the general consensus among operators that details that had proven satisfactory for earlier mild steel construction are not necessarily satisfactory for new vessel designs, particularly those with high tensile strength steels (HTS). Many structural details on these larger vessels have proven to be inadequate and subject to failure.

Lap joints are a common detail that has been subject to failure on older vessels. Fractures in lap joints are common in the transverse web structures in wing tanks. In general, operators are repairing fractured lap joints with butt-welded joints wherever possible.

The following precautions and preferred details are offered as a preliminary guide for structural design considerations for coating application:

- All surfaces of the tank interior should be readily accessible for surface preparation and coating application.
- Minimize crevices which form corrosion cells, collect dirt, and are difficult to protect with coatings. Typical crevice areas occur between intermittent welds, at weld undercuts and at lap joints that are not welded all around.
- Butt welded joints should be used whenever possible, and should be used in lieu of lap joints which increase the total length of weld and the possibility of fractures causing corrosion.
- When dissimilar metals are used in ballast tanks, both should be coated to avoid galvanic corrosion.
- Repaired pits should be cleaned and filled to avoid future accumulation of water and dirt.
- Rivets and internal bolted connections should be avoided.
- Threaded connections should not be used, or should be made using corrosion resistant materials.
- Structural support members should be of simple shapes such as smooth round bars for ease in applying coatings.
- All welds should be continuous - intermittent or spot welding should not be permitted.
- All weld spatter must be removed, and all sharp edges should be ground to a smooth radius of at least 3 mm (1/8 in), with 6 mm (1/4 in) preferred.

Coating application and performance can be improved by adopting the above measures at the design stage. In addition, the reduction of scallops, the use of rolled profiles and ensuring that the structural configuration permits easy access for workers with tools and facilitates the cleaning, drainage and drying of tanks will promote quality coatings.

2.2.1c Weld Design

Welding design, including proper sizing of the welds and the welding sequence contained in the design specifications, play an important role in preventing distortions and stress concentrations in the fabricated ship sections and the finished hull structure.

In general, welded seams are more susceptible to corrosion. Thus, the longer the weld seams are on any given structure, the greater is the risk of corrosion. Lap joints have also been subject to failure in older vessels. Fractures in lap joints on the transverse web structures of wing tanks are quite common. For this reason, wherever practical, lapped joints in ships are being replaced with butt joints during repairs to fractured welds.

Current weld designs also avoid intermittent or spot welding and employ continuous welding since the former is more prone to corrosion.

2.2.1d Coating Specifications

There are numerous options for coating a tank. The coating system selected will depend on the type of tank, the cargo being carried and the desired life expectancy, among other factors. Below are some options that have been used when coating a ballast tank [7]:

- Coat entire tank, single coat.
- Coat entire tank, two coats, and add anodes for secondary protection.
- Coat overhead and 6 feet down the sides and install anodes.
- Use pre-construction inorganic zinc primer with zinc anodes replaced at eight year intervals.

Most of the above options could be used with any type coating, with more or less satisfactory results dependent on the life expected. Some of the more common coatings are listed below:

- Post-cured inorganic zinc (one coat)
- Self-cured inorganic zinc (one coat)
- Epoxy or coal tar epoxy (two coats)

The following are coatings tested in Reference [1] based on Volatile Organic Compound (VOC) content regulations, commercial track record for long term corrosion performance, and a flash point requirement of greater than 37.8 degrees C (100 degrees F):

- High solid epoxies
- Silicone modified epoxies
- Electrodeposition epoxy
- Thermal spray thermoplastics (nylon 11 and ethylene-hydroxyethylene copolymer)
- 100% solids rust preventive wax
- Calcium sulfanate alkyd
- High solids epoxy over a waterborne epoxy zinc primer

The following points should be considered and analyzed to best plan and manage the coating of a space:

- Manual or automatic weld seams
- Plate edges
- Curvatures
- Drain holes
- Weld seam overlapping
- Adhering splatters

2.2.1e Corrosion Prevention Equipment

Various types of coatings currently being applied on ships' steel structure are of course themselves corrosion prevention measures. The equipment and systems, that are in use at the present time, to provide additional protection against corrosion range from cathodic protection systems including sacrificial anodes and impressed current equipment to inert gas systems and corrosion inhibitors.

Sacrificial anodes are an important part of the corrosion control process in tanks with electrolytic solutions. In most cases, they form a secondary defense against corrosion should the primary coating barrier fail.

2.2.1f Inspection Requirements

General condition surveys of coatings may be carried out at any convenient time as long as the tank is in proper order for inspection. However, if the survey is necessary due to dry-docking, the survey can be carried out at sea to the greatest extent possible, prior to dry-docking, so that survey data can be properly analyzed and repair decisions made. This probably requires that the survey be conducted about 6 months in advance of the dry-docking.

Special surveys require an overall survey of all tanks and spaces, with all components within close visual inspection range, preferably within hand's reach. Plate thickness measurements by an accredited thickness measurement company require similar access to the structure [8].

Safety procedures and standards vary among owners and ships and the survey team must be aware of these practices. Typical items of concern to survey personnel may include [9]:

- Suitable atmosphere certified as safe for entry in terms of oxygen content and hazardous gases by a Marine Chemist
- Temperature extremes resulting in heat exhaustion
- Lighting sufficient for inspection and safe movement
- Climbing equipment for safe access to the structure
- Rescue procedures for getting injured personnel out of a space
- Rafting

Surveys done at sea may impose additional areas of concern:

- Atmosphere testing is done by lesser qualified persons in that a Certified Marine Chemist is generally not available
- Staging cannot be used for access
- Rafting and climbing will be limited when ship motions increase
- Limited rescue capabilities

2.2.2 During Fabrication

2.2.2a Structural Tolerances

During progressive stages of ship construction, the work is inspected by the shipyards' own inspectors, by the regulatory body surveyors, and by the owners' resident inspectors. The objective of these inspections is to assure that structural deviations from the original design such as distortion, misalignment, out-of-roundness, weld imperfections, etc. which may cause structural failure are avoided or reduced to acceptable levels. The ship specifications should contain specific allowable tolerances for various types of structural components at various locations of the ship's hull. ASTM tolerances for commercial hull construction [10] generally permit gaps of 3 mm (0.12 in) and misalignments of up to one-half the plate thickness for various components. Adherence with these maximum allowable levels of distortion, unfairness, etc. will help reduce or eliminate the possibility of stress concentrations and other causes of structural failure. Freedom from structural failures, of course, also reduces or eliminates the occurrence of coating breakdowns and ensuing corrosion. Consequently, from a corrosion prevention viewpoint, the importance of meeting structural tolerance requirements cannot be overstated.

The design drawings and specifications for all U.S. Navy combatants and most auxiliary vessels currently contain strict requirements for structural tolerances and overall quality assurance systems.

Commercial ships being built in foreign shipyards are inspected in accordance with the requirements of one of the major international classification societies. Most major classification societies including Lloyd's Register of Shipping, Bureau Veritas, Germanischer Lloyd, Det Norske Veritas and Nippon Kaiji Kyokai, have published structural tolerance standards which ships being built to their class must comply with. Most U.S. commercial shipyards have either developed their own tolerance standards or adopted those of a classification society.

2.2.2b Compliance with Original Design

The original design of a ship usually consists of contract and contract guidance drawings and ship specifications and, in most cases, includes specific allowable maximum structural tolerance levels for various hull components and erection assemblies. As discussed above, adherence to these maximum allowable levels during ship fabrication work will reduce if not eliminate the occurrence of structural imperfections and will prevent damage and/or failure.

Compliance with the original design is being assured by periodic scheduled and unscheduled visual, non-destructive and, necessary, destructive examinations and tests during various stages of fabrication. Non-destructive tests commonly employed include dimensional checks, ultrasonic gauging of plates, ultrasonic and radiographic (X-ray) examination of welds and magnetic induction or eddy current measurements of dry-film point thicknesses. Destructive tests include ultimate strength "pull tests" of selected samples.

2.2.2c Surface Preparation

Surface preparation, particularly grit blasting, is the key to successful coating application because coatings literally hang on the structure. Virtually all marine coatings applied today adhere to their substrate through mechanical adhesion. It can be said that the coating stays in place by grabbing onto the raw steel surface. Having a good anchor pattern or surface profile is a key element in a coating's longevity. Scoring the steel surface with tiny crevices gives the coating a place to reside. If the coating were to be applied to a piece of steel polished to a slick, shiny surface the coating would simply sag away [11].

If salt in the air settles on the steel surface, it sets up a coating failure phenomenon due to osmotic pressure. If the steel surface is not properly prepared before the coating is applied, a contaminant such as salt can be covered by the coating. Osmosis, the process by which water can cross a membrane, comes into play. The salt can draw water, one molecule at a time, from the ballast water through the coating to the coating/steel interface. This then causes blisters to form that adversely affect adhesion [11].

Procedures recommended by the coating manufacturer should be followed without compromise. One of the most important factors is the preparation given the steel prior to the application of a coating. The basic requirement for conventional coatings is that they be applied over a clean, dry surface free from water soluble materials like sodium chloride which can cause blistering, soluble ferrous salts
which will, in contact with steel and moisture, initiate rusting of the steel, and oily residues which will reduce adhesion of the applied coatings [12]. As defined by the coating manufacturer, the degree of surface profile achieved by blasting, control of humidity and temperature of air and steel during application together with proper care of the new surface during curing can insure a quality, long lasting coating [7].

2.2.2d Coating Application

An item of considerable importance in the coating process is hand striping, which is the process of having a painter with brush manually coat all corners, angles and edges. Surface tension causes a drying coating to draw away from sharp edges. Hand striping, in effect, applies additional coating to these edges in the hope that the coating will build up with the addition of the final coats. It has been found that coatings on stiffeners tend to be thinner on edges of flanges than on their webs. Certain shapes, such as rolled sections and especially bulb flats, have advantages over fabricated sections when coating and corrosion are considered. The rolled shapes tend to have rounded edges, whereas fabricated shapes have cut edges which are sharper and require more attention with regard to striping and subsequent coating application and inspection.

High quality paint systems additionally require stripe coats with a brush on weld seams, drain holes, plate edges and damaged primer. Parts difficult to reach with a brush are stripe coated with a spray gun, where nothing else will do [13].

Primers can be applied with airless or conventional spray equipment. Most primers used in ship construction in Japan have drying times of 5 minutes (2 minutes to touch dry), while curing time is 7 days [14]. The drying times for other primers used world-wide as reported by manufacturers vary from 1 minute to 1.5 hours depending on the type and temperature.

Care should be taken to avoid increasing the thickness of coatings in an exaggerated way. Excessive thickness can lead to dangerous consequences, such as solvent and thinner retention, film cracks, gas pockets, etc. Wet coating thickness should be checked during application.

2.2.2e Construction Inspections

Inspection of the ship during construction starts with the receipt inspections performed at the delivery of materials and equipment to the shipyard by vendors and subcontractors. With regard to steel materials, the major concern here is the examination of physical dimensions, any apparent deviations from the design specifications with regard to thickness, material quality, surface condition, etc.

The next stage of inspections occur inside the various fabrication shops. Yard supervisors and Quality Assurance (QA) inspectors conduct their own inspections to assure compliance of the subassemblies with the design specifications and regulatory body requirements.

The construction stage inspections continue on the ways, in drydock, or on board ship when afloat depending on the "Build Strategy" adopted by the specific shipyard and conclude with a final inspection conducted jointly by class society and other regulatory agencies' personnel and includes inspection of coatings in addition to those accomplished both during and after the application of coatings.

2.2.3 During Operation

Regulatory agency rules are being revised to reflect the requirements of corrosion protection and high performance anticorrosive coating capabilities, especially epoxies. These include mandatory stripe coating of frame welds in cargo spaces, coating of ballast spaces in new ships, and enhanced surveys for vulnerable vessels, i.e., oil tankers, bulk carriers and combination carriers wherein coatings are inspected and evaluated [15,16]. These enhanced surveys are required at five-year intervals, but intermediate surveys may be required if coatings are rated "Poor." One study has shown that owners would be required to stop their ships 16 times instead of the normal 7 times in years 5 through 20 of the ship's life if ballast tank coatings are rated Poor in the enhanced surveys [13]

2.2.3a General Coating Problems

Protective coatings are perhaps the best way of preventing corrosion. The most efficient way to preserve the corrosion prevention system is to repair any defects, such as spot rusting, local breakdowns at edges or stiffeners, etc., found during the in-service inspections. However, the surveys conducted by shipowners have highlighted the fact that coatings have finite lives which depend on a number of factors, including the quality of the coating itself, surface preparation, quality of application and cargo/ballast history [9].

Structural details can cause coating breakdowns in a vessel during operations. Reference [17] presents the background of past mistakes that were made in this regard. Structural failures need not be catastrophic or even cause cracks to lead to coating failure. A structure that is more flexible under load than the applied coating will be sufficient to cause compromise of the coating and progressive corrosion if it is not repaired.

Several of the operators attribute many fractures to metal fatigue. However, as one operator astutely noted, the word "fatigue" doesn't identify the cause of a problem, it simply means that a structure has a lower safety margin. Therefore, proper terminology should refer to cracks due to lower safety factors rather than fatigue. The assessment of fatigue life is extremely complicated and requires evaluation of environmental conditions combined with cargo and ballast loading and distribution on the hull.

2.2.3b Damage to Ballast Tanks

Damage to coatings in ballast tanks due to operations can occur in several ways:

- Working of structure in a seaway causing cracking and deterioration of coating, especially with lighter HTS structure.
- Wear caused by crew members or other personnel moving within the tank.
- Wear can be caused when tanks are mucked out (cleaned) of mud silt and other debris.
- Abrasion of sands contained in ballast water possibly causing erosion of coatings by constantly sloshing back and forth in bays between structural members in partially filled tanks.
- Accelerated corrosion in the deckhead caused by increased oxygen availability near hatches.

- Sweating and condensation caused by the heating and cooling of tanks.
- Aggravated corrosion in tanks adjacent to tanks carrying high temperature cargoes.
- Pitting on horizontal surfaces low in the tank.

The following summarizes miscellaneous factors that should be considered in corrosion control as compiled from reviews of references [8], [9], [15] and [18].

- On short ballasting cycles, anodes may not provide adequate protection as immersion time is not adequate to polarize bare steel areas.
- Sloshing of ballast can cause accelerated wear of the coating system.
- Deflections of stiffeners and plating, due to cyclic loading of ballasting and deballasting, can cause coating cracks and corrosion at junctions of plating and stiffeners.
- Corrosion can accelerate on the upper surfaces of horizontal members with inadequate drainage.
- Local increase in fluid drainage velocity, especially in the bottom of a tank structure, can cause premature coating failures at the edges of stiffeners and around access holes.
- Welded seams tend to experience accelerated corrosion.
- The corrosion of side structure in ballast tanks is influenced by waves breaking against the side, and by fendering operations on overly flexible structure.
- Pitting corrosion of the bottom of ballast tanks, and horizontal girders may be severe because of water and mud left in the tanks.
- Extensive corrosion of large bottom panels may result in excessive longitudinal bending stresses causing the hull girder to collapse.
- Major problem areas on older ships are identified as highly stressed areas, permanent ballast tanks, bottom structure in cargo tanks, and ballast and void spaces adjacent to heated cargo tanks.
- Smaller individual tank sizes reduce the amount of oil spilled should a tank rupture to the sea. They are not however, production nor coating friendly.

Local corrosion and pitting do not generally represent a safety problem due to the robustness and redundancy of the ship structure. Local corrosion may initiate cracking and may, as pitting corrosion, result in cargo mixing and pollution when cargo tank boundaries are breached.

The classification societies have recently strengthened their requirements for visual and thickness surveys by specifying that suspect areas, exhibiting substantial corrosion or known to be prone to rapid wastage be scrutinized and that at least three cargo tanks be inspected, with cargo tanks used for carrying ballast be subject to close-up survey as the vessel ages.

2.2.3c Material and Coating Breakdown

High tensile strength steel is designed thinner than mild steel for the same application. Although it was recognized that corrosion rates would be similar to mild steel, potentially requiring earlier renewal of the initially thinner material, it was not fully appreciated that fatigue life was reduced owing to the higher working stresses, especially under dynamic loading from waves. Thus, there has been an increased prevalence of fatigue cracks in vessels containing high tensile strength steel, particularly at poorly designed or fabricated connections, sometimes accentuated by local corrosion. These cracks compromise coatings and cause corrosion by exposing uncoated steel to the elements.

One classification society has warned of the risks of structural failure due to the effects of corrosion in lighter weight, higher tensile strength steels, and believes that the trend towards increased numbers of segregated ballast tanks and the more extensive use of higher tensile strength steels will require a greater commitment to maintenance [19]. Tankers also suffer through the carriage of hot cargoes, abrasion of protective coatings and the repeated flexure of structural elements. This leads to diminution through corrosion of the hull scantlings, although the rates of corrosion vary between horizontal and vertical surfaces and also between locations for similar surfaces in the same tank.

2.2.3d Use of Inert Gases

The introduction of inert gas (IG) systems at the beginning of the 1970s caused a fundamental change in corrosion patterns and rates of the cargo area. Corrosion levels in the cargo tanks have been greatly reduced through the use of IG, but ballast tanks have corrosion rates up to about three times these rates [19]. The accelerated corrosion in the ballast tanks is probably caused by sulfur compounds in the IG, generated from by-products of fuel oil combustion, reacting with the ballast water to attack the steel.

3.0 TYPICAL COATING SYSTEM FAILURES

3.1 Coating Systems and Failure Types

Maritime regulations did not always require ballast tanks to be coated. A series of bulk carrier failures in the early 1990s and the advent of double-hull tankers precipitated recent changes in classification society requirements for the maintenance of coated spaces. While these are discussed later in this report, the prospect today is that a vessel may be required to be available for more frequent inspections and maintenance because of failing coating systems. Therefore, ship owners are looking for long-life corrosion protection systems that will reduce maintenance to a minimum. This means selecting high performance coatings and preparing the surface to a high standard, such as abrasive blasting.

In addition, the life span of a coating system can often be extended by supplementing the coating with a sacrificial anode system. Not only does this protect against general corrosion loss once coating failure begins, but it also prevents the rapid penetration of pits occuring at localized coating failures [7].

With double-hull Very Large Crude Carriers (VLCCs) having ballast tank surface areas in excess of 200,000 m^2, ship owners are recognizing that high-performance ballast tank corrosion preventive systems are essential at new building if costly future repairs are to be avoided.

3.1.1 Coating Materials

There is no shortage of corrosion treatment and prevention methods. Making the right coating choice means making a realistic assessment of the economic life expected from a ship and how much money is available in the initial stages of a ship's life for corrosion inhibiting coatings.

Coatings range from relatively inexpensive "soft" types that require minimal surface preparation and last up to 3 years to sophisticated hard coatings, such as solvent-free epoxies that require extensive preparation and last for 15 or more years. Hard coatings include paints, bitumastic, and cement in contrast to soft coatings, which are lanolin, oil-based and chemical reaction types.

Soft coatings are recommended by classification societies only as stop-gap measures to prevent progressive corrosion before a satisfactory permanent coating can be applied. However, soft coatings based on oils or waxes can fail prematurely when used with cathodic protection because of saponification of the oils in these coatings due to reactions with the alkaline conditions created by cathodic protection [8]. Surface tolerant coatings, which may be applied over tightly adherent rust, are also good for touching up failing coatings as part of a maintenance procedure.

A hard coating applied in accordance with the manufacturer's recommendations can be expected to prevent corrosion for its advertised life. However the coating will fail in areas where it is excessively thick, which can cause fractures. Other places where hard coatings can fail are the more difficult-to-reach areas for paint application, such as stiffener edges, passages, the underside of ballast pipes and scaffold supports where blistering, and occasionally corrosion, has appeared as a result of the paint being too thin (less than 200 microns) or non-existent.

Paints are comprised primarily of three components, a pigment, a binder, and a solvent. They are named based on the type of binder used. Paints are divided into two basic categories, thermosets and thermoplastics. After drying, the thermoset composition is radically different than that of the wet paint. During the drying process, the paint undergoes a chemical change and can no longer be removed with a solvent. Wet and dry thermoplastics differ only in the lack of solvent in the dry coating. Thermoplastics may be removed by simply reintroducing a solvent into the dry binder and pigment. The thermoset paints include:

- Air drying resins
- Oleoresinous varnishes
- Alkyd resins
- Epoxy ester resins (one-pack epoxy)
- Urethane oil/Alkyd resins (one-pack polyurethane)
- Silicon alkyd resins
- Styrenated and vinyl toluenated alkyd resins
- Epoxy resins (two-pack epoxy)
- Polyurethane resins (two-pack polyurethane)

The thermoplastics include:

- Chlorinated rubber resins
- Vinyl resins
- Bituminous binders

Since thermoplastics can be removed by solvents, their use in ballast tanks is somewhat limited because of the potential presence of hydrocarbon solvents. Due to the limited scope of this paper, only the most commonly used paints suitable for ballast tanks will be discussed.

Anti-corrosive paints work on three basic principles, the first being the barrier effect. The barrier effect simply involves covering the steel with a coating that is impervious to water. The oldest binders employed for this purpose are bitumen and coal-tar pitch [20]. These have traditionally been used because they are inexpensive and readily available. Modified coal tar epoxy coatings are perhaps the most common type of protection now being offered on new buildings world-wide. These coatings provide protection for well over ten years service life when properly applied, but are prone to localized breakdown in way of sharp edges and surface defects [21]. Coal tar-based systems, while still used in some parts of the world, are likely to decline in use as coal tar is a known carcinogen and lighter colored systems provide better visibility during inspections.

The best choice for barrier protection is two-pack epoxy resin. Epoxy resin provides good resistance to water and other chemicals and has outstanding adhesion to blast-clean steel. Epoxy resin's material properties can be varied to suit the application based on how it is mixed, although controlling this reaction to close tolerances is still more an art than a science. These new, lighter colored systems are becoming more common because of better visibility and the fact that the initial application may be executed in contrasting colors which reduces the risk of holidays (pin holes) and low film thickness [21]. Flake pigments may also be introduced into the binder to decrease the film thickness for the same level of protection (see Figure 3.1).

The failure of epoxy coatings usually occurs gradually over time. Under stress, the differences in cohesive strength and elongation can cause alligatoring and cracking. Pitting and grooving will occur, sometimes at a very rapid rate, in way of pinholes or other failures in the coating. These pitting failures occur particularly in cargo tanks on horizontal platforms, bottom plating and under bellmouths. For this reason, it is recommended to fit a light sacrificial anode system (22 mA/m^2 current density) in tanks with epoxy coating systems. Epoxies do not cure well at low temperatures. The curing agent can migrate to the surface and, under atmospheric condensation conditions present during cold weather, produce a greasy surface or, more commonly, blanching of the film which can lead to cracking and crazing of the coating. Incompatibility can occur in pitch epoxy coatings, creating separation and layers with different physical characteristics. Coating conditions with two-pack epoxy coatings in an uncontrolled atmosphere can be improved. After abrasive blast cleaning, application of two pack epoxy coatings must be completed before the surface re-rusts and blooming indicates that "the blast has gone off". Re-rusting is caused by atmospheric corrosion, which is partially due to high air humidity. Humidity in tanks after blasting and during coating and curing should be kept at or below 50% relative humidity [22]. Despite the problems, epoxy resin is still the best alternative for corrosion prevention.

The second principle is the inhibitor effect. Primers applied to a surface sometimes contain a corrosion inhibiting pigment such as red lead, zinc chromate, zinc phosphate, or inorganic zinc (IZ). The pigments are generally water-soluble, so a top coat must also be applied to prolong the primer life and applications involving prolonged immersion should be avoided. Red lead and zinc chromate are no longer commonly used due to the health risks associated with heavy metals. Zinc phosphate performs well, especially in highly acidic atmospheres. It can also be used with a variety of binders, and takes colored pigments well [20].

FIGURE 3.1 Coating Components

The third principle is the sacrificial effect. Sacrificial coatings use a metal (usually zinc) which is anodic to steel. In the presence of an electrolyte, a galvanic cell is set up and the metallic coating corrodes instead of the metal. The concept of sacrificial coatings is similar in many ways to the inhibitive coating principle. However, the reactions which take place are entirely different. In the case of zinc-rich coatings, the zinc acts as an anode to the steel and whenever there is a break in the coating film, the steel substrate tends to be protected. It has been observed many times that where scratches or damage to an inorganic zinc coating occur, the zinc reaction products proceed to fill in the scratch or minor damage and seal it against further atmospheric action. However, the surface of the steel must be cleaner when using IZ than with other pigments because there must be good contact between the paint and the plate for galvanic action to occur. Consequently, the surface preparation costs are higher.

Inorganic zinc primers and epoxy or coal tar epoxy topcoats are favored, with the top coat thickness of between 250 and 300 microns (10 to 12 mils) applied by airless spray techniques. Inorganic zinc is affected by the sulfur compounds in inert gas and hence is seldom used for cargo service in tankers. In addition, it is not recommended that IZ be used for partial coating systems because the zinc in the coating will act as an anode and will be rapidly consumed by the unprotected steel. However, the main advantage of IZ is that it acts as an anode to protect any pinhole failures in a complete, original coating. Thus, the coating will hold up very well over a number of years. The main disadvantage is that the zinc is gradually consumed and when failure occurs, it is very rapid. Because of these reasons, epoxy is the preferred choice for cargo tanks and partial coating systems. For the recoating of ballast tanks, epoxy is also the preferred choice simply because it is difficult to achieve the required surface preparation for IZ on corroded steel [9].

The choice of coating requires careful consideration. In the simplest case for ballast tanks, pure or modified epoxies are generally applied. Resins are added under some conditions to improve anti-corrosive properties. The expected life of epoxy is thought by some to be greater than IZ, but evidence to date is not very conclusive [9]. One source states that coal tar epoxies used in ballast tanks seem to have a mean life of approximately 10 years with a range from 7 to 15 years or more [8]. The large spread in coating life data is essentially due to differences in primer and coating types, initial workmanship regarding steel structure, paint application, and later maintenance and touch up of the coating [18]. In addition, light colored coatings are more conducive to satisfactory performance as the initial application may be executed in contrasting colors, reducing the risk of holidays and low film thickness. Light colored, hard coatings containing little or no solvent are likely to become the standard in the future [21].

Ballast tank coatings should have a reasonable resistance to oil contamination, present minimal toxicity hazard, and have a high solvent flash point to reduce fire hazards during application, with the ideal coating being solvent-free. The coating should also offer low flame spread. A high temperature resistance of up to about 120°C (250°F) is important for ballast tank coatings. A high temperature resistance is particularly important on bulkheads in tankers carrying hot cargoes, and on deck plating in the upper wing tanks of bulk carriers [7,21].

The International Association of Classification Societies (IACS) Unified Requirement UR Z9 for cargo hold spaces stipulates "epoxy or equivalent" for use as a protective coating on all surfaces of side shell and transverse bulkhead structures, including associated stiffening. In fact, for a ship under construction, the common interpretation of UR Z8 (concerning water ballast tanks) is to require a hard coating that has demonstrated its effectiveness and its ability to ensure a useful life of at least ten years. In wet tanks, the coating may be combined with cathodic protection, which is then regarded as additional protection. Such protection must be designed not to damage the coating, i.e., the coating and cathodic systems must be compatible [23].

If the required conditions for the application of the original coating are not achievable for a repair coating, a coating more tolerant of a lower quality of surface treatment, humidity and temperature conditions may be considered, provided that it is applied and maintained in accordance with the manufacturer's specifications.

Demands to reduce surface preparation costs and advances in coatings technology have led to the introduction of epoxy-based anticorrosive products capable of meeting the substrate/surface tolerance and performance demands for different areas of the vessel. Historically, epoxies were essentially used where water, chemical and abrasion resistance were required.

The new products greatly improve in-service periods over conventional surface tolerant products; consequently their use is expanding rapidly. Furthermore, controlled development of the surface tolerant characteristics in other generic types, e.g. surface tolerant recoatable polyurethanes (highly aesthetic, durable finishes for topsides, superstructures and decks) has demonstrated that the capability exists to focus on different areas of the vessel and engineer the required features for extended performance [15].

In the end, coating selection is frequently based on satisfactory experience with a known application and operational use. Independent of the coating, it is imperative that the coating manufacturer's recommendations regarding surface preparation, application and curing be followed to insure coating longevity. In this respect, it is very important to review coating application procedures and recommendations with regard to good practice to ensure that, as a minimum, the structure is ready for the coating.

3.1.2 Surface Preparation

Surface preparation is an integral part of any new construction or drydocking. Poorly prepared surfaces can result in poor corrosion protection leading to problems ranging from a speed penalty on the order of a knot or more to an eventual catastrophic structural failure.

Shipyards may employ various methods of surface preparation. The more common methods are:

- Solvent cleaning
- Hand tool cleaning
- Power tool cleaning
  - Rotary wire brushing
  - Mechanical descaling
  - Rotary power disking
- Abrasive blast cleaning
- Hydroblasting

Solvent cleaning often involves the use of strong and potentially dangerous chemicals. Care must be taken when handling these chemicals as well as in the disposal of and removal of any residue left on the material surface. This process is most effective when thermoplastic coatings are involved. This is very often an early step in the cleaning process.

Hand tool cleaning and power tool cleaning are both labor and time intensive. They can, however, be effective and economical if the area is sufficiently small as not to warrant assembly, clean-up and disassembly of another type of system, such as abrasive blast cleaning. Various tools are available for different types of surfaces with varying degrees of corrosion.

The most commonly used large scale surface preparation method is abrasive blast cleaning. Although it is the most effective, it requires protection of personnel and equipment and is subject to much environmental legislation. The surface profile left by this process is rough and well suited for good adhesion by most coatings [20].

There are three primary organizations involved in writing the standards for surface preparation, the Steel Structures Painting Council (SSPC), the National Association of Corrosion Engineers (NACE), and the Swedish Standards Institute (SSI). The four standards for blasted surfaces as written by the three organizations are:

- SSPC SP-5, SSI Sa 3, NACE No. 1 - White Metal Blast Clean Surface Finish. This blast standard is defined as a surface with a gray-white, uniform metallic color, slightly roughened to form a suitable surface for coatings. This surface shall be free of all oil, grease, dirt, visible mill scale, rust, corrosion products, oxides, paint or any other foreign matter. This surface shall have a color characteristic of the abrasive media used.

- SSPC SP-10, SSI Sa 2.5, NACE No. 2 - Near White Blast Clean Surface Finish. This finish surface is defined as one from which all oil, grease, dirt, visible mill scale, rust, corrosion products, oxides, paint or any other foreign matter have been removed except for very light shadows, very light streaks or slight discolorations. At least 95% of a surface shall have the appearance of a surface blast cleaned to a white metal surface finish, and the remainder shall be limited to the light discoloration mentioned above.

- SSPC SP-6, SSI Sa 2, NACE No. 3 - Commercial Blast Clean Surface Finish. This finish surface is defined as one from which all oil, grease, dirt, rust scale and foreign matter have been completely removed from the surface, and all rust, mill scale, and old paint, completely removed except for slight shadows, streaks or discolorations. If the surface is pitted, slight residues of rust or paint may be found at the bottom of pits. At least two-thirds of the surface area shall be free of all visible residues and the remainder shall be limited to light discoloration, slight staining or light residues mentioned above.

- SSPC SP-7, SSI Sa 1, NACE No. 4 - Brush Off Blast Clean Surface. This finish surface is defined as one from which all oil, grease, dirt, rust scale, loose mill scale, loose rust, and loose paint or coatings are removed completely, but tight mill scale and tightly adhered rust, paint and coatings are permitted to remain, provided they have been exposed to the abrasive blast pattern sufficiently to expose numerous flecks of the underlying metal fairly uniformly distributed over the entire surface.

Soft coatings require a minimum of commercial blast cleaned surface finish. Very often however, soft coatings are used on surfaces with a higher level of preparation as an interim coating until a more suitable coating can be applied. Abrasive blasted near-white metal (SSPC SP-10 or SSI Sa 2.5) cleanliness standards are almost exclusively specified for hard coating applications. Cleaner than necessary surfaces are always desirable from an adhesion standpoint, but not always from an economic standpoint. In addition to the paint not sticking to a poorly cleaned surface, there is a risk of the surface continuing to corrode even after a coating has been applied when the chloride ions in sea water pass through the coating and destabilize the oxide layer, setting up corrosion cells and causing blisters [24].

The newest method of surface preparation to be widely utilized is hydroblasting. It is very popular with European shipyards and its popularity is steadily increasing with American yards. Hydroblasting involves the use of water at pressures up to 2,800 bar/ 40,000 psi). Hydroblasting avoids the air quality problems associated with abrasive blast cleaning. It also removes water soluble salts that abrasive blasting may leave behind, especially in heavily pitted areas. Unlike abrasive blast cleaning, the profile left is the same as the underlying metal which may be too smooth. Hydroblasting is often used in conjunction with abrasive blast cleaning as a secondary surface preparation to remove residual contaminants.

A hybrid of hydroblasting and abrasive blast cleaning, known as slurry blasting, has also been developed. As defined by SSPC/NACE, slurry blasting is a form of air/abrasive blasting wherein water is injected into the air/abrasive stream at some point upstream from the blast nozzle. Water and abrasives are mixed with water in a pressure vessel, with the typical mixture being 80 percent abrasive and 20 percent water. Water pressure forces the mixture from the pressure vessel to the compressor-generated airstream, where it is accelerated toward the blasting nozzle. Advantages of this wet abrasive blasting process are:

- Reduction of dust emission by 95 percent in comparison with conventional blasting

- Low water usage in comparison with hydroblasting, with consequent lower disposal costs

- Decrease in abrasive consumption and disposal costs by 50 percent due to increased abrasive velocity resulting from reduced friction

- Removal rates equal to or better than that of dry blasting systems

The desired surface profile is attained while the used slurry may be drained from the drydock, separated and easily disposed of or reused [25].

3.1.3 Coating Application

While coating areas and preparation have been discussed above, together with possible coating options, the actual application of the coating system is critical to corrosion control. Normal methods of application are:

- Brush
- Roller
- Conventional spray
- Airless spray

However, from the standpoint of successful coating application, planning is one of the most important factors.

The end product of the coating process is not robust and can be damaged by subsequent shipyard operations. Painting has traditionally been viewed as an inconvenience since when coating work of any type is in progress, other activities on that block or zone of the ship must cease for health and safety reasons as well as for the practical necessity of waiting for the paint to dry and be inspected [26].

3.1.4 Types of Coating Failure

All coating systems will eventually fail with time. However, premature failures from either poor application or normal ships service will increase maintenance costs and out-of-service time. While some failures are due solely to ship operations, many failures result from poor surface preparation and poor application procedures. For purposes of this study, failures are considered as application-caused or service-caused. Only those application-caused failures that result in break-down of the coating and increased corrosion will be discussed.

3.1.4a Coating Application Failures

- **Sags** or **runs** are caused by excess flow of paint and can result from holding the spray gun too close to the surface, paint that is too thin or a surface that is too smooth for the coating to adhere properly. The thick coating is subject to cracking.

- **Orange peel** is an uneven surface resembling the skin of an orange and caused by the coating being too thick or not fully atomized by the spray gun. The rough surface traps moisture, salt, silt and other agents that lead to early coating failure.

- **Overspray** is a flat, pebbly surface caused by the solvent drying too quickly or the gun being held too far from the surface. The failure mode is similar to that of orange peel.

- **Cobwebbing** consists of thick, stringy, spiderweb-like paint particles caused by the solvent drying too fast. Cobwebbing leaves areas where moisture and salt can be trapped as in orange peel.

- **Cratering** is small indentations in the surface caused by air trapped during spraying. Indentations trap moisture and salt, and trapped air can cause blisters.

- **Fish eyes** are the separation or pulling apart of the coating, exposing the underlying surface. Fish eyes are caused by poor surface preparation resulting in application over oil, dirt or an incompatible coating.

- **Wrinkling** is rough, crinkled surface skinning caused by application over an uncured undercoat or when ambient temperature is too high. The uneven surface traps moisture and salt.

- **Blistering** is broken or unbroken bubbles in the surface caused by solvent entrapment or an oil-, moisture- or salt-contaminated surface. Blisters become corrosion sites.

- **Pinholing** is tiny, deep holes in the coating, exposing the substrate. Pinholing is caused by improper spray atomization or settled pigment.

- **Peeling** or **delamination** may have any number of causes, all of which relate to surface preparation: chalky or too smooth undercoat, application over galvanized surface, application over dirty or damp surface.

- **Irregular surface deterioration** is deterioration of the coating at edges, corners, crevices and other hard to coat areas. These irregular surfaces trap moisture and other contaminants.

3.1.4b Coating Service Failures

- **Abrasion** is mechanical wear of the coating from sand, mud, crew traffic, fendering or impact damages.

- **Fouling** is penetration or peeling of the coating by marine organisms such as barnacles.
- **Undercutting** is the blistering or peeling of the coating caused by corrosion of an adjacent exposed surface or edge which undermines and lifts the intact coating.

- **Pinpoint rusting** is corrosion caused by a roughened surface whose profile is higher than the thickness of the coating. It is also caused by pinholing in the application.

- **Fading** is a color change or irregularity resulting from ultraviolet degradation or moisture behind the coating.

- **Checking** is short, narrow breaks in the coating that expose the undercoat and result from limited paint flexibility. Checking results from a coating that is too thick or applied at too high a temperature and is caused by stresses in the structure combined with the limited flexibility of the coating.

- **Cracking** is deep cracks in the coating that expose the substrate. Cracking can be caused by coating shrinkage, limited flexibility of the coating or too thick a coating, as in checking.

- **Mud cracking** is deep, irregular cracks in the coating caused by an inflexible coating applied too thickly. As in checking, mud cracking can be caused by stresses in the structure.

- **Peeling** of thick inflexible paints or multiple multiple coats results when stress from the structure or weathering exceed the adhesion strength of the paint [27].

3.1.5 Coating Inspection

In accordance with IACS requirements, the classification societies have established standards for the inspection and grading of coatings in tankers and bulk carriers.

The condition of coatings will be graded as [16]:

- GOOD Condition with only minor spot rusting.
- FAIR Condition with local breakdown at edges of stiffeners and weld connections and/or light rusting over 20% or more of areas under consideration but less than as defined for 'poor' condition.
- POOR Condition with general breakdown of coating over 20% or more of areas of hard scale at 10% or more of areas under consideration.

Where the coating is found to be in GOOD condition, the extent and frequency of steel thickness measurement may be reduced. For water ballast tanks, where the coating is found to be in POOR condition, or where there is no coating, the tanks in question may be examined during each annual survey. Thus it is in the owner's best interest to maintain coatings so as to decrease out-of-service time for inspections and surveys.

3.2 Locations and Details Experiencing Failure

The spaces in single hull tankers which are prone to corrosion and fatigue cracking are summarized in Table 3.1. Figure 3.2 shows the locations where fractures may occur in a typical bulk carrier. For double hull tankers, in addition to the single hull tank areas, the knuckle connections of sloped hopper plating to inner bottom plating are also prone to corrosion. Table 3.2 is a compilation which presents the relative corrosion risk levels for various tanker spaces and coating systems.

3.2.1 Ship's Tanks

Stringers in the wing tanks of the first generation of double-hulled tankers create a "grillage" in which the side shell and inboard longitudinal bulkhead respond to forces as a single unit, thereby experiencing less flexure. Flexure has been thought to cause microscopic cracks in the epoxy coatings that normally protect the structural steel. These cracks lead, of course, to coating breakdown and eventual corrosion of the steel [28].

Ballast tanks typically have complex structures, are not easily accessed, are "non-earners," and have been neglected in the past. Excessive corrosion of ballast spaces has been identified as a significant contributing factor to the loss of structural strength. Consequently, ABS has required the coating of all steel work since January 1993. The coating of ballast tanks with corrosion resistant hard type coating such as epoxy or zinc has been a condition of class since 1994 [16].

The first task in improving corrosion control is to investigate typical coating failure and corrosion problems that can be attributed to the structure. The following paragraphs provide examples of typical corrosion problems both from a structural and operational viewpoint.

Ballast tanks frequently experience corrosion along the upper longitudinal stiffeners, with relatively poorer access to these stiffeners during original coating and subsequent repair procedures cited as a reason for these problems. In addition, air pockets in these bays would prevent the zinc anodes from performing effectively [8].

Paint loss and corrosion near the very tops of tanks are frequently caused by the following:

- The use of inert gas systems in this area, and the presence of moisture and/or sulfur compounds generated by these systems causing contamination.

- Condensation of moisture especially along flat surfaces and edges.

- Difficult access to these areas, thus preventing efficient inspection and maintenance.

- Air pockets at the tops of tanks, caused by insufficient cutouts or failure to press-up the tanks, rendering cathodic protection systems ineffective.

TABLE 3.1 TYPICAL CORROSION AND FATIGUE DEFECTS IN TANKERS [29]

Item	Corrosion	Cracks
Longitudinal Material	-Upper deck plating - Upper deck longitudinals - Welds between structural elements, deck longitudinals to deck plating in particular - Scallops and openings for drainage - Webs of longitudinals on long. bulkhead, longitudinals, high rates and localized corrosion (grooving) - Flanges of bottom longitudinals (pitting) - Bottom plating, pitting erosion near suctions - Longitudinal bulkhead plating	- At discontinuities - At openings, notches - At connections with transverse elements
Transverse Web Frames	- Upper part, connection to deck - Just below top coating - Flanges of bottom transverses - Cross ties	- Connection with longitudinal elements - Scallops in connection with longitudinals - Bracket toes - Holes and openings - Crossing face flats
Transverse Bulkheads	- Upper part, connection to deck - Stringer webs - Close to opening in stringers - High stress locations, i.e. around bracket toes etc.	- Connection with longitudinal elements - Connection between girder systems - Bracket toes
Swash Bulkheads	- Upper part, connection to deck - String webs - Close to openings in bulkhead plating - High stress locations, i.e. around bracket toes	- Connection with longitudinal elements - Connection between girder systems - Bracket toes - At openings in bulkhead plating

FIGURE 3.2 Typical Fracturing at the Connection of a Transverse Bulkhead Structure [30]

TABLE 3.2 RISK OF CORROSION AND PITTING IN TANKER SPACES [29]

Type of Tank	Fully Coated	Protection Upper Part Coated	New Upper + Lower Part	Anodes	None
Segregated Ballast	L	H+	H+	M-H	1)H++
Cargo/Clean Ballast (Arrival Ballast)	Lp	H	Mp	M	2)H+
Cargo/Dirty Ballast (Departure Ballast)	Lp	M	Hp	M-L	M-H
Cargo/Heavy Ballast	(L)	L	L	X	L-M
Cargo Only	X	L-	L-	X	L

H = High Risk   H+ = Higher Risk   p = Risk of Pitting
M = Medium   L- = Lower Risk   ( ) = Negligible
L = Low Risk   X = Not Considered

Notes:

1) Especially exposed items:
   - Horizontal stringers
   - Longitudinals on longitudinal bulkhead
   - Longitudinal bulkhead plating
   - Web frames upper part and close to longitudinal bulkheads
   - Cross ties
   - Transverse bulkhead plating, upper part

2) Exposed to pitting:
   - Horizontal surface of stringers
   - Bottom plating
   - Bottom longitudinal face plates/flanges

Experience has indicated that the breakdown of ballast tank coatings will probably lead to an increased risk of structural failure through corrosion. The main area of concern is the midship ballast spaces, where corrosion could rapidly diminish the hull girder strength below an acceptable level. Tolerance values against operational mishaps, or less than ideal maintenance, are therefore very much reduced. Corrosion rates in ballast spaces when the protective coatings have broken down are known to be very high, particularly when associated with repeated heavy weather operating conditions.

Accumulation of mud and residues, as well as water pools, reduces the lifetime of a coating system that is compromised due to holidays in coating coverage, cracked coating or any other condition causing a breached coating system. Water pools increase the wet period of the coating, and contamination creates corrosion cells, increasing the risk of pitting corrosion.

To limit mud accumulation in ballast tanks and minimize the microbiological influenced corrosion (MIC) under mud deposits during operation, a polymeric dispersant can be injected into the discharge side of the ballast pump during ballast loading.

3.2.2 Primary Strength Members

Corrosion of primary strength members such as upper deck, bottom, inner bottom, and longitudinal bulkhead plating, and their attached longitudinals will cause reductions in the hull girder section modulus and is limited by classification society rules. Coating breakdowns, which expose the steel to oxygen and electrolyte in the tank thereby causing corrosion and eventually leading to damage to or failure of the primary strength members, frequently occur not on the members themselves but on structural details attached to them. This can be true even if the original design is good and the quality and application of the coating is acceptable. Damage to the strength members can take place as a result of direct physical impact from an outside source such as striking by an object, trapping of water on horizontal surfaces, imperfections caused by weld repairs, and the condition of the underside of the deck.

3.2.3 Structural Details

Areas of stress concentration are usually the first areas to experience coating failure. This coating failure, in the form of cracked coatings, exposes the steel to the onset of corrosion and possible stress corrosion cracking as the ship works, exposing additional new steel in the cracks to corrosion. This localized coating breakdown at structural details in way of stress concentration areas can result in severely accelerated corrosion rates associated with enhanced crack propagation rates. These areas are potentially more difficult to coat, due to their complex geometry, and are therefore prone to corrosion due to uncoated or poorly coated surfaces. Fatigue cracking is prevalent in these areas. If the cracks are not discovered and the condition not rectified by redesign, accelerated corrosion and/or structural failure can result.

3.2.4 Impact of Joining Techniques

Coating loss at welds, caused by poor initial application and/or the working of the structure, causes the welds to corrode. This situation is frequently exacerbated by mud deposits which further promote corrosion of the exposed metal. Thin coatings on edges and poor access for coating application are frequently cited as causes of coating failure. Touch-up of coatings in difficult areas is frequently not done as part of routine maintenance. Survey data indicates that ballast tank areas experience severe paint degradation and significant corrosion around fillet welds where horizontal stiffeners are attached to inboard, outboard and athwartships bulkheads. Damage tends to be high up in the tanks where access, inspection and the washing of mud deposits from the top surfaces of the stiffeners are difficult. Large accumulations of silt (mud) on the horizontal top surfaces of stiffeners tend to coincide with paint loss and corrosion in areas where coatings are compromised. Paint loss and corrosion are also seen on rough welds and edges of stiffeners where proper surface preparation and adequate coating thickness tends to be difficult to achieve.

Many structural failures can be attributed to either poor welding in and of itself, e.g., undercut welds, lack of penetration, welds made using wrong amperage, etc., or to poor design which did not provide sufficient room for the welder to perform a good weld. There are other instances where an improper root gap, component misalignment and/or poor edge preparation, such as a jagged edge caused by flame trimming before welding, caused problems. In other cases, brackets and other components were either not installed or not completely welded [17].

The above weld deficiencies are also potential areas of poor coating quality. Therefore the design should take into account not only the possible causes of poor workmanship in construction, but also the ease and quality of coating application and subsequent quality inspections. Access to a space for coating should also be considered when planning the steel work assembly sequence, so that the steel and outfit work sequence can be optimized and damage to the coatings minimized.

Intermittent welding, where the largest discontinuous fillet welds that can be deposited in a single pass are used in lieu of small continuous fillets, is used for savings in welding time and labor. However, intermittent welds leave crevices between welds and rough surfaces at the weld ends that are difficult to coat. Poor coating adhesion leads to coating failure and creates points for corrosion to begin. Continuous welds do not have these crevices and rough surfaces and are less likely to propogate corrosion.

4.0 METHODS TO IMPROVE COATING LIFE

4.1 Design Philosophy

In the preceding sections, the effect of coating loss and subsequent corrosion on the strength of the vessel, and the areas of concern in both structure and operation, have been explored. Many of the concerns for coating compromises cited therein can be alleviated during design, which will be explored in this section.

Corrosion control by design can be achieved by giving due consideration to the following factors:

- Arrangement and access for ease of coating application and inspection and to avoid confined or inaccessible spaces.
- Selection of steel thickness and type, e.g., mild steel or high strength steel.
- Minimization of horizontal structures which can trap water.
- Minimization of deformations on horizontal surfaces.
- Minimization of high flexure structural components which promote coating breakdown and accelerate corrosion of unprotected surfaces.
- Provision of sufficient drain cut-outs and sloping structures to facilitate drainage and prevent accumulation of sediment.
- Provision of contoured metal surfaces (plate edges) and minimized shadow areas to facilitate application of coatings.
- Prevention of moisture entrapment at intersections of structural members [31].

Decisions affecting corrosion control will be made at every level of design. In Preliminary Design, the vessel arrangements and framing system will be selected and accessibility must be considered. In Contract Design, the structure will be developed further and major decisions regarding scantlings, typical details and coatings must be made. In Detail Design, the shipyard must interpret the contract documents in developing structural details, particularly at the ends of the vessel. The underlying design philosophy of corrosion control through improved coating life must be carried through the entire ship design and acquisition cycle, usually through the diligence of the owner.

4.1.1 General Arrangement and Access to Spaces

Early in the design process, the general arrangement of the vessel and its structural arrangement are decided upon. The need for easy access to all spaces must be considered at this stage with regard to the arrangement of spaces and the distribution of structure. In a tanker or a bulk carrier, the decision must be made as to the choice of conventional or unidirectional framing. If conventional framing is selected, deeper members and more flats may be required to place all structure within arm's reach for inspection without climbing to unsafe heights.

The inspection route through the vessel must be considered in locating manholes and other access openings. Manholes and ladders should be placed at each end of a space so that the inspector does not have to go back over a space to get to the next level. Access openings in double-bottom floors and girders should provide an efficient route through the space with dead-end bays reduced to the absolute minimum or eliminated entirely. The provision of adequately sized manholes and accesses may require the structure to be deeper than needed to satisfy strength and regulatory requirements.

The depth of the doublebottom and the inner hull spacing in a double hull tank may have to be increased beyond regulatory minima and the volume required for ballast to provide efficient access. The 2 m (6.6 ft) nominal required depth of the doublebottom is not sufficient for inspection in conventionally framed vessel in that the inspector is always stepping over and ducking under longitudinals. A depth of 3 m (9.8 ft) appears about optimum, as it provides sufficient clearance yet does not require staging to reach the overhead. Similarly, the 2 m (6.6 ft) depth of the wing walls may not be sufficient to allow adequate manholes to be cut in the structure.

Manholes must be of sufficient size to allow personnel to pass with tools, breathing apparatus and protective clothing. ABS Rules [16] specify a minimum clear opening of 600 mm x 600 mm (24 in x 24 in) for horizontal openings, but one source [32] recommends a larger opening of 760 mm (30 in) in one direction to allow for back-mounted air packs and the removal of injured personnel on a stretcher. This same source recommends that manholes at one end of a space be aligned vertically to allow lifting the stretcher, while the holes at the other end can be staggered to limit the distance personnel can fall.

Vertical manholes are required by ABS Rules to be 600 mm (24 in) wide by 800 mm (32 in) high and not more than 600 mm (24 in) above the deck or bottom. Reference [32] recommends a manhole height of 900 mm (36 in), again based on tests with personnel passing through with an air pack. Moreover, providing adequate manholes eliminates bending and crawling, greatly reducing inspector fatigue.

Confined and difficult-to-access spaces are usually located near the ends of the vessel and frequently do not become apparent until the contract or detail design phases. Moving a boundary upward or towards midship will often alleviate some problems for the space, but may have other impacts. Diligence in plan approval may be the owner's only defense against the creation of confined and difficult to access spaces during detail design and construction.

4.1.2 Optimization of Structural Design

A questionnaire on the design of vessels and corrosion by the Tanker Structure Co-Operative Forum (TSCF) asked "Can structural design of ships be modified to reduce the effects of corrosion at a beneficial economic ratio? Please suggest modifications" [33]. Six of nine members responded affirmatively and offered modifications and areas of attention relative to ship structural design as follows:

- Increase scantlings in general to effect an increase in corrosion allowance.

- Improved drainage of bottom waters.

- Modify scantlings to effect a stiffer structure, which is thought to lead to lower corrosion rates.

As stated in [21] "Effective corrosion control in segregated water ballast spaces, such as those envisaged in double hull designs, is probably the single most important feature, next to the integrity of the initial design, in determining the ship's effective lifespan and structural reliability." It is further stated that "Inadequate corrosion protection of the internal structure in these spaces at the new building stage could lead to significant problems for the shipowner in trying to maintain a ship's structural integrity when in service, and thus keep to the principal objective of avoiding oil pollution." The various ways that corrosion affects the integrity of ship structures is described in the paragraphs that follow.

4.1.2a Longitudinal Strength

Loss of thickness due to corrosion of the upper deck or bottom structure will cause a proportional reduction in hull girder section modulus. According to IACS Unified Requirements (UR) S7 and S11 [34], the midship section modulus of a ship in service is allowed a reduction of not more than 10% of the original minimum section modulus for a new ship. Severe corrosion of the bottom or deck can easily cause this allowance to be exceeded, requiring extensive steel renewals.

4.1.2b Buckling and Local Strength

Overall diminution in thickness due to general corrosion reduces the buckling resistance of plate panels and stiffeners. The ideal Euler buckling stress varies with the square of the thickness to breadth ratio of a plate panel, so that a 10% reduction in thickness results in a 19% reduction in Euler critical buckling stress. Normal buckling criteria, set by the classification societies, is based on the stiffener spacing of the panel divided by the remaining plate thickness (s/t). If this value is more than the allowable criterion, the plate will most likely have to be replaced.

Local loss of plate thickness from general corrosion will only be allowed to a certain predefined value determined by the classification societies, generally not exceeding 20% for strength members. Beyond this loss of thickness, the plate will probably need to be replaced. For thick plates, whose corroded s/t value for buckling may still be within the acceptable range, heavy thickness loss may nevertheless require the plate to be renewed.

4.1.2c Flexibility of Bulkhead Panels

Corrosion rates may be accelerated when inadequate panel stiffness leads to excessive flexure due to cyclic pressure or vibration. The welds attaching horizontal members to oil cargo or water ballast tank bulkheads can experience severe local grooving corrosion when subjected to flexural strains. This is a result of corrosion loss of the bulkhead panel around the heat affected zone of the welds which then weakens the panel, causing deflection of the plate panel between stiffeners under cyclic pressure loading due to cargo inertia. Under the action of cyclic pressure, early coating breakdown may occur, and rust and scale may become periodically detached from the corroded area of the structure, thus exposing fresh metal to the corrosive environment and promoting the corrosion process. Wasted tank or other structures, which may have their natural frequencies reduced to sympathetic vibration levels, could experience cyclic stresses in the welds similar to those referred to above, thus causing similar conditions of corrosion [31].

4.1.2d Thickness Considerations

Even after steps have been taken to optimize it, the structure will still be subject to corrosion. Another consideration then, for structures known to be subject to heavy corrosion, is the use of increased scantlings. While this may seem obvious, the trend has been toward lighter scantlings owing to improved analytical techniques for calculating design stresses and the desire to reduce construction costs.

Classification society rules on scantling reduction have been modified from their previous stance and have had the net effect of increasing steel thicknesses in ballast tanks as compared with previous requirements.

It is recommended today to design scantlings with a corrosion allowance between 1.5 and 3.0 mm (0.06 to 0.12 in), taking into account the allowable steel mill plate thickness tolerances.

Improvements in the ability of mills to control plate thicknesses and the negative side of the steel rolling tolerances previously used in shipbuilding could significantly cut into the corrosion allowance by having all plates installed on the low side of the rolling tolerance. However, in recent years the rolling tolerances have been significantly tightened by actions of IACS, all but eliminating this problem [35].

If found to be economically viable in specific situations, heavier scantlings than required for strength considerations could be used in areas which are difficult to protect or which have historically been prone to corrosion.
One study concluded "...on the basis of two vessels studied and the assumptions made, the use of reduced steel scantlings does not offer any significant economic advantage to a vessel over a 20 year life. Full scantlings in several cases examined proved to have roughly equivalent or lower life cycle costs and provide valuable insurance against unexpected coating failure" [9].

In at least one recent design [36], the concept of "....identical scantlings for all blocks, compensating for the additional weight through greater strength and longer life of the additional steel" was considered and found to have merit. The design innovation of the unidirectional type is described as follows:

"It was decided to use only two principal blocks, the A-block for bottom, sides and deck, and the B-block for bilge and gunwale areas. The uniformity of the hull design increased the strength, and the unobstructed spacing between the outer and inner hull plating improved access for inspection, cleaning and maintenance work. The design will also facilitate venting or inerting the ballast tanks, a likely future requirement. The design of the double deck makes it possible to install all piping, wireways and controls below deck, a feature that will eliminate one of the most costly elements of tanker maintenance."

4.1.2e Material Considerations

Ships using higher tensile strength steels for primary structures are normally more susceptible to corrosion in terms of strength and fatigue cracking. The reduction in scantlings, when compared to mild steel structures, incurs higher stress levels and a reduction of the inertia properties of structural members, thereby providing smaller margins against corrosion and a more flexible structure, which in certain cases can promote the corrosion process [31].

It can be shown that corrosion also affects the fatigue endurance limit, and that the fatigue limit can be drastically reduced or even eliminated by corrosion. Corrosion pits and grooves may act as stress raisers and thus contribute to crack initiation at an early stage in the life of a structure, and at lower nominal stresses than in air. For ordinary welded joints, this mechanism is probably less important because weld defects may be more critical than corrosion defects. Where weld improvement techniques have been used, corrosion defects on the material's surface become more important.

With current steel manufacturing processes, there is an inherent possibility that yield strengths of steels are significantly higher than the specified value, e.g. for nominal 355 N/mm^2 (51.5 ksi) yield strength steel, a yield strength of 475 N/mm^2 (68.9 ksi) has been recorded. Therefore, due consideration should also be given to the material selected when considering corrosion and fatigue durability.

4.1.2f Detail Design for Corrosion Control

While the provision of additional thickness will reduce stresses and cracking of coatings at details, the following measures can be taken to alleviate coating cracking due to excessively flexible details [17]:

- Minimization of stress concentration at structural detail discontinuities, or notches, in order to limit coating breakdown.
- Provision of appropriate welding sequences to minimize welding residual stress which may cause overflexing and coating cracking upon stress reversals.
- Application of permissible construction tolerances to minimize stress concentrations (weld shape, undercut, misalignment, fit up, etc.).
- Flexible coatings
- Not exceeding maximum coating film thickness

The first three measures above also accomplish fatigue control by design, which has far greater value than merely preventing coating cracks.

Structural design should be optimized to facilitate the drainage of water and the dispersal of contaminants. Horizontal areas where moisture collects should be kept to a minimum, especially at the bottom plating of ballast areas.

To do this, it is necessary to provide for positive drainage from all horizontal plates and stiffeners. Air escape paths for all seawater ballast tanks should be provided to prevent the formation of air pockets and to improve the effectiveness of sacrificial anodes, particularly in bottom tanks.

The following is one suggestion, given in Reference [9] and shown in Figure 4.1, to provide drainage from horizontal members:

"Stringer platforms and horizontal stiffening are the other two areas where improvements can be made. On side shell and longitudinal bulkheads, sloped longitudinals could be considered with, say, a 10 degree incline. Some compensation may be needed for section modulus and additional tripping brackets may need to be fitted, but superior drainage and reduced corrosion should result. Free climbing of these stiffeners would be more difficult but improved access for inspection will probably be incorporated into new buildings in accordance with recent trends. On transverse bulkheads, large vertical girders with relatively small intercostal, horizontal but sloped stiffening should be investigated to reduce the size of stringer platforms.

The details of the connection of the sloped longitudinal and transverse stiffening would require special consideration."

FIGURE 4.1 Stiffeners Welded at 10 Degrees from Horizontal for Better Drainage

These suggestions have not been incorporated into any new construction, perhaps due to the resistance to using innovative concepts in design and fabrication. There are obvious problems with the concept, which at this time may not be balanced by their possible economic advantages in terms of corrosion control.

Other large horizontal surfaces are, of course, the bottom and tank top. The tank top is usually smooth, allowing for relative ease of drainage. The bottom, on the other hand, is dependent on flow patterns and adequate drainage for emptying. Previously, vessels were typically designed with dead rise of bottom. This, among other things, allowed the cargo to more easily drain to the center of the vessel without the need to trim or otherwise manipulate the vessel. This idea was later resurrected, with thoughts of corrosion control, as quoted from Reference [9]:

"On modern tankers, the only way of minimizing or eliminating horizontal bottom plating would be to design the vessel with rise of floor. Rise of floor was more common two and three decades ago but disappeared in the push to achieve higher block coefficients and easier production techniques. Together with the changes in tonnage regulations, rise of floor is probably no longer practical but the advantages that can be achieved in terms of reduced corrosion and improved drainage should at least be considered in future designs. Operation alternatives include improved stripping systems and/or heeling and trimming of vessels to assist stripping of residual water."

Other possibilities for eliminating horizontal surfaces and improving cleaning and drainage include the use of corrugated bulkheads and truss frame construction. Both, however, require in-depth structural analysis to avoid design deficiencies, especially in way of connection details. Past experience has not been very good in this regard, particularly with corrugated bulkheads, which have experienced cracking at their lower edges as shown in Figure 3.2. However, recent classification society rule changes [16] should provide stiffer structure and eliminate this problem.

Another recent idea is the use of limited dedicated ballast tanks. One concept design for a double-hulled tanker by a Japanese shipyard utilizes specific tanks for ballast for all loading conditions. No condition of loading deviates from using ballast in only these tanks. The remainder of double bottom and wing tanks are held void. Critical in the design are the loading considerations. One major advantage is that most of the tanks that would otherwise be outfitted for ballast are not. Another is that the tanks held void are not subject to typical corrosion problems. Designs have also been proposed with ballast tanks inside the cargo block, i.e., no double hull tanks are used for ballast. In this case, the loss of cargo capacity must be weighed against the gains in reduced outfitting costs and improved corrosion control.

4.1.3 Use of Corrugated Bulkheads

Although corrugated bulkheads may not be suitable on some ship structures, the concept of corrugated bulkheads should nevertheless be considered for others, specifically for divisional bulkheads of small tanks. A study was performed to compare corrugated bulkhead construction with conventional bulkheads framed with tee sections. The study addressed labor hours and corrosion and dealt with an arbitrary tank area using the same pressure head for each calculation. The results of this study are presented in Reference [37].

This study shows that, for the particular ship investigated, there is an appreciable difference between a conventional bulkhead with tees and a corrugated bulkhead in terms of labor hours. With regard to surface area, which is the primary consideration in evaluating coating cost and corrosion control, the maximum difference is a reduction of 27.3% for the corrugated bulkhead with 27 inch (686 mm) spacing as shown in Table 4.1. In addition, its plate-like stiffeners make the corrugated bulkhead easy and fast to paint, requiring far less striping of welds and edges. Unlike tee sections, the corrugated bulkhead has few shadow areas that may not be reached by coating. As to weight, the maximum reduction for corrugated bulkheads is 43.6% with 24 inch (610 mm) spacing. The most significant reduction is 44.9% for the length of welds at 24 inch spacing. This is also a plus insofar as coatings are concerned, as coating failures frequently start at welds. As to labor hours for production, the maximum difference is a reduction of 20.4% with corrugated bulkhead on 24 inch spacing. This indicates that significant savings can be achieved by using corrugated bulkheads in lieu of conventional bulkheads with tees, for the size ranges of the bulkheads investigated, with significant gains in corrosion control.

4.1.4 Use of Bulb Angles

Bulb flats, which have compact rounded flanges, offer several advantages over conventional tee and angle shapes used in shipbuilding:

- The compact flanges promote better surface preparation for coatings.
- The rounded edges promote reception of paint and are less prone to physical damage than conventionally fabricated "T" or "L" stiffeners having sharper corners.
- The absence of weld during production of bulb shapes improves application and increases the life of the coating in comparison to fabricated sections.

A study was performed [38], comparing similar applications of bulb flats and conventional rolled tee sections with regard to labor hours of production and corrosion. The study was confined to the outboard ballast tank areas of the midship section of the U. S. Naval vessel LPD 17. While this vessel is typically US Navy, it is representative of other types of vessels, including double hulled tank vessels. Evaluations of the strength, stability and producibility aspects of these two different sections were accomplished to provide a basis of comparison.

The number of pieces, weight and center of gravity, one-sided surface area, volume and lengths of weldments and production labor hours for both the tee and the bulb flat section alternatives were determined in the study. The producibility comparison from the study is summarized in Table 4.2.

The tabulated characteristics indicate no appreciable differences between alternatives, except in weld volume. The 26% increase in weld volume indicated for the substitution of bulb flat sections for tee sections is due principally to the thicker webs of the bulbs in comparison to the webs of the tees.

Table 4.1
Producibility Comparison of Conventional and Corrugated Bulkheads for 24, 27 and 30 Inch Spacings [37]

Items (Combined Conventional/Corrugated Plating, Stiffeners, Brackets, Headers and Collars)	Conventional-Bulkhead w/ Tee	Corrugated Bulkhead	Difference
1. Total No. of Pieces			
Bulkhead w/ 24" Spacing	112	91	18.8%
Bulkhead w/ 27" Spacing	97	79	18.6%
Bulkhead w/ 30" Spacing	98	71	27.6%
2. Total 1-Sided Surface Areas			
Bulkhead w/ 24" Spacing	67 m^2	49 m^2	26.9%
Bulkhead w/ 27" Spacing	66 m^2	48 m^2	27.3%
Bulkhead w/ 30" Spacing	63 m^2	47 m^2	25.4%
3. Total Weight			
Bulkhead w/ 24" Spacing	5.5 t	3.1 t	43.6%
Bulkhead w/ 27" Spacing	5.3 t	3.6 t	32.1%
Bulkhead w/ 30" Spacing	5.8 t	4.1 t	29.3%
4. Total Volume of Welds			
Bulkhead w/ 24" Spacing	95.8 cm^2-m	40.8 cm^2-m	57.4%
Bulkhead w/ 27" Spacing	87.2 cm^2-m	53.9 cm^2-m	38.2%
Bulkhead w/ 30" Spacing	107.0 cm^2-m	71.7 cm^2-m	33.0%
5. Total Length of Welds			
Bulkhead w/ 24" Spacing	325 m	179 m	44.9%
Bulkhead w/ 27" Spacing	292 m	163 m	44.2%
Bulkhead w/ 30" Spacing	271 m	156 m	42.4%

6. Total Production Labor Hours			
Bulkhead w/ 24" Spacing	607 hrs	483 hrs	20.4%
Bulkhead w/ 27" Spacing	545 hrs	519 hrs	4.8%
Bulkhead w/ 30" Spacing	507 hrs	485 hrs	4.3%

4.1.5 Minimization of Stress Concentrations

The complicated structural connections between longitudinals and transverse webs is one area of detail that is prone to loss of coating and early corrosion and has been a weak point in fatigue strength design. Improvement in this area is a key step to structural safety and smooth construction of double hull crude carriers. At least one Far East builder has developed a new slot structure which offers increased structural safety while making construction easier. In this new structure, the web stiffening bracket (stiffener), which has been conventionally provided at a connection between a longitudinal and the transverse member, is removed. In this way, the new structure has no stress concentration parts (see Figure 4.2) [39].

The new structure works as follows:

- In a conventional structure, some of the load acting on the longitudinal is transmitted to the web through the web stiffener. If the stiffener is removed, the load previously transmitted to the web through the stiffener will be added to the web around the slot and the stress on the slot will increase.

- Through finite element analysis of various slot designs, an enhanced slot shape has been developed that maintains stress around the slot at levels lower than conventional slots, even with the web stiffener removed. Fatigue strength tests against in-plane and out-of-plane loads have proven that the new slot structure has superior fatigue strength for both types of loads.

- This design is considered to significantly reduce the probability of crack occurrence by eliminating a weak point in fatigue strength and a common source of nuisance crack propagation, thus contributing to a ship's safety. The vertical web stiffeners are replaced by horizontal web stiffeners located clear of the cutouts.

Care in the design and placement of longitudinals and stringers can reduce stress levels, improve coatings application and performance, and improve access for inspection.

4.1.6 Proper Welding Specifications

The design of welding for ships' hulls should be directed toward not only providing structural continuity and integrity, but also to reducing or eliminating the probability of weld distortions and fatigue cracks during the ship's service life. In this manner, it will be possible to attain welded joints that are not prone to developing and accelerating corrosion.

Both the U.S. Navy [40] and the American Bureau of Shipping [16] have very specific requirements for weld sizes and details. From a corrosion prevention viewpoint these requirements should be complied with, and (as discussed elsewhere in this report), special emphasis should be placed on the avoidance of lapped joints, the use of continuous welding vs. intermittent or spot welding, and the proper sizing of various weld details including fillet welds, which in most of ships constitute approximately 75% of all welds.

TABLE 4.2 PRODUCIBILITY COMPARISON [38]

Items (Combined Pltg, Stiffs and Collar PL's)	WT Section	Bulb flat Section	Difference (%)
1. No. of Pieces	2,352	2,352	0
2. Weight Total (t)	190.39	196.78	3.4
3. Vert. Center of Gravity (m)	5.02	5.05	0
4. ½ Surface Area (1 Side P & S) (m^2)	2196.36	2013.80	-8.3
5. Volume of Welds Total (cm^2-m)	3459	4366.7	26.2
6. Length of Welds, i.e.: (m)			
a. Automatic	4,555	4,503	-1.1
b. Manual	2,050	2,026	-1.2
7. Production Hours Total	14,341	14,234	-0.7

FIGURE 4.2 New and Conventional Slot Structures.
Conventional (top) and New (bottom) [39]

Detailed discussions on the avoidance of fatigue cracks and stress corrosion in fillet welds by proper design can be found in [41], [42], and [43].

4.1.7 Ease of Inspection Provisions

In inspections, the most important productivity concern is the blockage area within each space from the distributive systems. The type and density of the mechanical and electrical systems in each space and the relative location and orientation of the hatchways and the systems are the primary factors driving access and throughput capability. It is important to avoid electrical shock and thermal burn hazards from the systems closest to workers moving through a space.

Hatchways through the underside of the weather deck need to allow a full body length between the very end of the intrashell space to facilitate access to that area of the intrashell space to perform tasks and to attend to an incapacitated worker. Significant effort should be made to locate these openings at least six inches from the longitudinal girder or any similar structure.

Passing materials or tools through the hatches and manholes is possible but component dimensions will be geometrically constrained by the distributive system densities within the intrashell space and the location of the opening. For example, a six inch diameter pipe would be typically constrained to a length of about ten feet in some small spaces such as wing or double bottom spaces. This requirement should provoke significant thought in the design phase concerning manufacturing and maintenance strategies [44].

The requirements for the movement of personnel, the handling and conveyance of materials, and the conduct of work are determined for the following processes and safety issues:

- Life Support
- Extraction of Injured or Ill
- Lighting
- Smoke, Fume and Debris Removal
- Burning
- Welding
- Brazing
- Machining
- Corrosion Removal
- Coating Application
- Weight and Bulky Object Handling
- Personnel Movement
- Component Insertion and Positioning
- Utility and Process Line Tending
- Tool Delivery and Containment

Stringers in the wing tanks of the first generation of double-hulled tankers have provided many benefits, one of which is convenient, stable access to the entire tank for inspection and repair.

In recent years, with increasing concern about coating life and inspections, stringers and supplemental horizontal members have been recognized as advantageous. Both side stringers and bulkhead webs are favored for construction and careful consideration in initial design will improve their placement and utilization in the structure. With double hull tankers, stringers in the wing tanks are a common occurrence, and attention is paid to additional stringers, essentially unnecessary for strength, but installed for inspection purposes only. As an alternative, GRP ladders and walkways may be utilized to provide access.

Double hull unidirectional vessels inherently provide horizontal surfaces in the wing tanks which could enhance inspections. On the other hand, the spaces in wing tanks of these vessels, although large in length, are usually not very high. This can lead to other problems with inspections, and some innovative methods have been devised to surmount their inherent problems with regard to inspection. Individual bays should be large enough to allow for easy movement throughout the space, but small enough to allow the overhead areas of the space to be within easy reach. Access should be provided at the forward and aft ends of each cell, with minimum opening sizes of 450 mm by 600 mm (18 x 24 in) [8].

For improved and efficient surveys, the following recommendations are made by ABS:

- Use stringers in the wing tanks to allow for convenient inspection and maintenance of double hull spaces.

- Use light-colored coatings to provide better contrast for detection of corrosion or fractures.

- For unidirectional vessels, provide two separate means of access to each cell for safety, help in removing injured personnel and to allow for hoses used for vacuum blasting and painting. Minimum manhole sizes are 600 mm x 800 mm (24 x 32 in.) for vertical surfaces, and square openings of 600 mm x 600 mm (24 x 24 in.) or round openings of 570 mm (22.5 in.) for horizontal plates.

Inspection of deckheads of V/ULCCs can be difficult owing to the deep transverse webs. On older vessels, close-up inspection may have to be done in dry dock when proper staging can be erected. For newer vessels with deckhead walkways, inspection is improved around the periphery of the tank but staging may still be needed for the center.
One promising development is the adaptation of small, submersible, remotely operated vehicles (ROVs) for tank inspections that make deckheads accessible with tanks fully ballasted [9]. Once the ROV reaches a repair area, the repair procedures can begin. The operator uses the mouse to

circle the repair area in the live-video picture. The control system transforms this data into the necessary information for automatically guiding the tool cluster through the proper motions to effect washing, sand blasting, or painting depending on which task activity the operator has selected [45].

Water test kits are applicable for seawater ballast, potable water, distillate, and possibly collection/holding/transfer (CHT) system water. CHEMet, or similar, ampoules and test kits for zinc, iron or other elements are available which consist of vacuum sealed glass ampoules and visual comparators. The ampoules contain reagents which will react to with the particular analyte of interest and form a color complex. Water tests revealing zinc and/or iron could be used as an indicator of corrosion occurring in the cell. Sudden changes in cell chemistry could be used as an indicator that further inspection of the cell is required. The costs of these kits are very reasonable; estimated time to test a sample is 10 minutes. Testing of the cells of a unidirectional tanker, prior to inspections, will be more time consuming, due to the potential for gas pockets to form in each cell.

As recommended by the Tanker Structure Co-Operative Forum (TSCF), continuous forced ventilation should be provided to tanks while workers are present. For cells of a unidirectional tanker, access manholes may be restricted by ventilation tubing and additional hoses and cables for lighting, welding, abrasive blasting or painting. This can be a problem as there does not appear to be a simple solution to providing ventilation any other way.

Hot climates may pose other problems with access to a unidirectional ballast tank. The insides of the cells can become extremely hot, and concerns over worker heat stress may significantly limit the amount of time that a person may spend in the space unless it is cooled.

If cells are accessible only via the weather deck, a significant amount of time may be needed just to get to the cells in the double bottom.

4.1.8 Corrosion Protection Systems

While it is generally not advisable to install distributed systems in tanks that will be used for fluid services, such as seawater, potable water, collecting and holding (sewage), fuel oil, etc., the installation of certain systems and equipment in tanks is necessary and can be beneficial, or at least not detrimental, to corrosion control.

Piping and systems frequently introduce dissimilar metals into tanks and the possibility of galvanic corrosion. Brass, bronze, and copper-nickel components in these systems will be cathodic to the hull steel and can cause aggressive pitting of the steel at any breaks in the coating unless sacrificial zinc anodes are provided in the tank. Therefore, systems in tanks should always be coated to prevent galvanic action. Glass-reinforced plastic (GRP) and other composite materials can be used for ballast piping, ladders, walkways, gratings, handrails, etc. to reduce the potential for galvanic corrosion to the maximum extent possible.

There are several system design options that can be helpful in corrosion control. A number of these systems are offered below for consideration.

4.1.8a Cathodic Protection Systems

Sacrificial anodes are an important part of the corrosion control process in tanks with electrolytic solutions. In most cases, they form a secondary defense against corrosion should the primary coating barrier fail. It is important to point out what anodes will and will not do to help prevent additional corrosion in a tank. These are delineated in [2] as follows:

Anodes will not:

- Protect air pockets which can be caused by certain stiffener details and will prevent anodes from performing properly to protect any cracked coatings in the area.
- Protect overhead surfaces of tanks if there are air pockets.
- Protect tank bottoms from corrosion under residual wet silt after deballasting if they are mounted above the wet surface.
- Protect a ballast tank if the ballast voyage is too short because bare steel may not have enough time to polarize.

Anodes will:

- Help prevent undercutting and subsequent pitting of coatings around coating damaged areas, resulting in a longer service life of the structure.
- Provide the best protection against corrosion in seawater, next to coatings.
- Generally afford greater protection against corrosion at higher current densities. However, limits must be put on current so that there is no damage to coatings.
- Only function when immersed in an electrolytic solution.
- Benefit only compartments containing electrolytes, such as seawater ballast tanks.

The location and density of anodes play a major role in deterring corrosion. But, as seen above, anodes do not completely stop corrosion. Furthermore, they must be renewed periodically and are not effective in splash zones and non-immersed spaces such as underdeck structure. As a result, they may not be a suitable choice for a particular application. In addition, it is also important to ensure that a coating is compatible with the cathodic protection system when a coating is supplemented with anodes. Cathodic protection is without effect when the tank is empty, and it requires some time (a day or more) to become effective after the tank has been filled [46].

The adequacy of a sacrificial anode system can be determined if the system is properly monitored. Reference [9] comments on the effectiveness of anodes with regard to corrosion rates and states that by using proper current densities, it is possible to achieve up to 70% reduction in the corrosion rate. This means that the corrosion rates with protective anodes will be only 30% of the rates for unprotected steel.

A questionnaire on the design of vessels and corrosion by the Tanker Structure Co-Operative Forum (TSCF) [33] asked what coating and anode material selections should be used to control pitting? The answers were:

- A combination of coating and anodes was suggested by all nine members of the TSCF as a solution to control pitting corrosion. Recommended combinations are epoxy/zinc anodes, coal-tar epoxy/zinc anodes, epoxy/aluminum anodes and coal tar epoxy/aluminum anodes.

- Proper location of anodes, especially at bottom locations to ensure protection against bottom waters and at other problem areas, was suggested.

One coating manufacturer states that a properly prepared and coated tank, in conjunction with sacrificial-anode protection, can be expected to allow a vessel working life of up to 15 years. The company emphasizes that using a single source for coating and anodes avoids the system mismatches which often occur when separate suppliers are involved. For ballast tanks that are already badly corroded, the company is able to combine recoating and cathodic protection techniques with electrolytic descaling [21].

In electrolytic descaling special magnesium strips, with an iron core, are installed over the corroded steelwork, and the ballast tank is filled with seawater. A heavy electric current passes through the strips, and results in the rust being detached from the tank's surfaces. After washing down and drying, the steel surfaces are then ready for recoating and the installation of sacrificial anodes [21]. The limitation of this approach is that the magnesium strips need to be in place for some time to achieve the desired objective. As a result, this operation is usually carried out at sea prior to the vessel's availability at a shipyard or repair facility.

4.1.8b Inert Gas Systems

Although not required for non-cargo tanks at this time, inert gas piping can be run to all tanks adjacent to cargo tanks to inhibit volatile gas accumulation in empty or partially-filled tanks. This gas accumulation could be caused by cargo leaks due to cracks or other compromises of the cargo bulkheads. In addition, inerting could inhibit the progression of corrosion by providing an oxygen-depleted atmosphere. This system could be used in dry void spaces to remove accumulated moisture to prevent condensation. The installed piping would have the added benefit of being able to provide forced air ventilation to the spaces, especially during inspections when a gas-free, "safe for entry" atmosphere is required. The piping could also be used to provide ventilation to help prevent coating blisters or damage due to solvent entrapment during maintenance coatings. This would particularly be beneficial in those tanks in the bottom of the vessel. It should be noted that inert gases, such as argon or nitrogen, should not be used for corrosion protection in accessible spaces due to the potential problems that may be encountered in obtaining a breathable atmosphere for inspections [8].

4.1.8c Remote Monitoring Systems

Remote monitoring systems are being used on US Navy vessels and some commercial platforms to monitor the structural conditions of spaces. Presumably a system could be designed to monitor any condition that would be helpful in determining the corrosion aspect of a tank. Humidity, salt concentrations, voltage potential would be able to be monitored. Any increase in, for example, the potential of the steel in a tank would be able to be monitored from a norm established when the coatings were first installed. A change in potential would indicate a breach of coating within the tank. Monitoring the levels of voltage, against an established criteria, would enable the crew to monitor the degree of corrosion in each tank and logically plan inspections [45].

This remote monitoring system could incorporate permanently installed sensors to monitor steel potential, coating impedance or steel polarization inside the spaces to be periodically monitored by personnel or computer. Conceivably, all remote monitoring could be accomplished via computer and trending or statistical analyses performed at a central location within the ship. This first line of inspection would offer the greatest opportunity for effecting a large scale inspection assessment with minimum personnel requirements [45].

4.1.8d Desiccant, Dehumidification and Vapor Phase Systems

In dry spaces or voids, protection by desiccant, dehumidified air and/or vapor phase corrosion inhibitors is possible. In this case a permanently installed moisture sensor and/or humidity indicator would be periodically monitored by personnel and data entered to a log or central computer. Trending of the individual spaces would indicate the need or requirement to augment the original corrosion protection system. For example, additional amounts of vapor phase corrosion inhibitor could be injected to the cell via one way valves to maintain proper protection levels. Repeated failure of individual cells to maintain maximum humidity requirements would alert personnel to schedule more in-depth inspections or repairs [8].

4.1.9 Thermal Spraying

Thermal spraying, or metallizing, is the process of spraying a layer of molten metal onto the substrate to provide corrosion protection. The sprayed metal is usually aluminum or zinc, or a combination thereof. Thermal spraying of aluminum has been used by the U.S. Navy for corrosion protection of steel on weather decks, oil tanks, bilge tanks, ballast tanks, sanitary spaces, sewage holding tanks, fresh water tanks, fuel tanks and steam valves for more than 15 years [47].

Thermal spray coatings protect by forming a physical barrier beatween the environment and the base metal. Some degree of sacrificial protection is offered to the base metal by aluminum coatings, while zinc and zinc alloy coatings offer a high degree of sacrificial protection. The long-term protection offered by aluminum coatings is due to the air-formed passive oxide film that forms on the surface and within the coating [48].

The oxide layers and voids within the coating provide paths for the ingress of chlorides into the coating and cause delamination failures of the coating in salt water service. Thus the requirement for a sealant over the thermal sprayed coating to provide a physical barrier to the ingress of chlorine and provide long coating life.

Thermal spraying can be done as flame spraying or arc spraying. Flame spraying uses an oxygen/fuel flame to melt the aluminum in wire form and propel it onto the steel surface. Arc spraying uses an electric arc between two consumable wires and compressed air or inert gas to propel the aluminum onto the surface.

The surface preparation for thermal spraying is essentially the same as that for paint coatings. The surface must be free of oil, grease, paint corrosion, moisture or other contaminants. The surface must be abrasively blasted, not only to remove contamination, but to also provide a roughened surface for good adhesion, particularly for flame spraying which requires two blast operations, one to clean the surface and one to give the required surface profile.

The overall advantages of thermal spraying are:

- Predictable life
- Single application system
- Bonds to sharp edges
- No drying or curing time
- Cathodic protection of damaged areas
- Resistance to abrasion
- Any size structure can be coated

Thermal spraying has the disadvantage that it cannot be applied to all surfaces:

- Surfaces exposed to strong acids or bases

- Exterior underwater hull surfaces

Several tests have been performed to compare the performance of thermal spray coatings with other corrosion protection systems. In one series of salt fog tests lasting more than 2,000 hours, the following systems were compared [49]:

- Wire sprayed aluminum with Navy seal coating
- Wire sprayed aluminum with commercial seal coating
- Navy epoxy polyamide
- Commercial epoxy polyamide
- Navy inorganic zinc
- Commercial inorganic zinc

This test of intact and compromised (scratched) test panels revealed that wire spray aluminum with commercial seal was more resistant to corrosion than the other systems.

Other salt water exposure tests lasting nearly five years concluded [48]:

- Zinc aluminum pseudo-alloy coating produced the best performance, combining the sacrificial properties of zinc with the long-life coating integrity of aluminum.

- Unsealed flame- and arc-sprayed coatings demonstrated lives of over five years in the marine environment.

- Thermal spray coating life is increased by the application of a sealer and epoxy coatings.

- Arc-sprayed coatings were found to perform slightly better than flame-sprayed coatings.

High deposition arc spray technology has lowered the cost of flame spray application to a point where it is comparable to or less than the cost of paint coatings [47]. Comparison of life cycle costs for thermal sprayed aluminum and painted coatings were made for Navy service at low temperatures and high temperatures above 79°C (175°F) [49] with the following results:

Thermal spraying:

- 20 year life cycle
- 10% renewal of paint every 5 years (20% for high temperatures)
- 1% renewal of thermal spray every 5 years

Epoxy paint:

- 5 year life cycle
- 100% renewal every 5 years
- 15% renewal annually (20% for high temperatures)

With the initial cost of thermal spraying comparable to that of paint, the savings over the life of the ship can be signicant because of the less frequent and smaller renewals as compared with paints for certain applications.

4.2 Fabrication Methods

4.2.1 Fitting Accuracy to Avoid Rework

The first and most important corrosion control measure to be adopted during fabrication is the provision of the greatest possible degree of accuracy in fitting the ship structural components together. Fitting accuracy can be accomplished by observing and complying with instructions, standards, guidelines, precautions, tolerances and inspection requirements contained in the detail design drawings and specifications.

By assuring a high level of fitting accuracy, both during the fabrication of individual structural components and the joining of these components in the erection stages, the probability of structural imperfections in the end product, and therefore the possible onset of corrosion, will be greatly reduced, if not eliminated. Rework and consequent damages to shop-finished surfaces are also eliminated.

Consequently, the design approach should include specific detailed requirements for quality control in general, and especially for structural tolerance limits to achieve good fitting accuracy.

4.2.2 Proper Surface Preparation

To the greatest extent possible, procedures recommended by the coating manufacturer, should be followed. One of the most important factors is the preparation given the steel prior to the application of a coating. The basic requirement for conventional coatings is that they be applied over a clean, dry surface free from water soluble contaminants like sodium chloride which can cause blistering, soluble ferrous salts which will, in contact with steel and moisture, initiate rusting of the steel, and oily residues which will reduce adhesion of the applied coatings [12]. As defined by the coating manufacturer, the degree of surface profile achieved by blasting, control of humidity and temperature of air and steel during application together with proper care of the new surface during curing can insure a quality, long lasting coating [7].

To insure long lasting coating performance, complete removal of all weld spatter prior to coating should be required. However, this requirement must be modified by reality. The best procedure is to have agreement between the shipyard and the owner as to the acceptable level of weld spatter removal, and then adhere to it.

All sharp edges should be ground smooth. A minimum required radius of 3.2 mm (1/8 in) on all edges prior to coating is one recommendation. A National Shipbuilding Research Program (NSRP) study of the effects of flame cut edge preparation on coatings used in the marine environment [50] found that the best overall coating performance was obtained with samples having the maximum edge radius of one-half the plate thickness. While full rounding of edges is extreme, the level to which the edge smoothing requirement is met must be agreed upon by the owner and shipyard. Quality assurance must be provided to keep to this minimum to help prevent premature coating failures at these locations.

It is important that as much welding work as possible, if not all, be completed prior to surface preparation and coating application. For instance, brackets for bolting ladders, walkways, handrails, etc. should be installed prior to coating. This will minimize coating rework, particularly coating burn beyond the weld area into less accessible locations.

4.2.3 Suitable Environment for Coating

Reference [26] discusses the coating environment in detail and states that shipbuilding is a multi-stage process starting with the treatment of stiffeners and plates, progressing through sub-assembly and assembly to erection. In this process outfit work, including painting, has generally had less investment than the highly developed steelwork facilities. The resulting longer cycle times for outfit work may create an imbalance with the shorter cycle times for steelwork.

At the tactical planning level, the work loading of coating must be considered more carefully as the environmental legislation requires more work to be undertaken within controlled environments. This means that the use of the paint cells, or pockets of coating work, needs to be evaluated with regard to their cycles in the work process. This is possible through computer simulation. Evaluation will enable a better prediction of work cycles and hence help to manage the bottleneck area effectively at the same time minimizing the investment in facilities. Again at the tactical level, the sequencing of steel and outfit work must be well defined to ensure that as much hot work as possible is completed before coating takes place. This should take into account the use of fairing aids, the fitting of small pipe systems and cable trays and any other outfit work that is often a cause of considerable damage to coating systems.

At the detail planning level, the resources available must be organized not only to conduct the coating process but also to undertake the rework process. The resources available must be balanced with the workload demands so as to minimize idle time and the consequent need for subcontract labor.

The build strategy must lay down the importance of coating and this must be reflected within the tactical and detail planning levels. If this is not done, rework will continue as a convenient, though expensive way of overcoming inadequacies in the production control system.

The physical application of coatings is a known factor based on a tank space and its geometry. Other factors, which can be improved upon and should be taken into account in the planning stage of tank coating are discussed in Reference [44]. While that document referred specifically to the intrashell spaces of double hull unidirectional combatants, the principles are applicable to almost all situations involving tanks and access to tight spaces.

As in conventional shipbuilding, certain tasks on double-hull ships will require more protection for the worker than others. The processes that will produce the most detrimental conditions to the safety of the worker in the intrashell space environment are thermal cutting and joining processes, and coating application and removal processes. These processes will typically require various levels of ventilation and breathing air, additional protective clothing, respirators, and will account for the bulk of the safety problems. Some of these hazards are electrical shock, airborne debris and particles, weighted objects, smoke, and fumes.

4.2.4 Proper Application of Coating

After the above is accomplished, rework, however much reduced, will still have to be dealt with. The need then is to identify where and when rework is taking place, to quantify it, to put in place a method of managing it, and to methodically identify the root causes of the subsequent rework and set about eliminating them.

A good method of achieving identification of rework in ship production is through the process of prototype modeling, in which the production engineering of the shipbuilder can be integrated with design to assure a match between design requirements and process capability.

The basis of this approach is the use of statistical quality control to stabilize and monitor the processes. This implies data collection routines matching the subsequent statistical analysis. To achieve this, the inspector must have access to all areas of a block to ensure an adequate sampling process. In this way the coating activity can be brought under control and the causes of rework identified, quantified, managed and eliminated. Attribute charts can be used where a subjective measure of quality is all that is available. Typical charts are the chart for fraction rejected (the P-chart) and the chart for non-conformities per unit (C-chart). These charts would be suitable to control the quality of activities such as [26]:

- Surface cleanliness after preparation
- Tears
- Sags

- Runs
- Drips
- Overspray
- Heat damaged areas
- Secondary surface preparation area
- Weld spatter

Variable charts can be used where an objective measure of quality is available, e.g. the chart for mean process performance (X-bar chart) and the chart for the variability of the process performance (R-chart). These charts would be suitable to control the quality of activities such as:

- Coating thickness
- Surface profile
- Overcoat time

- Curing time
- Cutting speed performance
- Welding speed performance

It is interesting to note that methods for the statistical analysis of hull roughness measurements have been exhaustively treated in the literature and that thickness analysis may be treated by the same statistical procedures.

Clearly, the timing of these measurements and access for measurement must be considered, but unless these measures are undertaken, the results analyzed and action carried out to improve the process, there is little chance that the process can be brought under control.

Maintenance of the coating environment during coating preparation and application is of paramount importance. Walking on the coating before it is cured or disturbance of vertical surfaces by workers at building and dry-docking can cause damage to the coating.

4.2.5 Coating Inspection Guidelines

Any damage to or failure of ship's coating systems should be identified as soon as possible by means of frequent inspections. One of the essential factors for conducting inspections with ease and efficiency is to make the coated areas "inspection friendly." Provision, the design of ship, of proper and practical means of access to the areas to be inspected and the use of a light colored final coat of paint will make it easier for paint inspectors to locate and remedy any coating imperfections.

Coating inspectors are generally highly experienced in similar work; however, the ship specifications should still include requirements for compliance with specific coating inspection guidelines such as those contained in [51,52,53] which are ASTM Standard Practices, and in [54] which is an ABS

Guidance Manual. The ASTM standard gives descriptions of and guidelines for the inspection of coating failures such as delamination, cracking, blisters, flaking, sags, chalking, discoloration, softening, etc., and provides levels of acceptability. The ABS manual is intended for use by field surveyors.

5.0 COST/BENEFIT ANALYSES

The recommended manufacturers' specifications for a good coating system would include the requirements of blasting, the stripe coating of seams, ratholes, edges and corners, and the application of two coats of at least 200-300 microns each, for a total of 400 microns dry film thickness. The additional cost of this, compared to a conventional single-coat treatment, could be in the order of $\$3\text{-}5/m^2$, depending on the conventional system proposed. This must also be compared with repair costs associated with a less effective coating system, possibly after a relatively short working period, of some $\$50/m^2$ for blast cleaning and recoating. Costs of about $\$500/m^2$ must also be anticipated for the renewal of heavily corroded steelwork that may have to be done at the same time.

In a paper published in 1984, Weber [9] reports (on the basis of surveys conducted on Exxon tankers) that it was found to be four to fourteen times more expensive to renew corroded steel than to coat the area subject to corrosion. It was also found that the installation of anodes has proven to be even less expensive than coating; the cost of anode installation was in the order of about one third of that for coating. Furthermore, as published by ABS in an article in the Surveyor magazine [11], the cost of actual epoxy material constitutes only a very small part of the total installation cost. Current estimates place the costs expended on coatings at upwards of 10% of construction costs for a crude oil carrier, 7% for a bulk carrier and nearly 27% for a products carrier.

The above-cited article goes on to state that the cost estimates for the coating repairs of a 40,000 DWT ship ran to $1 million in paint alone; the total cost of all coating repairs on the same ship ranged to approximately $5 million. It becomes clear that the owner of a ship which may have cost about $40 million to construct would want to avoid spending another $5 million or more for steel and coating repairs in the ballast tanks after several years.

It is reported in a Motorship magazine article [14] that the Shipbuilders Association of Japan, after comparing vessels coated with a newly developed shop primer to those coated with traditional zinc-silicate primers, has concluded that by the use of the former, the outer hull corrosion was reduced by 35% and ballast tank corrosion was reduced by 30%. In addition, the manhours needed for secondary preparation of the corroded areas alone was reduced by an average of 20-30%.

The results of another study, presented to the "International Conference on Marine Corrosion Prevention" in 1994 [26], indicate that the amount of coating re-work reflects the relative dominance of steel-work activity in ship production. However, as the world's leading shipbuilders see their annual labor costs increase to $50-60,000 per worker (salary, benefits and overhead costs), the need to manage and eliminate labor intensive activities becomes acute, in particular if those activities have a large rework element.

The additional labor-hours needed for coating re-work (30-40% in a typical European shipyard) will result in an increased labor demand and consequently an increased labor cost. As the need for direct labor increases, so will the need for indirect labor to coordinate production activities. It is important therefore, that the detail design of the vessel be carefully tailored to the capabilities of the facility where the construction will take place, so that the rework can be minimized.

6.0 RECOMMENDATIONS

Methods and procedures for controlling corrosion in ships' structures can be adopted during all phases of the ship acquisition process, i.e., during design stages, during fabrication, and after the vessel enters service. Such measures, the discussions of which are interspersed in Sections 2, 3, and 4 of this report, are summarized below for each phase. Some of the recommendations are similar in scope and objective for more than one stage of the process; they are nevertheless listed for all applicable stages since the approach in accomplishing them may be different at different stages in a ship's life.

Most of the methods/procedures cited are currently being used in many applications; they are repeated here for the sake of completeness. Furthermore, not all of the measures are universally accepted methods for corrosion reduction nor are they applicable to all types of ships. Where differences in opinions exist, the pros and cons of each recommendation are stated to enable designers, shipyards, and operators to select the methods most suitable to their facilities and to their specific ship project and operations.

6.1 During Design Phases

6.1.1 Design for Access

Access to all parts of the structure must be considered in developing general arrangements and the structural configuration to facilitate coating application and inspection. The depth of members and the location of flats and stringers must be based on safe access to the structure as well as structural considerations. All structures should be within arm's reach for inspection from climbing positions. Efficient inspection methods and routes through the vessel must be considered in locating manholes and accesses. The choice of vertical versus inclined ladders and their locations should be considered early-on.

The depth of doublebottoms and the width of intrahull spaces may have to be increased beyond regulatory body-required minima to provide adequate manholes and safe access. In general, doublebottom heights and the distance between flats and stringers should not exceed 3 m (9.8 ft) so to allow easy close-up visual inspection.

6.1.2 Selection of Design Scantlings

In recent years, it has been possible to design ships with lighter scantlings than normal, owing to the availability and use of improved analytical techniques for calculating design stresses and driven by the continuing desire to reduce construction costs. However, reduced scantlings due to the incorporation of corrosion control measures are no longer allowed by the classification society rules. Only full scantlings or increased scantlings are permissible. Scantling reductions achieved through the use of higher tensile strength (HTS) steels are still permitted, but fatigue life of critical areas must now be investigated to preclude the cracking experienced in earlier HTS ships as they reached mid-life.

The deliberate selection of scantlings greater than classification rule minimum requirements for ship structural members which have historically been found to be prone to corrosion, or of areas that are difficult to protect, will provide an additional corrosion allowance and lower the working stress. However, the specification and application of a good coating system may be more cost-effective than increased scantlings to guard against corrosion, particularly since classification now requires the coating of all areas.

6.1.3 Material Selection

The selection of materials used in construction of the ship will have a role in achieving good corrosion control. Materials other than steel, e.g., aluminum, bronze, glass reinforced plastics (GRP), composites, etc., may be used for primary structure or for various outfit items such as ladders, gratings, walkways, pipes, etc. Such materials, especially GRP, should be used wherever practicable and economically feasible since they do not corrode.

If metallic materials dissimilar to steel are used, dielectric barrier materials or sealants should be provided to isolate the two dissimilar metals. Also, the relative positions of the metals in the electrochemical (Galvanic) series and the area ratio to the steel structure must be considered to prevent either metal becoming a sacrificial anode to the other.

As mentioned in 6.1.2, higher tensile steels usually result in thinner scantlings for the primary structures and normally provide smaller margins against corrosion. Reduced scantlings have higher stress levels and reduced inertia properties and are therefore susceptible to greater deflection and possible fatigue cracking. Consequently, it is recommended that stresses always be examined with net scantlings, i.e., minus the corrosion allowance, if higher strength steel is the construction material.

6.1.4 Preventing Water Entrapment

The structural design of the ship's hull should be optimized to facilitate the drainage of water and the dispersal of contaminants from horizontal surfaces. This can be accomplished in a number of ways, including minimizing the horizontal areas where moisture can collect by using corrugated bulkheads instead of stiffened plate bulk-heads, using angles or bulb plates instead of tees for horizontals, providing generous scallops and drain cut-outs, and installing longitudinals at a slope. Some of these approaches may be objectionable for some shipbuilders and owners, e.g. despite their advantages in providing good drainage and being easier to coat, corrugated bulkheads are not being used in large tankers due to the problems with peripheral weld cracks experienced by some operators. However, changes in classification society requirements for these bulkheads are now under consideration. Also, sloping the longitudinal attachments to the hull creates fabrication problems when crossing transverse structure and may require increased scantlings due to loss in strength compared to longitudinals at right angles.

Scallops and drain holes require care in their shape and location if maximum drainage is to be provided without decreasing the strength of the member or causing stress concentrations. Elliptical cuts in horizontal webs can provide adequate drainage without the hard corners and welding problems typically presented by semicircular cuts (rat holes).

The bottom and the tank top, of course, constitute large horizontal surfaces. The tank top is usually a smooth surface and allows for relatively easy drainage. The fitting of bilge wells in way of stripping suctions can greatly improve stripping and remove most of the liquid in a tank. The bottom, however, requires adequate drainage for emptying through all the internal structure. One way to provide easy drainage would be to design the bottom with a deadrise which was more common two or three decades ago. The preferred practice today is to trim the ship aft to achieve emptying and avoid designing with rise of floor since flat bottoms are more producible. Adequate drain holes in vertical double bottom structure, increased in area near the suction, will aid drainage.

6.1.5 Minimizing Flexure and Stress Concentrations

Inadequate panel stiffness leads to excessive flexure due to cyclic pressures or vibrations and this may cause coating breakdowns. Stress concentrations at structural details, discontinuities, and notches also cause coating breakdowns and should therefore be avoided in design.

6.1.6 Proper Welding Specifications

The established methods, during design stages, of eliminating or reducing the possibility of corrosion due to weld defects include avoiding the use of lapped joints, specifying continuous welding rather than intermittent or spot welding, sizing weld details correctly, and providing appropriate welding sequences to minimize residual stresses in welded joints.

6.1.7 Coating and Inspection Friendliness

The design aspects that provide for coating friendliness include:

- Using contoured metal surfaces, such as rounded edges, corrugated bulkheads and bulb angles
- Specifying bulb angles with rounded edges in place of T-sections or built-up stiffeners with sharp edges
- Minimizing the shadow areas in the arrangement of structures to facilitate coating application
- Providing easy assess for coating applicators to reach the structure

The key to providing inspection friendliness is access:

- Manholes must be of sufficient size to allow personnel to pass with tools, protective clothing and breathing apparatus
- Manholes should be located to allow an efficient inspection route through the structure
- Climbing poles and hand holds should be provided to aid personnel in climbing the structure and going through manholes
- Ladders and walkways should be of sufficient width
- Horizontal stringers should be provided on vertical surfaces to the extent possible for use as inspection platforms, especially at deck heads

Oversizing of the double bottom heights and wing tank widths (to facilitate access) for inspections may also be considered if found practical and economical for the specific application.

6.1.8 Corrosion Protection Equipment and Systems

The design must include provision of one or more corrosion protection measures such as sacrificial anodes, impressed current equipment, inert gas systems, dehumidification/vapor phase inhibitor systems, etc., as desired and approved by the prospective owner.

6.2 During Fabrication

To minimize corrosion on edges and at drainage and access holes, all sharp edges should be ground smooth and stripe coated. Generous scallops should be provided.

As much welding work as possible, preferably all, should be completed prior to surface preparation and coating application. For example, ladders, walkways, handrails, piping, etc. should be installed prior to coating. This will minimize coating rework.

Piping and other systems in tanks, which may introduce dissimilar metals to the tanks, should always be coated to prevent galvanic action.

Field welding should be reduced to an absolute minimum since the coating in way of the field welds may burn far beyond the weld area and such damaged areas may be less accessible for recoating.

With the objective of assuring good surface preparation, all temporary construction fixtures and brackets, all weld spatter, arc strikes, previously applied hard or soft coatings, and all rust or scale should be completely removed prior to coating. Badly undercut welds must also be removed and rewelded before starting the coating application.

Coating applications should only be performed under suitable environmental conditions as specified by the coating manufacturer.

A high degree of fitting accuracy should be achieved and constantly monitored by the yard's quality assurance personnel as well as by the regulatory body and owners' inspectors.

Surface and coating inspections during and after construction should concentrate on any horizontal surfaces that may trap water, mud, and debris.

6.3 During Service Life of Ship

During the service life of a vessel, the corrosion protection system employed must be maintained and any coating breakdowns should be repaired and touched up as required.

Proper tank inspection and maintenance on a regular basis is a must for all coating systems. Where existing means of access are not sufficient to inspect all areas of the structure or coating, appropriate staging must be erected or rafting or other means should be employed to conduct complete inspections.

If the coating shows signs of cracking at a typically flexible structural detail and if the coating specification, application, and inspection have been found in good order, then redesign or reinforcement of the connection should be explored rather than attempting to use a more flexible coating material.

Accumulation of silt in the ballast water should be prevented to the extent possible since wear may result when tanks are mucked out of sand and silt with shovels, etc., prior to inspections. Although not a serious problem, partially filled ballast tanks containing silt in the water could cause erosion over the long term due to sloshing in bays between structural members. However, abrasive particles in ballast water will cause erosion at the ballast line entry and suction points. When soft zinc coatings are used, the plates under the bellmouths wear excessively. Coatings under the bellmouth strainers should therefore be well maintained in service.

The sweating and condensation caused by heating and cooling of partially filled tanks with cargoes having high temperatures is generally not a problem. However, the coating applied should be properly selected for the heat application and the surface should not be compromised, i.e., cracking, peeling, or holidays must not be present.

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APPENDIX A. PROPOSED DRAFT FOR STANDARD

Standard Guide For Commercial Ship Design and Fabrication For Corrosion Control

1 Scope

1.1 This guide outlines procedures and recommendations for the design and construction of fresh and salt water ballast tanks and void spaces to minimize corrosion. Corrosion can be dangerous to the safety of the ship, crew, and cargo. Installation of an effective coating system during construction may increase initial construction costs but will be cost effective over the life of the ship.

2. Reference Documents

2.1 ASTM Standard F 1131, Standard Practice for Inspecting the Coating System of a Ship's Tanks and Voids

2.2 Coating Systems; A Guidance Manual for Field Surveyors ABS, 1995

2.3 1985 Steel Structures Painting Council Surface Preparation Standards

3. Definitions

3.1 *Binder*- the component of the coating which binds the constituents to the surface.

3.2 *Film Thickness* - the thickness of the paint or coating system.

3.3 *Hard Coating* - a coating which forms a non-convertible hard surface film chemically converts during its curing process or by air drying.

3.4 *Soft Coating* - a coating that remains and retains its chemical composition and remains soft so that it may be removed easily.

3.5 *Pigments* - powders, insoluble in resins, which give the coating its color finish and protective properties.

3.6 *Thermoset* - are coatings in which curing involves a chemical reaction that changes the chemical structure of the binder.

3.7 *Thermoplastic* - are coatings in which the binder remains unchanged and drying involves only the evaporation of the solvent.

4. Coating Properties

4.1 Soft coatings should be avoided as a permanent solution because of their short service life. Soft coatings may be used as temporary protection until more suitable coatings can be applied.

4.2 Hard Coatings

4.2.1 Bitumin and Coal Tar Pitch are inexpensive and readily available but should be generally avoided. Sharp edges and surface defects may cause premature local breakdown. Their dark color makes finding coating defects difficult. Also they are known carcinogens and their application is banned in many localities.

4.2.2 Epoxy resins should be the first choice. Material properties may be modified to suit individual needs. They provide good resistance to most chemicals. Care must be taken to insure good surface preparation and environmental conditions during application.

4.3 Pigments

4.3.1 Pigments such as red lead, zinc chromate, and zinc phosphate inhibit corrosion. Use of red lead and zinc chromate should be avoided because of health risks associated with heavy metals. Zinc phosphate performs well especially in highly acidic environments.

4.3.2 Pigments such as inorganic zinc protect with galvanic action. In way of small pinholes and cracks, the pigment will sacrifice itself to the metal to prevent corrosion. Inorganic zinc should not be used in tanks with inert gas systems.

5. Selection of Ballast Tank Coatings

5.1 Several factors will govern the selection of a coating for a ballast tank. In an effort to avoid structural failure from scantlings decreased by corrosion, classification societies have incorporated requirements for ballast tank coating systems and maximum allowable corrosion into design regulations. Consideration must be given to the following.

5.2 Type of ballast being carried in the tank (clean/dirty).

5.2.1 Thermoplastics - In a dirty ballast tank, a thermoplastic paint may be dissolved by a solvent mixed with the ballast water.

5.2.2 Thermosets - Care must be taken to make sure there will be no reaction between the coating and the ballast water.

5.2.3 Inorganic zinc paints are only effective in salt water.

5.3 Amount of time ballast will be carried in the tank.

5.3.1 Surfaces that will be immersed for long periods of time should not use pigments that are inhibitors or inorganic zinc. Pigments that act as inhibitors are water soluble and if they are dissolved, the paint will no longer be effective. Paints with inorganic zinc will sacrifice themselves quickly if left immersed for long periods of time.

5.3.2 Paints that create a barrier between the ballast and the metal such as epoxy resin or coal tar pitch should be used.

5.4 Frequency of ballasting and deballasting.

5.4.1 Cathodic protection requires a day after submerging to become fully effective. Tanks that are full for short periods of time should not rely on sacrificial anodes.

5.5 Level at which the ballast will be carried.

6. Structural Design

6.1 Avoid Areas of Stress Concentration

6.1.1 Areas with stress concentration and large deflections should avoid thick or brittle coatings.

6.2 Avoid stiffener/girder shadow area (bulb/angle/tee)

6.2.1 Shadow areas may be neglected or receive poor covering during the final tank painting and should be avoided.

6.3 Stiffener Selection

6.3.1 Smooth bulb flat stiffeners are preferable. If not then use angles or rolled Tees. Fabricated Tees would be the last choice because of flame-cut edges and welds.

6.4 Wherever possible provide means for drainage.

6.4.1 Intersection of longitudinals and frames.

6.4.2 Use lightening holes or scallops in horizontal members.

6.5 Joining of structure

6.5.1 Butt welded structures are preferable to lap welded.

6.5.2 Use continuous fillet welding rather than intermittent welding.

6.6 Edge rounding and grinding

6.6.1 Edges should be rounded or beveled to avoid breaks in the coating.

7. In-Tank Piping Requirements

7.1 Strainers

7.1.1 Doubler plate or fiberglass plate under bellmouth strainer.

7.2 Threaded connections

7.2.1 Threaded connections inside ballast tanks should be galvanized and coated.

7.3 Inert gas system

7.3.1 Provide adequate means for inert gases and gas freeing.

7.4 Pipe coatings

7.4.1 Care should be taken to insure that the underside and backside of metal are properly coated.

8. Surface Preparation

8.1 Soft coatings require a minimum of Commercial Blast Cleaned Surface Finish (SSPC-SP-6, NACE No. 3, SSI Sa 2) and a reasonably dry surface.

8.2 Hard coatings require a minimum of Near White Blast Cleaned Surface Finish (SSPC-SP-10, NACE No. 2, SSI Sa 2.5) for acceptable adhesion.

8.3 Inorganic Zinc requires a White Metal Blast Cleaned Surface Finish (SSPC-SP-5, NACE No. 1, SSI Sa 3) for galvanic action to occur.

9. Design of Other Protection Systems

9.1 Anode placement
9.2 Anode sizing

APPENDIX B. SURVEY QUESTIONNAIRE AND RESPONSES

A questionnaire concerning corrosion control and the service, design and production of ships' tanks was distributed to vessel builders, owners and operators. The questions were compiled from corrosion control information found in recent literature. In addition, several new and previously suggested concepts for corrosion control in tanks were presented to elicit industry comments. The questionnaire was aimed at the double hulled ballast spaces of new tankers, but had broad general application to all vessel types and tank services. Some respondents had experience with double hulled vessels and their answers reflect that fact.

Twenty eight questionnaires were sent out and twelve completed questionnaires were returned. Some responders offered qualifying comments regarding the questions, while others provided additional suggestions. Addressees and those returning the questionnaires are listed in Appendix A. Two participating companies provided interviews:

- Maritime Overseas Corporation (Messrs. James Cruikshank and Jan Ziobro)
- Military Sealift Command (Mr. James Baker)

These interviews helped to temper the simplicity of the questionnaire and provided insights to the reality of operating considerations as well as the parameters of existing regulations.

The questions broached by the questionnaire and the answers provided by the respondents are given below. Each question was followed by a numerical answer to be selected by the responder, with 1 indicating agreement with the question and 5 indicating disagreement. The numbers in between allowed a weighted answer with regard to the strength of agreement or disagreement. Immediately following each question below is the range and the average of all answers received. Also included, and perhaps more meaningful, are synopses of the comments by the respondents. As mentioned above, the questions were divided into categories of service, design and production.

SERVICE

Damage to coatings in ballast tanks can occur in several ways with regard to service:

1) Working of flexible structure in a seaway causing cracking and deterioration of coating. This is especially prevalent with lighter high tensile steel structure and thickness reduced due to classification society allowance for corrosion control.

Range = 1-4 Average = 2.3 (Slight Agreement)

- The coating can be more elastic than the steel structure. Research has led to the development of coatings which take on a flexibility ratio very similar to that of the surfaces on which applied. Choice of the right coating can negate the flexing structure effect.

- Severe flexure is an indication of high stress. If the structure flexes enough to cause the coating to crack, the structure may be inadequate. In time, the steel may fracture due to fatigue.

- The structure must be made adequate to support the coating without damaging it, not vice versa. If the coating shows signs of cracking at a typically flexible detail, and if the coating specification, application and inspection have been found in good order, then redesign or reinforcement of the connection should be explored. A more flexible coating is not the answer in these cases. Flexing and cracking of coatings could be more problematic with high strength steel, if the connections are not adequately designed.

- Although a possible problem in the past, reduced thickness for corrosion control are no longer allowed by classification societies. Reduced scantlings are undesirable from both a corrosion and a fatigue point of view.

2) Wear and tear caused by crew members or other personnel moving about the tank.

Range = 1-5 Average = 2.7 (Indifference)

- In the operation of the vessel this is not a problem as any wear of this type is a long term factor. Normal routine inspection by the crew is at about 6 month intervals. Inspections are usually accomplished over the same path in each tank, therefore, there is not a lot of traffic to deteriorate the coating to any great extent.

3) Wear can be caused when tanks are mucked out of sand and silt with shovels or other convenience.

Range = 1-4 Average = 1.7 (Slight Agreement)

- Ballast tanks are generally cleaned up prior to survey, inspections, etc., which also keeps any possible wear down.

- Normal practice is to use a hose to rid tanks of accumulated sand and silt from ballast. The debris is herded toward the suctions and pumped out. Portable eductors are also used. This is adequate where clean, fresh water ballast is used. Where ballast is pumped aboard from below the vessel while docked, the bottom is inevitably stirred up and mud and silt will accumulate. In this case, the majority of the debris is hosed and the remainder is then dug out at aft end if needed. In double bottom tanks, access to the tanks for cleaning can be facilitated by the use of vertical trunks. These trunks are designed into the vessel on centerline at the aft end of the tanks.

- It takes approximately eight to ten days for silt to settle out in a ballast tank. If properly done and before the silt has settled, dockside ballast water could be changed with clean water mid ocean. This is one way to partially eliminate the many faceted problem of silt in the ballast water.

4) Erosion of coatings by constant sloshing of ballast water, containing abrasive particles, back and forth in bays between structural members.

Range = 1-4 Average = 2.3 (Slight Agreement)

- Partially filled ballast tanks, containing silt in the water, could cause erosion over the long term due to sloshing. However, ballast tanks are normally pressed full, which precludes the effects of sloshing, greatly reduces circulation in the tank, and allows the silt to settle. Also, the ballasting operation is usually accomplished in port, without ship motions. Therefore, sloshing is not considered a real factor in the erosion of coatings, and can be disregarded.

- Ballast water with abrasive particles will cause erosion at the ballast line entry and suction points, especially with soft zinc coatings. The plates under the line entries and the suction bellmouths will wear excessively. These plates should be increased in thickness and coatings under the bellmouths should be maintained in service. The use of 800 microns of fiber-glass flake coating is recommended in these areas.

5) Heating and cooling of tank causing sweating and condensation.

Range = 1-5 Average = 2.3 (Slight Agreement)

- Cargo temperatures of 120 to 160 degrees Fahrenheit (50-70 ^{o}C) in tanks properly coated for these temperatures should not cause a problem with corrosion. Sweating and condensation, due to heating and cooling of the cargo in a partially filled tank should also not cause corrosion. The tank coating must be suitable for the temperature and its surface must not be compromised (cracked, peeling, holidays, etc.).

- The heat, sweating and condensation will accelerate corrosion in way of any compromised coating and cause additional damage of the coating due to spawling of the lining attached to corroded steel.

6) Corrosion is aggravated in tanks adjacent to tanks carrying high temperature cargo.

Range = 1-4 Average = 2.0 (Slight Agreement)

- Modern practice moves fuel oil away from double bottom ballast tanks, alleviating part of this problem. However, it is still a problem if the cargo tanks above the double bottom ballast tanks are heated. Proper coatings should be used in adjacent tanks to resist heating. In this case, conditions causing corrosion to be prevented or accelerated are the same as in Question 5 above.

7) Pitting is likely to occur on horizontal surfaces low in the tank with inadequate drainage at the edges of stiffeners and around access holes.

Range = 1-4 Average = 1.6 (Slight Agreement)

- Pitting on horizontal surfaces can occur anywhere in inadequately protected cargo tanks or those in which the corrosion protection system has begun to fail. Under these conditions, major pitting can appear in the aft bays of cargo oil tanks, especially if high sulfur oil is being carried. Pitting is not usually a problem in ballast tanks.

- The primary protection against pitting is an adequate corrosion protection coating, supplemented by cathodic protection with anodes properly located and providing the correct current density.

- Corrosion at the edges of stiffeners and around access holes is exacerbated by sludge, silt, or mud accumulation in way of the compromised coating.

- Scallops, which aid drainage, should be generous with at least 50 to 75 mm (2 to 3 inch) radii.

- Horizontals with flanges rising above the web, e.g., tees and fabricated angles, do not drain freely and should be avoided.

- Corrosion on edges can be minimized with sufficient edge grinding and stripe coating. Two stripe coats are desirable. Timing of the coats is important. Application of the stripe coats, if done first, must not delay the finish coats to the point where the steel loses its blast. If striping is done between finish coats, time must be allowed so that uncured coatings are not damaged by worker activity, yet maximum curing intervals between coats must not be exceeded.

DESIGN

For longest life of coatings, the following recommendations should be adhered to with regard to design:

1) Butt welded joints should be used whenever possible; lap joints, rivets and internal bolted connections should be avoided.

Range = 1-2 Average = 1.2 (Agreement)

- Not many lap joints, nor riveted or bolted connections, are utilized in tank construction today. Butt welding is the preferred method of attachment.

- Where these other attachment methods are employed for brackets, ladders and possibly pipe support attachments, the attachment points should be adequately protected against corrosion.

- Threaded fasteners should be galvanized and coated.

2) Threaded connections should not be used, or should be made using corrosion resistant materials.

Range = 1-3 Average = 1.3 (Agreement)

- The only threads normally allowed would be on bolts for ladders and pipe supports.

- Monel is the preferred material for bolts. They may be galvanized and coated.

3) Structural support members should be of simple shapes, such as smooth round bars or pipe for ease in applying coatings.

Range = 1-2 Average = 1.2 (Agreement)

- Usually hollow sections are utilized on deck, for main pipe supports, not in tanks. In tanks, only solid sections should be used, to prevent undetected internal corrosion.

- Round bars and pipe, while good for coating, may not be the most efficient sections to use in some cases due to either strength or structural limitations, or both.

4) Bulb flats, which have contoured rounded edges promote better surface preparation for coatings, promote reception of paint, and are less prone to physical damage than conventionally fabricated "T" or "L" stiffeners having sharper corners. The absence of weld

during production of bulb shapes increases the life of the coating.

Range = 1-3   Average = 1.2   (Agreement)

- Larger bulb flats are fabricated by welding the bulb to the web and require striping like any other built-up section.

- While good for coating, bulbs are heavier than equivalent rolled angles and fabricated angle and tee sections and are not used by shipyards because of the additional cost.

- Japanese bulb flats are made from flat sections and have sharper edges around the bulb than the European bulb flats, negating some of the advantages of bulb flats.

- Yards with automatic welding equipment capable of producing built-up sections cheaply will prefer to use built-up sections. Extra effort, including edge grinding and striping, must then be put into the corrosion control coating system, its application, inspection and upkeep.

5) Diaphragm plates, where they can be logically fitted in lieu of stiffeners, are useful to provide stiffer structure and minimize sloshing of ballast which has been shown to erode coatings.

Range = 1-5   Average = 2.2   (Slight Agreement)

- Initial design should provide adequate thicknesses and minimize the use of panel breakers, but conventional structures with edge grinding and stripe coating are the reality. (See also the reply to Service Question 4 above regarding sloshing).

- Diaphragm plate structures can be difficult to construct, inspect and maintain. They also increase coating areas.

6) A reduced number of horizontal stiffeners on vertical surfaces reduces corrosion problems by minimizing horizontal surfaces that create standing pools of water.

Range = 1-4   Average = 1.7 (Slight Agreement)

- Normally a minimum of 3 horizontal stringers are fitted on the transverse bulkheads of each tank. Adequate drainage is usually provided where vertical stiffeners pass through these stringers. These, together with access and scallop holes in the stringers, can minimize water and sludge retention.

- In double hull tankers with one center tank, the longitudinal bulkheads are smooth on the cargo tank side. Accumulation of sludge is not a problem.

- In double hull vessels with multiple longitudinal bulkheads and cargo tanks across the vessel, some tanks will have horizontal stiffeners. To minimize the pooling of water, silt and sludge on the stiffener side of these bulkheads, a number of measures may be taken. Bulb flats or rolled angles may be used, allowing the water and silt to shed as the vessel rolls. Where tees or built-up sections with vertical lips above the web are used, generous scallops are helpful in draining liquid, silt and sludge. The scallops should be as large as possible, with experience being the best guide. Although these steps prevent the accumulation of unwanted liquid and debris, the best prevention is a properly maintained effective coating.

7) The negative side of the rolling tolerances of the steel used in shipbuilding can significantly cut into the corrosion allowance. It is either recommended to either tighten the rolling tolerances or increase the corrosion allowances accordingly.

Range = 1-5 Average = 2.4 (Slight Agreement)

- In the past, the inability of steel mills to produce plate to the specified thickness resulted in plates being slightly thicker or thinner than the nominal thickness and rolling tolerances were the accepted norm. Today, thickness controls at mills are much tighter and plates can be rolled very close to the ordered thickness. Some builders have ordered plates to the low end of the rolling tolerance for the specified thickness. This results in a vessel with a reduced corrosion allowance. When the plates are gauged, corrosion will be determined on the basis of the original specified thickness and under-tolerance plates will require premature replacement.

- The rolling tolerance is insignificant compared to the classification society corrosion requirements of 1-2 mm.

- A change in the International Association of Classification Societies (IACS) requirements, initiated through the Tanker Structural Cooperative Forum, has limited the under thickness tolerance to 0.3 mm below the nominal plate thickness. This has helped to retain the intended corrosion allowance and lessened the early replacement of wasted plating.

8) To supply fresh air into tanks during inspections provide inert gas (IGS) and ballast piping systems that have connections to fresh air supplies.

Range = 1-5 Average = 2.3 (Slight Agreement)

- International Maritime Organization (IMO) recommends that a vessel be capable of supplying fresh air from the Inert Gas System (IGS) to the double bottom tanks using a fixed tap into the IGS between the deck seal outlet and the nonreturn valve. Fresh air is also supplied from IGS main using portable ducting which is directed into ballast tank cleaning hatches on deck.

- Gas freeing, especially in the double bottom, is extremely difficult and time consuming. Some vessels are fitted with vertical trunks on the centerline at the transverse bulkheads which allow an additional air path for gas freeing and ventilation, as well as providing access to the tanks for cleaning.

9) Use fiberglass reinforced plastic (FRP) or composite gratings, walkways and ladders wherever possible. If these items are made of items dissimilar to steel, provide dielectric barrier materials or sealant to isolate dissimilar metals. For the same reason FRP can be used for ballast piping.

Range = 1-5 Average = 2.3 (Slight Agreement)

- The use of FRP grating is a good idea, but definitely an extra cost item. Walkways and ladders would also be a possible alternatives to steel. However, service experience is that FRP gratings often fracture on impact and should not be used where heavy objects may be dropped on them.

- It is impractical to use FRP or composite gratings extensively because stock sizes do not always match application requirements.

- The need for isolation of dissimilar metals is dependent on their relative positions in the galvanic series and their area ratios.

- FRP piping is functional and easy to repair if damaged and has been used extensively on some vessels. The major objection is its initial cost, with one operator paying more than $500,000 extra for FRP piping in a 300,000 dwt tanker built in Japan. Cost effectiveness, even on a life cycle basis, is probably not in favor of FRP piping.

10) Minimize structural features that can cause shadowing of areas during paint spraying.

Range = 1-4 Average = 1.9 (Slight Agreement)

- Judicious placement of structure during the design phase, with consideration given to coating during construction, can decrease shadow areas. The use of coating-friendly structural sections can also minimize shadow areas. However, in reality, the structure must first serve the strength requirements of the vessel, and the paint application secondly.

- To guard against corrosion caused by holidays in the coating in shadow areas, cathodic protection is used as a backup system.

11) Provide air escape paths for all seawater ballast tanks to prevent the formation of air pockets and to improve the effectiveness of sacrificial anodes, particularly in bottom tanks.

Range = 1-3   Average = 1.3 (Agreement)

- Provision of venting of trapped air should be a normal feature of the tank structure. Generous scallops of 50 to 75 mm or greater radius should be applied to structures to alleviate any air pockets at the tops of tanks.

12) The design should take into account not only potential causes of damage to the coating but also ease of coating application and subsequent quality checks. The designers should consider the coating of the space when considering the steel work assembly sequence, so that the steel and outfit work sequence can be optimized to minimize damage to the coatings.

Range = 1   Average = 1.0 (Agreement)

- The ideal environment for coating life is to have no activity in a tank after the coating is applied, or at least until the coating has cured. In addition, a tank designed with total access and no sharp edges would increase the overall life of coatings and require a minimum of touch up through out its life.

13) Deadrise of bottom achieves reduced corrosion through improved drainage and should therefore be considered in future designs.

Range = 1-5   Average = 2.2   (Slight Agreement)

- Deadrise of tank top is not needed in double hulled vessels as the bottom of the cargo tanks are smooth, without protruding structures. Drainage is achieved operationally by trimming the ship aft.

- Deadrise improves drainage, but producibility is the overriding concern.

- There is no point in providing deadrise in ballast tanks, since operators rarely strip out these tanks because of the time required.

14) On side shell and longitudinal bulkheads, sloped longitudinals could be considered with, say, a 10 degree incline to shed water and debris.

Range = 1-5   Average = 2.2   (Slight Agreement)

- Sloped longitudinals are difficult to construct and less effective structurally. They are not used because of overriding concerns for producibility and strength.

15) To eliminate horizontal surfaces and improve cleaning, coating, and drainage, corrugated bulkheads can be used.

Range = 1-5   Average = 2.3   (Slight Agreement)

- Despite their attributes, corrugated bulkheads have a history of cracks and leakage in service.

- Corrugated bulkheads are not used in large tankers because of their strength limitations.

16) For structures and details known to be subject to heavy corrosion, use increased scantlings.

Range = 1-5   Average = 2.5   (Slight Agreement)

- Increased thicknesses in areas subject to heavy corrosion are all right in theory, but with the new classification society rules on coating integrity, an initial good coating is more desirable to guard against corrosion. If coating breakdown exceeds the classification criteria, the space would be subject to more frequent and intense survey at additional cost and time for the operator. The added first cost of increased scantlings is of no benefit and the money is better spent in purchasing a more effective coating system.

- Redesign of details is preferable to heavier scantlings.

17) Full scantlings as opposed to reduced scantlings can be proved to have roughly equivalent or lower life cycle costs and provide valuable insurance against unexpected coating failure over a 20 year life.

Range = 1-3   Average = 2.2   (Slight Agreement)

- Under current classification rules, reduced scantlings for corrosion control measures are no longer accepted. Only full or increased scantlings are permitted. Use of full scantlings, together with tighter survey requirements, is insurance on structure's life.

18) Oversizing double bottom heights and wing tanks widths facilitates easier access for construction and maintenance while increasing the ship's safety.

Range = 1-3 Average = 1.9 (Slight Agreement)

- Access is an important consideration in the sizing of double bottom heights and wing tank widths, in addition to other considerations, such as tank shape and type.

- Oversizing must not be without limit. The intent is to permit inspection without staging or having to climb, while at the same time meeting ballasting and safety requirements. Oversizing ballast tanks results in significant cost increases.

- Double bottom heights greater than 3 m will make inspection and maintenance of the tanktop underside structure more difficult.

PRODUCTION

For the longest life of coatings, the following recommendations should be adhered to with regard to production:

1) In order to avoid the creation of tight crevices that will retain water and rapidly corrode tanks, all welds should be continuous - intermittent, spot, stitch, or skip welding should not be permitted.

Range = 1-3 verage = 1.4 (Agreement)

- Continuous welds should be used in all "wet" areas, e.g., in accommodation structures inside and out, as well as in tanks or anywhere liquid collects.

2) All temporary construction fixtures and brackets, and all weld spatter, arc strikes, etc. must be ground smooth prior to painting. Badly undercut welds must be removed and rewelded.

Range = 1-5 Average = 1.3 (Agreement)

- The shipyard standard practices should limit these items and the owner's inspection team must hold the yard to those limits. Many of these problems occur in the prefab shop where inspection teams must be on the alert to discover the problem before the assembly is ready for the block move stage, where any rework will almost certainly hold up production and will be more difficult to rectify.

- In some instances it may be advantageous to leave brackets and staging in place to facilitate post-construction inspections. Brackets and staging left in place must be properly coated.

- Undercut welds need only be rewelded rather than be removed.

- Grinding smooth is not necessary to achieve a good coating application.

3) Best overall coating performance can be obtained when all sharp and flame cut edges are ground to a maximum edge radius of 1/2 the plate thickness.

Range = 1-5 Average = 1.8 (Slight Agreement)

- A radius of 3/8 inch is sufficient for all plate thicknesses.

- Edge grinding should be independent of plate thickness. Studies indicate a 5 mm radius or a 120 degree bevel is equivalent to a flat surface in terms of coatings. Most ship specifications permit a 1-2 mm radius as acceptable.

- A 1 mm chamfer (each leg) will provide adequate coating performance.

- The shipyard should demonstrate the edges they are willing to include in the specifications. The agreed-upon edge is included in the specifications and all production edges must "feel smooth to the touch" comparable to that edge. The yard should not have difficulty producing this edge and coatings will generally conform to an edge that is "smooth to the touch." However, two stripe coats are still recommended to insure coating integrity at the edges.

- Use low surface tension coatings which do not thin out as they dry at sharp edges and leave more coating protection than possible previously.

4) Field welding should be reduced to an absolute minimum as the coating may burn far beyond the weld area and the damaged area may tend to be less accessible for recoating.

Range = 1-2 Average = 1.4 (Agreement)

- This must be clearly stated in the Specifications and the Yard Standards Booklet and must be strictly enforced by the owner's inspectors. Normally, grinding and recoating should be permitted on erection joints only. Specifications should require all other field welds to be approved by inspectors.

- Galvanized piping may be damaged by field welding and prying pipes together on location instead of welding the pipe in the sheds and providing flanged field joints. Damaged galvanizing can be repaired by the specified field procedure, but this should be avoided.

5) Surface and coating inspections during and after building should concentrate on any horizontal surfaces that will trap mud and debris, since this is where most coatings failures initiate.

Range = 1-5   Average = 2.8   (Indifference)

- Concentrating inspection efforts on the bottoms and horizontal surfaces will provide little control or continued protection. It may improve pitting control, but tank vessel corrosion is not selective and all areas of the tank must be thoroughly inspected.

- Sharp edges of stiffeners and corners of slots should also be inspected.

- Provision of accessible structure with climbing aids and safe walkways will facilitate the inspection of horizontal surfaces..

SUGGESTED IDEAS

The following are some ideas that were proposed in the past or conceived for the future to help alleviate the problem of corrosion by design or positive action. Here indication of response was by comments in the space below each entry.

1) Use a ballast additive that, when combined with the salt water, will decrease the effect of corrosion.

- Oxygen scavengers are used successfully in ballast water of laid-up vessels. Experience with a VLCC laid up for 13 years showed the ballast tanks to be perfect. However, use on a regular basis would be too expensive and owners might not see a tangible result for at least ten years.

- Possible toxicity and environmental issues which may restrict the discharge of ballast.

- Use fresh water ballast where possible, as it may be less costly.

- Proper coating with cathodic protection and periodic touch-up probably more cost effective.

- Requires space for additional equipment and supplies. Adds maintenance and an additional operation not needed by the crew.

2) Make the tank shell and boundary bulkheads from plate stiffener combinations. These units will be made up of one stiffener spacing of plate and run in the longitudinal direction. Each

unit is fabricated by bending a plate forming a stiffener section at one edge, the other edge being flat to be able to weld to the adjacent unit. A tank shell or bulkheads are made up by welding these units edge to edge. The advantage is that there is only one weld seam, where the units weld to one another, not the usual two where the stiffener welds to the plate. Therefore there is less chance for weld corrosion.

- Flanged plates do not fit into current shipyard production facilities and processes and are not normally acceptable to shipyards.

- Less welding is always better and cheaper.

- Increases the risk of stress corrosion at the plate bending edges, possibly creating an additional problem area.

- This is not a recommended solution to corrosion. Particular concerns include excessive fit-up time, reduced section modulus, lack of stiffening to the flange, and significant production problems in areas of hull curvature. It is possible that such a structural arrangement would not be acceptable to classification societies.

- Improved preparation and inspection of welds and fabrication details may accomplish the same at less cost.

- Weld corrosion in erection joints and field welds is the larger problem. Method increases the shell welds which are a large cause of structural problems.

- This method limits design flexibility and complicates fabrication and alignment practices.

3) Filter ballast water to prevent silt and mud from scouring the tank coating or collecting on horizontal surfaces. This also helps reduce microbiological influenced corrosion (MIC) in these areas.

- Most ballast pumps have suction filters. Debris can be a problem at the beginning of ballasting with the vessel at deep draft and the sea suction boxes near the harbor bottom. Can overcome this problem by exchanging ballast water mid ocean before silt and mud settle.

- Delay ballasting until the end of the discharge cycle when there is more clearance between the sea suction and the bottom. Practice “good housekeeping” by periodically cleaning tanks.

- Impractical for heavy mud situations.

- Very fine filters would be required. The first time they clogged during a tight discharge/ballast operation, they would be dispensed with by the small, hard-pressed crew.

- An impractical approach to corrosion control in that the benefit would never outweigh the cost. The frequent changing of filters during port time would be unacceptable operationally.

- Good idea, but does such a system exist? What would the system cost?
- Would be quite costly and would tend to slow ballasting rates significantly or require extremely large filtering units, with attendant maintenance and repair costs.

- Scouring/erosion of coatings is not a major problem.

4) A venting and desiccant system could be developed to remove moisture in the air when the ballast tanks are empty.

- Nice in theory, but the equipment and material costs could be prohibitive, considering a VLCC has about 110,000 tons of ballast water. Where would

  you store desiccant and how would you handle it? Stored desiccant would decrease deadweight.

- DH systems are fairly common for void spaces on certain types of vessel where "sweating" is a problem. It is doubtful that they would work or be effective on ballast tanks with residual free water available in empty tanks.

- Impractical when trading on short loaded trips of say less than 3 days. Probably uneconomical too.

- Such a corrosion control measure would prove expensive and maintenance intensive and create storage/handling problems.

- Good idea.

- Would it prevent corrosion? As long as tanks are washed and dried when empty, proper coating should do the rest.

- A venting and desiccant system appears to be overkill and impractical. Good venting system design is always desirable.

5) Install removable inspection ladders, that can be mounted on permanent non corrosive tracks

in the tanks. These ladders would be positively mounted but be able to roll forward and aft as needed by the inspector.

- Good in theory, but it can be dangerous to climb a ladder that may move in a slippery situation. Better to provide accessible structure that allows close-up inspection.

- An impractical solution with extra costs and excessive corrosion problems.

- Good idea, or have permanent CRES ladders.

- Probably a good idea to enhance inspection of coatings and tank internals.

- Given the amount of structure in the double skin tanks, this system may not be practical.

- Providing improved means and access for inspection will improve the comprehensiveness of inspections and reduce the time required, which will pay off in the long-term.

- Should use stainless steel tracks and fiberglass ladders, but how much cost would be added to vessel?

- Improved inspection during coating is the biggest factor in improving coating life. Installation of tracks in tanks is not clear.

- Moving portable ladders can damage coating. Use permanent ladders, which are safer.

- Portable inspection ladders are always being discussed but are costly, difficult to maintain, and have safety problems. There are many new methods and types of equipment available which negate the consideration of built-in inspection facilities.

- Conventional tankers have transverse webs at about 4 m intervals which would prevent these ladders from rolling forward and aft as needed.

6) In unidirectional double skin tankers, install an adjustable portable trolley system in the ballast tanks that can be moved unimpeded without rails (using the sides of each cell for guidance). Then each of the double bottom cells, as well as the wing tank cells may be inspected with a minimum effort and energy.

- With a minimum double bottom height of 2 m, inspection is easy.

- Adjustable trolley would prove expensive, difficult to install and would cause excessive damage, thereby increasing corrosion rather than decreasing it.

- Probably a good idea to enhance inspection of coatings and tank internals.

- Good idea, but system needs to be better defined.

- The trolley should not be an installed item, which implies some fixtures in the cell.

- Use a lifeline with safety harness for fall protection and climb or crawl these spaces. Staples should be installed as necessary for the lifelines.
- Inspection during service is not the problem, it is the inspection and quality control during coating that is important.

- Adjustable portable trolley systems may be helpful for barges and very small vessel inspections, but proper design, such as strategically located floors, can eliminate the need.

- A mechanical system, such as a trolley, is expensive and restricts arrangements. Maintenance of this system can be difficult. Best design features are fixed structures, such as stringers and walkways, which can be installed at reasonable cost and allow inspection and repair work to be carried out safely and efficiently.

7) Keep tanks small - Small tanks would have less forces on them (less flexing). The eroding effect of silt and solids in the tank would be minimized, coating and maintenance may be easier, controlling the environment in the tank may be easier.

- This would cause an increase in light ship weight and unacceptable increases in initial and operating costs.

- To provide the required ballast capacity, the number of tanks and painting area will increase and maintenance will be more difficult.

- Smaller tanks are more difficult to coat than larger tanks at the manufacturing stage. However, smaller tanks would be easier to maintain.

- Small tanks are more expensive due to added piping, and are less producible.

- Smaller tanks mean greater steel weight and far greater cost at new building. Coating maintenance would probably be more difficult as the space is constricting.

- A large part of inspection and maintenance time is set-up or preparatory activities. Smaller tanks imply a greater number of tanks, which increase total preparation time and cost.

- What is the percent contribution of flexing to corrosion, is it large? Smaller tanks mean more places for coating to fail. They are higher cost to repair and provide limited access for equipment and removal of abrasives.

- Larger tanks are easier to prepare, paint and maintain.

- Smaller tanks increase corrosion areas.

- Use of smaller tanks would provide stiffness achievable through normal design practices while increasing the number of tanks. Effects of silt and solids in the tanks would be reduced per tank, but not in total for the vessel. More tanks mean more steel, more complex piping and pumping systems, greater stripping operations, etc. "There are no free lunches!"

8) Use struts in lieu of solid floors in double bottom and intermediate side stingers. Less welding and less material to corrode will be the results. Scaffolding will easily be able to be placed on struts to facilitate inspection in side tanks.

- Use of struts would present more problems with edges to be coated. Also there would be many point loads instead of spreading loading/stress throughout the hull structure by transverses/diaphragms.

- Struts are common practice in barges. There must be sufficient material to satisfy the strength requirements. Struts represent more sharp edges and potential points of failure.

- Structural considerations are more important than coating.

- Struts are lightweight solution, however, they encourage the very problems addressed by this survey. The sharp edges, weld areas, etc. are subject to corrosion. The struts are also subject to structural failure over time.

- Agree that there is less welding and less material to corrode, however, proper coating and application should also minimize corrosion.

- Not suggested for a ship that can possibly go aground.

- Using struts in lieu of floor plates would only tend to increase corrosion control and inspection problems. With proper design, floor plates can eliminate the need for scaffolding and plates are much easier to coat and maintain than structural shapes.

- Struts cannot be substituted for floors in VLCCs from a strength point of view.

9) To limit mud accumulation in ballast tanks and minimize the microbiological influenced corrosion (MIC) under mud deposits, a polymeric dispersant can be injected into the discharge side of the ballast pump during ballast loading.

- May present operational cost and environmental problems. Currently, many ports require vessels to arrive with clean ballast taken on in mid-ocean to avoid transfer of microorganisms and aquatic life. This is the better solution.
- Environmental impact when deballasting.
- Not a good idea for short trips, based on experience with currently available dispersants. It is not known how they work for ballast legs longer than six days.
- Because of cost, dispersants are generally used only to clean up ballast tanks prior to surveys, inspections, etc.
- Will polymeric dispersant prevent MIC? Proper coating and maintenance at all times should avoid corrosion. No mud, no MIC.
- We have used dispersant extensively. The effectiveness in mud removal is questionable, but it does seem to improve coating life.
- Not cost effective. Would opt for a good coating system instead.
- Paint provides sufficient protection against MIC, which is not a significant problem.
- Dispersants are very beneficial in reducing mud deposits. Experience shows that without continual attention, mud deposits will form, but they will not be as large as without a dispersant.

The following item and general comment were added by one respondent:

10) Sacrificial anodes installed at newbuilding act as a back up to the coating system and need only be relatively few in number. This has proven successful and is pretty much a standard process.

GENERAL COMMENT - In a ballasted tank, sloshing occurs at the surface and any silt should be at

the bottom in dead water areas. Erosion does occur at ballast line entry and suction points (this is a major problem with soft zinc coatings.)
Modern and even older generation coal tar epoxy coating systems are lasting 10-14 years without appreciably failing, without any of the technical niceties suggested. Unless there is a clear demonstration of short term saving to the owner, “extra” cost items will not be implemented.

Structural design changes, such as using good old-fashioned European bulb bar, are however, seen as a positive move in the US - accepted by both yards and owners.