CORROSION PROTECTION OF CARGO TANKS

PRESENTED BY:

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ABSTRACT

Since the seventies, a few generations of crude oil tankers of both single hull and double hull types have been brought into service by the owners / operators belonging to the Tanker Structure Cooperative Forum, and of course others. A number of these vessels have encountered corrosion problems in cargo oil tanks, in particular vapor space corrosion, pitting, and microbial influenced corrosion. This paper looks at such cargo tank corrosion – its reasons and remedies.

The potential causes, mitigation strategies and maintenance methodology related to the control of cargo tank corrosion are discussed in this paper. Among other measures, the control of risk associated with excessive vapor space corrosion, pitting, and microbial influenced corrosion is addressed. Both existing vessels and new building are considered.

TABLE OF CONTENTS

Section **Contents**

1.0 **Background**

1.1 Types of Corrosion
1.2 TSCF Experience Related to Cargo Tank Corrosion
1.3 Questions Raised by the TSCF Experience

2.0 **Objectives and Methodology of the Study**

3.0 **TSCF Investigations of Cargo Tank Corrosion**

3.1 Corrosion Probe and Coupon Investigations
3.2 Vapor Space Gas and Water Condensate Analyses
3.3 Laboratory Simulations using Bottle Tests
3.4 TMCP Steel Investigations
3.5 Biocide and Other Control of MIC in Cargo Tanks
3.6 Effects of COW on Corrosion
3.7 Bacterial Resistance Tests on Tank Coatings
3.8 Cargo Tank Temperature Profile Studies
3.9 In-Service Corrosion Experience and Corrosion Rate Investigations

4.0 **Conclusions Pertinent to Cargo Tank Corrosion Phenomena**

5**.0** **Conclusions Pertinent to Existing Vessels**

5.1 Implementing Ongoing Inspections
5.2 Coating of the Vapor Space and Bottom
5.3 Installation of Anodes for Tank Bottom Pitting
5.4 Ongoing Pit Inspection and Repair
5.5 The Biocide and Chemical Intervention Options

TABLE OF CONTENTS, Continued…

Section **Contents**

6.0 **Conclusions Pertinent to New Building**

- **6.1** Use of Increased Corrosion Margins
- **6.2** Use of Coatings
- **6.3** Structural Design Changes to Improve Drainage
- **6.4** Improvement of Access for Inspection and Maintenance
- **6.5** Other Possible Measures Requiring Further Study

7.0 **Recommended TSCF WG Action Plan**

8.0 **Selected Bibliography and References**

TABLES :

Corrosion Experience and Corrosion Rate Data for Cargo Tanks

1.0 BACKGROUND

A description of TSCF investigations related to cargo tank corrosion are presented in this paper, together with interim results where warranted and a discussion of selected in-service and new building mitigating and remedial actions. Needed future studies are recommended.

1.1 Types of Corrosion

General Corrosion: This type of corrosion generally occurs in areas that are un-coated, and is seen as a crumbly scale over large areas. The process is electrolytic, caused in this case by local electric potential differences between anodic and cathodic sites on the material surface. General corrosion levels currently allowed for in design are typically around 0.1mm per year or less.

Local Corrosion: Highly stressed structural components may tend to flex during alternate compression and tension cycles when the ship is in-service. Surface rust or scale on such components become dislodged, exposing further bare steel. As the material thickness diminishes, the stress on the component is incrementally raised. These effects may contribute to localized increases in corrosion. Corrosion in grooving form may occur at structural intersections. Grooving may also occur because of adverse electrolytic action between the weld material and the base metal. Localized corrosion can also occur in areas of coating failure.

Pitting: Pitting corrosion is commonly found in the bottom plating of tanks and horizontal surfaces of major structural members. On coated surfaces, concentrated attacks of pitting occur at anodic sites of coating damage. Bare steel plates in cargo tanks are often coated with black rust and a residual waxy oil coating from previous cargoes. Breakdown or removal of existing rust patches or cargo residue can also facilitate pitting. Pitting effects are greater where acidic water precipitating out of cargo collects. Pitting is also known to be facilitated by the presence of certain microbes. In some cases, pits may show a tendency to merge to form long grooves and wide scabby patches.

1.2 The TSCF Experience Related to Cargo Tank Corrosion

The TSCF member experience with cargo tank corrosion that lead to the work described in this paper involved the following two main phenomena:

- Accelerated Pitting of Cargo Tank Bottom Plating
- Accelerated Vapor Space Corrosion

Accelerated Pitting of Cargo Tank Bottom Plating

During a 1992 TSCF Work Group meeting, an owner reported excessive pitting in the cargo tanks of a 7 year old VLCC, and during the 1993 Work Group meeting, another owner reported potential MIC in water ballast tanks. These cases were attributed to Microbial Induced Corrosion (MIC), and raised significant concerns.

Similar excessive pitting in the uncoated bottom plating of cargo tanks was again reported in 1995 (TSCF, 1995 and NACE, 1997). A case in point was that of a 150,000 DWT SH tanker less than 5 years old, the average pit depth was 2 to 3 mm, with a density of around 200 to 400 pits per m2 and a maximum pit depth of 5 mm. The pitting corrosion rate of bottom plating in this case is about 0.5 to 1 mm per year, which is about 4 to 5 times higher than normally predicted. This is in addition to any general corrosion wastage in bottom plating.

In another study (TSCF, 1995), pit densities of 200 - 400 pits per square meter were found in tankers of both single hull and double hull types, at only 2 to 5 years of age. These tankers were constructed using either conventional high tensile steel (HTS) or Thermo-Mechanically Controlled Process (TMCP) steel. The average pitting corrosion rate is 0.6 to 1.5mm per year, but the maximum pitting corrosion rate as high as 2.0mm per year has been recorded. Acidity as high as pH 1.0 - 2.0 are measured at the bottom of pits.

The accelerated pitting corrosion rates experienced were thus as high as 4 to 5 the normally anticipated rates, and these experiences were again thought to be due largely to Microbial Influenced Corrosion (MIC) attack. The presence of MIC attack is typically indicated by the appearance of pits-within-pits and stair step look, and was present in these cases.

Bacteria test results related to the TSCF member experience indicated that Sulfate Reducing Bacteria (SRB) existed in the settled water at a high concentration rate of 1000 to 100,000 cells per cubic cm. Later bacteria test results on 11 tankers undertaken by a TSCF member indicated that MIC bacteria consortia exist not only in the settled water and sludge at the bottom of cargo tanks, but also in the water droplets in the crude oil itself. Bacteria having large corrosive effect on steel, namely sulfate-reducing bacteria (SRB) were found in concentrations as high as 100,000 to 10,000,000 per milliliter in the settled water.

Accelerated Vapor Space Corrosion

The corrosion rate for uncoated cargo tank deck plating is ordinarily expected to be 0.10 mm or less per year. However, annual wastage rates as high as 0.25mm have been reported on some ships.

In one class of vessels, excessive scale was found falling off from deckhead structures in uncoated cargo tanks, particularly in the forward part of cargo areas adjacent to the fore peak tank. The general corrosion rate of deck plating amidships was 0.02 to 0.1mm per year which is within the range normally anticipated. However the general corrosion rate at the forward cargo areas is 0.1 to 0.25 mm per year, which is approximately 2 to 3 times greater than normally anticipated.

Normally the thickness at both the forward and after ends of ship have been tapered to levels that are thinner than that amidships. For example, a typical 150,000 DWT Suezmax tanker has 15.0 - 17.0mm deck plate thickness amidships but only 12.5mm in the forward end of ship. The combination of higher general corrosion rate and thinner deck plate thickness increases the related corrosion concerns.

1.3 The Questions Raised by the TSCF Experience

The TSCF experience lead to several questions, leading to the present work. Of particular interest to TSCF were (a) whether currently used TSCF corrosion data and scantling margins were adequate, (b) further understanding the causes and remedies of cargo tank corrosion in general, and (c) development of strategies to combat accelerated corrosion in cargo tanks.

The factors that potentially affect cargo tank corrosion include the composition of crude oil, COW, inert gas, humidity and structural factors including flexibility effects.

Role of Structural Factors: The optimization of structural design and the use of high tensile steels have undoubtedly led to a reduction in the stiffness of the ship's structural members over time. The result may have been an increased degree of flexing which presumably contributes to the shedding of scale on vertical and inverted surfaces. The newly exposed steel presents a renewed opportunity for general corrosion to occur at an accelerated rate. In addition to structural flexibility effects, other structural factors that may affect corrosion rates include member orientation, enhanced local stresses, vibration and slamming.

Role of Inert gas quality: Inert gas should have an oxygen content of less than 8% and at these concentrations the rate of corrosion of steel structure should be reduced. However, for corrosion rates to be essentially not affected, the oxygen content should be below 1% which is not possible to achieve with flue generated inert gas systems.

Sulfurous compounds, and soot in the flue gas, if not sufficiently removed in the water washing process, can also cause accelerated corrosion due to relatively strong concentrations of acid compounds being introduced into the tank along with the inert gas. If the quality of the inert gas is allowed to deteriorate due to in-attention or poor maintenance, then the corrosion rate may increase, particularly on the overhead surfaces in the vapor space of the tank where moisture tends to condense.

Role of Microbial Influence: Microbial Influenced Corrosion is a combination of normal galvanic corrosion processes and the presence of active microbial metabolites which generate corrosive environments that in turn promote galvanic corrosion at an accelerated rate. Bacteria occur in cargo, and their growth may be promoted by various factors, including increased temperatures and stagnant water.

The accelerated pitting of cargo tank bottom plating appeared to be predominantly due to microbial enhancement. Pitting effects are largely local, and hence cannot be economically mitigated by added corrosion margins. Rather, in-service measures to prevent, detect and mitigate the pitting effects are needed.

The bacteria most frequently associated with corrosion of steels are those that generate sulfides, commonly called sulfate-reducing-bacteria (SRB). Shipboard, when bacteria find a niche on a steel surface they can proliferate and a corrosion pit can develop at the site. Evidence of microbial contamination has been confirmed by the presence of bacteria in water samples taken from the bottom of the tank and the presence of active corrosion pits in the bottom plating.

Generally, small lumps with a crust of scale over them are seen and underneath this crust, oily sludge and a few drops of water is found.

Pitting corrosion in tanks contaminated with sulfate reducing bacteria (SRB) is apparently caused because during their life-cycle, the anaerobic (living only in the absence of free oxygen) SRB extract the oxygen from sulfates found in the cargo to oxidize their organic food source and form sulfides, including hydrogen sulfide. These sulfides may be re-oxidized to form acidic sulfates, e.g. sulfuric acid, during the ballast voyage when the cargo tanks are empty.

Typical signs of microbial influenced corrosion are as follows:

- Clusters of pits several cm in diameter found under a cover of organic deposits, for example dirt and rust scale mixed with oil residue.
- High local corrosion rates in pit clusters
- In oil cargo tanks, flat bottomed pits which show a stepwise development with ``stairs'' at the pit edge
- Black color of iron sulfides appearing during removal of cover (quickly disappearing due to oxidation)
- Sulfurous smell, quickly disappearing after ventilation (and possibly pockets of the very poisonous H_2S gas).

Role of TMCP Steel: Some of the vessels involved had been constructed of TMCP steel. Hence there was the added concern as to whether the usage of TMCP steels was a factor that was relevant to the increased corrosion effects experienced. Construction techniques now include the use of higher tensile steels manufactured using the Thermal Mechanical Control Process (TMCP). Compared to conventional air cooled steels, TMCP steel is seen to contain micro-layers at the surface, although differences in chemistry appear to be small. The concern here is whether steels manufactured by TMCP are inherently more prone to corrosion or show greater corrosion rates under marine conditions than the other types of steels.

Role of Coatings and Anodes: The cargo tanks in which these phenomena were experienced were largely uncoated. The need to study the effective and economical use of coatings to mitigate such phenomena thus arose as well. Perhaps the best way to prevent corrosion in tanks is to apply a high quality coating, preferably during new building. Coating of cargo oil tank inner bottom plating and other structure of existing ships has also been occasionally carried out in order to stop pitting attacks, with apparently good results. The coatings used are epoxy based, and applied on properly washed, blast cleaned and salt decontaminated steel surfaces.

When no protective coatings is applied, general corrosion may occur across a large extent of the tank. When applied coatings have failed for whatever reason, corrosion that was previously inhibited will tend to occur. For instance, localized coating defects can lead to breakdown of coating which in turn can lead to accelerated pitting corrosion due to concentrated electrolytic action in the area of the breakdown.

For new-builds, the essential question is whether there are areas of the typical cargo tank structure that may under given circumstances benefit by coating. Where coating will be or has been applied, the issues are the details of the coating to be used for a target life of coating, and how to maintain those coatings in service so that they continue to be effective. It was noted that some companies offer coatings that are validated specifically to cope with cargo oil tank bottom pitting for specified periods of time.

Installation of sacrificial anodes in cargo oil tank inner bottom to avoid pitting that might otherwise occur at locations of coating breakdown is another possibility.

Role of Increased Temperature: That some of the vessels involved in the experience were double hulls lead to questions of whether an enhanced temperature effect was present. The wing and double bottom spaces of a double hull tanker act as thermal barriers which insulate the cargo tanks from the cooling effect of the sea. Elevated temperatures in oil cargoes may be maintained for longer periods of time in double hull tankers than in single hull tankers due to this isolating effect of the empty water ballast tanks, the so-called thermos bottle effect. Consequently, the cargo tank structure may tend to remain at higher cargo temperatures for longer periods of time.

Chemical corrosion processes generally occur faster with increasing temperature. A temperature increase of 10 degree C may approximately double electrolytic reaction rates. Corrosion rates may thus double for every 10 degree C increase in temperature. Also, bacteria in the hot crude oil may thrive for a longer time at the higher temperatures, with consequent increases in any microbial influenced corrosion rates.

Other possibilities to consider as confounding factors in cargo tank corrosion include :

Role of Tank Cleaning Procedures : Crude oil cargoes may cause a waxy or other protective layer to form on the cargo tank steel structures and this layer will help inhibit corrosion. However, certain washing mediums such as hot and cold sea water can remove this protective layer; an increased frequency of crude oil washing can also affect its integrity.

Role of Sulfur Content of Cargo : Crude oils that contain high concentrations of sulfurous constituents can cause high levels of general and pitting corrosion when these components react with entrained or residual sea water to form acidic compounds. In addition, sulfur is cathodic by nature and can promote the formation of an active corrosion cell.

Role of Residual Water: Such water can originate from a number of sources and when it settles out from the cargo can cause electrolytic or microbial influenced corrosion of structural components, particularly on after end tank bottom plating around the suction bell mouths where water tends to accumulate due to the trim of the ship. Excessive residual water creates high humidity conditions in the vapor space, exacerbating corrosion processes therein.

Role of Sludge and Scale: It is usual for significant quantities of sludge and / or scale to be found accumulating in the bottom of cargo tanks. This debris from previous cargoes or dislodged corrosion scale can create an ideal breeding ground for bacteria and also can hide subsequent pitting damage. Accumulated scale / sludge also inhibits proper draining of tanks by blocking drainage holes.

Subsequent TSCF investigations, now described, threw light on some of the above factors involved, and were beneficial in indicating how accelerated cargo tank corrosion can be anticipated and controlled. The efforts also indicated several areas for further study.

2.0 OBJECTIVES AND METHODOLOGY OF THE STUDY

The study reported in this paper has been undertaken by TSCF Work Group 2 lead by Chevron Shipping, and has been carried out over the past five years. The aims of the study are as follows:

- Identify types and extents of corrosion problems in cargo tanks.
- Develop mitigation strategies for the service life
- Consider and recommend related corrosion control requirements for new buildings
- Recommend modifications to the corrosion rate tables V.2, V.3 and V.4 in the existing 1997 TSCF Guidance Manual for Tanker Structures, as warranted.

The methodology used in the study to accomplish the above consists of (a) various TSCF member and committee investigations, and (b) surveys of corrosion experience including corrosion rates and corrosion control practices.

The overall TSCF program investigating various aspects of cargo tank corrosion, in particular vapor space and bottom pitting corrosion in cargo tanks, consisted of the following:

- Corrosion probes and coupon investigations
- Vapor space gas and water condensate analyses
- Laboratory simulation - bottle tests (MIC, Temperature Effects)
- TMCP Steel Investigations
- Biocide and other Control of MIC in Cargo Tanks
- Effects of Crude Oil Washing on Corrosion
- Bacteria resistance tests on Tank Coatings
- Cargo tank temperature profile monitoring on five tankers.
- Collection and analysis of actual in-service data related to corrosion experience, in particular cargo tank corrosion

These investigations and their results are discussed in the next section of this paper.

As one aspect of the TSCF investigations of Cargo Tank Corrosion, the following two questionnaires were used:

Survey I - Corrosion Control Practices
Survey II - In-Service Corrosion Rate Survey

Survey I was first sent in 1998, the responses analyzed. Survey II was sent in 1999. It is of interest to note that Survey II was sent to TSCF members, and also to several others under the auspices of Intertanko. This technical co-operation was aimed at reducing the duplication of effort regarding matters of mutual interest.

The responses to Survey I were helpful in providing data on corrosion related design and corrosion control practices for 79 crude and product carriers. The responses to Survey II provided corrosion rate data for some 29 crude and product carriers. The unscreened data base consisted of about 850 gaugings, which reduced to about 600 after screening, primarily to omit data resulting in negative corrosion rates. All except 50 of these 600 odd screened data pertained to Cargo Only tanks. There was minimal or no information on tanks with anodes, and minimal or no information on pitting or grooving. Hence only the cargo only tank data were analyzed for general corrosion rates.

Survey results are discussed later in this paper.

Based on the various studies, survey responses and committee deliberations, mitigation strategies for both existing vessels and new building were developed to anticipate and control the effects of accelerated cargo tank corrosion. The results are presented in later sections of this paper.

3.0 TSCF INVESTIGATIONS OF CARGO TANK CORROSION

The following is a discussion of the various investigations related to cargo tank corrosion, undertaken by TSCF and its members.

3.1 Corrosion Probe and Coupon Investigations

Corrosion probes and coupons were installed on four tankers. These were bolted to structural members, and were not affected by the ship bending stresses, motions and vibration to any significant degree.

The correlation of corrosion rates between probes and coupons was good, but the correlation with corrosion rates obtained on the basis of actual thickness measurements (gaugings) of adjoining deck plates and deck longitudinals was in general poor.

The obvious conclusion from these experiments is the lack of usefulness of corrosion coupons and probes as an easy substitute for direct experience

3.2 Vapor Space Gas and Water Condensate Analyses

Vapor space gas and water condensate analyses were carried out on four tankers, with the following illustrative results.

Gas in the vapor space was found to be a mixture of inert gas, water vapor and oil vapors as expected. Results from measurements of 4 tankers indicated relatively high contents of carbon dioxide (11%) and water vapor (0.46 gram/liter gas). Oxygen content was in the 5 to 6 % range, and the nitrogen content was a little above 80%. Depending on the type of crude oil, hydrogen sulfide content could be more than 600 ppm.

The presence of water condensate in the vapor space of these four vessels was evident by the appearance of widespread, small, round and shallow pits on the under deck side of deck plating. Vapor space water condensate was in some cases very acidic, with pH values as low as 1.0.

Related to this, Miyuki, et al. (1998) have studied the effect of environmental variables on vapor space corrosion behavior using laboratory simulations of corrosion in a wet inert gas environment (13% CO_2, 5% O_2 and a small amount SO_2). They found that corrosion rates increased with increasing O_2 and SO_2 contents in inert gas.

3.3 Laboratory Simulations using Bottle Tests

Five test bottles containing crude oil and synthetic sea water, inert gas (four bottles) and nitrogen gas (one bottle) were tested for 5 months at room temperature (23 degree C, two bottles) and elevated temperature at 40 degree C (three bottles). Probes for corrosion, temperature / humidity and oxygen were also included. The tests covered a 5 month period that essentially represented the beginning phases of corrosion.

Four bottles in these tests had also been inoculated with SRB. No micro-organisms were present in the bottle vapor space. Evidence of Microbial Influenced Corrosion was seen to manifest itself in a color change of settled water that turned black.

Pits were randomly formed regardless of type of steel. It was seen that inherent surface roughness and inclusion of micro-pits could affect initial formation of macro-pits in bottom and vapor space. However, in the longer term, these differences generally diminished. Pitting corrosion in bottom coupon showed the same patterns in cargo tank bottom.

3.4 TMCP Steel Investigations

In our laboratory simulations of corrosion using bottle tests, four bottles had two types of steel coupons (mild steel and TMCP steel) in the bottom of the bottle and its vapor space. These bottle test results, and inspections of cargo tanks, indicate the following preliminary indications regarding whether TMCP steels behaved differently from conventional steels with regard to corrosion:

- TMCP steel shows no difference with conventional mild steel or high tensile steel in so far as the pitting corrosion rates in bottom plating in the presence of SRB are concerned.

- TMCP steel with an untreated surface may perhaps be initially more susceptible to localized pitting corrosion due to the increased initial roughness of steel surface resulting from the accelerated water spray cooling and hot press during the rolling process.

- TMCP steel would have higher density of complex, large face, stair step type pits possibly due to the peeling effect of thinner micro-layers between pearlite and ferrite during the corrosion process.

Regarding TMCP steels and corrosion, results of a recent study (Miyuki, et al., 1998) undertaken in Japan are also of interest. In order to investigate the corrosion resistance of TMCP Steels by comparison with conventional mild steels and Controlled Rolling (CR) Steels in upper deck environments of double hull VLCC cargo oil tanks, corrosion tests were conducted with cyclic immersion in sea water, and exposure to simulated wet inert gas environments. Test were of 30 to 90 day duration. The TMCP and CR steel specimen used were of 32 kg/mm^2 yield strength, with shot blasted surfaces.

The production processes for the three steel types are of course different. Although little difference in chemical composition of the steels were observed, differences in microstructure were found. Lamellar structures of ferrite and pearlite were observed for both TMCP and CR steels.

The results so far obtained seem to suggest that the three types of steel have almost the same corrosion resistance in sea water and wet inert gas environments, and only general corrosion was observed. Similar indications have also been reported by DnV (1988).

We note that Japan has an ongoing national project studying the corrosion of TMCP steels, including possible causes and remedies. This three year project project started in 1999 and will be completed in 2001.

3.5 Biocide and other Control of MIC in Cargo Tanks

The following are some of the possibilities for dealing with microbial influenced corrosion in cargo tanks (Hill, 1998):

- Applying a coating to steel. This is the classical barrier method, and a potentially effective one. The practical difficulties in retro-coating are in preparing the surface and producing a sound adherent coating. Any defects would be the focus of pitting, not necessarily dependent on intervention of SRB. It is thus necessary to thoroughly clean the steel surface before coating it. The use of back up anodes could be considered, however, anodes are active only when submerged in sea water.

- Suppressing electron flow by cathodic protection. Overall corrosion rates could be reduced, but the microbial population will continue to flourish and become corrosive in poorly protected locations. More CP will be needed if bio-film is present.

- Use biocides. Broad spectrum biocides are likely to be less toxic to both man and environment, and can act against both aerobic and anaerobic bacteria. Alternately, if SRB is confirmed as the major contributing factor in any particular case, a narrow spectrum biocide active only against SRB is probably more effective.

Biocide field tests were carried out by a TSCF member during 1995. Initial shock treatment with high dosage of biocide was effective in killing all bacteria in settled water; however, after 2 months of loading / discharging of crude oil, the bacteria began to “re-grow”. After 9 months, the bacteria count was 100 times greater than it was originally. This may imply that a continuous biocide treatment or stronger or different biocides may be necessary because of acquired resistance. The tests also raised the concern that biocide treatment will not be cost-effective in the long run due to the sheer size of the bottom area.

3.6 Effects of Crude Oil Washing on Corrosion

Crude oil washing can remove the protective waxy layer on steel surfaces thus exposing the steel to corrosion. On the other hand, one may also think that effective crude oil washing may also serve to lessen the conditions that lead to corrosion.

Tests conducted by TSCF have thus far not indicated that COW and oil sediments have a direct effect on bottom pitting corrosion. The tests indicated that COW could not effectively penetrate or remove sludge accumulations. Tests also have appeared to indicate that COW has no direct effect on vapor space corrosion.

3.7 Bacterial Resistance Tests on Tank Coatings

In cooperation with the International Paint, bacteria resistance tests were carried out on four different epoxy paints coated on coupons that submerged in SRB inoculated mixture of oil and sea water. After a 40-day test, it has confirmed that pure and modified epoxy coatings have good bacteria resistance.

Regarding the resistance of coatings to MIC, the effectiveness of coal tar coatings should be evaluated in an environment that includes microbial influenced corrosion.

3.8 Cargo Tank Temperature Profile Studies

Elevated temperatures of the cargo tank structure of oil tankers are conducive to accelerating general corrosion and also the rate of proliferation of microbes that influence corrosion. For instance, our own corrosion bottle tests indicated that the general corrosion rate at 40 degree C was approximately twice that at 23 degree C. Laboratory tests by Miyuki, et al., (1998) also indicated a similar strong temperature effect.

Various measures for reducing cargo tank temperatures while in service have been suggested. For instance, the temperature of the steel could be reduced by changing out the ballast loaded alongside with cooler deep sea ballast on the way to the load port. Another possibility could be to replace the relatively warm inert gas in the cargo tank while at sea when the scrubber plant temperature is lower.

The effectiveness of such methods has not been quantified. Further, since cargo tanks are not insulated, practical difficulties exist in the ability to adequately control the temperature inside the cargo tanks as a means of reducing corrosion rates. Thus, to the extent possible, temperature effects on general corrosion rates are best controlled by use of added scantling margins.

Our tests involving measurement of temperature profiles in tankers indicated that in the case of single hulls, the temperatures in the cargo tank were most affected by cargo heating and outside ambient temperatures. The tests were inconclusive regarding the insulating effect of double hull spaces in tankers. Corrosion rates themselves were not measured in these tests.

Regarding the effect of temperatures on coatings, there is little published information, although coating manufacturers typically cite temperatures up to 60 degree Celsius as being of no long term concern.

Regarding temperature effects, whether existing practice needs to be improved is a matter for future study. One question is the extent to which currently used corrosion rate data include temperature effects.

3.9 In-Service Corrosion Experience and Corrosion Rate Investigations

The Forum initiated its first program to study in-service corrosion trends in 1988. Corrosion data were collected from Forum members, representing the empirical information that their tankers had experienced in real environments in the past three decades. One result was the corrosion rate tables in the 1992 TSCF ``Condition Evaluation and Maintenance of Tanker Structures''.

The tables cited, and the data behind them, show that depending on their function, orientation and location in the tank, some structural components are more susceptible to corrosion than others. Examples of the more susceptible structures are the top side of horizontal surfaces and the underside of deck head structures. The previous Forum studies indicate that the general corrosion rate in cargo tanks does not usually exceed 0.1 mm per year. In the bottom shell plating, pits or grooves were experienced with growth rates of 1 to 2 mm per year.

In part with a view to update the previous information published by TSCF, corrosion experience and corrosion data were collected from TSCF members and others. As previously noted, there were two surveys, one related to corrosion experience and corrosion control practices, and the other aimed at updating the corrosion rate tables. Regarding the latter, the data available were such that only the table for Cargo Only tanks can potentially be updated.

Results related to corrosion control practices, obtained from Survey I, are given in the attached tables. The primary value of such results is to identify and rank dominant trends. Results pertaining to general corrosion rates for uncoated cargo tanks, obtained using the data from Survey II are also presented as an attached table. The rates are in mm per year. The notation 'na' means that the relevant data were not available.

Of main interest are the results for deck and bottom plating. Here the data indicate that the previously used 0.1 mm / year corrosion rates may possibly be optimistic, better upper bound estimates being about 0.2 mm / year for deck plating and 0.15 mm / year for tank bottom plating. Corrosion rates in the other cases investigated were found to be generally well within 0.1 mm per year.

Future revisions to the previous TSCF published corrosion data for ``Cargo Only'' tanks could be based on such accumulated data, after appropriate analysis as a function of various parameters of interest, such as single hull versus double hull differences.

4.0 CONCLUSIONS PERTINENT TO CARGO TANK CORROSION PHENOMENA

Effect of Structural Factors: The TSCF investigations with corrosion probes and coupons, discussed in the previous section, lend credence to the hypothesis that the vessel structural behavior itself is a factor in the corrosion rates the structure experiences. This is also supported by the TSCF investigations of vapor space corrosion, in which the corrosion diminution of deck head structures in the forward body was greater compared to those in the mid body.

The structural parameters that are pertinent to corrosion rates in the ship structure (e.g. stresses, flexibility, levels of vibration, slamming, etc) have so far not been identified. Further research in this regard would be beneficial in our understanding of the basic corrosion processes involved. A starting point may be to reanalyze existing corrosion data with a view to estimating rates of corrosion as a function member thickness in addition to the number of sides exposed to corrosion. Investigating the influence of the cyclic deflection of steel structures on corrosion rates could also be undertaken.

Vapor Space Corrosion: Our previously described tests on vapor space gas and water condensate analysis showed that very acidic water condensate can be present in the vapor space. The most likely origin of this is water vapor from deck water seal interacting with the oil vapors. Depending on the type of crude oil, it was found in the tests that hydrogen sulfide content could be relatively high. Although additional studies are needed, a first hypothesis is that the presence of acidic water condensate is the most likely factor in enhanced rates of vapor space corrosion experienced on many vessels. The exact role played by inert gas in this is unclear at this point. Flue generated inert gas can have some extent of carry over moisture (entrained water), sulfur oxides and other products from the fuel used to generate it, and some of these components, especially related to sulfur, can presumably adversely can affect vapor space corrosion rates.

Aerobic micro-organisms when they aggregate in slimes or crevices use up oxygen and create an oxygen deficient zone around them, which is anodic in relation to relatively oxygen rich zones where there are new microbes. Anodic corrosion pits can then develop. There is sufficient oxygen in inert gas to promote the action of such aerobic bacteria, although the relative importance of MIC to corrosion related degradation in the vapor space remains to be established and may not be significant.

Effect of Inert Gas Systems: Inert gas systems now in use include independent inert gas generators, boiler flue gas systems, nitrogen generators and others, and the specific characteristics of each system must be considered in evaluating its potential impact on vapor space corrosion. The purer the inert gas, the less its likely effect on vapor space corrosion. Concerning boiler flue systems, which happen to be the most prevalent, purity of the gas has by tradition not been paid too much attention, perhaps for competitive reasons. The necessary investments to improve the gas quality with regard to sulfur oxide content and particle removal have not generally been widespread.

Although the exact role of inert gas in enhanced rates of vapor space corrosion remains unclear, the fact remains that it is only inert gas quality (in terms of water, oxygen and sulfur impurity content) that is potentially controllable by shipboard equipment as a means of reducing vapor space corrosion. The role of composition and moisture content of inert gas should be further examined to determine its influence on corrosion rates. Methods for decreasing the corrosive constituents and humidity of the gas need to be further considered.

Accelerated Cargo Tank Bottom Pitting: Accelerated corrosion in cargo tanks appears to be largely a problem that is unique to certain ships. For instance, due to different trading routes and cargo types carried, some tankers experience accelerated corrosion, while most do not. However, a sufficient number of tankers do experience accelerated corrosion, either in the vapor space or at the tank bottom. Hence the phenomena are of concern, and need to be addressed.

MIC appears to be the major contributing factor in accelerated cargo tank bottom pitting. Cargo tank bottom water may be oxygen free and thus directly encourage anaerobic bacteria. Sulfur, mercaptans and sulfites can be reduced to corrosive sulfide by the so-called sulfate reducing bacteria (SRB) which thrive in the absence of oxygen (anaerobic). These presumably produce hydrogen sulfide and some ions which are highly aggressive to steel, and characteristic craters form. Our various laboratory tests related to MIC in the presence of SRB showed phenomena such as a skeleton of remaining carbon, lead pencil in color, and usually black (ferrous sulfide) pit bottoms, consistent with observations on vessels.

Control of MIC in Cargo Tanks: Our biocide related tests generally indicate that biocide treatment is not likely to be either the preferred or the most effective option in controlling MIC. Since the biocide may not penetrate the scale to reach inside the pits, the efficacy of biocide treatment will vary. Furthermore, cargo loss due to biocide / treated water weight, inability to dispose of biocide / treated water residuals, and refinery unwillingness to accept treated crude oil are some unfavorable factors concerning the biocide treatment. In addition, handling of toxic biocides by tanker personnel on an ongoing basis may increase the safety risk to a level that is unacceptable by company risk management standards.

Our experience also indicates that coatings have the most potential to work, and that MIC resistant coatings are indeed available. Regarding cathodic protection and back-anodes on MIC, indications are that these are to be considered in conjunction with coatings than alone.

Effects of Crude Oil Washing: COW may have an indirect and possibly minor effect on corrosion, the importance of which so far has not been studied. In theory, consideration could be given to reducing the amount of deck head and tank side washing whilst instead focusing the washing medium on the tank bottom to facilitate the flow and discharge of liquids and entrained solids. Attention could also be placed on reaching shadow areas in order to remove ‘dams’ formed by sludge and scale. To the extent the role of COW in double hull tankers may be subject to some re-thinking, and considering its rather indirect effect on corrosion, it is unclear if it is appropriate to place any emphasis on COW related effects in the future.

Temperature Effects: Tests have well established that in uncoated steel, elevated temperatures have a rather strong effect on general corrosion. It also appears that MIC related bacterial proliferation would be comparatively greater at increased temperatures, although the likely magnitude of such increases and their effect on pitting corrosion rates does not appear to have been thus far quantified. The most obvious source of temperature effects in tankers is the use of heating coils, although there are other possibilities as well, such as the relatively higher insulating effect of double hulls which may tend to maintain cargo temperatures at higher levels for increased periods of time. Regarding temperature effects, additional investigations are needed, starting perhaps with the assessment of the extent to which currently available corrosion rate data account for temperature effects.

Role of TMCP Steel: Test conducted by ourselves and others to date appear to indicate that (a) the chemistry of TMCP steels is similar to comparable conventional ship building steels, although there are micro-structural differences related to the manufacturing processes, which may appear as micro-layers through the thickness (b) general corrosion rates for TMCP steels are comparable to the other steel types, (c) Rates of pitting of TMCP steels are similarly comparable, and (d) the pits in TMCP steel typically appear to develop with a stair case pattern which is different from pits in conventional steels. Aspects about which additional data are necessary include whether uncoated but perhaps surface treated TMCP steels corrode or pit sooner than conventional steels, and how the pits once initiated subsequently develop / merge or otherwise may become a serious concern.

Role of Double Hulls: Corrosion rates corrosion experience in double hull vessels need ongoing study. The structural effect on corrosion could be different from single hulls. Temperature effects can, likewise, be different. Existing studies and corrosion data are inadequate to draw any definite conclusions regarding such potential effects particular to double hulls, whose numbers will only tend to increase with time.

5.0 CONCLUSIONS PERTINENT TO EXISTING VESSELS

This section discusses some measures to consider for existing vessels, to address cargo tank corrosion in general, and accelerated corrosion in particular.

5.1 Ongoing Inspections.

Ongoing in-service thickness monitoring is a necessary part of the corrosion control program. Thickness measurements for selected structural members in selected cargo tanks at 30-month intervals can normally provide an adequate corrosion database for developing the mitigation strategy and maintenance methodology. The data would be statistically analyzed to obtain corrosion rates and related trends.

Biological samples should be taken during these inspections as needed.

5.2 Use of Coatings

For existing tankers, multi-layer coating is the suggested practical method to mitigate vapor space corrosion. However when and to what extent (which tanks have to be coated) must be tailored for each tanker depending on the actual in-service corrosion monitoring results. The forward part of cargo areas where the corrosion rate is higher and plate thickness is thinner may be coated first. The coating should extend down from the deck plate to cover deck longitudinals and other under-deck structural members at least 1.0 meter down. The horizontal surfaces of main supporting members such as bulkhead stringers may need to be preferentially addressed. Surfaces would be grit blasted and coated with a modified epoxy coating preferably of light color.

Similarly, grit blasting and epoxy coating of the lower areas of cargo tanks may be beneficial to controlling corrosion at the bottom. An epoxy coating with anti-bacterial properties may need to be employed. Surface sterilization may be necessary prior to coating, if microbial influence is evident. Blasting and coating of bottom plating should include at least 300mm high of adjacent bottom structural members.

An epoxy coating will provide a barrier that prevents bacteria from contacting the bottom plating directly. However, since the bacteria could still reach the bottom plating through coating breakdown areas, the coating must be regularly inspected and maintained. Although pitting inspection and repair must still be performed for coated bottom plating, one expects an advantage in having to deal with a lesser number of pits.

Any coating system needs to be regularly inspected and maintained. Localized damage to a coating can cause accelerated pitting corrosion to occur regardless of whether bacteria are present or not.

5.3 Installation of Anodes

The installation of anodes close to the tank bottom has been suggested by some. Anodes are only effective when immersed in water and are not effective in inhibiting microbial influenced corrosion. Hence the efficacy of this option is not yet established for a cargo tank.

5.4 On-going Pit Inspection and Repair

The condition of bottom for pitting corrosion is to be monitored at specific intervals. Any pits discovered are to be repaired according to specified criteria that meet each individual tanker design scantling and operation requirements. This strategy will effectively eliminate the likelihood of deep pits. Pitting inspection and repair is usually performed in a ship yard. during voyage or in shipyard. However, in the face of MIC, bottom pitting can occur at rapid rates, and hence an on-going pit inspection and repair program programs may include either company personnel or outside contractors performing pit inspections and repairs between dry dockings, at specified intervals, in conjunction with regular tank inspection and maintenance programs, see Huang (1999).

For general guidelines on pitting repair, the reader is referred to Table 3.2 of the TSCF Guidance Manual for Tanker Structures. Central to this is pit repair by thoroughly cleaning or blasting the pit and surrounding area and then filling the pits either by welding or with epoxy filler or by welding and over-coating with an epoxy paint or filler.

5.5 Biocide and Chemical Intervention

As previously noted, biocide treatment does not appear to hold promise as a viable option in tankers. Once microbial enhanced corrosion has started, it cannot always be stopped simply by adding biocides, which cannot penetrate bio-film, sludge or mud at safe to use concentrations. Nevertheless, individual cases may potentially benefit from the biocide option or chemical intervention, and if so, expert help should be sought.

Regarding chemical intervention, we should note here that certain options may exist (Hill, 1998), that have thus far not been investigated:

- Chemical additives (alkaline) may be introduced into the bottom water to modify the pH beyond the range which facilitates the proliferation of SRB.

- A nitrate rich chemical may be introduced to the bottom water to divert SRB away from reducing sulfate. Most SRB are said to prefer nitrate to sulfate and relatively harmless nitrogen gas and ammonia are the resultant products of reduction.

6.0 CONCLUSIONS PERTINENT TO NEW BUILDING

For new building, one may consider the following options with a view to minimizing cargo tank corrosion and its effects.

6.1 Use of Increased Scantling Margins

Cargo tank vapor space, bottom plating and related bulkhead plating material thickness can be increased to accommodate any increased corrosion rates anticipated. The main purpose of these corrosion margins is to avoid the problem of extensive steel renewal at unreasonably short periods of time. Hence these corrosion margins are normally not a protection against pitting, which remains a concern in the bottom regions of the tank.

6.2 Use of Coatings

Consideration could be given to coating all or parts of the internal surfaces of the cargo tank, similar to the discussion above for existing vessels.

A prudent practice is to coat the under deck down to below the brackets of the deck transverse. This covers the vapor space and splash zone to minimize the possibly deleterious effects of the inert gas. Coatings of the tank bottom, especially in the after parts of the tank, may similarly help reduce pitting from sediment in the cargo.

The coating process starts with the selection of the coating type and finishes with its proper application. The steps between the start and finish are critical to a proper adhesion of the coating to the steel it is to protect. The cleanliness of the steel and its preparation are essential. Some of the steps of the preparation process to consider are: removal of weld splatter, smoothing edges, repair of weld porosity, removal of lifting lugs and temporary construction fittings, and cleaning the steel to remove dirt film and other impurities that will prevent good adhesion of the paint. Improperly prepared steel will result in lack of adhesion that will cause blistering of the coating or complete failure.

General guidelines for tank coating during new building may be found in Huang (1999). For more detailed information, the reader is referred to the new TSCF Guidelines for Ballast Tank Coating and Surface Preparation.

6.3 Structural Design to Improve Bottom Drainage

Consideration should be given at the design stage to ensure that the "in tank" drainage is effective and capable of reducing retained water to a minimum. Enlarged and / or additional well placed drain holes in the tank bottom structure will facilitate the removal of liquids from the tank, thereby lessening the amount of standing water remaining after cargo discharge.

6.4 Improvement of Access for Inspection, Maintenance and Repair

Improved accessibility, particularly in narrow spaces such as wing tanks should be considered, so that inspection and repair are facilitated. Some examples in this regard include the incorporation of horizontal stringers at 4 -6 meters interval, installing walkways around the perimeters of wing tank spaces, and installing ladders to assist climbing during inspections.

6.5 Other Possible Measures

The following are some other potential measures applicable to new building:

- Use of reduced frame spacing and longitudinal spacing to improve the stiffness of the structure and thereby reduce structural flexing.
- IGS system changes

There is little data today to assess the effectiveness and manner of employment of these methods. Hence these potential options require further study.

7.0 RECOMMENDED TSCF WORK GROUP ACTION PLAN FOR THE FUTURE

In light of the experience, issues, studies and uncertainties discussed thus far, the following is suggested as a plan of action for the work group to pursue in the near term:

- Continue to collect and analyze data related to Cargo Tank corrosion, to validate the indications, trends and conclusions thus far developed. The data collection and analysis efforts need to concentrate on double hull vessels, to sufficiently account for their unique structural characteristics and behavior (loading patterns, stresses and deflections, hull flexibility, thermos bottle effect).

- Study the effects of temperature on corrosion rates, and determine whether presently used corrosion margins are in general adequate for heat affected areas such as the boundaries of tanks with heating coils and more particularly the ballast and other tanks that are adjacent to them. The reason for suggesting this study is not because there is reason to suspect a concern, but because the issue seems to be a pertinent one that has so far not been studied.

- Review the corrosion properties of TMCP steel further, to determine whether or not they differ from steels manufactured by other methods, and possible remedies. Rather than undertaking any new additional study, a critical review and summary of ongoing and completed studies pertaining to the issue are suggested as being of value.

- Undertake further investigations regarding MIC as to causes, behavior and treatment, for example using chemical intervention. The connection of crude oil source to MIC is also in principle worth examining, but quite difficult to accomplish.

- Study of measures to improve industry awareness of the issues of cargo tank corrosion including MIC, the interaction of design aspects and corrosion considerations, the effective application of coatings, and the increased use of feedback to improve the various processes involved. This would be a joint effort involving various industry players.

Since the phenomenon of corrosion is the result of a combination of many factors, studies need to be carefully thought out and followed through.

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TABLE 1 : VESSEL COMPOSITION IN THE SURVEY RESPONSES

		Practices		Rate	
		Survey 1		Survey 2	
		No	%	No	%
Cargo Type	Crude Oil	71	90	26	81
	Product	8	10	3	9
	Chemical			2	6
	N/a			1	3
Hull Type	Single hull	55	69	18	56
	Double hull	20	25	4	13
	Double sides	2	3	7	22
	Double bottom	2	3	3	9
DWT Range	VLCC (200+ kdwt)	48	60	15	47
	Suezmax (120-200)	14	18	5	16
	Aframax (80-120)	2	3	5	16
	Panamax (60-80)	3	4	2	6
	Handysize (10-60)	9	11	5	16
	N/a	3	4		
Age Range	< 5 years	26	33	9	28
	5-10	21	27	13	41
	10-15	8	10	5	16
	15-20	8	10	1	3
	20-25	13	16	3	9
	25+	3	4	1	3

N/a : Not Available

TABLE 2: COATING USAGE AT NEWBUILDING, CARGO ONLY TANKS

A. COATING USAGE

			Age		
COATING USAGE	0-5	5-10	10-15	15-20	20+
AT NEWBUILDING	%	%	%	%	%
Entire tank	0	0	13	0	17
Underdeck only	0	17	38	33	17
Bottom only	27	0	0	0	0
Underdeck & bottom	5	6	0	0	17
Uncoated	68	77	49	67	49

B. COATING DATA

EXTENT OF COATING	%	TYPE OF PAINT	%	# OF COATS	%	COATING DFT	%
Uncoated Tank	61	Coal Tar Epoxy	40	One	28	< 100 microns	6
Underdeck & Bottom	5	Pure Epoxy	31	Two	53	200-300	73
Bottom Only	9	Modified Epoxy	12	Three	13	300-400	9
Underdeck Only	14	Inorganic Zinc	10	Five	3	400-500	3
Entire Tank	9	N/a	7	N/a	3	N/a	9
N/a	2						

C. INITIAL SURFACE TREATMENT

	%		%
COATED AREAS		UNCOATED AREAS	
Grit blast & shop primed	12	Untreated	56
Shot blast & shop primed	43	Shot blast & shop primed	8
Others	11	Grit blast & shop primed	3
N/a	34	Others	3
		N/a	30

TABLE 3: ANODE USAGE AT NEW BUILDING, CARGO ONLY TANKS

Location	%
None Installed	57
Bottom Only	9
Middle Portion & Bottom	2
Entire Tank	2
N/a	30

TABLE 4: LOCAL COATING, SURFACE AND EDGE TREATMENT AT NEW BUILDING

# OF STRIPE COATS	%	SECONDARY SURFACE PREPARATION	%	TREATMENT OF FREE EDGES	%
None	34	Mechanical Cleaning Only	53	No Treatment	30
One	21	Grit Blast Only	13	2 mm Radius	9
Two	19	Grit Blast & Mechanical	3	1 mm Radius, 3 Cuts	19
Three	5	Shot Blast & Mechanical	2	Others	1
N/a	21	Weld Seam Grit Blasting	3	N/a	41
		N/a	26		

TABLE 5: EXPERIENCE PERTINENT TO ACCELERATED CORROSION

A. LOCATION WHERE EXPERIENCED

Location	%
Top / Deckhead	8
Middle Portion	3
Bottom	18
None	43
Unknown	4
N/a	32

B. MIC

MIC	%
Yes	8
No	22
Unknown	25
N/a	45

C. RELATED VESSEL DATA

STEEL TYPE	%	HEATING COILS	%	IG SYSTEM	%	IG DECK SEAL	%
TMCP	28	Yes	25	Flue Gas	87	Wet	67
Conventional	72	No	70	IG Generator	4	Semi-Wet	24
		N/A	5	None	1	Dry	1
				N/a	8	N/a	8

D. RELATED FACTORS EXPERIENCED

EXCESSIVE SLUDGE / SCALE	%	EXCESSIVE RESIDUAL WATER	%	EXCESSIVE VIBRATION / FLEXING	%
Yes	9	Yes	1	Yes	4
No	72	No	80	No	78
N/a	19	N/a	19	N/a	18

TABLE 6: EXPERIENCE WITH CORROSION RELATED FAILURES

Bottom Pitting Not Included

COATED AREA FAILURES					UNCOATED AREA CORROSION				
Age	5	10	15	20+	Age	5	10	15	20+
	%	%	%	%		%	%	%	%
No breakdown	61	67	55	25	No corrosion	0	1	0	0
Blistering	13	10	27	5					
Spot/light rust	26	33	18	35	Spot/light rust	84	88	50	8
Edge/welds	4	0	27	0	Edge/welds	5	0	0	17
Hard scale	0	0	10	0					
General breakdown	0	0	0	25	General corrosion	16	6	50	75

TABLE 7: EXPERIENCE WITH BOTTOM PITTING

BOTTOM PITS	COATED AREAS				UNCOATED AREAS			
MAXIMUM DEPTH	5	10	15	20+	5	10	15	20+
	%	%	%	%	%	%	%	%
0-5 mm	36	46	18	0	25	27	22	0
5-10	46	63	55	27	75	73	78	20
10-15	18	25	5	46	0	0	0	40
15-20	0	0	0	27	0	0	0	40
AVERAGE DEPTHS								
Age	5	10	15	20+	5	10	15	20+
0-3 mm	50	25	64	9	69	15	22	0
3-5	50	38	18	9	19	77	67	20
5-7	0	37	18	64	12	7	11	60
7-10	0	0	0	18	0	0	0	20

TABLE 8: IN-SERVICE CORROSION RATE (MM/YEAR) FOR CARGO TANKS

Member	Mean	Upper Bound	Previous Data
Longitudinal Elements			
Deck Plating	0.057	0.2174	0.03-0.1
Web of Deck Longs	0.018	0.0874	0.03-0.1
Face Plate of Deck Longs	0.04	0.0404	Na
Side Plating	0.02	0.0688	0.03
Web of Side Longs	0.011	0.0454	0.03
Face Plate of Side Longs	0.007	0.0284	Na
Bottom Plating	0.09	0.1264	0.04-0.3 (MIC)
Web of Bottom Longs	0.004	0.019	0.03-0.1
Face Plate of Bottom Longs	0.008	0.025	Na
LBHD Plating	0.037	0.1272	0.03-0.1
Web of LBHD Longs	0.009	0.044	0.03-0.1
Face Plate of LBHD Longs	0.019	0.0778	Na
Transverse Web Frames			
Deck Transverse Web Plating	0.017	0.0484	0.04-0.1
Deck Transverse Ring Face Plate	0.019	0.0594	Na
Horizontal Tie Beam Web Plating	0.005	0.0182	Na
Horiz Tie Beam Ring Face Plate	0.009	0.0334	Na
Bottom Transverse Web Plating	0.021	0.0354	0.03
Bottom Transverse Ring Face Plate	0.022	0.069	Na
Side Shell Transverse Web Plating	0.005	0.0214	0.03
Side Shell Transv Ring Face Plate	0.003	0.013	Na
LBHD Transverse Web Plating	0.002	0.0102	0.03
LBHD Transverse Ring Face Plate	0.007	0.0188	Na
Transverse Bulkheads			
TBHD Plating	0.015	0.0698	0.03-0.1
TBHD Vertical Stiffener Web	0.02	0.1042	0.03-0.1
TBHD Vertical Stiffener Face Plate	0.034	0.152	Na
TBHD Horizontal Stringer Web	0.01	0.0346	0.06-0.1
TBHD Horiz Stringer Face Plate	0.01	0.0392	Na
Swash Bulkhead Plating	0.02	0.0204	0.03