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# A Review of Test Protocols for Assessing Coating Performance of Water Ballast Tank Coatings

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***Abstract*****—**Concerns on corrosion and effective coating protection of double hull tankers and bulk carriers in service have been raised especially in water ballast tanks (WBTs). Test protocols/methodologies specifically that which is incorporated in the International Maritime Organisation (IMO), Performance Standard for Protective Coatings for Dedicated Sea Water ballast tanks (PSPC) are being used to assess and evaluate the performance of the coatings for type approval prior to their application in WBTs. However, some of the type approved coatings may be applied as very thick films to less than ideally prepared steel substrates in the WBT. As such films experience hygrothermal cycling from operating and environmental conditions, they become embrittled which may ultimately result in cracking. This embrittlement of the coatings is identified as an undesirable feature in the PSPC but is not mentioned in the test protocols within it. There is therefore renewed industrial research aimed at understanding this issue in order to eliminate cracking and achieve the intended coating lifespan of 15 years in good condition. This paper will critically review test protocols currently used for assessing and evaluating coating performance, particularly the IMO PSPC.

***Keywords*****—**Corrosion Test, Hygrothermal Cycling, Coating Test Protocols, Water Ballast Tanks.

## I. Introduction

WBTS are found in ships, oil platforms, submarines and floating wind turbines. WBTs are employed in all these structures to regulate stability.

For merchant ships, WBTs are an essential part of the ship as they provide the needed stability and propeller immersion particularly when the ship is in the un-laden (unloaded) condition.

Before 1880, solid ballast media such as stone, sand and rock were used [14]. These media were bulky and very difficult to handle especially during voyages in extreme sea conditions and resulted in long delays while ballasting or de-ballasting was carried out. These challenges drove the need for an alternative ballast medium and from the 1880s to the present day seawater became the preferred medium [14]. However, this medium came with the challenge of corrosion that ultimately led to the need for WBT coatings.

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Fig. 1 Marine coating degradation showing rust in water ballast tanks [15]

During the last 25 years in the shipping industry [8], [11], [13], there has been renewed emphasis on corrosion and coating performance of WBTs coating a result of considerable vessel losses in the 1980's and 1990's in particular among bulk carriers and tankers e.g. Erica, Torey Canyon. Following the Exxon Valdez accident in 1989, the potential for corrosion in ballast tanks was inadvertently increased through (by increasing temperatures in the ballast tanks - the so called Thermos Effect) the introduction of Double Hull Tankers under the requirements of the USA Oil Pollution Act of 1990 (OPA 90). This led to the transition from Single Hull (SH) to Double Hull (DH) design of tankers in order to reduce the risk of oil spill and pollution from subsequent accidents. This transition in design has not only increased the temperature in the tanks but also dramatically increased the surface areas and complexity of WBTs in DH ships to about 3 or more times those of SH ships made in the 70's [3]. In addition to the change in size, the complex geometric structure and the increase of incorporated stiffeners in WBTs made it extremely difficult and very challenging to achieve high quality coating application.

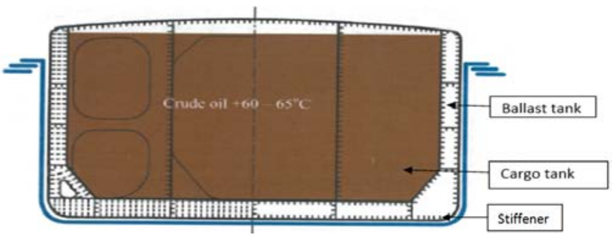


Fig. 2 A ballast tank with stiffeners as compared to a cargo tank in a Crude Oil Carrier

The challenges faced by WBTs coatings in DH are further compounded by the environmental conditions in which they operate. The result is early coating degradation and higher corrosion rates in DH WBTs when compared to SH [3], [8], [9]. Coating degradation can take several forms including cracking, flaking and blistering [5]. Of these three forms of coating degradation, cracking, in particular, is found to occur on power tooled welds in WBTs of DH [3], [7], [12].

Other notable issues potentially contributing to coating failure of WBTs in DH are:

- ❖ Changes in formulations in order to comply with volatile organic compounds (VOC) regulations and other health, safety and environmental (HS&E) regulations. This has resulted in new products that may perform differently to traditional products [2], [4].
- ❖ The lack of clarity as to what is in the generalised epoxy formulation. Generalised classification of epoxy formulation can be misleading.
- ❖ Constant exposure to severe in service conditions: seawater immersion when in ballast; and high humidity and condensation when empty; cyclic heating and cooling from both atmospheric and hot cargo exposures especially for oil and chemical tankers. DH spaces insulate the cargo, slowing its cooling. The delayed temperature dissipation increases the rate of corrosion within WBTs. These severe in service conditions make WBTs more vulnerable to corrosion when compared to other vessel areas of the ship [12].
- ❖ Current test and prequalification standards only evaluatec oatings with regards to anti-corrosive failure properties for example blistering and rust creepage. Typical pre-qualification tests (also known as test protocols) used by the shipping industry in measuring WBT coating performance include among others the IMO Performance Standard for Protective Coating (PSPC), NORSOK M-501 and ISO 20340.

## II. Test Protocols

The shipping industry applies test protocols to measure coating performance. Significant drivers for the application of test protocols include:

- ❖ The demands for better performance and longer asset life from coating improvements have led to the introduction and modification of several test protocols.
- ❖ Increasing legislative pressure on VOC emission reduction from coatings has required the development of new formulations.

Based on the above drivers, test protocols used by the industry have evolved from static exposure testing to cyclic exposure testing. A static test protocol is an exposure of coated test specimen(s) to only one environmental condition. Test specimens are subject to one particular exposure for example a hot salt spray (ASTM B117, ISO 7253:1996).

Cyclic test protocols subject test specimen(s) to more than one exposure condition and the specimens are alternated between them. For WBT coating assessment, cyclic test protocols are more relied on and applied because in general better correlation with in service performance can be achieved. Some of the test protocols commonly employed include: ASTM D5894-10, ISO20340:2009 (E), NORSOK M-501, NORDTEST, NACE TM0104-2004, NACE TM0304-2004 and IMO PSPC.

### *A. ASTM D5894-10 (Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal)*

ASTM D5894-10 subjects test panels to cyclic corrosion testing by alternating UV/Condensation cycles and wet/dry salt fog cycles. The UV/Condensation cycle is a 4 hours exposure using UVA-340 nm at 60$^{o}$C. This UV exposure is then followed by a 4 hours condensation exposure at 50$^{o}$C, using UVA-340 lamps. The duration for the UV/Condensation exposure cycling is 1 week (168 hours). The cycled test specimens from the UV/Condensation cycling are then transferred for fog/dry cycling. The fog chamber runs a cycle of 1 hour at ambient temperature and 1 hour dry-off at 35$^{o}$C. The duration for this cycle is 1 week (168 hours). The electrolyte employed in the fog chamber is dilute solution of 0.05% sodium chloride and 0.35% ammonium sulphate. The dimensions of the specified flat specimen are 150 by 75 mm.

The above protocol could be described as a cyclic corrosion test where a weathering exposure is alternated with an electrolyte exposure. The usage of a flat test specimen to simulate a cracking test for WBTs seems unsuitable as the occurrence of any cracking failure on any flat surface/area is extremely uncommon in service when compared against power tooled welds at corners. In this test, coating application in terms of dry film thickness and surface preparation are not taken into account. Assessing WBT coating by this protocol will not score in service coatings that deviate in dry film thickness (DFT) to as much as 2x or 3x or more the recommended thickness. Again, the application of UV is unrealistic as WBTs have very little exposure to UV.

### *B. ISO 20340:2009 (E) (Paints and Varnishes – Performance Requirements for Protective Paint Systems for Offshore and Related Structures)*

ISO 20340:2009 (E) deals with performance requirements of paint systems applied on offshore and related structures. This standard specifies additional test requirements over and above those specified in ISO 12944-6 for corrosivity category C5-M (marine & offshore environment). Also, ISO 20340 is applied in qualifying structure(s) of category Im2 (immersed in sea water). The dimensions of the specified test panel are 150 by 75 by 3 mm. The specified surface preparation is by grit blasting to at least Sa 2.5. The recommended maximum thickness of each coat on each panel is as follows: less than 1.5 x the nominal dry film thickness (NDFT) if the NDFT is $\leq$ 60µm; less than 1.25 x the NDFT if the NDF is > 60 µm. Conditioning period is in accordance with ISO 3270 (temperature: 23±2$^{o}$C and relative humidity: 50±5%) for 7 days or 1 week. The test panel is horizontally scribed parallel to one of the width sides. The scribe dimension is 50mm long, 2 mm wide, 12.5mm from each long edge of the panel and 25mm from the bottom (short) edges of the panel. ISO 20340 qualification tests used in the assessments of coating performance include ageing resistance, cathodic disbonding and sea water immersion. The ageing resistance is a cyclic exposure test consisting of UV/Condensation, Salt Spray and sub-zero dry out. An exposure cycle for one (1) week (168 hours) includes the following:

- Starts with 72 hours exposure of UV/Condensation: alternating periods of 4 hours UV exposure at 60±3°C and 4 hours for condensation exposure at 50±3°C
- Followed by 72 hours salt spray in accordance with ISO 9227 at 35±2°C using 5 % sodium chloride electrolyte
- 24 hours of exposure to low temperature at -20±2°C

Also, it is advised to rinse the panels with deionised water between the salt spray and low temperature exposure but avoid drying them. Also, this -20±2°C low temperature of the panels is required to be achieved within 30 minutes. Duration of exposure for the test panels is 25 cycles or 4200 hours (25 weeks).

ISO 20340 and ASTM D5894-10 are cyclic corrosion tests. The distinguishing characteristic between these two standards is the freeze cycle in ISO 20340. Another distinct feature of ISO 20340 test specimens is the introduction of a mechanical damage through a scribe marking. The mechanical damage would drive a different failure mode from cracking. A corrosion assessment is performed on the scribed specimen by removing all loose/corroded areas at a number of predefined points and averaging to obtain the final figure. The analysis of this corrosion assessment could be considered to be subjective as it depends on the ability of the operator.

Common in both the ISO 20340 and ASTM D5894-10 test protocols is the alternate exposure of the test specimen to uv/condensation and salt spray cycles. The weekly test durations for uv/condensation and salt spray exposures as shown in ASTM D5894-10 have been reduced in ISO 20340 to 72 hours (3 days instead of the 7 days interval as in ASTM D 5984). The overall test protocol duration is longer for ISO 20340, extending to 25 weeks when compared to 6 or 12 weeks for ASTM D5894-10.

The incorporation of UV light in the test also negates and undermines the kind of in service exposure as seen in WBTs. Finally, flat specimens (grit blasted to Sa2.5) employed in ISO 20340 tests are highly unlikely to produce cracking failure of WBT coatings as they lack the required geometry as explained earlier. Also majority of the cracking failure reported occur at corners on power tooled welds.

### *C. NORSOK STANDARD M-501(Surface Preparation and Protective Coating)*

NORSOK M-501 is targeted towards offshore and associated facilities. This test attempts to address different coating system functional requirements in offshore corrosion protection, such as prefabrication primers, deck systems, passive fire protection and linings including ballast coatings. Norsok M-501 is more prescriptive with regards to paint application (number of coats, stripe coating and DFT) when compared to ISO 20340. Also, NORSOK M-501 prescribes pre-blasting preparation on sharp edges, fillets and corners by rounding and smoothing whilst welds are prepared by grinding. In this test, coating system 3B refers to coatings applied to WBTs. The performance testing of the protective coating is similar and in accordance with ISO 20340 as enumerated before. So in essence the NORSOK test for WBTs is a reflection of ISO 20340. Also, the IMO PSPC MSC 215(82) pre-qualification or performance testing has been accepted as an alternative qualification method for ballast tank coatings (coating system 3B) employed by NORSOK M-501. So NORSOK M-501 shares the same highlighted issues with ISO 20340 and IMO PSPC MSC 215(82) when applied to performance testing of WBT coatings.

### *D. NORDTEST Method NT POLY 185 (Determination of Flexibility and Fatigue Resistance of Aged Ballast Tank Coatings)*

NORDTEST NT POLY 185 is intended to determine flexibility and fatigue resistance of aged ballast tank coatings. The test piece is a flat steel substrate with a thickness of 3 mm and 30 mm in width and 150 mm in length. Coating thickness is specified at about 300 µm on both side of the test piece. The ageing test consists of three stages: immersion conditioning, air conditioning and damp heat cycling. One cycle of the test consists of three stages which are completed in one week.

- 72 hours exposure to artificial seawater immersion at 40°C
- 24 hours air conditioning exposure at 23°C and relative humidity is 50%
- 72 hours damp heat including condensation according to IEC 68230 combined with temperature interval 20 – 90°C

Maximum exposure time shall be 12 weeks (12 cycles) and mechanical testing after every three weeks.

Mechanical testing is achieved either through a four point bending or cylindrical mandrel bending test. This test protocol is intended for assessing coating flexibility with a flat test specimen. This test protocol doesn't take into consideration thicker coating films, i.e. above 300 µm or more. The test mentions the blasting of test specimen but does not say specifically to what cleanliness. Also, the test lacks the structural geometry in a WBT where the majority of coating breakdown by cracking is reported other than a flat plate.

### *E. NACE TM0304-2004 (Offshore Platform Atmospheric and Splash Zone Maintenance Coating System Evaluation)*

NACE TM0304-2004 is targeted at the offshore platform maintenance coatings. This test protocol contains seven test types including: rust creepage resistance, edge-retention, thermal cycling resistance, sea water immersion resistance test, cathodic disbondment, flexibility, impact resistance.

The rust creepage resistance test is in accordance with ASTM D 5894 but the electrolyte is replaced with synthetic sea water. Test panels are scribed for UV exposure. Test duration of 12 weeks is recommended. Performance is determined by measurement of rust creepage from a scribe marking. The test specimen is flat with dimension: 150 by 76 by 4.75 mm.

Edge-Retention test uses a 90° aluminium substrate bar with a curvature of 0.7± 0.1mm. Dimension: Long = 150mm, 19 by 19 by 3.18 mm.

Thermal cycling resistance test is performed on a coated C-Channel block (dimension: 76 by 50 by 3.18 mm) which is post cured at 60°C for one week before undergoing the thermal cycling. A cycle is carried out in two hours at an upper temperature of 60°C and a lower temperature of -30°C. Test duration is at least three weeks or 252 thermal cycles.

Seawater Immersion Resistance test: Test specimens are cleaned by blasting to Sa 2.5 before coating application. Coated test specimens, cured at room temperature for one week, are immersed in synthetic seawater at 40±2°C. Coating adhesion is evaluated by either a pull-off test in accordance with ASTM D 4541 on test specimens without holiday or wet coating disbondment test that uses test specimen with circular holiday in the coating film. Dimension of the flat specimen is 150 by 76 by 4.75 mm.

Flexibility is carried out on the coated panels that have been post cured at 60°C for one week using a fixed radii mandrel bending machine as described in NACE RP0394. The dimensions of flat test specimen are: Length = 150mm, Width = 12.7 to 25 mm, Thickness = at least 10 times coating system DFT.

Most of the testing in this protocol is carried out on flat specimens except in the edge retention and thermal cycling resistance tests. Dry out cycles are not included in any of the tests (when compared to ISO 20340) except for a sub-zero temperature cycle which is used in the thermal cycling resistance test. The sub-zero temperature cycle is highly unrepresentative of WBT exposure temperature. The test specimen does not incorporate welds and power tooled preparation by grinding at the corners as seen in service. Rather the prescribed surface preparation of the C-channel test piece is a near white metal blast cleaning only. Also, the angle of the C-channel is undefined which may lead to the use of various test specimen which may be similar but provide different result. Bending test specimens by mandrel bending also does not replicate in service conditions as higher strains than expected are observed to be applied by this test.

### *F. NACE TM0104-2004 (Offshore Platform Ballast Water Tank Coating System Evaluation)*

NACE TM0104-2004 is a test protocol specifically dedicated to ballast water tank coatings of offshore platforms. As a test protocol, NACE TM0104-2004 has three tests which are similarly to NACE0304-2004. These tests are edge retention, sea water immersion resistance and cathodic disbondment. In addition to these three tests it also includes dimensional stability, ageing stability, thick film cracking and hot/wet cycling which is only for Floating Production Storage and Off-loading (FPSO) Structures.

The Dimensional Stability test is intended to track a coating system's swelling or shrinkage on immersion. Room temperature cured free films are immersed in synthetic seawater at 40±2°C for 12 weeks. The changes in length, width and mass of the free films are measured.

Aging Stability test: Test specimens that have been cured are exposed to an ageing test by seawater immersion for 12 weeks at 40±2°C. Thereafter, flexural strain is obtained on fixed radii mandrel bending for both the aged and non-aged test specimens. The rationale is to compare the aged test specimens against the non-aged/ control test specimens. The flat test specimen dimensions are: Length = 150mm, Width = 12.7 to 25 mm, Thickness = at least 10 times coating system DFT

Thick-Film Cracking test: In this case, the test specimen used is the same test specimen employed in the thermal cycling resistance test for NACE TM304-2004. However, for this test protocol, the test specimen is immersed in synthetic seawater at 40±2°C for 12 weeks. Thereafter, the coating system is assessed for cracks.

Hot/Wet cycling: The test is intended to assess coating performance by simulating wet/dry exposures which may be encountered in ballast tanks on an FPSO. This is a cyclic salt-fog test carried out in accordance with ASTM G 85-A5. This test alternates cycles of 3 hours wet at room temperature and 3 hours dry at 60°C. Flat test specimens with vertical scribe on one side are used for this test. Their dimensions are: 150 by 76 by 4.75 mm.

Amongst the four tests, two (aging stability and hot/wet cycling) employ flat test specimens while the others (dimensional stability and thick-film cracking) employ free film and c-channel specimens respectively. The use of the flat specimen and free film is unrepresentative of the in service location where cracking is observed in WBT. All the other tests except the hot/wet cycling test can be linked to a static exposure condition test. However, the hot/wet cycling test assesses corrosion from rust creepage of the mechanically induced damage.

### *G. IMO PSPC (Performance Standard for Protective Coatings for Dedicated Seawater Ballast Tanks in All Types of Ships and Double-Side Skin Spaces of Bulk Carriers)*

From 1990 to 2000, the shipping industry continuously focused on the consequences of corrosion and increasingly demanded better performance from protective coatings used for corrosion control [1], [14]. These concerns led to the introduction to an amendment of Safety of Life At Sea Convention (SOLAS) in Chapter II Part A-1 Regulation 3-2 which specified the need for protective coatings for dedicated ballast tanks and double-sided skin space of bulk carriers in compliance with the PSPC mandated by the IMO [1]. IMO responded to the need of members of International Association of Classification Societies (IACS) and other stake holders through the adoption and amendments made to the SOLAS 74/78 by resolution 216 (82) of the Maritime Safety Committee (MSC) on page 3. One of such stakeholders that set the pace for a standard for the protective coatings in WBTs was the Tanker Structure Cooperative Forum (TSCF). The TSCF was formed by Shell International Marine in 1983 as a group with initial members as ship owners and class societies but its current membership also include oil majors and coating producers [16]. The group's rationale is to share experience and knowledge on technical matters concerning the performance of tanker structures in service. From the shared experience, several publications have emerged in the shipping industry. One of such publication in 2002 was the TSCF guidelines for WBT coating systems and surface preparation

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which set the foundation for the IMO PSPC [13]. The IMO PSPC exceeds and renders more precisely each classification society's own standard as well as the existing "Unified Requirement Z8," issued by the IACS in 1990 and revised 1995 [10]. The PSPC was approved in December 2006 and first adopted 1st July 2008. The requirement is now mandatory and applies to protective coatings in WBT of all type of ships of not less than 500 gross tonnage and double side skin spaces arranged in bulk carriers of 150m in length and above [6].

The PSPC requirement can be summarised as selection, application and maintenance of protective coatings within WBTs. The requirement defines coating practices such as shown in the table below:

TABLE I
CONTENTS OF COATING SPECIFICATION

| Scheme for (ref. SOLAS Reg. II-1/3-2) | Items to be described in specification |
|---|---|
| General (Tri-Partite Agreement) | The yard's, owner's and coating manufacturer's agreement on the specification |
| Selection of coating | Coating type – epoxy base, other alternative systems |
| | Coating Pre-qualification test |
| | Definition of coating systems, including number of applied coats and minimum/maximum variation in NDFT with 90/10 rule |
| Application of coating | Surface preparation (primary and secondary) including preparation for edges and welds, surface cleanliness and profile requirements ( e.g. blasting to Sa. 2.5 with profile between 30 -70 µ) Environmental conditions in terms of maximum allowable air humidity in relation to air and steel temperatures during surface preparation and coating application Also, environmental conditions for coating application shall conform to coating manufacturers specification Other practice prescribed include dust quantity, water soluble salts and oil contamination |
| Maintenance of coating | In service maintenance, repair and partial recoat |

The goal of PSPC is to achieve a target coating life of 15 years in good condition with maintenance [6]. This requirement and the accompanying IACS Procedural Requirement (PR) 34 has brought more awareness of the importance of protective coating practices that have been long neglected in the shipbuilding/shipping industries. However, the long-term impact of the PSPC on the industry is yet to be seen as it is still early days.

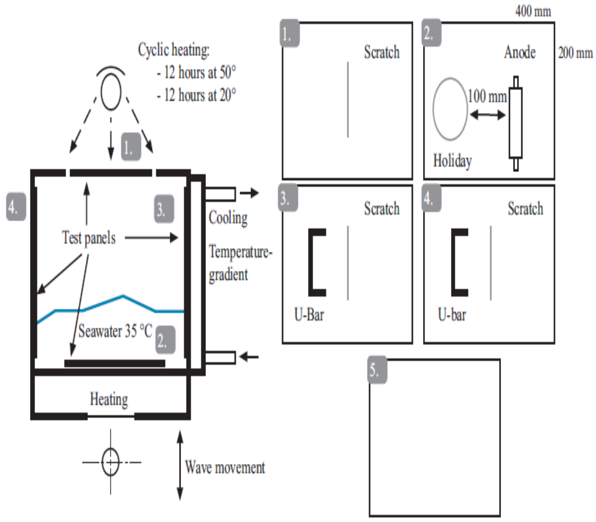


Fig. 3 Wave tank laboratory testing of ballast tank coatings [10]

According to the IMO PSPC, one of the methods of accepting a coating system for application in WBTs is to undergo a pre-qualification in a laboratory test (also known as type approval). The test facilities, test panels, test duration and acceptance criteria to be achieved are vividly described in the PSPC. However, there is no data or requirement to adequately benchmark coating embrittlement in WBTs from the current proposed coating pre-qualification test. For the test; two principal tests chambers are recommended for coating testing. They are: the use of a wave tank chamber to simulate supposed service conditions inside a ballast tank, and also the use of a condensation chamber to simulate condensing condition.

After performing the PSPC testing from both chambers, one of the measured data to be reported is coating flexibility which is highlighted in MSC 82/24Add.1 Annex 1&2, section 2.2.4 and stated as follows: "*flexibility modified according to panel thickness (3mm steel, 300µm coating, 150 mm cylindrical mandrel gives 2 % elongation) for information only*". Although, the PSPC has mentioned and acknowledged the need for a flexibility test for assessing WBT coatings, it does not have a specified test method in this regards.

The PSPC recommended acceptance criteria from these tests are with regards to blistering which is a different coating degradation from cracking. Also, the PSPC pre-qualification standards evaluates mainly anti-corrosive coating properties such as delamination from mechanically induced damage made from a scribe marking, under film cutting from corrosion and in other cases water resistance and UV resistance.

In practice however, Safinah Limited has reported that PSPC pre-qualified WBT coatings (i.e. the coatings that have passed the PSPC pre-qualification test) can suffer early or premature in service failure especially in the form of cracks around structural areas like corners, edges, welds and joints of WBTs as the applied coating ages.

This issue seems more complicated because of the different generic WBT epoxy coating types. These coatings respond differently when used in service. Some develop and show early cracking failure whilst others don't when operating in the same environmental conditions.

Similarly, the Performance Standard for Protective Coating for Cargo Oil Tanks of Crude oil Tankers (PSPC-COT), whose test protocols are lined up and copied from the PSPC, also shares and contains the same short falls of the PSPC test protocols already mentioned especially the flexibility testing.

Thus, these concerns indicate that there is a need to investigate different WBT epoxy coating formulations (types) further on cracking failure. Most especially the changes that occur in the coating film that significantly brings about loss of its applied (flexibility or ductility) properties with respect to coating life. This is confirmed by Det Norske Veritas (DNV) [17] and IMO MSC (82) [6] in the below two quotes respectively:

"*It is due time that the shipping industry together with the paint/coating manufacturers start investigation of how coating flexibility changes with time due to ageing processes. The behaviour of coatings under simulated ballast tank deckhead conditions is primarily of interest".*

*"Coatings for application underneath sun-head decks or on bulk heads forming boundaries of heated spaces shall be able to withstand repeated heating and/or cooling without becoming brittle".*

## III. Conclusion

From the critical review of the standards, it has been demonstrated that these test protocols/methodologies do not satisfactorily reproduce cracking failure in WBT in its service environment.

Therefore, the design of an effective test protocol that will adequately characterise coating performance of WBT coatings by reflecting the environmental conditions and failure modes will be highly beneficial. It will reduce the likelihood of cracking failure and extend the intended lifetime of coating. Thus suggesting the increasing importance to further investigate and understand cracking failure in WBT coatings.

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