A STUDY INTO THE COATING THICKNESS OF SHIP BALLAST TANKS

(DOI No: 10.3940/rina.ijme.2020.a3.618)

R Willemen, **D Luyckx**, and **R Meskens**, Antwerp Maritime Academy, Belgium, **S Lenaerts**, University of Antwerp, Belgium and **K De Baere**, Antwerp Maritime Academy, Belgium

KEY DATES: Submitted: 24/02/20; Final acceptance: 01/07/20; Published: 07/10/20

SUMMARY

Ballast tanks are expected to be coated according to the IMO Performance Standard for Protective Coating regulations ($PSPC_{15}$), in addition to the paint application requirements of the paint producer. In general, a coating system should consist of minimum two spray coats of light-colored epoxy coating on flat surfaces with a Nominal total Dry Film Thickness (NDFT) of 320 µm and 90% of all thickness measurements greater than, or equal to the NDFT and none of the remaining measurements below 0.9 x NDFT (the "90/10 rule"). Allegedly, the value of 320 µm in this $PSPC_{15}$ rule may be misconstrued as a benchmark for coating application on flat surfaces, eventually leading to a non-$PSPC_{15}$ compliance due to the resulting variation in coating thickness violating this 90/10 rule. This study indicates that over the years, the arithmetic mean in-situ DFT appears to be 498±18 µm and that too high and low thicknesses, below 288 µm and above 800 µm, were noted in the field. Analysis of a survey of ballast tank coating performance of ships indicates that too low thicknesses appear to be negatively impacting the average theoretical ballast tank performance. However, when an application mean DFT benchmark of 525 µm is used, the coating will almost surely comply to the 90/10 rule and the risk of falling below the 288 µm threshold is small, less than 2% in most cases. Consequently, using 320 µm as a mean DFT benchmark could result in a non-$PSPC_{15}$ compliance with the in-situ ascertained coating thickness variation as this does not exclude coating thicknesses below 288 µm, which may then result in a significantly less than average theoretical coating performance. If the coating application is performed very evenly, the benchmark may be reduced to 429 µm with a probability of falling below 288 µm reduced to 0.1%. It should therefore be emphasized that the $PSPC_{15}$ requirement is a coating system framework description, and that the requirement should be broadened to include a mean DFT as a coating applicator benchmark together with a clearly specified minimum and maximum DFT, in order to avoid any misinterpretations.

1. INTRODUCTION

A ballast tank is a complex structure, with many longitudinal and transverse reinforcements with openings such as manholes, welding scallops and drain holes. This structural complexity results in many areas which are hard to coat and difficult to access. To apply an adequate anticorrosion protection of the tank walls, ballast tank coatings are to be coated according to the Performance Standard for Protective Coating regulations, $PSPC_{15}$ (IMO, 2006). $PSPC_{15}$ has been adopted by the International Maritime Organization (IMO) Resolution MSC.215 (82), and became mandatory on 1 July 2008 for dedicated seawater ballast tanks on all types of ships of not less than 500 gross tonnage and for double-side skin spaces arranged in bulk carriers of 150 m in length and upwards. $PSPC_{15}$ regulates surface preparation, coating thickness and application conditions, in order for the ballast tank coating to remain in a "GOOD" condition for at least 15 years.

Within the frame of the $PSPC_{15}$, the recommended nominal total dry film thickness (NDFT) is a partially defined range with an absolute minimum. In respect of the coating thickness, $PSPC_{15}$ states the following three elements/bullet points (IMO, 2006):

- *"NDFT 320 µm with 90/10 rule for epoxy-based coatings; other systems to coating manufacturer's specifications."*

This 90/10 rule means that 90% of all thickness measurements shall be greater than, or equal to, the NDFT and none of the remaining 10% measurements shall be below 0.9 x NDFT (IMO, 2006). According to the 90/10 rule, the minimum NDFT would be 288 µm.

- *"Maximum total dry film thickness according to manufacturer's detailed specifications."*

Numerous ballast tank coating data sheets indeed mention DFT requirements (for instance 2 x 160 µm; Table 1), which could often be interpreted as the minimum specified DFT. In most cases, the maximum allowable paint thickness is rarely mentioned, and paint manufacturers maintain a general rule of 2.5 and even 3 times the advised DFT (Akzo Nobel, 2017). Kattan (2017) mentions on the other hand that "*Good practice from paint company guidelines would mean that the maximum DFT applied should be x2 the specified DFT for each coat and for the total scheme. These would give a maximum scheme of 2 x 320 µm*".

- "*There shall be a minimum of two spray coats.*"

The thickness of each individual coating layer has not been defined, but it is common practice to use a minimum of 2 spray coats of 160 µm, as mentioned earlier (Wei et al, 2011). The 90/10 rule results in a minimum of 2 x 144 µm. However, paint manufacturers generally mention only the DFT of a single coat (Table 1). Recommendations for a minimum and maximum

©2020: The Royal Institution of Naval Architects

Table 1: Overview of 4 epoxy ballast tank coating thickness recommendations for newbuilding from four different paint manufacturers obtained from publicly available product data sheets

Coating	*Recommended DFT*	*System minimum thickness*	*System maximum thickness*	*Remarks mentioned in the data sheet*
Coating 1	= min thickness	2 x 160 µm		applications according to IMO PSPC
Coating 2	125 - 200 µm depending on system		1500 µm in critical areas, applied in two equal coats	slight modification of the product is sometimes necessary to comply with local or national rules/ circumstances
Coating 3	350 µm			
Coating 4	125 – 300 µm			Approved for PSPC for Water Ballast Tanks according to IMO Res. MSC 215(82)

thickness of the total coating system are rare. As the 90/10 rule indicates that 90% of the NDFT can be equal to 320 µm, it is not uncommon to put forward 320 µm as a mean application DFT benchmark, for instance in maintenance and repair. For example, the guidelines for long term maintenance and repair of protective coatings (IMO, 2009; ABS, 2017) recommend a DFT of 320 µm with minimum two spray coats. Further on in this document we will discuss the coating thickness measurements on board of a ship (ship C), inspected at a construction yard in March 2019. Its paint specification document upon newbuilding states for the water ballast coating system: *"2 x epoxy coating IMO PSPC approved 160 µm"*. This can be read as 2 x 160 µm.

However, Kattan & Fletcher (2015) challenge this common interpretation (as well as the wording of the PSPC requirements themselves) by stating that "*The range of DFT is more important than a specific DFT value. The range would reflect any minimum/maximum values recommended by the paint supplier. The challenge is to specify a range that is achievable by the application process.*" In this paper, we will test the validity of this statement based on in-situ findings and evaluate the typical applied coating thicknesses in ballast tanks. We will compare the coating thicknesses with the $PSPC_{15}$ requirements and the industry benchmarks, knowing that is quite a challenging task to coat a ballast tank due to spraying in a complex structure. We will also examine the impact of too high/low measured thicknesses on the coating performance.

2. MATERIAL AND METHOD

2.1 COATING PERFORMANCE AND THICKNESS MEASUREMENTS

Ballast tanks of 172 randomly chosen ships were inspected between 2007 and 2019 according to the protocol presented by Verstraelen et al. (2009a), De Baere et al. (2014) and Willemen et al. (2017). No selection criteria whatsoever were taken into account and the ships were visited as the opportunity arose. The average theoretical coating performance, expressed as corrosion index (CI) was described in function of the coating age and the degree of corrosion (Willemen et al., 2017). Coatings can then be rated "GOOD", "FAIR" or "POOR" in function of the presence of spot rusting, coating breakdown and/or rust penetration (IMO, 2009; IACS, 2015), albeit that the CI is only expressing the coating performance with a continuous number, whereas the IACS uses three stepwise grades of coating performance. A further description is given by Verstraelen et al. (2009b). On average, a coating turns from "GOOD" to "FAIR" at the age of 18.5 years (Willemen et al., 2017). 85 of these 172 ballast tanks coatings had thickness measurements on the flat surfaces with an ultrasonic coating thickness gauge (Elcometer a456 cfss). All observations are related to epoxy coatings, albeit of different types. Only ballast tank coatings which were representative for the original application condition were retained in this study, avoiding the effect of touch-ups to compromise the assessment of the actual coating performance (CI). Coats on edges and welded areas were not considered in the present study. The general distribution of the coating thickness was determined, as well as the average thickness, the standard deviation (sd) and the too high/low thickness values. In 18 cases, solely the average coating thickness value was noted upon inspection and from one ballast tank the coating thickness reading was only a minimum value. This lead to a total of 84 coatings measurements with average thicknesses, 67 coatings with minimum thickness values and 66 coatings with maximum thickness values.

Four ballast tanks out of these 85 ships were used for a more detailed in-situ evaluation of the ballast tank coating thickness. Each ballast tank belonging to a

©2020: The Royal Institution of Naval Architects

different ship (labelled A, B, C and D). Ship A, B and C were coated after 1 July 2008, meaning after the $PSPC_{15}$ resolution became mandatory. The inspection of Ship C took place in 2019 during construction. The application of the coating of Ship D was performed before 2008. A large number of measurements (varying between 300 and 500 per ship) was taken concentrated on the flat surfaces, organised in multiple sets of 12 measurements, spread out evenly on surface area patches of 50 x 100 mm. For each ship, the distribution of coating thickness was determined, as well as the average thickness, the standard deviation and the too high/low thickness values. Finally, it was verified whether the respective tank is in compliance with $PSPC_{15}$.

2.2 STATISTICAL ANALYSIS

The impact of ballast tank coatings with too high/low thicknesses was investigated by analyzing the respective coating performance. Too low ballast tank coating thickness values were defined as those below 288 μm, following the PSPC 90/10 rule. Too high thickness values were defined as those above 800 μm (i.e. 2.5 times the PSPC NDFT of 320 μm), in accordance with paint manufacturer HEMPEL's declaration. Performances of coatings with too high /low thickness values were compared to the average theoretical coating performance; the performance of the coatings with a thickness between 288 μm and 320 μm was also investigated.

The statistical thickness distribution, the average of the coating thickness as well as the too high/low thickness values were determined for each of the 4 in depth individual ballast tank coating analysis. These values were interpreted to describe the way the respective coatings were applied by the paint applicator with a possible compliance or non-compliance of $PSPC_{15}$ as a result. Based on the distribution observed on these four ships, an application benchmark for the ballast tank coating industry has been estimated.

3. RESULTS

3.1 DATASET ANALYSIS

3.1 (a) Average coating thickness

Figure 1 shows the histogram of the mean coating thickness measurements of the 84 ballast tanks (except for one, where only a minimum coating thickness had been noted). The average coating thickness is 498±18 μm. The standard deviation of 162 μm indicates a rather large variation in coating thickness between ships. The smallest measured average coating thickness is only 115 μm, well below the $PSPC_{15}$ lower bound of 288 μm. The largest observed average coating thickness is 1100 μm. 70% of the observed thicknesses vary between 301 and 600 μm. Moreover, the coating thickness appears to follow a positively skewed distribution.

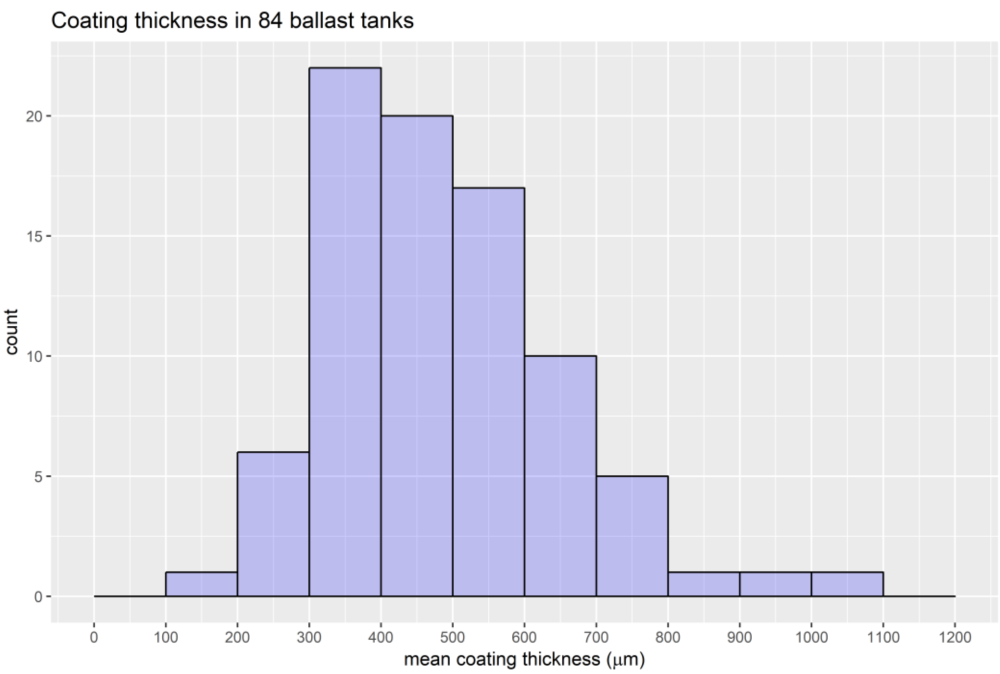

Figure 1: Average coating thickness measured in 84 ballast tanks

3.1 (b) Ships with minimal coating thickness less than 288 μm

Strikingly, from the 67 ballast tank coatings with noted minimum values, 19 (28%) displayed values below 288 μm, which implies a non-compliance with the $PSPC_{15}$ requirement. On one ship two tanks were inspected resulting in 19 evaluated tank coatings but 18 vessels. As presented by Willemen et al. (2017), the coating performance can be represented as a logistic curve. The performance was modelled for the 18 vessels, (Figure 2, blue curve), with a 95% confidence interval (blue area), and compared with the average theoretical coating performance (Figure 2, yellow curve). The CI of the ships with a minimal coating thickness of less than 288 μm starts to deviate significantly from the average corrosion index when the coating age reaches 12.9 ±0.4 years, and those ships will, on average, fall in the FAIR region at coating ages of less than 15 years.

3.1 (c) Ships with maximal coating thickness greater than 800 μm

A similar analysis was done for the 14 ballast tanks (21%) with maximum thickness measurements exceeding 800 μm (Figure 3). No statistically significant difference exists between the theoretical average performing coating and coatings with thicknesses above 800 μm. Zooming in on coatings with ages between 10 and 15 years reveals that one case out of four is deviating from the respective average performance and is ranked as "FAIR" instead of "GOOD". For coatings of less than 10 years old, one case out of 8 had become "FAIR" instead of "GOOD".

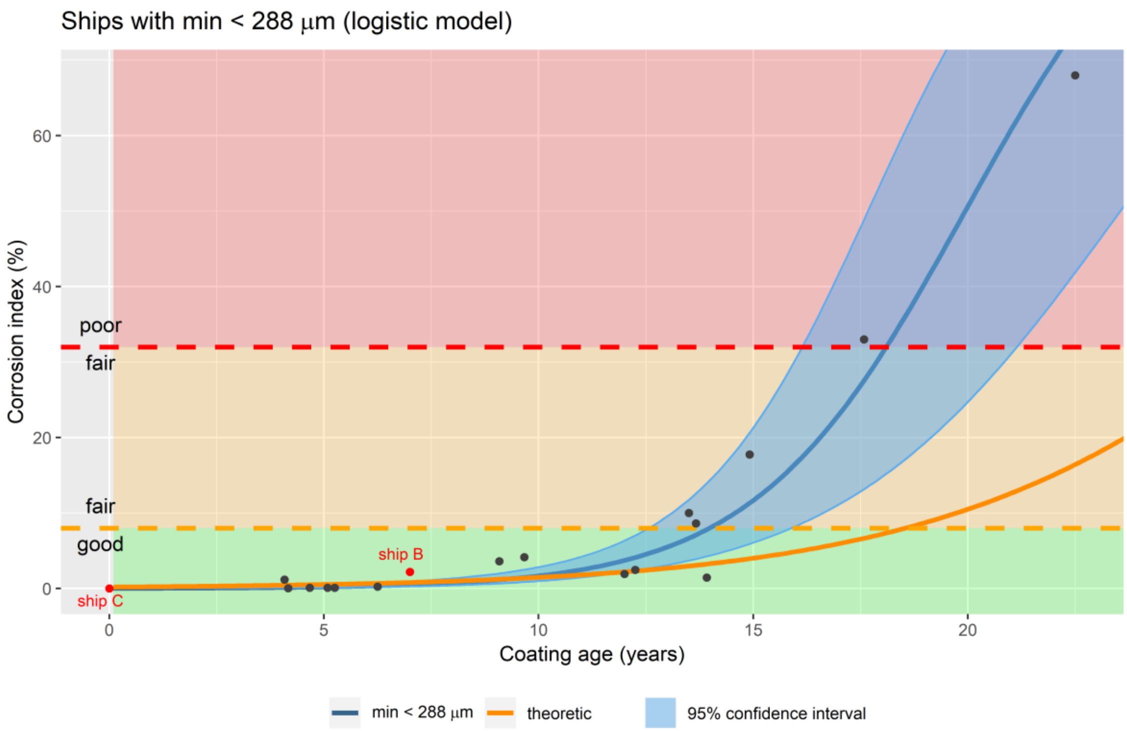

Figure 2. Ballast tank coating performance of coatings with DFT values below 288 μm versus the average theoretical coating performance

©2020: The Royal Institution of Naval Architects

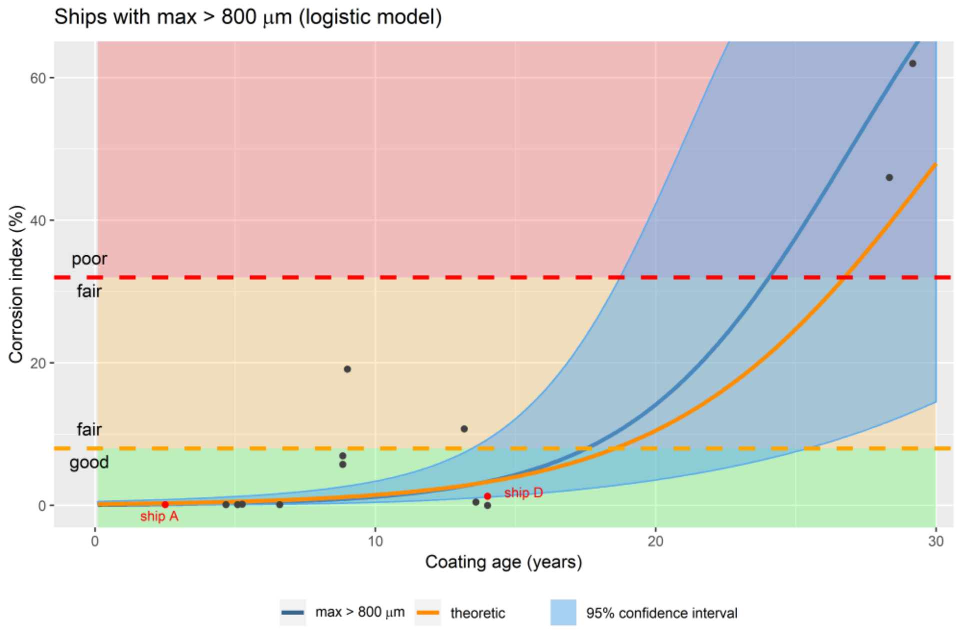

Figure 3. Ballast tank coating performance of coatings with DFT values above 800 μm versus the average theoretical coating performance

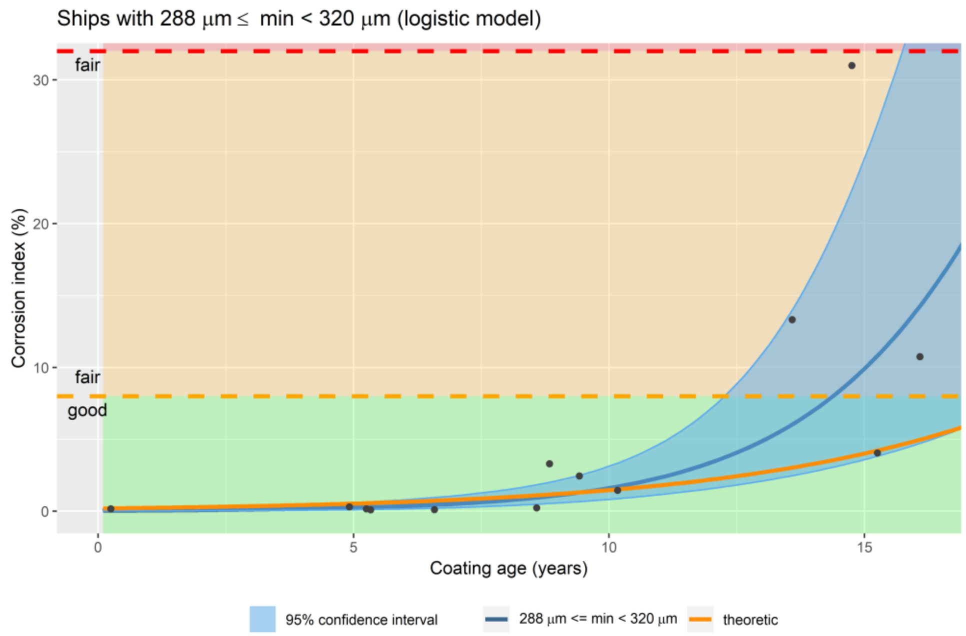

Figure 4. Ballast tank coating performance of coatings with DFT values as of 288 μm and not exceeding 320 μm versus the average theoretical coating performance

3.1 (d) Ships with minimal coating thickness between 288 μm and 320 μm

Finally, for 13 vessels (19%), minimum DFT measurements had a value ≥ 288 μm and < 320 μm (Figure 4). Notwithstanding the DFT being above the minimum thickness, it cannot be confirmed that in these cases the NDFT is in accordance with the $PSPC_{15}$ requirements due to a lack of sufficiently detailed measurements. Three ships out of 13 have a coating age between 10 and 15 years, 2 of which fall in the FAIR region. There is no statistically significant difference between the average CI and that of the coatings in the group presented here. Nevertheless, the theoretical coating performance resided on the boundary of the 95% confidence band (Figure 4). It could be surmised that the coating performance of ships with a minimal coating thickness between 288 μm and 320 μm might fall below average coating performance after 15 years and more.

As far as coatings with thickness ranges between 320 μm and 800 μm are concerned, it is noticed that they perform on average at least as good as the theoretic average coating (Figure 5).

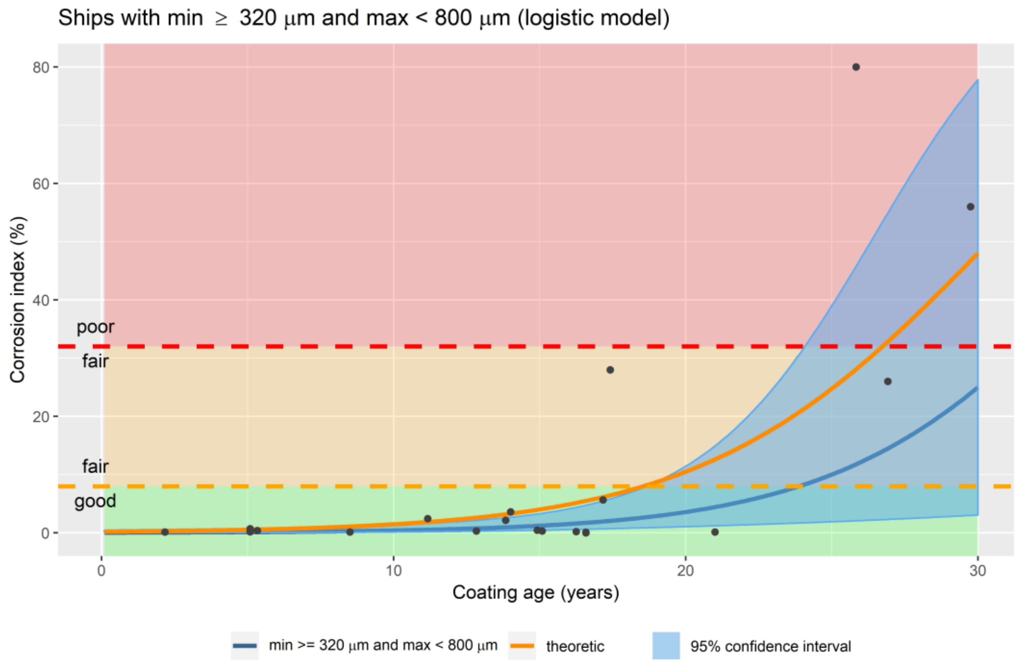

Figure 5. Ballast tank coating performance of coatings with DFT values ranging from 320 μm to 800 μm versus the average theoretical coating performance

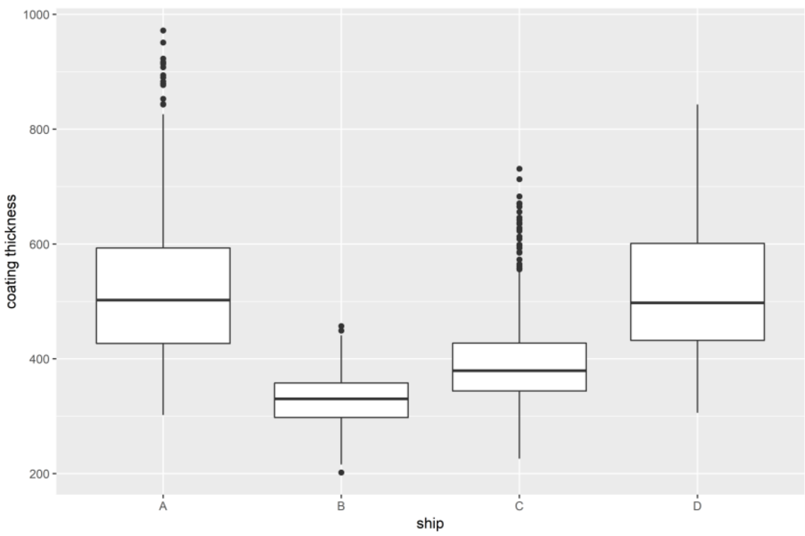

Figure 6: Boxplots of measured coating thickness on ships A, B, C and D

3.2 IN DEPTH ANALYSIS OF INDIVIDUAL BALLAST TANKS

The outcome of the in-depth measurements of one ballast tank on board of ship A, as well as ship B, C and D, is shown in Table 2 and Figure 6. Upon comparison of the respective thickness measurements, ships A and D show a considerably higher mean coating thickness than ships B and C. For ship B, 16.4% of coating thickness measurements are below the absolute minimum of 288 μm and 41.4% of the measurements were below 320 μm, which is considerably more than the admitted maximum of 10%. For ship C, 4.8% of coating thickness measurements were below the absolute minimum of 288 μm and 12.5% of the measurements were below 320 μm, again more than the maximally admitted 10%. The coatings of ships B and C do not comply with $PSPC_{15}$, whereas coatings of ships A and D meet the requirements. Additionally, there appears to be a link between the too thin coating thicknesses following $PSPC_{15}$ and the average coating thickness. Two out of three inspected ships with ballast tank coatings applied after 2008 showed too thin coating thickness having 330±2 μm and 396±4 μm as an average coating thickness. Interestingly, the third ship as well as the one coated before 2008 showed acceptable minimum thicknesses but remarkable higher average thickness values, namely 524±6 μm and 525±7 μm.

 ©2020: The Royal Institution of Naval Architects

Table 2: Statistical overview of the coating thickness data based on in situ findings. Conformity with $PSPC_{15}$ 90/10 rule practice is indicated by a green background color and an inconformity by a red background color

	Ship A	*Ship B*	*Ship C*	*Ship D*
Coating age	2.5 years	7 years	newbuilding	14 years
Average coating thickness	524 μm	330 μm	396 μm	525 μm
General standard deviation	130 μm (of all 492 measurements)	46 μm (of all 348 measurements)	83 μm (of all 456 measurements)	118 μm (of all 300 measurements)
General standard error of the mean	6 μm	2 μm	4 μm	7 μm
Local average standard deviation (patch of 50 mm x 100 mm)	40 μm	29 μm	29 μm	41 μm
Local average standard error of the mean	12 μm	8 μm	8 μm	12 μm
min thickness	**302 μm**	**202 μm**	**226 μm**	**306 μm**
90/10 rule considered readings % < 320 μm	**1.6%**	**41.4%**	**12.5 %**	**0.3%**
90/10 rule considered readings % < 288 μm	**none**	**16.4 %**	**4.8 %**	**none**
Max thickness	972 μm	457 μm	731 μm	843 μm
90/10 rule considered readings % ≥ 320 μm	**98.4%**	**58.6%**	**87.5 %**	**99.7 %**
Calculated target mean thickness for compliance with 90/10 rule	434 μm	378 μm	411 μm	423 μm
Calculated target mean thickness corresponding to 2 % risk of non-compliance with minimum of 288 μm	469 μm	382 μm	431 μm	450 μm
Calculated target mean thickness corresponding to 0.1 % risk of non-compliance with minimum of 288 μm	599 μm	429 μm	528 μm	564 μm

Coating application was performed with care on board of ship B, given the limited standard deviation and standard error of the mean (Table 2), where ship A, C and D show a much higher standard deviation. Furthermore, even thickness deviations within each of the small patches of 50 x 100 mm were higher on ships A and D (with a value of 40 and 41 μm) compared to the deviation of 29 μm in both other ships, indicating a more irregularly applied coating on the former. Notwithstanding this, the average coating thickness on ship B was too low, resulting in ballast tank areas where the overall coating was too thin.

The overall coating thickness varies considerably in case of ships A (sd = 130 μm), C (sd = 83 μm) and D (sd = 118 μm); on ship B the coating has been applied more evenly with a standard deviation of only 46 μm. When considering the distribution of the coating thickness for the four ships under study, ship B is the only case where the coating thickness follows a normal distribution. In case of ships A, C and D, the distribution of the coating thickness is positively skewed and approximates a lognormal distribution, as can be seen on figure 7.

4. DISCUSSION

A coating applicator has a target application thickness in mind whilst spraying. Coating manufacturers refer to the IMO DFT of 320 μm (or 2 x 160 μm) for the coating system (Table 1). Jotun specifies for instance "*DFT control: one or more pass will provide the 160 DFT specified by the coating standards*." As a coating applicator uses a target application thickness, the 320 μm (or 2 x 160 μm) could easily be mistaken for a benchmark. However, the $PSPC_{15}$ rule is not an effective application rule for coating applicators, but merely a paint system framework description.

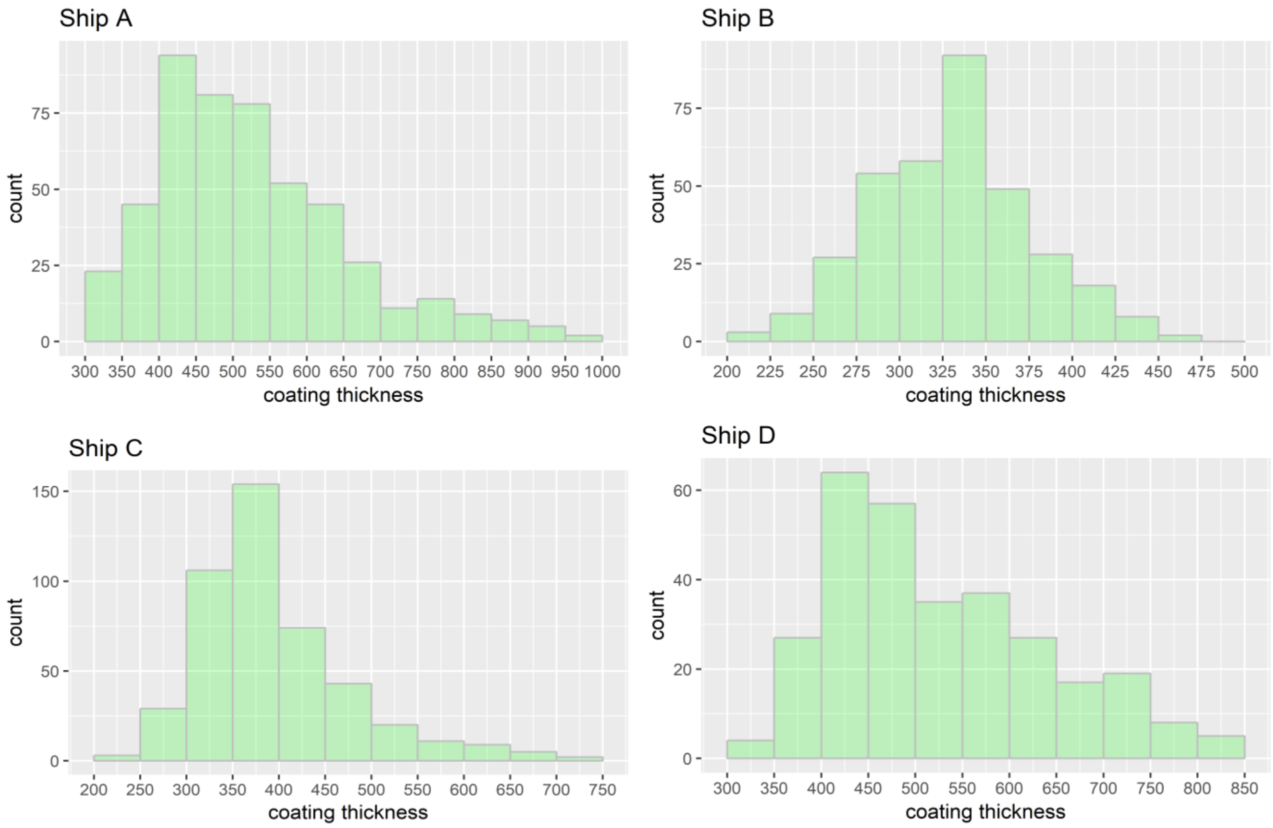

Figure 7: Histograms of the measured coating thickness on ships A, B, C and D

Table 3: Calculated application benchmarks for ships A, B, C and D; and for the 4 ships taken together

Ship	*90/10 rule*			*Probability of falling below 288 μm reduced to 2 %*			*Probability of falling below 288 μm reduced to 0.1 %*		
	Mean (μm)	*Median (μm)*	*Mode (μm)*	*Mean (μm)*	*Median (μm)*	*Mode (μm)*	*Mean (μm)*	*Median (μm)*	*Mode (μm)*
A	446	434	410	482	469	443	616	599	566
B	378	378	378	382	382	382	429	429	429
C	419	411	396	439	431	414	538	528	508
D	433	423	403	461	450	429	577	564	538
A, B, C and D	472	455	422	525	506	469	698	672	624

Nevertheless, it can be calculated what the mean coating thickness at application should be in order to comply with the 90/10 rule of $PSPC_{15}$, when assuming a lognormal distribution for coating thickness on ships A, C and D, or a normal distribution for coating thickness on ship B. However, the probability of occurrence of a coating thickness below the absolute minimum of 288 μm can never be totally excluded and thus cannot be reduced to 0 from a statistical point of view. Therefore, two possible values of mean coating thicknesses are calculated with respect to the lower bound of 288 μm, namely averages corresponding to a probability of 2 % and 0.1 %, that thicknesses below 288 μm occur. The lower the risk to obtain thicknesses below 288 μm, the higher the mean target thickness at application should be. These calculated target mean thicknesses also reveal that compliance with the 90/10 rule of $PSPC_{15}$ is more easily achieved than compliance with the absolute minimum of 288 μm. It is thus the threshold of 288 μm that determines the practical benchmark for coating application.

Due to the differences in variation of the coating thickness on one single ship, the target values for mean coating thickness vary considerably among the 4 ships under study. In general, target values for mean coating thickness can be lower if the coating is more evenly applied. This is obvious when comparing the target values with the standard deviations of coating thickness on the 4 ships under study: the lower the standard deviation, the lower the target values. For ship B for instance, which has the most evenly applied coating with a standard deviation of only 46 μm, the target values for the mean are considerably lower than for the other ships.

 ©2020: The Royal Institution of Naval Architects

However, the observed mean coating thickness of ship B is below any of the target values for $PSPC_{15}$ compliance, resulting in a non-compliant coating.

Based on the measurements on ships A, B, C and D, an application benchmark for coating application in the industry can be estimated, based on the lognormal distribution of coating thickness as observed for ships A, C and D. Such a benchmark highly depends on how evenly the coating is applied. If the coating is very homogeneous and coating thickness variations are small, comparable with ship B (sd = 46 μm), a mean coating thickness of 429 μm reduces the risk of falling below the 288 μm threshold to 0.1 %. As only one of the 4 ships under study has an evenly applied coating, a general application benchmark should consider variations in coating thickness as observed on ships A, C and D. For ship A, which shows the largest variation in coating thickness of the 4 ships under study, a mean coating thickness of 616 μm is required in order to reduce the risk of falling below the 288 μm threshold to 0.1 %. Similar calculations can be made for each of the 4 ships, and for coating thicknesses on all ships taken together. In table 3 an overview is given of target values for these cases, in order to reduce the risk of falling below the 288 μm threshold to 0.1 % and 2 % respectively. As can be concluded from table 3 it is difficult to formulate an overall application benchmark for coating application in the industry so that $PSPC_{15}$ requirements will always be met. However, when using the mean to stay on the safe side, if a benchmark of 525 μm is used, the coating will almost surely comply with the 90/10 rule and the risk of falling below the 288 μm threshold is small, less than 2 % in most cases. If the coating application is performed very evenly, the benchmark may be reduced to 429 μm with a probability of falling below 288 μm reduced to 0.1%.

Furthermore, this study supports that the application of a coating in a ballast tank implies a considerable variation in coating thickness. Focussing on patches of 50 mm x 100 mm we even notice a standard error of the mean (SEM) much higher than the overall SEM. In case an insufficient target DFT is used upon application this variation can lead to a too thin coating possibly resulting in a significant less performing coating. On the other hand, this study indicates that when taking the on-site noted variation in coating thickness in mind, due to the application procedure, it is possible to identify a specific target application DFT, which is considerable higher than the $PSPC_{15}$ NDFT. We therefore suggest a $PSPC_{15}$ requirement addition, to implement a target application mean DFT of 525 μm with a small risk to fall below the 288 μm threshold of less than 2 % in most cases, to ensure that paint application immediately results in compliance with the 90/10 rule. This reflects on the comment of Kattan & Fletcher (2015), mentioned in the introduction. Their challenge *"to specify a range that is achievable by the application process"* could thereby be answered. It should be emphasized that the skills of the sprayer applying the coating is a crucial element in the application process. A really good sprayer can achieve the $PSPC_{15}$ required thickness with a lower average than a less skilled sprayer.

Seeing that coating thicknesses vary considerably on patches, it could be questioned how a paint applicator should verify its maximum and minimum coating thickness obtained. Stating Johnny Eliasson of Chevron: "A single point measuring will not be sufficient, knowing that a paint drop can easily give higher than maximum values. The Society for Protective Coatings SSPC formulated a paint application standard no. 2, concerning the measurement of dry coating thickness with magnetic gages. Following this standard, the maximum here could be defined as the average on 5 single readings within a space of 10 cm x 10 cm" (Eliasson, pers. commun.).

Lastly, a few caveats should be mentioned.

In this study the thickness of the coatings is assumed to remain constant over time, even when being immersed (ballast tank filled with water). Per coating manufacturers' declaration, the coating thickness of epoxy ballast tank paints remains constant after curing. It is therefore feasible to predict the DFT on the basis of the application, and therefore to assume compliance with the $PSPC_{15}$ requirements. As the coating thickness remains unaffected (impact and friction damages disregarded), failure mechanisms to ballast tank coatings are linked to stress that develops in the coating over time. This will eventually negatively alter the adhesion of the coating by making it less flexible and thus increasing brittleness. This is supported on one hand by the acceptance criteria of ballast tanks coatings upon manufacturing. The acceptance criteria are linked to this adhesion loss in the form of determining the adhesive and cohesive failure as well as the failure by blisters and undercut (IMO, 2006). IACS Recommendation 87 (2015) on the other hand links the possible failures to bad preparation or application and no link is made to a possible loss of coating thickness. No public available studies were found related to unaffected ballast coating thicknesses, impact and friction damages disregarded (an abrasion sensitive area could be around the suction pipe). If ship-owners would allow insight in the coating technical files (CTFs) of the vessels, the inspected thicknesses at a certain age could be placed next to the initial thickness after curing. Unfortunately, up to today we were not granted access to CTFs.

The general performance of a ship's ballast tank (CI) also takes edges and welds into consideration. When it comes to the data of thickness measurements only the flat surfaces were used in this study. These flat surfaces are representative for the paint applicator on how he performs the paint job (with what benchmark in mind), and thus the topic of this discussion. When it comes to edges and welds more elements should be considered as a stripe coat is added and applied differently, namely by brush. For edges one should also consider the treatment of the edges, namely chamfering or a radius.

Furthermore, coating thicknesses over 1500 μm, as mentioned in table 1, were not observed. After all, the thicker the coating, the higher the probability the coating will crack and affect the whole coating performance. When attempting to reduce the risk of obtaining a coating layer that is too thin (below the threshold of 288 μm), higher average coating thicknesses are required, as can be seen in Table 3. Nevertheless, in all scenarios considered in Table 3, the risk of trespassing the coating thickness of 1500 μm can be calculated and appears to be very small. For all ships taken together, the probability of obtaining a coating thickness of at least 1500 μm is found to be 0.17%. For each individual ship this probability is still at least a factor 100 smaller. We may conclude that the risk of cracks to occur in the coating because of a coating layer that is too thick, is negligible.

5. CONCLUSION

The analysis revealed that coatings with noted DFT measurements below the absolute minimum (288 μm) of the $PSPC_{15}$ recommendations, have a significantly different performance than the theoretical average performing coating. The in-situ measurements performed on board ships A, B, C and D revealed on one hand a presence of a large variation in coating thicknesses on ballast tank flat surfaces well away from welds and scallops. Even within small area patches a big variation was observed. On the other hand, it revealed that if a paint applicator would use the 320 μm as a benchmark to apply its paint (like ship C, following the yard paint specification guide), we can conclude, from the large variations observed and more specifically from the measurements noted from ship B & C, that $PSPC_{15}$ will not be met, resulting in DFT thicknesses lower than the minimum allowable thickness. Using 320 μm as a benchmark implies possible DFT measurements below 288μm and thus bears the potential risk of a significant different performance in respect of the theoretical average performing coating. It is of utmost importance not to misread the $PSPC_{15}$ requirements and not to use the 320 μm as a benchmark. It should be emphasized that the $PSPC_{15}$ requirement is a paint system framework description and not indicating the paint applicator's target coating thickness.

A reasonable approach to tackle this issue could be to broaden the requirement and to include an average DFT as a paint applicator benchmark. In order to comply with the $PSPC_{15}$ requirement not to have lower coating thickness readings than 288 μm, the in-situ data represented in table 2 and figure 6, reflecting the application process in the industry, reveals in table 3 that it is difficult to formulate an overall application benchmark for coating application in the industry so that $PSPC_{15}$ requirements will always be met. The present study indicates that, when a benchmark of 525 μm as mean DFT is used, the coating will almost surely comply with the 90/10 rule and the risk of falling below the 288 μm threshold is small, less than 2 % in most cases. If the coating application is performed very evenly, the benchmark may be reduced to 429 μm with a probability of falling below 288 μm reduced to 0.1%.

6. ACKNOWLEDGEMENTS

This work was supported by a BOF grant from the University of Antwerp and Antwerp Maritime Academy (PS ID (Antigoon): 34052), as well as by NATO SPS grant G4834. G. Potters is thanked for his assistance in the discussions and the formatting of the text.

7. REFERENCES

1. ABS (2017). *Guidance notes on maintenance and repair of protective coatings*, Houston USA.
2. AKZO NOBEL (2016). *Technical data sheet Interbond 998*, ref 846.
3. AKZO NOBEL (2017). *Application Guidelines Intergard® 343*, Revision 10 Date 21st November 2017.
4. DE BAERE K, VERSTRAELEN H, WILLEMEN R, MESKENS R, POTTERS G (2014). *Taking care of Ballast Tank Coatings = Green Ballast Tanks Coatings*. Alexandria: SNAME, p. 1-14.
5. HEMPEL (2018). *Product Data Sheet & Application Instructions HEMPADUR QUATTRO 17634* INTERNATIONAL MARITIME ORGANIZATION (2006). *Resolution MSC.215 (82) Performance Standard for Protective Coatings for Dedicated Seawater Ballast Tanks in all Types of Ships and Double-Side Skin Spaces of Bulk Carriers*. London: IMO; adopted on 8 December.
6. IACS (2015). *Recommendation 87 Guidelines for coating maintenance & repairs for ballast tanks and combined cargo/ballast tanks on oil tankers Rev.2 May 2015.*
7. INTERNATIONAL MARITIME ORGANIZATION (2006). *Performance standard for protective coatings for dedicated seawater ballast tanks in all types of ships and double-side skin spaces of bulk carriers*, RESOLUTION MSC.215(82), MSC 82/24/Add.1. London: IMO.
8. INTERNATIONAL MARITIME ORGANIZATION (2009). *Guidelines for maintenance and repair of protective coatings* MSC.1/Circ.1330. London: IMO.
9. JOTUN (2018). *Technical data sheet Balloxy HB Light,* Norway, Norway, Jotun.

 ©2020: The Royal Institution of Naval Architects

10. JOTUN (n.d.). *A guide to ballast tank protection ensuring IMO compliance, lifetime protection, economy and much more*, Norway, Jotun.
11. KATTAN R (2017). *The Impact of Minimum & Maximum DFT Values on Coating Performance*. Corrosionpedia Inc, https://www.corrosionpedia.com/2/3068/environments/marine/the-impact-of-minimum-maximum-dft-values-on-coating-performance (Accessed 28th March 2018).
12. KATTAN R. FLETCHER JF (2015). *The Problem with Meeting Dry Film Thickness Specifications*. Society for Protective Coatings, SSPC.
13. PPG (2018). Product data sheet SIGMACOVER^{TM} 380, ref 7979.
14. VERSTRAELEN H, DE BAERE K, SCHILLEMANS W, DEWIL R, LENAERTS S, POTTERS G (2009a). *In situ study of ballast tank corrosion on ships. PART 1.* Materials Performance; 48(10): 48-51.
15. VERSTRAELEN H, DE BAERE K, SCHILLEMANS W, DEWIL R, LENAERTS S, POTTERS G (2009b). *In situ study of ballast tank corrosion on ships. PART 2.* Materials Performance; 48(10): 54-57.
16. WEI C, ELIASSON J, JANSEN E, WANG G, BASU RI (2011). *IMO PSPC implementation and 15 years of target useful coating life*, ABS, CORROSION 2011, 13-17 March, Houston, Texas.
17. WILLEMEN R, VERSTRAELEN H, MESKENS R, LUYCKX D, VASTMANS K, LENAERTS S, POTTERS G, DE BAERE K (2017). *The economics of a long term coating*, The transactions of The Royal Institution of Naval Architects, Vol 159, Part A3, Pages 237 – 247.

 ©2020: The Royal Institution of Naval Architects