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HUSBANDRY OF OPTIMAL MAINTENANCE FOR SURFACE NAVY TANKS AND VOIDS

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ABSTRACT

Over the past 30 years, coating conditions in tanks and voids were intermittently recorded across the naval surface fleet by individual maintenance teams. The tank condition reports were not centrally located for further comparison or for historical analysis to accurately project future maintenance. Consequently, it was discovered in 2010 that approximately 50 percent of the coating condition of surface Navy tanks and voids were not documented in the Corrosion Control Information Management System (CCIMS). The CCIMS database is the official repository for all surface Navy tank and void survey data. Therefore, surface Navy needed to identify coating conditions on surface Navy ships before it became exceedingly expensive and timely to repair. Surface Maintenance Engineering Planning Program (SURFMEPP) improved survey execution rigor and standardized survey documentation procedures used to measure and house the condition of coating systems in tanks and voids, eventually realizing 98 percent known material condition by 2016. The coating inspection data from surveys was analyzed by a complex statistical reliability modelling software, which determined the survivability of coatings on a system (fuel oil, ballast, etc.) and class level. Coating analysis indicated that time intervals between coating application and repairs could be increased resulting in future cost avoidance. SURFMEPP developed strategies, such as the Tank Directive Maintenance Strategy (TDMS) that aligned the surveys concurrently with projected repair periodicities, while maintaining low risk to structural degradation. This strategy further optimized planning and execution of maintenance for tanks and voids by aligning predictable tank maintenance packages to availability types, such as dry dock or waterborne, considering budgetary constraints and duration requirements. This tactical development leads to improving inspection data and predicting overall reliability of a ship to direct proper maintenance actions at the optimal time. SURFMEPP continues to employ these methods on future coatings on tanks and voids and other corrosion affected system and determine the best action to take to ensure that the U.S. surface Navy is combat ready and achieves expected service life (ESL).

INTRODUCTION

The main objective for tank and void husbandry is planning the execution of the maintenance at the precise time while retaining low structural risk. Standardization of maintenance requirements allows for improved operational availability and increases in potential cost avoidance for tanks and voids on surface Navy ships. This also leads to an increase in the likelihood of each ship achieving its

ESL of required maintenance actions are accomplished.

History of Tank and Void Maintenance

Before converting into a tank directive strategy, tanks were strictly maintained under an as-found condition based maintenance (CBM) approach as outlined in the Corrosion Control Assessment and Maintenance Manual (CCAMM). CCAMM provides process requirements and guidance for the survey, assessment and repair or replacement of coatings and structures on naval surface ships. [Mandatory tank and void coating and maintenance requirements are derived from NAVSEA Standard Item 009-32, Naval Standard Technical Manual (NSTM) Chapters 100 and 631 and from the Joint Fleet Maintenance Manual (JFMM). The challenges imposed by strictly CBM is the inability to complete tank and void inspections along with required remediation due to limited availability durations, changes in maintenance and operational deployment cycles, programmed budgets and integration of modernization. CBM utilizes periodic inspection to determine if tank coating is degraded to a certain measurable condition and requires a maintenance action where coating conditions are exceeded. The maintenance action is either added to the ongoing availability or it is programmed as required for remediation in the following availability dependent on criticality of the condition. Each maintenance cycle varies by geographic region but is typically 36 months in duration. The inclusion of as found items presents budgetary integration in sequencing challenges for existing work in execution.

Establishment of SURFMEPP

Integrated Class Maintenance Plans (ICMPs) were developed by Naval Sea Logistics Center (NSLC) to consolidate maintenance plans on a class level. ICMPs set the technical requirements for maintenance and assessment for each surface ship class. In May 2009, Surface Ship Life Cycle Management activity (SSLCM) was created by NAVSEA to centralize lifecycle management of surface ships. In November 2010, SSLCM transitioned into Surface Maintenance Engineering Planning Program (SURFMEPP). SURFMEPP Corrosion missions include but are not limited to:

- Manage corrosion related maintenance requirements by developing Class Maintenance Plans (CMPs) for each surface ship class to reach expected service life
- Collecting and analyzing maintenance execution data to support existing and future corrosion strategies to reduce growth, new work and risk to On Time Delivery from maintenance availabilities
- Serves as the NAVSEA corrosion control life cycle manager for the surface Navy ships.

To develop and maintain tasks within the CMP, the Corrosion division analyzes trends from surveys executed by the fleet tank surveyors. There was a noticeable trend in 2011 that showed only approximately 60 percent of tanks and voids in the surface fleet had reliable data in CCIMS. The tank and void requirements are one of the largest risks in cost and maintenance duration when entering Chief of Naval Operation (CNO) availabilities. Recording accurate conditions of tanks and voids ensures critical information about the overall ship structural health and it frames the decision making process on when to conduct programmed maintenance. With aggressive and disciplined scheduling, execution and documentation of surveys, the surface fleet increased the known condition of tanks to 98% in 2016. The remaining 2 percent accounts for tanks that have not been opened since the ship has been commissioned, however this population's condition can be accurately projected to determine the maintenance required. Optimizing maintenance aids in determining the most effective maintenance at the right time in the ships service life. To optimize maintenance plans for tanks and voids, it is a comprehensive effort of inspecting and forecasting coating conditions, determining costs and durations, integrating with other critical maintenance and modernization into efficient and executable maintenance strategies at a hull level. These comprehensive strategies support minimizing the risk to deferral of maintenance as well as maximize the quantity of maintenance that can successfully execute in a maintenance period. The primary goal is to complete the life cycle maintenance on time thus allowing the ship to return back to warfighting operations.

METHODOLOGY

The approach to optimizing maintenance begins with collecting useful data, then analyzing and validating the collected data. After a comprehensive analysis, strategies are developed, implemented, and projected maintenance schedules are created. Lastly, inspection data is continuously recorded to calculate new coating technology and application method improvements.

Tank and Void Data Collection

SURFMEPP supports all classes of conventional surface ships, each with unique tank and void configurations. Tanks are defined as compartments that contain fluids such as potable water, fuel oil, salt water, etc. Voids are typically empty compartments used to limit extent of flooding or reserve buoyancy of a ship.

In accordance with maintenance requirements detailed in CCAMM, non-destructive Tank and Void Structural and Coating Condition Level 1 Surveys (Appendix A) were periodically scheduled to document structural and coating conditions of components within the tanks. For surface ships periodic surveys were separated by service types. Some contents are more corrosive like gas turbine drain tanks which degrade quicker while requiring more frequent maintenance. Other tank or void fluid mediums do not degrade coatings at the same rate so they are inspected on a less frequent periodicity.

Under a completely CBM approach, periodic Level 1 surveys are conducted with the objective of finding a remediation requirement and pushing a maintenance task within the same or next availability if a coating failure criterion is met. The failure criterion is set by the percentage of coating failure on a calculated surface area and percentage ranges are evaluated by the ASTM 610 standard. This designates a measurable inspection value for coating failure and the standard of corrosion. Table 1 outlines the four coating integrity criteria ranges based on the percentage of apparent coating defects and corrosion.

Table 1
Percentage of Corrosion per ASTM 610 Rust Grades

Condition P1 – Green **≤ 0.03% Failure**	**Condition P3 – Orange** **≥ 1% to 10% Failure**
Condition P2 – Blue **≥ 0.03% to 1% Failure**	**Condition P4 – Red** **> 10% Failure**

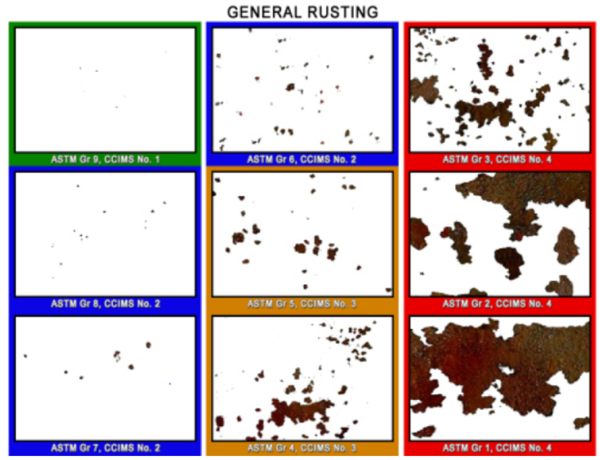

Figure 1
Condition Criteria for General Rusting

The survey is divided into four separate zones as listed below:

- Overhead (T, Top)
- Bulkhead/Shell (S, Side)
- Stiffeners (T, T-Bars)
- Bottom (B, Bottom)

The four zones create a TSTB Max number which is used to describe the overall degradation value of the tank or void based on zone with the worst identified condition. TSTB Max stands for Top, Side, T-Bars and Bottom. It is critical to measure the coating degradation in different sections of the tank because most tanks are adjacent to other tanks. To avoid the risk of contamination of fluid mediums, tank boundaries must be considered when remediating a tank.

Tank and Void Reliability of Coating Analysis

Filtering and Validating Data

SURFMEPP collected Approximately 49,000 data points from surveys but approximately 18,000 data points were deemed useful. These data points include baseline records, which indicates either when the hull was commissioned or when the tank coating has been reset. In order to draw a trending line, a minimum of two data points are needed for a singular system. Surface Navy tanks and voids are designated with a unique sequence number. There are approximately 15,000 tanks and voids across the surface Navy. The number varies over time due to hull configurations and commissioned status. The coating in a tank is assumed as one system. If a new coating is applied then it is considered a new system.

The tank sequence numbers did not indicate a new coating system. For the cases where a tank has been recoated multiple times, a modified sequence number was necessary. To define each coating re-set, the coating application date and whether it was the first or second or n^{th} time that the tank was opened and assessed was appended to the sequence number. For example a sequence number of the tank is 1234, and the baseline coating was applied 05/06/2003, this is the first coating for this tank. The sequence number was modified as:

1234_05062003-1

For example purposes, if this tank was assessed in 04/08/2006, and the tank has the original coating system, then the modified sequence number would be:

1234_05062003-2

This indicates that there are 2 data points for this particular coating system and marks the coating application date. Then to account for full coating resets, in 06/24/2009 a new coating system was applied to the same tank. This is the second coating system and the sequence number for the inspection data was set as:

1234_06242009-1

This allows readability of a specific tank with respect to class and service and the date when the coating system was applied and the assessment dates that followed.

Every data point was analyzed and retained, but a few noticeable discrepancies were flagged and filtered from the final data set to ensure trends weren't biased by the following cases:

- Partial coating repairs (Touch-Ups)
- Repeated TSTB Max score
- Decrease in TSTB Max score
- Condition greater than P1 at a coating reset point
- Lack of transition points

There are occurrences with coatings remain intact during a partial coating repair, which is called a touch up. A touch up indicates that the coating can be partially remediated which is up to 10 percent of the total surface area of the tank and it does not receive an extensive surface preparation. Also, current inspections do not record the locations of where touch ups are applied or measure the overall improvement of coating condition with a touch up. Therefore, it is difficult to predict if a touch up improves the reliability of the coating system or maintains the coating until it is fully remediated. In order to maintain the integrity of the accumulated data, coating systems that received a touch up action were removed from the dataset.

In some results, inspected tank showed the same condition rating as the previous inspection. In order to analyze the transitional period of one condition to the next, the first indication of transition was retained but the repeated conditions were removed. The dataset could not indicate how close, in percentage, was condition P2 to P3.

Many baseline records were recorded but tanks were being repaired before another inspection or there were cases of repairs in between inspections were not recorded. This created incomplete or out of order data points for a specific coating system. Data was removed if the baseline records were not paired with an inspection record greater than a P1 because there weren't clear-cut causes as to why this occurred.

<u>Inferences</u>

For a system to be unreliable, a failure criterion must be set. A coating condition of P3 or higher provided a gauge of when severe coating failure occurs creating a higher cost of not just coating repairs but structural repairs as well.

The collected data displayed three distinct forms of data, right censored, interval censored and left censored. Right censored is defined in this analysis as tanks that were inspected but not recorded as a coating failure. Interval censored is defined in this analysis as the interval of time from the previous inspection date until the assessed date of when the coating system is evaluated as a failure. Left censored is defined in this analysis as tanks that may have had premature coating failure, or the assessment was delayed and the coating system already degraded.

Groupings of data with similar relations can allow a system to be analyzed as a whole. This is the concept of how data was sorted for the reliability analysis that was performed for the variant types of tanks and voids. The first method was from a fleet perspective with separation between the service types of the tank. Then a second method provided a granulated approach by separation between service types and the classes of ships.

<u>Analysis</u>

Weibull analysis produces statistical predictions about the life cycle of a component or a process. Coating degradation is considered time-to-failure data, since the life of the coating is observable. The objective of the analysis was to determine the amount of time (in months) for a coating applied in a tank or void to degrade to a critical condition set at P3. This is designated as Mean Time To Failure (MTTF) to describe the average time for a system to reach a measureable failure. Mean Time to Failure and Mean Time between Failures are used interchangeably. MTTF means that the system is not repairable, and that it will fail and be fully replaced or remediated after failure. MTBF means that the system may fail and it is repairable throughout its operational life. The coating system is considered non-repairable in this analysis to determine how long a coating can withstand its conditions before degrading to a condition P3.

Maximum Likelihood Estimation (MLE) analysis is implemented. This analysis is appropriate for data sets with a high proportion of suspensions, interval data or many observed failures. This considers each time-to-suspension in the estimate of the parameters.

Fisher Matrix Confidence Bounds (FM): These bounds are considered more confident (optimistic) than non-parametric rank based bounds, although FM shouldn't be used for small sample sizes. If sample size is too small, then use likelihood ratio bounds. Confidence bounds were set at 95% likelihood.

For each statistical analysis, the best fit model that is applicable to non-destructive degradation analysis was applied to each dataset broken into service types.

Tank Directive Maintenance Strategy (TDMS)

Strategy Overview

SURFMEPP was directed by Commander, Naval Surface Forces (COMNAVSURFOR) to determine the feasibility of converting from strictly CBM to a combination of directive and condition based. Due to limitations of availabilities, duration, and expense of manned entry into tanks, survey periodicities were based on service type of the tank and historical assessment data. For tanks required blasting and recoating during a dry dock, the survey periodicity was adjusted to align with a dry dock period in combination with meeting the reliability requirements.

Implementation Process

The implementation of TDMS converted Tank and Void maintenance from Condition Based Maintenance (CBM) to a combination of time directed and condition based maintenance. For each ship class, a notional schedule was developed to schedule maintenance over the ESL based on results of MTTF for each service type.

Tank Planning Reports (TPR)

The TPR provides Last Maintenance Actions (LMAs) and current tank coating conditions allowing upcoming maintenance availabilities to be accurately programed for the specific hull.

Long Range Tank Planning Report (LRTPR) is derived from the TPR and projects tank and void maintenance actions to be accomplished over three CNO maintenance availability cycles. It also provides a notional duration estimate for projecting workload requirements.

Tank planning utilizes Objective Quality Evidence (OQE) from previous availabilities to accurately frame the actions completed or uncompleted. This contributes to prioritizing tanks and ensuring that incomplete actions are programmed for the next availability. Overall, this process organizes maintenance actions.

RESULTS

Using a multi-directional approach, SURFMEPP Corrosion team established periodic maintenance values due to projected conditions, service types and duration. The graphs produced from the statistical modelling software forms a visualization of corrosion conditions in various types of tanks and voids.

Analysis of survey records between 2010 and 2015 indicated that approximately 75 percent of tanks surveyed had been evaluated as a coating condition P1 or P2. These tanks did not require an immediate maintenance. This led to questioning if periodic surveys were performed too frequently.

The Appendices listed below are extracted examples of one particular service, salt water ballast tanks, which were analyzed due to their highly corrosive content.

Appendix B: Failure/Suspension Histogram provides the failure and suspension data at specified time intervals. The time intervals are set at 36 months because CNO maintenance availabilities are regularly scheduled every 36 months. This indicates the point in time of a coating system when most failures are recorded.

Appendix C: Reliability vs. Time graph shows the reliability values over time. It provides a graphical display of trends of the failure behavior of the coating system.

Appendix D: Unreliability vs. Time is the inverse of Reliability vs. Time. This shows the probability of failure of the product over time.

Appendix E: Probability Density Function (PDF) shows the PDF of the data over time, it allows a visual analysis of the distribution of probability of failure within a set range of time. The sum of the area under the curve in between time intervals equates to the probability in the specified time interval of identifying the tank at a P3 or higher.

Appendix F: Coating and Structural Degradation plot shows a window when the structural loss would occur in the tank. If over 50 percent of structural loss is found or projected, then the tanks would need base metal repair. The window gives a better gauge to repair the tanks, not too early or too late.

The results of this evaluation had three major categories of conclusions. The first identified systems which required additional data collection to initialize or improve the accuracy of the reliability model – no changes in assessment periodicity are recommended for these. The second found that survey periodicities listed for some systems are optimal, and no changes are needed. The third category of results identified systems where adjustments to the survey periodicities will continue adequate control of risks and applicable performance margins, while reducing the total ownership cost in the area of maintenance. Data supporting conclusion for Ballast tanks can be found in Table 2.

Table 2
Ballast Tank Survey Periodicity

Type of Service	Original Survey Periodicity	Updated Survey Periodicity
Ballast Tanks	72 months	108 months

Salt water ballast tanks are typically remediated during dry dock availabilities due to physical locations in inner-bottoms and underneath machinery spaces. The data analysis projects that the coating service life typically lasts 15 years until it degrades to condition P3. Based on dry docking cycle of 9 years, it is more efficient to plan the remediation of these types of tanks earlier rather than try to accomplish waterborne maintenance at the 15 year failure point. This is a conservative approach in that there is potential high risk if the service type is maintained at the next docking availability (approximately 18 years) due to increased risk to structural integrity.

Analysis has indicated that time between CCAMM required coating application can increase which reduces surveys and future maintenance actions. With this process we can improve inspection data and refine the predictions of overall reliability to direct proper maintenance actions at the optimal time.

CONCLUSION

Optimizing tank and void maintenance establishes a higher predictability in cost and foreseeable coating conditions. This capability of projecting conditions justifies maintenance actions to allocate budgets and industry resources. The prevalent constraint in maintenance availabilities is duration; therefore scheduling maintenance prioritized actions which consider the type of availability and duration programmed allows for a reduction in maintenance downtime while maximizing availability of the ship to the combatant commanders.

There are indicators to improve inspection data and determine the data to be collected, so that inspection time can also be reduced. Also, better predictors in the assessment of coating will give a more detailed analysis of timeframes of when transition from one coating condition to another occurs. Trends from the reliability graphs can assist in evaluating where the failures are occurring, determine reasons behind failures to drive innovation or technology updates to ensure that coatings of tanks and voids stay intact between maintenance windows. The overarching goal is to sustain the integrity of the substrate over the ship's service life to reach expected service life. It also provides examples of successful coating systems and allows for further investigation to develop and implement verified best practices for coating applications across the fleet.

Table 3
Other Tanks Survey Periodicity

Type of Service	Original Survey Periodicity	Updated Survey Periodicity
JP-5 Contaminated	36 months	72 months
CHT and VCHT	48 months	72 months
Compensated Fuel Oil	72 months	108 months
Floodable Voids	72 months	72 months
Fresh Water	72 months	108 months
Potable Water	72 months	72 months
Chain Lockers	144 months	108 months

Along the lines of technology, the modelling software provides automation of the degradation graphs and improves the accuracy and precision in projecting coating performance reliability. Additionally, it reduces the amount of manual effort and time previously required in the calculating the reliability of coating systems.

SURFMEPP will continue to monitor coating and structural conditions discovered during scheduled tank remediation. Continuous data collection on all variations of ship tank services will allow the technical authority to update maintenance periodicities accommodating new coating technology and application processes. Periodicities between coating application or repairs may be refined without increasing risk of structural deterioration.

SURFMEPP expects to influence maintenance further by expanding degradation and reliability analysis to other systems supporting integrated maintenance solutions for ships at the optimal time in the ships service life.

APPENDIX A: TANK AND VOID STRUCTURAL AND COATING CONDITION SURVEY (MRC G1N5)

NAVSEA T9630-AB-MMD-010 Rev. 3

TANK AND VOID STRUCTURAL AND COATING CONDITION SURVEY (MRC G1N5)

I. SURVEYOR DATA

1. Surveyor's Name:	2. Organization:	3. Phone Number:
4. Date:	5. Survey Reason:	6. Survey Completed: ☐ Y ☐ N

II. GENERAL DATA

7. Ship's Name:	8. Hull:	9. Access Via:
10. Tank/Void Number:	11. Tank/Void Service:	
12. Solid Ballast Present: ☐ Y ☐ N ☐ N/V	13. APL:	14. Painted Surface Area (sqft/sqm):

III. PENETRATION DATA

15. Manhole/Cover Condition: ☐ SAT ☐ UNSAT ☐ N/V | 16. Other Penetration Condition: ☐ SAT ☐ UNSAT ☐ N/V

IV. LADDER DATA

17. Ladders Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V | 18. Damaged Ladder(s) Type, Material:

V. TANK LEVEL INDICATOR (TLI) DATA

19. TLI Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V | 20. TLI Type:

VI. SOUNDING TUBE DATA

21. Sounding Tube Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V | 22. Striker Plate Damaged (>25% worn): ☐ Y ☐ N ☐ N/A ☐ N/V

VII. CATHODIC PROTECTION DATA

23. Sacrificial Anodes Present: ☐ Y ☐ N ☐ N/V | 24. Number of Anodes > 50% Depleted, Damaged, or Missing:

VIII. DESICCANT DATA (VOIDS ONLY)

25. Total Number of Desiccants Requiring Removal ("N/A" if none present):

IX. PIPING / VALVE DATA

26. Piping Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V | 27. Valves Damaged or Leaking: ☐ Y ☐ N ☐ N/A ☐ N/V

28. Piping Supports Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V | 29. Waster Plate Damaged: ☐ Y ☐ N ☐ N/A ☐ N/V

X. BLISTERING DATA

Survey Zone per CCAMM:	Overhead	Bulkheads/Shell	Stiffeners	Bottom
Blistering Size:	30.	31.	32.	33.
Blistering Density:	34.	35.	36.	37.
% Unacceptable Blistering:	38.	39.	40.	41.

XI. COATING AND CORROSION DATA (if any area not visible, make note in comments section)

Survey Zone per CCAMM:	Overhead	Bulkheads/Shell	Stiffeners	Bottom
% Corrosion:	42.	43.	44.	45.
% Corrosion + % Unacceptable Blistering:	46.	47.	48.	49.
Coating Condition:	50.	51.	52.	53.
Corrosion Local, Scattered, or N/A:	54.	55.	56.	57.
Local Corrosion Square Footage:	58.	59.	60.	61.

62. Select All Applicable Corrosion Issues: ☐ Pitting ☐ Scaling/Exfoliation ☐ General/Surface Corrosion ☐ None

XII. STRUCTURAL INTEGRITY DATA (evaluate structural condition regardless of coating condition)

63. Select All Applicable Structural Findings (all of the findings below require a Level 2 Structural Inspection):

☐ Holing	☐ Plate/Stiffener Crack	☐ Buckling/Distortion
☐ Doubler Plate Installed/Damaged	☐ Local Dent/Crease	☐ Weld Crack/Separation
☐ Structural Integrity Compromised	☐ Other Damage (Explain in Comments)	

64. A Level 2 Structural Inspection is Required: ☐ Y ☐ N | 65. UT Gauging Performed: ☐ Y ☐ N ☐ N/A

XIII. ADDITIONAL INFORMATION

66. No. of Pictures Taken: | 67. Picture File Number(s):

68. COMMENTS: (Provide specific detail for each discrepancy for generating 2-KILOs. Continue comments on additional pages.)

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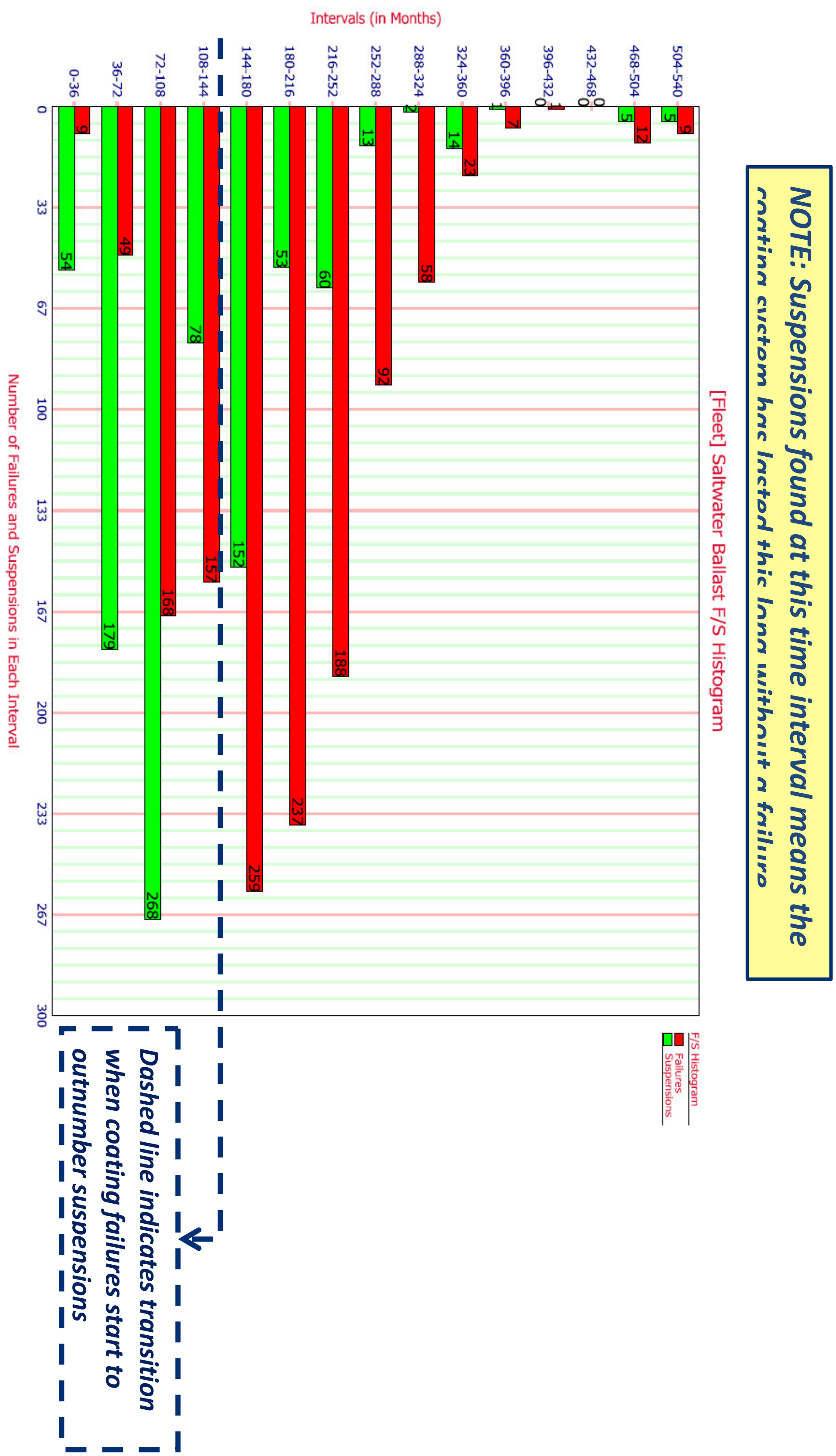
APPENDIX B: FAILURES AND SUSPENSION HISTOGRAM FOR SALTWATER BALLAST TANKS



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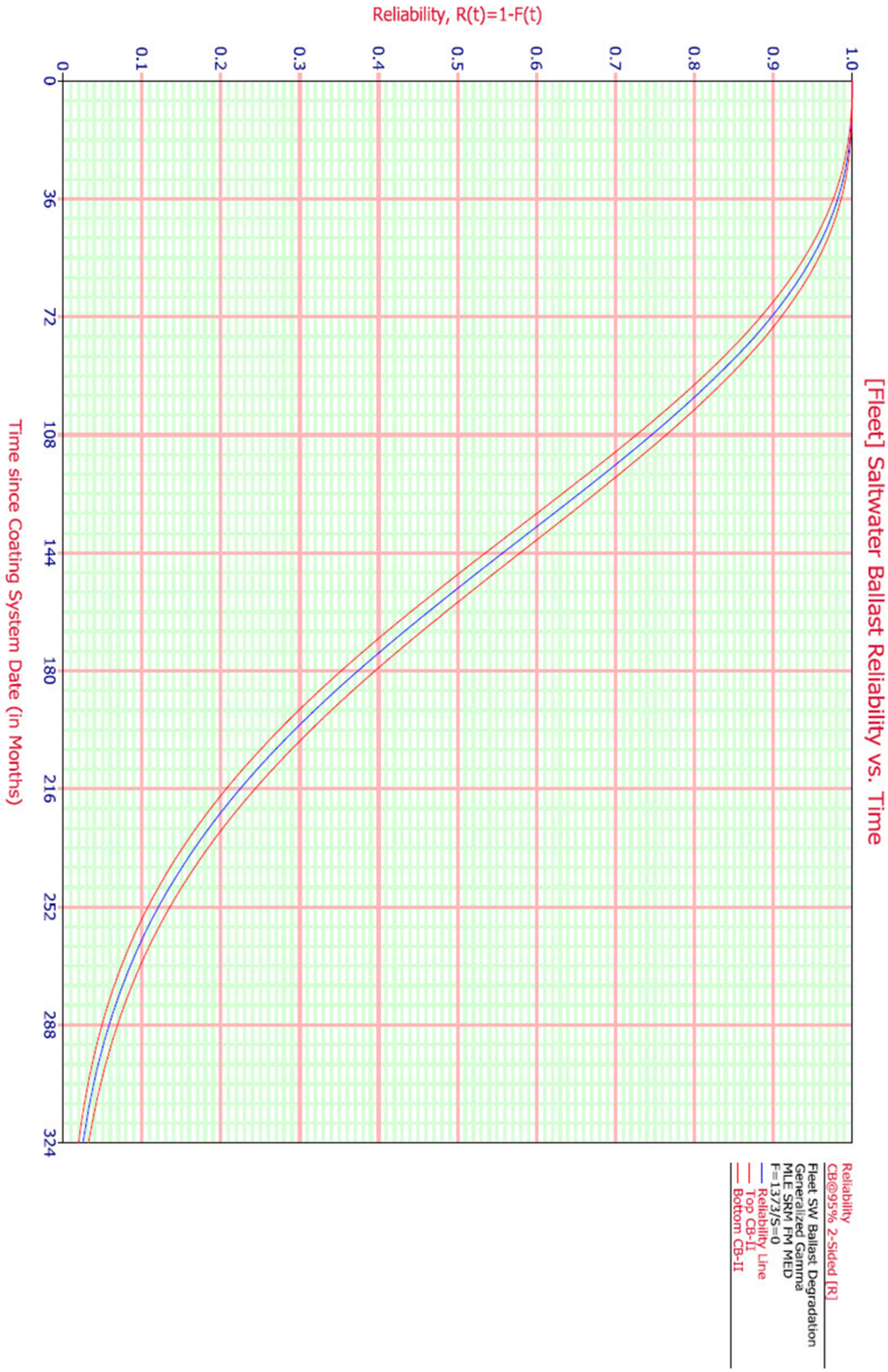
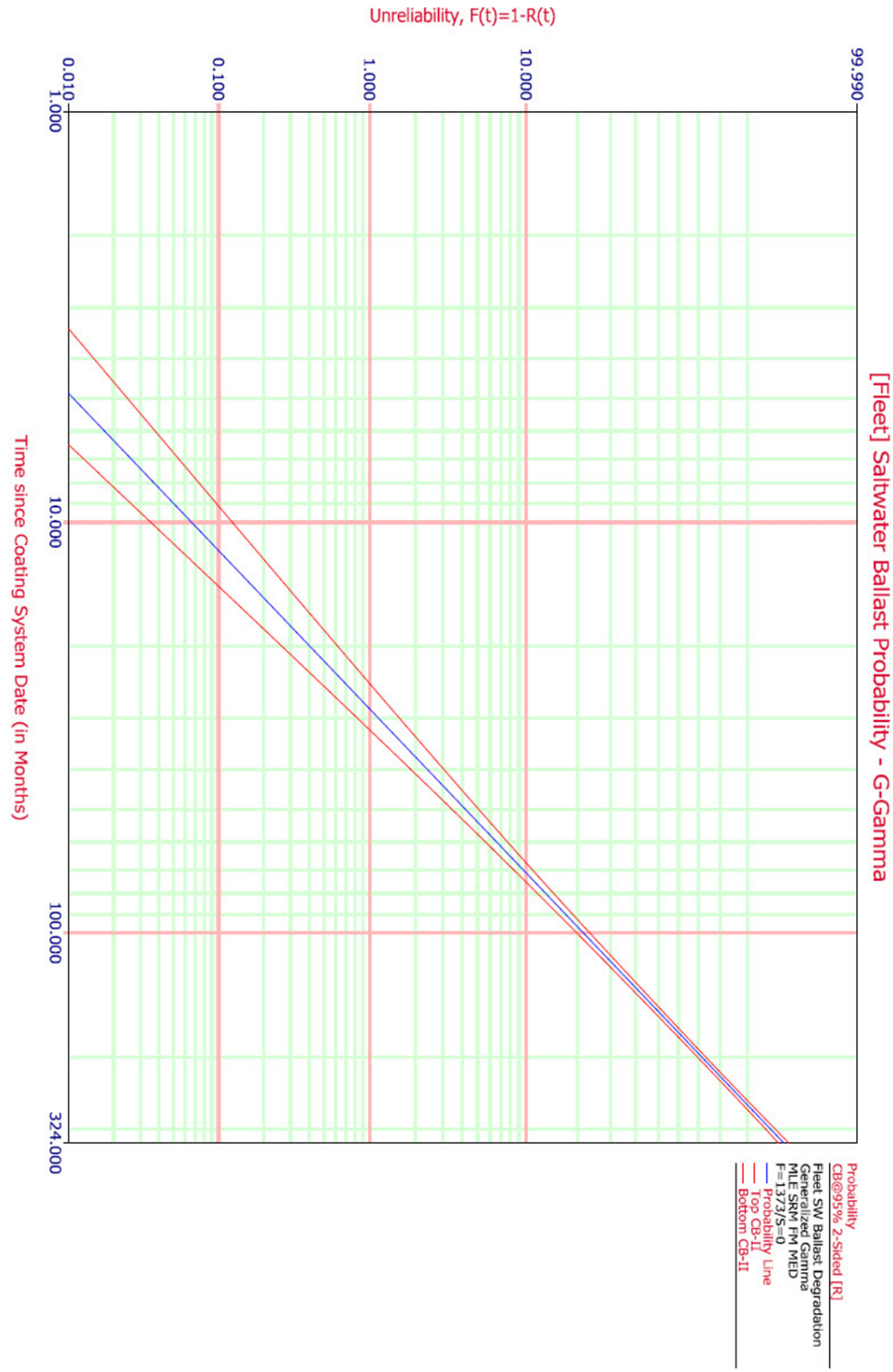
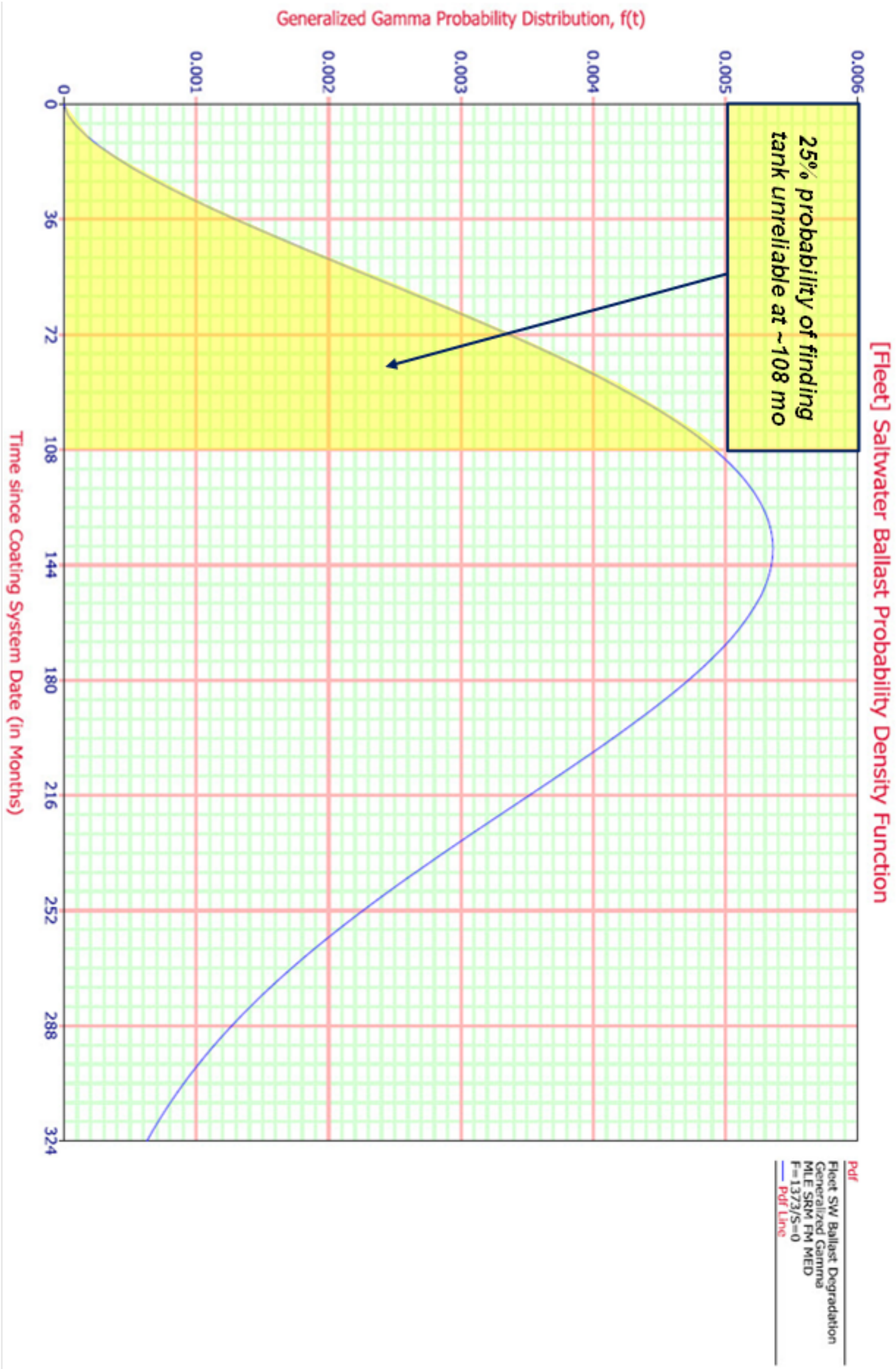
APPENDIX C: RELIABILITY VS. TIME FOR SALTWATER BALLAST TANKS



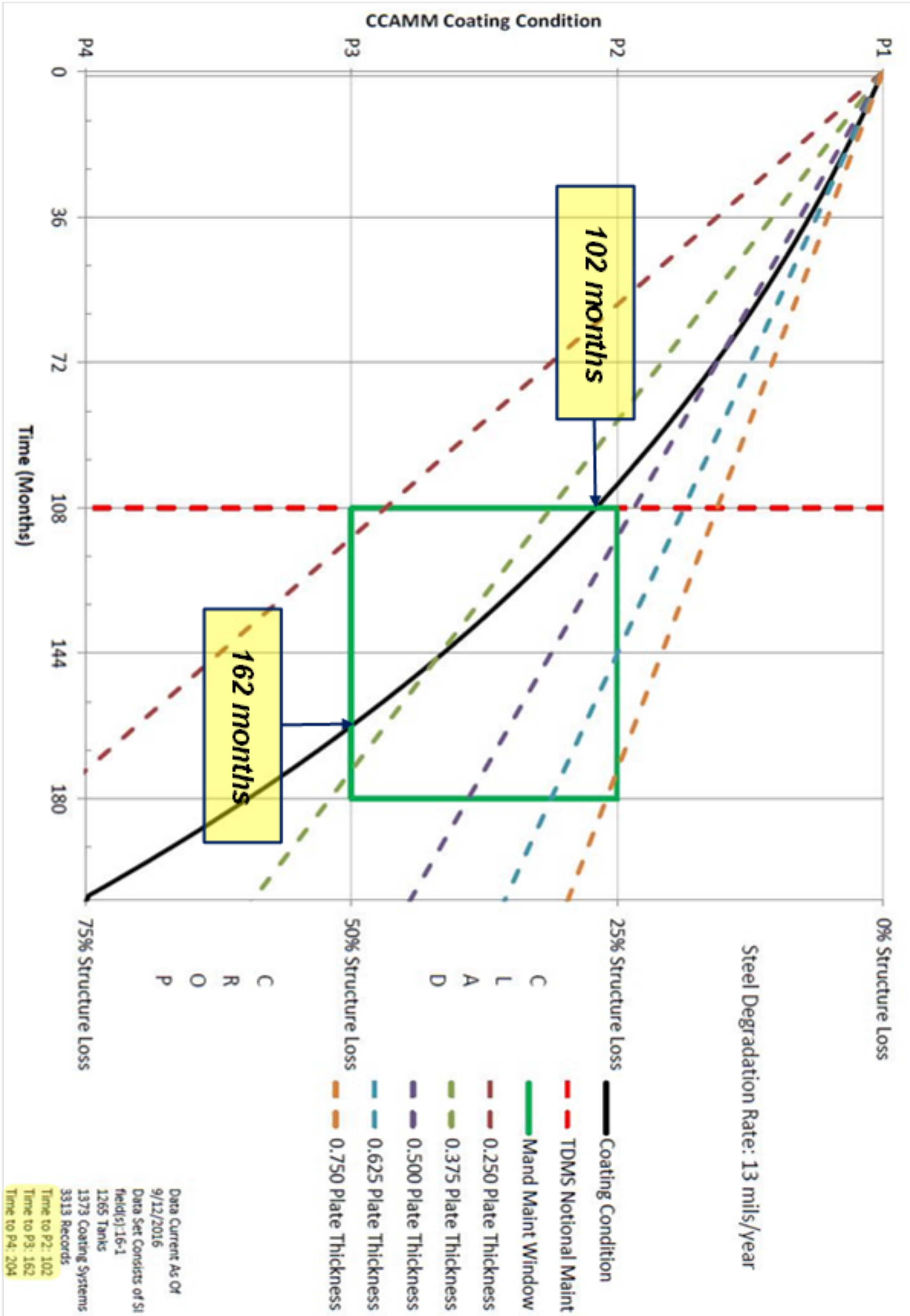
APPENDIX D: PROBABILITY TO REACH CONDITION 3 (G-GAMMA DISTRIBUTION) FOR SALTWATER BALLAST TANKS



APPENDIX E: PROBABILITY DENSITY FUNCTION FOR SALTWATER BALLAST TANKS



APPENDIX F: PROJECTIONS FOR COATING CONDITION AND STRUCTURAL DEGRADATION FOR SALT WATER BALLAST TANKS



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