Fuel Tank Corrosion Impacts on Future Fleet Readiness

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Fuel Tank Corrosion Impacts on Future Fleet Readiness

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of
Master of Science in Naval Architecture and Marine Engineering and
Master of Science in Mechanical Engineering at the
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Abstract

*Ticonderoga*-class cruisers face significant readiness problems stemming from widespread corrosion of an aging hull. This corrosion severely impacts shipboard safety and operational readiness when it compromises the integrity of compensated (pressurized) fuel storage tanks. In most cases these leaks require immediate repair to restore the engineering spaces to a safe operating condition, and nearly always impact time-critical fleet operating schedules. This thesis studied cruiser fuel storage tank maintenance records contained within the Navy Maintenance Database (NMD) with two purposes in mind. The primary objective was to find commonly-repaired structural features to either be improved upon or avoided in future ship designs. Data was collected on the tank location, structural feature, and repair method to produce a class-wide distribution of all fuel storage tank repairs. The data showed that nearly all cruisers have experienced fuel tank leaks, with some suffering as many as twenty. The secondary objective was to assess how accurately the Navy forecasted and planned cruiser tank repair under old and new contracting strategies. New work discovery during a maintenance period often increases schedule and cost, and is even more important to control under the Navy’s newly adopted fixed-price "MAC-MO" contracting strategy that relies upon private contractors to produce accurate work specifications. A proxy for new work discovery, "contract change requests" were assessed for both legacy cost-reimbursable and current fixed-price contracting strategies. The results showed a promising initial reduction in new work discovery that will need to continue for the Navy to return ships to the fleet on time and under budget.

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Chapter 1

Introduction

1.1 Background

1.1.1 Shipbuilding Uncertainty

A 2018 United States Government Accountability Office (GAO) report outlined a Navy shipbuilding trend that is producing fewer than expected warships at higher than expected cost.[1] Adjusted for inflation, ships cost nearly double what they cost back in the 1980s.[2] This trend has resulted in either the truncation or cancellation of the destroyer and cruiser replacement classes and is causing top Navy leadership to consider more sustainable fleet architectures. In 2019, GAO reported regular maintenance delays which are compounding fleet readiness problems.[3] The Congressional Research Service recently advised Congress that the pending 2020 Force Structure Assessment could “result in a once-in-a-generation change in the Navy’s fleet architecture... that includes a reduced proportion of larger ships [and] an increased proportion of smaller ships”.[4]

1.1.2 Service Life Extensions

These changes to the expected shipbuilding production schedule have led to service life extension of ships already nearing retirement, making the maintenance and modernization processes an even larger part of the Navy’s strategy to grow the fleet.
To retain surface combatant capability until newer programs like Future Frigate and Large Surface Combatant reach the fleet, the Navy is extending certain Ticonderoga-class cruisers and all of the Arleigh Burke-class destroyers out to 40 and 45 years, respectively. Ships inducted into the Service Life Extension Program (SLEP) transfer ownership from their respective fleet (US Fleet Forces Command or Pacific Fleet depending on the coast) to Naval Sea Systems Command (NAVSEA) and are considered out of service until provided critical maintenance and modernization.

1.2 Problem Statement

Due in part to the acquisition environment outlined above, cruisers are facing significant readiness problems stemming from widespread corrosion of an aging hull. This corrosion severely impacts ship safety and operational readiness when it compromises the integrity of pressurized (compensated) fuel storage tanks. Fuel leaks typically require immediate repair (called "emergent repair" by the Navy) to restore the engineering spaces to a safe operating condition, which nearly always impacts fleet operating schedules. This thesis studies the cruiser service environment, fleet maintenance processes and fuel tank repair history to determine the most problematic tank features that may benefit from improved design or be excluded from consideration in future ship designs.

1.3 Motivation

This thesis was motivated by the difficulty I faced while preparing an aging cruiser for deployment. Corrosion holes in fuel storage tanks sidelined our ship during critical training exercises, caused us to miss a scheduled strike group deployment, and led to the disruption of other ships’ operating schedules. Conversations with fellow sailors led me to understand that my ship was not the only cruiser to experience fuel tank corrosion issues.
1.4 Methodology

I conducted a literature review to understand contributing factors, trends and processes for maintenance of corroded fuel tanks. I then reviewed all fuel storage tank work specifications for the cruiser class within the Navy Maintenance Database (NMD) dating back to 2008. I recorded repair type, quantity and location to determine where corrosion occurs most often and how it is typically repaired. Much of the analysis focused on repairs occurring during emergency maintenance periods (called "Emergent Availabilities") that are the most disruptive to the ship’s operating schedule. Lastly, I tracked contract change metrics to determine if the new Multiple Award Contract, Multi Order (MAC-MO) contracting strategy has resulted in more stable fuel tank work requirements compared to the legacy cost reimbursable Multi-Ship, Multi-Option (MSMO) strategy.
Chapter 2

Literature Review

Ship corrosion is caused by many factors that occur before and after the ship enters the fleet. Studying nearly all phases of the acquisition cycle (design, production, operation and maintenance) was essential for a holistic view of the environmental factors that influence ship corrosion. Sources studied fall into several different categories; design and acquisition, fleet scheduling, technical requirements, contractual requirements and current acquisition/maintenance environment. Review of these subject areas provided insight into the data that should be gathered from NMD.

2.1 Design and Acquisition

The acquisition phase offers the first opportunity to mitigate corrosion through design choices that will impact the ship over its service life. There are regular trade-offs between designing for corrosion resistance and designing for high performance. Because warships exist to defend against constantly evolving threats, emphasis is often placed on delivering capability in the form of speed, payload and survivability. These attributes are measurable and verifiable at ship commissioning and are bestowed on the ship for life. Because the impacts of corrosion are not apparent during ship delivery, it is natural that corrosion resistant attributes are not given the same importance. When deciding whether to purchase a new weapon system or provide a structural corrosion margin, the weapon system often wins. This becomes problematic when a
drop in new ship production makes service life extension necessary.

The following sources relevant to design and acquisition were reviewed:

1. *Department of Defense Instruction (DoDI) 5000.02 Operation of the Defense Acquisition System* establishes the requirement for defense acquisition programs to conduct corrosion prevention and control planning (CPCP).

2. *DoDI 50000.67 Prevention and Mitigation of Corrosion on DoD Military Equipment and Infrastructure* outlines policy for making corrosion design trade-off decisions, establishing required programs and preservation techniques, and conducting CPCP program reviews.

3. *Corrosion Prevention and Control Planning Guidebook for Military Systems and Equipment* provides the military with corrosion management best practices to be applied throughout acquisition and sustainment phases.

4. *Corrosion Prevention and Mitigation Strategic Plan* establishes policies, strategies and objectives to standardize DoD’s approach to CPCP.

### 2.2 Fleet Scheduling of Operations and Maintenance

Navy ships are built to operate at sea under severe conditions. Out of a 36-month deployment cycle, 20-months are earmarked for at-sea operations and training before undergoing depot-level maintenance. There is a natural tug-of-war that occurs between time required at sea and time required in the shipyard for maintenance. Depot-level maintenance periods provide limited time to assess and repair corroded fuel tanks, and are sometimes deferred due to operational priorities.

The following sources describe Navy fleet scheduling policy:

1. *OPNAV Instruction 3000.15A Optimized Fleet Response Plan (OFRP)* outlines the macro-level operating schedule that governs naval operations.

2. *COMNAVSURFPAC/COMNAVSURFLANT INSTRUCTION 3502.7 Surface Force Training and Readiness Manual* promulgates required training and maintenance assessments that occur throughout the OFRP to ensure material and crew readiness.
There is practically no time during a ship’s lifetime where it is not at sea or undergoing in-port assessment or repair. Unplanned (emergent) maintenance comes at the cost of another critical part of the ship’s schedule.


2.3 Technical Maintenance Requirements

NAVSEA establishes technical requirements for operation and maintenance of both ship systems and processes. Relevant to cruiser fuel storage tank maintenance, technical manuals establish requirements for assessment, application and repair of marine coating systems and ship structure. These requirements support the technical community and ship repair contractors in the conduct of preventative and corrective maintenance.

The following establish technical requirements and guidance for assessment, preservation and repair of ship structures:

1. Corrosion Control Assessment and Maintenance Manual (CCAMM) outlines the methods and requirements for assessment and repair prioritization of degraded coating systems and corroded structure. CCAMM classifies the fuel tank top region as both a Critical Corrosion and Structural Integrity Area (CCSIA) and a Critical Coating Area (CCA) to denote its elevated corrosivity and marine coating quality control requirements, respectively.

2. Naval Ships’ Technical Manual (NSTM) Chapter 100: Hull Structures establishes requirements for assessment, maintenance and repair of ship structure. NSTM 100 classifies all fuel storage tanks as "critical structure" for their role in resisting longitudinal bending stresses.

3. NSTM Chapter 631: [General] Preservation of Ships in Service establishes requirements for prevention of corrosion and deterioration of ships through surface
preparation and painting.


### 2.4 Contractual Maintenance Requirements

Non-nuclear ship repair is a contracted process managed by requirements set forth in Work Specifications ("work specs"). NAVSEA maintains a list of common repair instructions applicable to all ship classes (called Standard Items) for standardization and efficiency. All shipboard repair requirements are provided in work specs, in accordance with NAVSEA Standard Items. Work specs, the building blocks of a ship’s Availability Work Package (AWP), are organized according to Ship’s Work Breakdown Structure (SWBS) groups. For example, 123-series fuel tank work specs and 110-series structural work specs can both direct the repair of fuel tanks (which double as ship structure).

Review of all available fuel storage tank-related work specs yielded the data provided in Chapter 3. The following Standard Items applicable to fuel tank repair were also reviewed:

1. *NAVSEA SI 009-12 Weld, Fabricate, and Inspect* provides requirements for most of the metal work associated with fuel tank repair.

2. *NAVSEA SI 009-25 Structural Boundary Test* specifies post-repair testing requirements for fuel tanks.

3. *NAVSEA SI 009-32 Cleaning and Painting* provides substrate cleanliness and surface roughness preparation standards for paint adherence. It further specifies paint types authorized for different purposes and zones within the ship.
2.5 Current Acquisition and Maintenance Environment

A variety of studies highlight the challenges of maintaining an aging fleet in a constrained fiscal environment. Several governmental reports indicate fleet material condition will continue to suffer as maintenance costs per hull rise. A recent cost control initiative was to abandon "cost-reimbursable" for a "firm fixed price" ship repair contracting strategy. This will be explored in Chapter 3.

The following reports highlight current plans, challenges and initiatives:

1. GAO-18-238SP. Navy Shipbuilding: Past Performance Provides Valuable Lessons for Future Investments reports on a number of under performing shipbuilding programs which are (in part) necessitating service life extensions for several ship classes currently in service.

2. GAO-20-257T. Navy Maintenance: Persistent and Substantial Ship and Submarine Maintenance Delays Hinder Efforts to Rebuild Readiness reports on a trend in ship maintenance where availability cost and schedule are regularly exceeded.

3. GAO-17-54. Navy Ship Maintenance: Action Needed to Maximize New Contracting Strategy’s Potential Benefits reports on the inherent challenges of the Navy’s initiative to change ship maintenance contracts from cost-reimbursable (Multi-Ship-Multi-Option or "MSMO") to fixed price (Multi-Award-Contract-Multi-Option or “MAC-MO”).

4. [NAVSEA] Report to Congress on the Long-Range Plan for Maintenance and Modernization of Naval Vessels for Fiscal Year 2020 forms the basis for maintenance industrial base capacity and capital investment requirements to properly maintain a 355-ship Navy.

6. [Congressional Research Service] Navy Force Structure and Shipbuilding Plans: Background Issues for Congress reports on how the Navy’s anticipated 2020 Force Structure Assessment will likely produce a revolutionary fleet architecture that relies more on smaller autonomous vessels and less on traditional capital warships.
Chapter 3

Data Analysis and Discussion

Review of all cruiser fuel storage tank work specs in the Navy Maintenance Database (NMD) from 2008 to 2019 revealed a significant repair history. Of the 764 work specs studied, 430 specified corrective maintenance to fuel tank structures. The remaining work items specified either preventative maintenance to the marine coating system (which includes coating condition assessments) or basic access to the tanks to achieve ship stability or support surrounding maintenance. A total of 1456 individual tanks (an average of 69 per ship) required structural repair to prevent or recover from a tank failure. While many of the preventative repairs occurred (and to some extent were absorbed) during regularly scheduled maintenance availabilities, several tank leaks demanded schedule-impacting emergent repair. Also noteworthy were the number of contract changes that characterized maintenance conducted under the cost-reimbursable MSMO contracting strategy, and how their existence under the fixed price MAC-MO strategy could lead to escalating maintenance costs. This chapter provides a detailed view of the fuel storage tank repairs needed to keep *Ticonderoga*-class cruisers operational.

3.1 Limitations

Work specs and “condition found reports” were the primary documents reviewed within the NMD database. Work specs either direct repair of a specific location
or the entire tank. In either case, the quantity and type of metal replaced (plate, “T” beam or “I” beam, weld, or angle) is clearly specified. This is not necessarily true for the repair location within the tank. For example, direction to “Clad weld a total of 111 isolated areas (2-inch diameter each area) in tanks listed” assumes the reader has access to the locations listed in the appropriate assessment reports. Researching each assessment report for the exact location repaired was beyond the scope of this study. It was therefore necessary to organize the data around commonly repaired tank features, which provide ship designers with candidates for improved design.

This study captured all fleet-funded fuel tank repair, but only a fraction of NAVSEA-funded structural modifications. Once fuel tank leaking and cracking became a widespread problem, larger NAVSEA-funded tank stiffening and strengthening modifications were planned for the class to restore their structural integrity. These account for a significant amount of new or replaced structures. NMD merely referenced these hull modification drawings without providing specifics. This research was able to attain, study and report approximately one third of these drawings which makes the repair quantities presented conservative.

Research was limited to the available NMD time period of 2008 – present. Contract change metrics that indicate new work discovery are only complete after an availability has closed, thereby excluding in-process availabilities (many of which are the large SLEP availabilities). As the newer contracting strategy, there are fewer MAC-MO work specs than MSMO work specs. The smaller data set of work specs under the MAC-MO contracting strategy (which commenced in 2015) would have been richer with the addition of these ongoing SLEP availabilities. This limitation does not apply to planned repair work, which is conducted before availabilities commence and contributed greatly to this study.

As NMD is used for ships undergoing maintenance in the United States, this research did not collect data on ships stationed in Japan. Ships in Japan are maintained under the Advanced Industrial Management (AIM) software and framework. Of the 22 cruisers, only one was permanently stationed in Japan and four others have rotated between Japan and the United States.
In addition to the 123-series (fuel tank) and 110-series (internal structure) work specs, there are others that could specify repair of fuel tanks. The 631-series bilge work specs involve tank top preservation within the engineering space. The 110-series work specs cover repairs to the external portion of the hull (which also doubles as a fuel tank boundary). Due to limited time available, the 631-series and underwater 110-series work specs were not reviewed in this study. The vast majority of tank repairs were captured in the 123 and internally conducted 110-series work specs. As a result, the repair data presented in this research remains conservative.

3.2 Assumptions

NMD work specs are used to communicate work requirements to the contractor, not to report deficient material conditions. This necessitated some degree of interpretation to understand the ship condition that prompted repair. Most assumptions related to the method of classifying a repair as a leak. With experience repairing fuel tanks during Emergent Availabilities, I looked for certain profiles that indicated a leak repair as opposed to normal preventative maintenance. Many work specs contained all the symptoms of a leak without explicitly referencing one. Leaks were tallied when specifically referenced in the work spec, when a temporary patch was either removed or installed, or when a single tank was repaired during an Emergent Availability. The time and expense of removing the fuel, cleaning and preparing the tank for personnel entry, conducting repairs, and refueling would not be expended unless made absolutely necessary by a leak.

Tank structure was defined as any portion of the tank (tank top, bulkhead, hull plating, stiffener, or penetration) not shared by another structure. For example, 110-series repairs to corroded vertical bulkhead stiffeners were not considered tank repairs because they doubled as structure for an adjacent engineering space. Conversely, tank penetrations like stuffing tubes, equipment foundations and deck support angle were considered fuel tank repairs because these features were not shared by any other structure.
3.3 Fuel Tank Maintenance

3.3.1 Navy Maintenance Organization

There are several organizations responsible for overseeing or executing contracted ship maintenance. [5] Figure 3-1 shows the organizations with Title 10 responsibility and budget authority to “man, train and equip” the surface forces. Figure 3-2 shows the NAVSEA organization with technical authority and contract administration responsibilities for the “equip” portion of Title 10, which includes acquisition and maintenance.

Figure 3-1: Navy Administrative Chain of Command with Title X Authority to Man, Train and Equip Surface Forces
3.3.2 Fuel Tank Assessment

All ship structures (fuel tanks included) are assessed periodically as part of the Surface Maintenance Engineering Planning Program (SURFMEPP) Class Maintenance Plan. SURFMEPP “pushes” inspections and surveys to a ship’s Port Engineer who screens the task for execution by a capable repair entity in a properly sized availability. Structural coating and condition surveys of fuel tanks and engineering spaces are typically accomplished during Docking Availabilities (or wherever time and circumstances allow) in accordance with Maintenance Requirement Cards G1N5 and G1N6. Level 1 surveys involve a minimally invasive overall visual survey that may prompt a more focused Level 2 structural survey if significant deterioration is present. CCAMM prioritizes tank repair based on a matrix that measures both coating integrity and/or
structural integrity against the criticality rating of the structure. Repairs are screened to future availabilities, or if serious enough conducted immediately. Classified as “severe service tanks”, compensated fuel storage tanks are given the highest criticality rating.

3.3.3 Repair Methods

The following are the Navy’s authorized structural repair methods as referenced in NSTM Chapter 100:

- Renewal: removing and replacing non-compliant structure with new material
- Weld Buildup: augmenting or filling thinned structure by welding
- "Doubler plate": installing a plate over corroded structure
- Weld seam renewal: cutting a "V" shape into an existing weld seam and re-welding [6]

Fuel tank repairs studied in NMD adhered to these repair methods. Permanent repairs included renewal via insert, weld buildup, or removing and replacing damaged weld. Temporary repairs were conducted via doubler plate or (as a last resort) patch installation. Time permitting, the Navy generally pursues permanent repairs for fuel tanks because they are seldom open for inspection and repair. The cost to the ship’s schedule of a failed repair is too high. If urgent repairs are needed, the Navy will assess the risks to the ship’s operational schedule of a temporary repair by considering the current availability length and the time until the next availability. Repair methods used are found in Figure 3-3. The most common permanent repair was by plate renewal, followed by weld buildup of plate, and then weld seam renewal.
3.3.4 Temporary Repairs

While generally uncommon, temporary repairs were evenly distributed between doubler plate and polysulfide patch installation. The patch is the least effective at isolating the engineering space from the fuel tank leak. However, as the only repair method that can be accomplished without emptying the fuel tank, patches become attractive if operational considerations preclude a longer Emergent Availability.

Polysulfide patches were only used as a fuel tank repair method in 1.6 percent of non-Emergent Availabilities studied, but were utilized in 18 percent of the Emergent Availabilities. This shows the fleet is willing to assume some technical risk to meet scheduled operational commitments. In this context, assumed risk is a function of the patch’s ability to fix the leak and the time horizon until the next scheduled maintenance availability. Yet polysulfide’s potential as a time-saving repair method is not guaranteed. Failure of the initial patch installation caused some availabilities to either be extended or to run into other planned availabilities. 18 percent of the reported polysulfide repairs failed during the availability in which they were applied once the tank was returned to normal operating pressure. One of those availabilities involved two consecutive patch failures before polysulfide was abandoned for a weld build-up repair. These additional repair cycles undoubtedly lead to the availability’s extension and missed operational commitments. Figure 3-4 shows the willingness
to attempt polysulfide repairs increases when an emergent availability is delaying execution of operational commitments.

3.4 Tank Leaks

A central research objective was to determine the impact fuel tank corrosion was having on the entire cruiser class. Figure 3-4 demonstrates that fuel leaks are impacting readiness of nearly every cruiser in the fleet. All but one of the 21 cruisers studied have experienced tank failure at some point. The most leaks reported by a single ship were 20. The youngest ship to have a fuel storage tank leak was 14 years old. The average age for the class at first NMD-reported fuel tank leak was just under 20 years. For perspective, cruisers inherited a near identical hull from the Spruance-class destroyers whose average age at decommissioning was 23.6 years. Assuming similar coating technologies, application processes and maintenance periodicity, this suggests fuel tank corrosion is a problem the Navy may have been able to see coming.

Of the 84 reported fuel leaks, 46 of them were repaired during Emergent Availabilities and 38 were absorbed into scheduled availabilities. Twelve patches installed by the crew as a leak isolation measure were removed prior to executing repairs, and 16 more were installed as a repair method. Doubler plates were installed on 15 occasions.
3.4.1 Leaks by Tank

Each engineering space has an underlying pair of port and starboard tanks separated by a centerline longitudinal bulkhead. For simplicity, this research refers to port and starboard tanks collectively by their shared forward transverse bulkhead frame number. Transverse bulkheads generally constitute the forward and aft boundaries of both the engineering space and its underlying fuel storage tanks. For example, the "220" tank tops are the structural foundation and bilge area of auxiliary space 1 whose forward transverse bulkhead is at frame 220. The engineering space and tank share forward and aft transverse watertight bulkheads and a service environment at the tank top boundary.

The tank leak distribution presented in Figure 3-5 shows the cruisers’ most prob-
lematic engineering spaces. While a detailed structural analysis was outside the scope of this thesis, there are structural and human factors that may explain why certain tanks leaked more than others.

Figure 3-5: Leaks By Tank with Linearly-approximated Longitudinal Bending Moment

Surface ships experience the highest stresses amidships due to cyclical flexing from wave-induced longitudinal bending moments (Figure 3-6). NSTM 100 approximates longitudinal bending moments by applying beam theory to the hull (which it represents as a complex box girder). It classifies the tanks within the center 60 percent of the ship’s length between perpendiculars (LBP) as critical structure due to the elevated bending moments they experience (depicted in Figure 3-7). Corrosion reduces a tank’s ability to resist these stresses, which causes larger plating deformations from ship flexing, more aggressive flaking of corrosion scale, and further tank deterioration. To test the notion that tanks located amidships present higher incidence of failure over time, an arbitrary bending moment curve was overlaid to show a linear increase toward the longitudinal center of LBP.
Relative bending moments did not reliably explain the tank leak distribution. Only six of the ten groups closely adhered to the bending moment curve. The four groups whose leak rate deviated from the curve displayed greater relative resilience in the presence of higher shear stresses. These tanks were either found in propulsion spaces, an auxiliary space with a subdivided fuel tank, or an auxiliary space called “shaft alley”. Assuming no significant difference between the corrosion rates of the various engineering spaces, this could indicate structural differences allowed these tanks to withstand the elevated stresses. For example, structural foundations in propulsion spaces are designed to support the heaviest shipboard machinery and fluid tanks (reduction gears, gas turbine modules, lube oil tanks and fuel service tanks) which provides the tank top with extra rigidity. Also, auxiliary space 2 is uniquely supported by two underlying fuel storage tanks as opposed to one, which may provide added structural rigidity to resist tank leaks over time. Further analysis is needed to pinpoint which structural features contributed most to tank top rigidity in these
more resilient spaces.

Relaxing the assumption that all spaces corrode equally leaves room to consider the impact human and organizational factors have on varying engineering space corrosion rates. Proper corrosion control requires early identification and documentation of deficiencies by trained personnel. The size and workload of a division affect their ability to identify and fix problems. Feature accessibility also determines how well problems can be identified. For example, leaks are common in bilge sumps because they are hard to inspect when full of bilge water. Personnel watch routines also contribute to these differences. Main propulsion spaces are constantly manned at sea, while other engineering spaces need only be visited hourly. Human and organizational factors are significant considerations during ship design, and should be acknowledged for their contribution to the material condition of engineering spaces.

3.4.2 Leaks Over Time

Of the post-2008 NMD maintenance records studied, fuel storage tank leak incidence jumped approximately 16 years after ship commissioning and continued for nine years at an average annual occurrence rate of 7.4 leaks for the class. After year 24, the leak occurrence rate dropped to an average of 2.1 annually which could indicate the Navy’s assessment and repair strategy was paying off. The leak distribution can be found in Figure 3-8. The ship with the most leaks is displayed in Figure 3-9. This chronological sequence shows how emergency tank repair interferes with a ship’s operational schedule. Suffering 11 leaks over a three-year period, it was impossible for this ship to meet its operational commitments.

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3.5 Commonly Repaired Features

A feature-based view of the tank repair data is presented in Figure 3-10. This is a simple aggregate view of which features were repaired for each corrective work spec. Notable limitations of this distribution are that it does not specify repair quantity, which tanks were repaired, or if repairs were concentrated or distributed. It is a basic count of the commonly repaired tank features found in corrective maintenance work specs. This distribution includes larger availabilities with proactive structural repair within the engineering space and fuel tank. Looking only at repairs conducted during Emergent Availabilities gives a better approximation of the features that have already failed or are nearing failure (Figure 3-11). If a pinhole leak prompts assessment and
repair of the area surrounding the leak, those additional repairs are captured in this distribution.

For Emergent Availabilities, the tank top plate was the most common structural repair followed by weld seams, drain wells, bulkhead plating, and equipment foundation/coming. This distribution is consistent with the CCAMM and NSTM classification of the tank top/bilge region as highly corrosive and difficult to maintain. Drain wells and equipment foundations present the same corrosion control challenges referenced in the NSTM 100 of poor accessibility and the presence of oxygenated saltwater. NSTM 100 describes the boundary shared by the bilge and fuel storage tanks as one of the most corrosive shipboard environments due to the presence of bilge water and limited access for tank top coating preservation.[6]

The bulkhead plating was a surprising result because of the relatively lower cor-
rosion rates of internal to external tank plating. A closer look revealed some of these repairs were to “wing tank” bulkhead boundaries within the engineering space, leaking bulkhead piping penetrations, and in one case buckled structure.

3.6 Quantities of Metal Replaced

Another indication of the extent of cruiser corrosion is the quantity of metal used to repair tank structure. Figure 3-12 shows the quantity of structural steel that has been replaced or added since 2008, organized by repair method. Work specs denote area in individual square foot or square inch tiles. For example, 100 square feet is equivalent to 100 one square foot tiles (not 100 feet squared). To compare like units, the chart displays all repair methods in square or linear feet. This understates the scope of repairs accomplished via weld buildup, a repair method typically specified in square inches.

The 600 square feet of weld buildup is more appropriately conveyed as 87,000 square inches. Over 12,000 square feet of steel plate and nearly 5,000 combined linear feet of either weld or tank structure has been renewed or is planned for renewal in upcoming availabilities. Figure 3-13 graphs quantity of steel replaced that includes the retroactive fuel tank strengthening modifications required of the class by NAVSEA. These quantities represent only what could be pulled from a fraction of engineering drawings that were provided on request from NAVSEA. Only reporting a fraction of the total structural modifications, the growth of the green bar between these two figures still shows the considerable undertaking required to keep these ships seaworthy.

![Figure 3-12: Quantity of Metal Replaced or Added For All Availabilities Excluding NAVSEA Structural Modifications](image)

Figure 3-12: Quantity of Metal Replaced or Added For All Availabilities Excluding NAVSEA Structural Modifications
3.7 Contract Metrics

NAVSEA recently adopted a fixed price contracting strategy that makes it increasingly important to accurately forecast work requirements. The pre-existing funding stream available under legacy cost reimbursable contracts implied a certain level of forgiveness for underestimating required repair work. That safety net vanishes under fixed price contracts that require subsequent negotiations for each round of new work discovery. GAO’s 2016 report on the initial implementation of MAC-MO highlighted contract changes as a significant challenge to the strategy’s effectiveness, with the potential to extend maintenance availabilities beyond scheduled completion dates. [5]

Requests for contract change (RCC) tracked within each work spec serve as proxies for new work discovery. RCCs are originated by the contractor to add previously unplanned work to an availability. This scope creep often jeopardizes availability schedule and increases costs. Contract changes under MSMO contracts were easier to authorize than those under MAC-MO contracts because the latter requires outside funding authorization from either the fleet Type Commander or NAVSEA.

Illustrative of the potential for contract changes to disrupt schedule, GAO’s study of piloted MAC-MO availabilities found that contract changes took a median of 18 days to process (well in excess of the 5-day NAVSEA standard). While these elevated processing times have likely been reduced through familiarization and process improvement, the complicated task of work planning will remain a significant challenge.
This is particularly true for repair of fuel tanks which are planned years in advance and rarely open for inspection before the availability starts. The past few years of MAC-MO availability RCC data allowed a comparison of work planning accuracy between MSMO government planning and MAC-MO contracted third-party planning (TPP).

3.7.1 Third-Party Planning Contracts

Occupying a traditionally governmental role, contracted third-party planners now produce the work specs for the repair contractor to price and execute. This process relies on SURFMEPP to produce accurate work requirements for planning and pricing. In the case of a specific repair, this may be straightforward. But when planning work for general overhaul and preservation of entire tanks, SURFMEPP must use historical tank data to estimate the scope of needed repairs. These estimated work requirements are pre-loaded into work specs to avoid unnecessary contract changes throughout the availability. Imperfect planning results in contract changes that have historically extended availabilities, and will be especially problematic for fixed price availabilities.

These challenges are particularly daunting for fuel tank repair as a full material assessment cannot be completed until after personnel enter the tank. Furthermore, the tank maintenance period can itself accelerate corrosion by replacing the protective fuel coating with a salty and humid environment. Even more vital to fleet readiness is the reality that fuel tank work is often in the “critical path” of work that if delayed causes the availability to miss its completion date.

The contract change metrics found in Tables 3.1 and 3.2 were pulled from the 12 years of NMD data. RCCs are applied to work specs, which are the fundamental building blocks of a maintenance availability. Since the importance of this data became apparent as research progressed, RCC numbers were unable to be correlated with actual availability schedule delays. This analysis should be viewed only as a preliminary measure of RCC prevalence under MSMO and MAC-MO contracts. The data does not capture how work specs are sequenced in the schedule or if the RCCs
were found early or late in the work period. It therefore cannot measure how contract changes affect the overall availability completion date. For example, several work specs each with multiple RCCs would have different impacts on availability schedule if completed in series or parallel. Similarly, RCCs negotiated early have less of an impact on schedule when compared to those negotiated during final tank testing.

Table 3.1: MAC-MO and MSMO RCC Statistical Comparison for All Availabilities

<table>
<thead>
<tr>
<th></th>
<th>Number of Work Specs</th>
<th>Percent with Contract Changes</th>
<th>Number of RCCs</th>
<th>Average RCCs per Work Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC-MO</td>
<td>77</td>
<td>0.65</td>
<td>138</td>
<td>2.8</td>
</tr>
<tr>
<td>MSMO</td>
<td>353</td>
<td>0.75</td>
<td>1016</td>
<td>3.8</td>
</tr>
<tr>
<td>Total</td>
<td>430</td>
<td>0.74</td>
<td>1154</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 3.2: MAC-MO and MSMO RCC Statistical Comparison for Emergent Availabilities Only

<table>
<thead>
<tr>
<th></th>
<th>Number of Work Specs</th>
<th>Percent with Contract Changes</th>
<th>Number of RCCs</th>
<th>Average RCCs per Work Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC-MO</td>
<td>10</td>
<td>0.6</td>
<td>17</td>
<td>2.8</td>
</tr>
<tr>
<td>MSMO</td>
<td>46</td>
<td>0.72</td>
<td>102</td>
<td>3.1</td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
<td>0.70</td>
<td>119</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The data shows that 74 percent of the 430 work specs that specified repairs (vice preservation) had at least one RCC. MAC-MO third-party planning produced an average of 2.8 RCCs per work spec, which was better than the 3.8 RCCs averaged under MSMO contracts. The meaning of this varies depending on when the RCCs were negotiated, what work they required, and if they were distributed amongst parallel work or applied to the same sequence of work. The contract change could have simply expanded a steel plate renewal from 5 to 7 square feet (called “growth work”), or instead involved removing machinery for an overhaul of a foundation not
previously identified for repair (called “new work”). Many RCCs are either found upon initial assessment of the tank or during final testing, each scenario having different implications for the schedule. Assuming standard Navy processing times of 5 days, 3 RCCs per work spec could take anywhere from 5 to 15 days to negotiate (which does not yet consider the additional repair time). This time frame applied to the end of an availability could cause the ship to miss critical unit level certifications or strike group training exercises.

The RCC data from only Emergent Availabilities shows that the average difference between MSMO and MAC-MO (3.1 and 2.8 respectively) narrows. This is likely due to both strategies contracting Emergent Availabilities at cost, which reduces the impact RCCs have on the availability with a quicker work authorization (funding) process. This could be further attributed to a narrower work scope and compressed time period within which to identify new work. Urgent repairs do not allow time for proper work planning, so it is difficult to assess third-party planning in this context.
Chapter 4

Conclusions and Recommendations

Conclusions and recommendations from this research address results from the NMD work spec analysis and themes captured during the literature review. The ship design and acquisition period provides an important foundation of corrosion resistance. By establishing structural requirements, material properties, intended service life, operating profile and class maintenance plans, it determines the vessel’s corrosion risk before it even enters the water. While there is always room for maintenance process improvement, a common theme uncovered during the literature review was that the largest potential for change is in the design phase.

CONCLUSION 1: The lack of new surface combatants in production is forcing ships into longer service and increasing the likelihood of further corrosion.

Cruisers have been in service on average six years longer than the Spruance-class parent hull that they inherited. They are now being extended to 40-year service lives until the Large Surface Combatant arrives to the fleet. Cancellation of the prohibitively expensive CGX cruiser replacement class kept Ticonderogas in service beyond their intended use. These unsteady supply signals force fleet operational planners and maintenance organizations to continually reassess what is possible for the class. Extensive cruiser coating failure and substrate loss have been demanding a growing portion of limited maintenance budgets. Without a replacement in produc-
tion, these ships will continue to burden the fleet for the foreseeable future. Due to the truncation of an equally expensive Zumwalt-class destroyer, all Arleigh Burke-class destroyers are being extended to 45 years. Figure 4-1 from a RAND Corporation study shows the increasing trend in per hull maintenance costs.[8] Since older ships consume a greater portion of the maintenance budget, they will continue to be a challenge to maintain until replaced by newer ships.

![Figure 4-1: Downward Trend in Fleet Size and Upward Trend In Per Ship Maintenance Costs](image)

**RECOMMENDATION 1: Refocus on technologically mature and affordable warships to reconstitute the fleet.**

The Navy should reevaluate how pursuit of undeveloped technologies has impacted fleet recapitalization. Ship acquisition programs should generally rely on proven technologies unless new technology is needed for certain critical systems. This “evolutionary, not revolutionary” approach is vital for cost control and steady ship production. Pursuing prohibitively expensive warships that cannot be funded stresses the existing fleet and costs more in long-term maintenance as the fleet ages.

**CONCLUSION 2: Fuel storage tank top plating has both high consequence and high likelihood of failure.**

Fuel storage tank top plating provides vital resistance against global bending moments and separates pressurized fuel from manned engineering spaces. Unfortunately, as part of the bilge structure fuel tank tops are heavily prone to corrosion. Navy tech-
Nautical manuals are clear on the structural importance and vulnerability of tank top plating, which must retain design thickness to ensure ship safety. As the most commonly repaired feature, tank top plating was specified in 74 percent of work specs. Nearly all of the 85 reported leaks occurred in the tank top. These leaks pose a serious fire hazard and typically remove the ship from service for an approximate 30-day repair period. There are few other deficient conditions that have such a disruptive impact on ship operational commitments and resources.

RECOMMENDATION 2: Future ship acquisition programs should reassess the use of compensated fuel storage tanks or find ways to ensure their structural integrity.

The Navy utilizes compensated fuel storage tanks in part for their role in lowering center of gravity and improving ship stability. Cruisers have proven this structural design has flaws. The Navy should evaluate alternative designs that do not place pressurized fuel tanks in such a corrosive environment and eliminate areas that are inaccessible to the crew for inspection and maintenance. They should further evaluate the benefits of applying a corrosion margin only to the fuel storage tank top plating. The decision to continue with compensated fuel storage tanks should be supported by analysis of the appropriate thickness, protective coating characteristics and assessment periodicity that will ensure its integrity. Recent development of an ultra-high solid marine coating that lasts 15 years should remove some of the maintenance burden from the fleet.

CONCLUSION 3: The coating-reliant corrosion control strategy was insufficient for Ticonderoga-class cruisers.

The Naval Ships’ Technical Manual for Hull Structures (NSTM 100) and the DoD Handbook for the Design and Assessment for Naval Surface Ship Structure (MIL-HDBK 519) outline the Navy’s approach to achieving ship performance through efficient structural design. Their trust in aggressive maintenance plans and need for ship performance has served as justification for building ships without a design corrosion margin. This approach places undue burden on ships, their crews and the
maintenance community to aggressively find, report and fix structural corrosion. It also relies on sufficient future maintenance funding and perfect adherence to class maintenance plans, both of which are difficult to predict. Cruisers have exposed inherent weaknesses in light-weight ship designs that depend heavily on time-critical maintenance. Cruisers had leaking fuel tanks as early as 14 years after commissioning. All but one cruiser in the fleet has reported at least one fuel storage tank leak. More than 12,000 square feet of steel plate, 5,000 combined linear feet of welds or plate stiffeners, and 87,000 square inches of weld buildup has been specified for the class.

RECOMMENDATION 3A: Study the effectiveness of fleet maintenance processes to identify corrosion. Further study how fleet operational commitments, port maintenance capacity and maintenance funding levels support or hinder the accomplishment of needed maintenance.

Recommend studying if current maintenance processes are sufficient to find and report corrosion before it becomes widespread. Also recommend studying the factors that obstruct maintenance once deficiencies are reported. Ship operational commitments, limited port maintenance capacity and available funding are factors that often delay needed maintenance. The fleet is able to accept deficient conditions (and thus delay required maintenance) by issuing “departures from specifications”. These decisions permit continued ship operation until an operation is complete or a maintenance window and/or funding become available. Studying the eDFS database that tracks these departures would show how long fuel tank deficiencies were tolerated. The other half of this study would be to determine to what extent the fleet accepts such technical risk out of operational necessity, lack of funding or limited port maintenance capacity.

RECOMMENDATION 3B: Align traditional corrosion control assumptions with modern day operational and maintenance realities such as longer ship service life, longer deployments, reduced manning and reduced maintenance capacity.

The changes brought about over the last century justify a reassessment of tradi-
tional corrosion control strategies. While aggressive maintenance of structural marine coating systems proved effective in the past, the conditions that faced past fleets are not comparable to those facing the current. Fleet size, underway time, and maintenance capacity have undergone significant change in recent history. The long-term reduction in fleet size since the 1950s (Figure 4-1) has occurred alongside a similar consolidation of fleet maintenance facilities. While lost maintenance capacity was offset by a smaller fleet, per ship underway time has actually increased over the years to meet operational commitments. The changes to the traditional deployment cycle under the Navy’s Optimized Fleet Response Plan keeps ships at sea 25 percent longer than under the legacy Fleet Response Plan (Figure 4-2). Taken together, these changes and the string of fleet material failures should prompt the Navy to reassess old assumptions.

![Surface combatants](image)

**Figure 4-2: Optimized Fleet Response Plan vs Legacy Fleet Response Plan**

[9]

For example, is the commercially-accepted practice of including a structural corrosion allowance more attractive now that the Navy is making 50-year warships? The military understandably designs ships for performance in battle. But given how warfare has changed so rapidly with technology, future battles may look entirely different than those of the past (where attrition was common). Satellite positioning and remote operation of a variety of unmanned craft are spreading out the fleet and fundamentally changing how ships are used. Regular service life extensions and 50-year ship designs suggest that maintainability is becoming just as important as performance.
Perhaps the design assumptions of the past are less applicable to the demands we are placing on ships today.

RECOMMENDATION 3C: Update Navy corrosion management information systems to meet current commercial shipping industry standards.

Management of a multi-billion dollar annual corrosion problem requires the proper tools. The commercial shipping industry has developed a number of software tools to manage corrosion for a fleet of over 50,000 merchant vessels. With so many requirements competing for the fleet’s attention, crews and maintenance communities should be provided improved information systems that present data intuitively. Classification agencies like American Bureau of Shipping (ABS) have developed software programs that display corrosion on a 3D computer ship model in a “red-yellow-green” severity scale. Programs also exist that combine structural analysis with corrosion reporting software to produce real-time structural assessments based on the extent of substrate loss. Color coded models provide a quick view of the problems areas within the ship. Advanced tools like these would empower crews, maintenance teams and funding organizations to make informed maintenance decisions.

CONCLUSION 4: Third-party planning under MAC-MO has reduced new work discovery during fuel storage tank maintenance.

Minimizing scope creep is imperative to the success of the MAC-MO fixed-price contracting strategy. As evidenced by the lower average number of contract changes under MAC-MO, third-party planning has done an admirable job initiating this trend. Continued reduction of the nearly three contract changes per fuel tank work spec is still necessary to reduce maintenance production schedule risk. While complete elimination of new work is an unlikely outcome, work planners should nevertheless be incentivized to reduce new work discovery as much as possible.

RECOMMENDATION 4: Incentivize early accomplishment of fuel storage tank work to minimize impact of new work discovery on availability completion dates.

This recommendation is particularly important if the tanks in question are known
to already have significant coating failure. Fuel storage tanks are prone to new work discovery because they are not available for inspection before the availability commences. It is customary to find new work upon initial inspection or after final tank inspection and closeout, the latter being able to extend the maintenance period for as much as a month. To avoid such disruptions, fuel tank work should be accomplished at the earliest opportunity within the availability assuming the manpower is available to do so.

4.1 Suggestions for Future Work

The following studies are intended to address fuel tank top plating vulnerabilities. The results of these studies should be forwarded to naval ship acquisition programs and NAVSEA structural technical warrant holders to inform design of future ships and/or structural features.

1) Study the impacts that varying tank top plating thicknesses would have on ship stability and performance for existing ship classes.

2) Develop a more corrosion resistant steel for fuel tank top plating. Previous studies of seawater corrosion of carbon steel have shown that copper additions as small as 0.2 percent can reduce long-term corrosion thickness by a factor of 2 to 5 times.[10] The proposed study would ideally explore the effects that small additions of copper, chromium and phosphorous have on corrosion resistance, weight and cost of steel.

3) NACE International maintains a Standard Practice (SP0178) for the Design, Fabrication and Surface Finish Practices for Tanks and Vessels to Be Lined for Immersion Service. Produce a similar design standard for the external portion of the fuel storage tank top (bilge region) with the intent of maximizing accessibility to, and corrosion resistance of, tank plating. This should cover the design and surface finishes of all tank interferences such as equipment foundations, deck grating support angle, piping penetrations and bilge sumps.
Bibliography


