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# Risk Based Decision Making for the Deferment of U.S. Navy Submarine Maintenance

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Maintenance of United States Navy submarines is a complex set of operations comprised of scheduling, budgeting, and executing a continuous stream of work across multiple vessels in the same maintenance facility year after year. Local personnel are involved in the details of the day to day operations and focus deeply on today and tomorrow, with little bandwidth to focus on larger, systemic issues with impacts far removed from today. The addition of fluctuating annual funding levels, a younger workforce, and the pressures to meet national defense requirements add complexity and

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# Risk Based Decision Making for the Deferment of U.S. Navy Submarine Maintenance

by

J. Matthew Washko

B.S. Aerospace Engineering

United States Naval Academy, 2006

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

Maintenance of United States Navy submarines is a complex set of operations comprised of scheduling, budgeting, and executing a continuous stream of work across multiple vessels in the same maintenance facility year after year. Local personnel are involved in the details of the day to day operations and focus deeply on today and tomorrow, with little bandwidth to focus on larger, systemic issues with impacts far removed from today. The addition of fluctuating annual funding levels, a younger workforce, and the pressures to meet national defense requirements add complexity and compound the pressure to mortgage tomorrow for today by deferring work without regards to its later impact. Recently, the maintenance community has begun to invest time and resources in these larger, systemic issues. This thesis investigates the impacts of deferred maintenance actions on the timely completion of submarine maintenance periods by analyzing data from 50 refits executed over a decade at Trident Refit Facility in King's Bay, Georgia.

The results of this thesis are best understood in three parts: the impact of deferred maintenance actions on submarine refit on-time completions, the development of a technical, risk-based deferment decision tool, and the possible application of deferring or canceling certain maintenance items as a way to reduce the maintenance workload across the fleet. The first part shows the quantitative analysis of the data demonstrating that deferred maintenance actions are not having any negative impacts to on-time schedule execution. The second part shows how through technical analysis and application of a probability and consequence risk framework, deferment decisions can be analyzed to ensure that only low-risk work is being deferred. And finally, an application of that same framework can be made across the fleet to lower the maintenance backlog.

Thesis Supervisor: Themistoklis Sapsis

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Numerous professionals and organizations from across the fleet assisted me in completing this thesis. Their hard work and desire to go above and beyond and get involved in a project that is far outside their own busy careers is a testament to their outstanding dedication; I cannot thank them enough. From SUBMEPP, I would like to thank Captain Carey Pantling, Mark Dolan, Bob Marshall, David Carey, Danny Matsuo, Travis Jones, and Preston Hogshead. From Trident Refit Facility King's Bay, CDR Meier, the Repair Officer; Robert Thran, the Chief Engineer; and Chris Richardson, the local SUBMEPP representative have all been invaluable in their helping me obtain data and local knowledge of the SSBN maintenance community.

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# Chapter 1

# Introduction

This thesis quantitatively addresses several recent trends in submarine maintenance and repair, focusing on one specific area for analysis to better inform this extremely broad and diverse topic: deferment of intermediate level maintenance actions performed on ballistic missile submarines (SSBN) at Trident Refit Facility King's Bay (TRF). Although SSBN maintenance performed at TRF is a small sliver of the overall submarine maintenance performed each year throughout the fleet, the analyses and lessons learned within this thesis are applicable across the fleet to both submarine and surface ship maintenance. Maintenance planners and executers are often deeply engaged in the day to day operations and emergencies that are common in naval repair facilities, and do not have the time to dedicate to separate analyses of the larger challenges facing the fleet; there simply are not enough hours in the week. This thesis attempts to tackle one of these larger challenges by deriving insights from the analysis of aggregated maintenance and cost data from TRF to quantify the impacts of deferring maintenance actions and to generate a risk informed tool for deferment decisions.

## 1.1 Submarine Maintenance Overview

The execution of submarine maintenance is a combined effort involving planning, budgeting, materials, and, most importantly, thousands of personnel from dozens of organizations throughout the public and private sectors. The major organizations involved include the four public shipyards, the intermediate maintenance facilities (IMF), the planning yards, Trident Refit Facility (TRF), and Submarine Maintenance Engineering Planning and Procurement (SUBMEPP). Submarine maintenance is divided into three levels, based on the complexity of the maintenance action and the organization performing the action:

1. Organizational Level (O-level): O-level is the lowest level of maintenance actions, performed by the ship's crew (hence the name). Examples of O-level maintenance actions include cleaning and inspecting electrical cabinets and lubricating pumps and other rotating machinery.
2. Intermediate Level (I-level): I-level is the next highest level of maintenance actions, performed by a mix of ship's crew and intermediate maintenance facility personnel. These items are generally more complex and often require specialized equipment that the ship does not maintain onboard. Examples include electrical tests with specialized equipment and heat exchanger cleaning.
3. Depot Level (D-level): D-level is the highest level of maintenance, performed mainly by shipyard personnel with ship's force supporting them. These actions often require specialized equipment or for the ship to be in a dry dock where seawater intrusion is no longer a concern. Examples include blasting and painting of tanks and removal and restoration of major valves.

Each submarine class has its own life cycle maintenance plan that is carefully managed throughout its lifetime, specifying when each maintenance item at all three levels is to be performed. All submarines go through various periods of training in port, training at sea, deployment, and maintenance periods which are split between intermediate (pierside) and depot (dry dock) level time periods. There are no periods of time dedicated solely to O-level maintenance, as that is done on a continuous basis, with some items completed as often as daily. Attack submarines (SSNs) call these maintenance periods "availabilities" and ballistic missile submarines (SSBNs) generally refer to them as "refits." A typical submarine hull is designed to last 30 to 40 years, and the life cycle maintenance plans for fast attack submarines is shown in Figure 1.

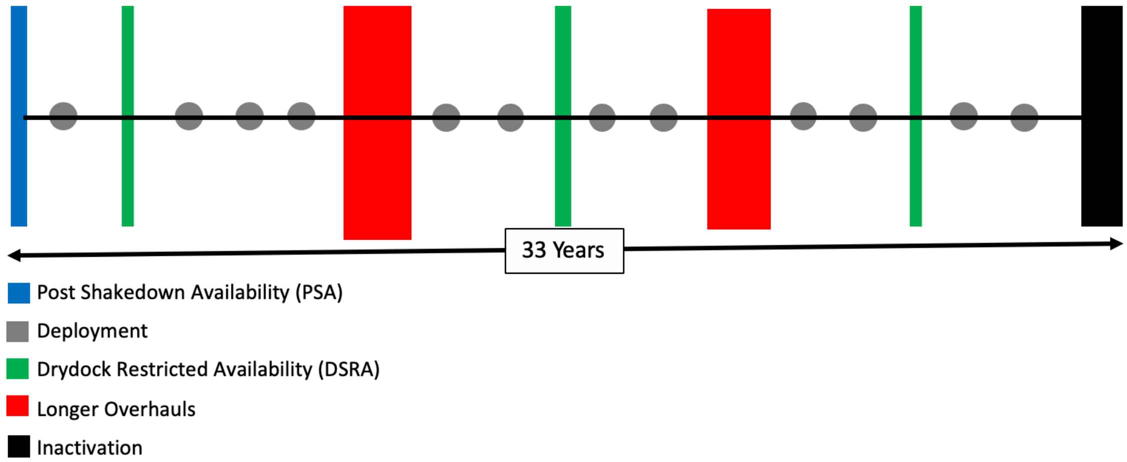


Figure 1: Nominal Fast Attack Submarine Life Cycle

A partial, nominal life cycle for a ballistic missile submarine is shown in Figure 2. This figure shows only a partial view to emphasize its more regular routine of a patrol followed by a refit, in or out of the drydock. Due to their strategic mission and limited numbers, ballistic missile submarines have a much more rigid time limit for their refit periods than attack submarines do for their availabilities. They have only one large engineered refueling overhaul (ERO), a large D-level maintenance period, once in the middle of their lifecycle.

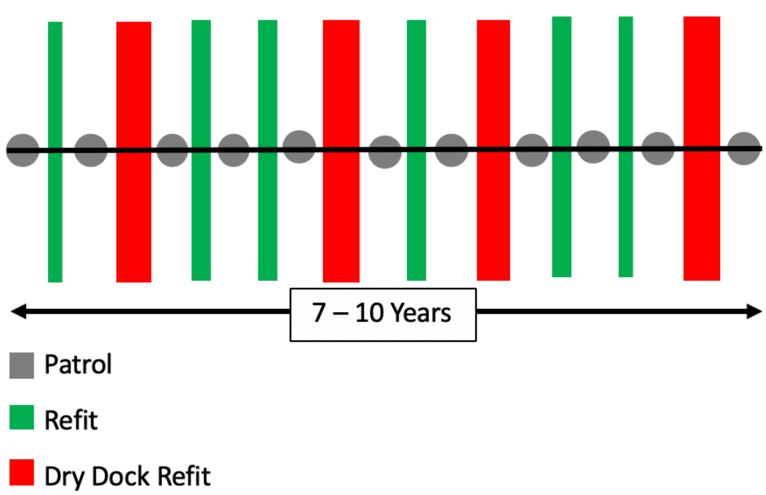


Figure 2: Nominal Ballistic Missile Submarine Partial Life Cycle

Ballistic missile and fast attack submarines share a significant amount of similar maintenance actions; aside from a few specialized systems on each ship and the large superstructure (commonly known as a "turtleback") on the top of a SSBN, they are essentially the same except for their sizes.

The individual maintenance actions are generally homogenous across the submarine fleet. However, as shown above, ballistic missile and attack submarines have very different life cycles and these differences result in very different maintenance philosophies. Ballistic missile submarines have a steady flow from refit to patrol with little room for schedule overruns, so their maintenance is heavily I-level and executed in an incremental way to support this steady flow from at sea to refit and back again. D-level work tends to be far more invasive with a significant amount of work needed just to remove items in the way of those to be repaired, so SSBNs have far more I-level than D-level to maintain their very high operational tempo. Fast attack submarines have longer depot level maintenance periods built into their life cycles, and they are often used as buckets into which a candidate maintenance action for deferral can be thrown. The phrase "let's just toss that into the next yard (D-level) period" is a not-uncommon phrase within the fast attack maintenance community, and the number of deferrals always rises significantly before a D-level availability.

## 1.2 Recent Submarine Force Maintenance Issues

Reports of maintenance issues within the U.S. submarine force have been overflowing in the national media over the last few years. These issues have included schedule delays and overruns of months and, in some cases, years, and cost overruns in the hundreds of millions of dollars. The Government Accountability Office released a report in November, 2018 detailing the costly maintenance delays across the submarine fleet:

> "The Navy has been unable to begin or complete the vast majority of its attack submarine maintenance periods on time resulting in significant maintenance delays and operating and support cost expenditures. GAO's analysis of Navy maintenance data shows that between fiscal year 2008 and 2018, attack submarines have incurred 10,363 days of idle time and maintenance delays as a result of delays in getting into and out of the shipyards… GAO estimated that since fiscal year 2008 the Navy has spent more than $1.5 billion in fiscal year 2018 constant dollars to support attack submarines that provide no operational capability—those sitting idle while waiting to enter the shipyards, and those delayed in completing their maintenance at the shipyards." [1]

The RAND Acquisition and Technology Policy Center is a private think-tank that is often contracted by different federal offices to tackle large problems that they themselves are not able to handle due to a lack of resources or personnel. In 2017 Commander, Naval Sea Systems Command sponsored an investigation into the Navy ship maintenance community by RAND. Their conclusions highlight the Navy's need to better understand and execute maintenance deferrals:

> "Historically, there has been a propensity for the Navy to defer maintenance, with a resulting impact on both the current workload and the amount of work that needs to be executed across ship service lives… Deferral of maintenance actions will complicate the management of maintenance demands. Deferrals occur for a variety of reasons—including funding shortfalls, scheduling demands, and capacity shortfalls—and it is unrealistic to simply insist that they not occur. However, it is important to understand the impact… Our models indicate that this is likely due to an attempt to recover lost maintenance and that the impact on out-year requirements gets more severe the longer the maintenance is deferred. At a minimum, if maintenance is to be deferred, there should be a conscious effort to retire the deferrals on a consistent basis." [3]

The poster child for these maintenance issues, and the one most frequently mentioned in government reports, speeches by senior leaders, and news reports, is the USS BOISE (SSN 764), the ship on which the author served. Schedule overruns and delays on dozens of boats across all four public shipyards finally led to a crisis point where BOISE had no dry dock to be put into to begin its two-and-a-half-year maintenance period. Submarines have carefully engineered operational time periods between dry dockings during which the hulls can be inspected for defects. During these operational periods between dry dockings, submarines can submerge and operate to the safe limit of their operational envelopes, but once that time period has elapsed, a submarine can no longer submerge or provide any useful time at sea deployed on mission or engaged in training. A small extension can be granted, but after that extension, the submarine is effectively welded to the pier until after it completes its dry dock maintenance period. BOISE has sat next to the pier in Norfolk since June 2016 and is scheduled to enter Newport News Shipbuilding in spring 2019 to begin its scheduled maintenance period nearly six years after it was scheduled to start. Of note, completing this D-level availability in a private yard will be much costlier than executing it in a public shipyard, but the public shipyards just do not have the room for one more attack submarine maintenance period. BOISE is shown in

Figure 3 sitting at the pier in Norfolk where it has sat, idle, for nearly three years.

Figure 3: USS BOISE Sitting Pierside, Unable to Go to Sea with No Dry Dock Open

## 1.3 The Work Brokering Process

To fully appreciate the impacts and the deferment decision model presented in this thesis, the reader must understand how work is assigned to the maintenance facility and how those who accept or defer maintenance actions, referred to as maintenance "brokers," make their decisions. Although this process is similar across all submarine maintenance facilities, this thesis focuses on Trident Refit Facility King's Bay, Georgia and their work on ballistic missile submarines. Jobs that the maintenance facilities execute come from two difference sources: the class maintenance plan that shows which preventive maintenance actions will be executed and when, and from the ship identifying needed repairs. All of these jobs combine to form the candidate jobs for the next refit and from this list, the Chief Engineer and mainteance brokers together determine which jobs will be worked and which will not, according to several criteria:

1. Material: TRF must have the required parts and equipment on hand to complete the job.
2. Paperwork: The job must be written and approved so that the work package can be given to the mechanic to execute the job.
3. Personnel: TRF must have the correct, trained personnel available to complete the job. This means that not only are the right personnel assigned to TRF, but that they must have a large enough workforce to complete this specific job during the time it is scheduled. This is not always easy to determine.
4. Schedule: TRF must have enough personnel and a long enough time in the refit to complete the work. For instance, if a tank is required to be sand blasted and repainted, this work needs to be identified up front due to the high volume of work and the long cure time for some paints.

If TRF determines that a specific job meets all of the listed criteria, then they will execute the job if they are able to do so. However, not all jobs will be able to be executed during every refit, so some jobs will get deferred until a future refit. Reasons for deferment can include:

1. Material: Required parts or equipment are not available in a timely enough manner to support execution.
2. Personnel: The right personnel are not available at the right time to execute the job, and waiting for them may incur schedule delays.
3. Schedule: The work was identified too late to be included in this refit, or there are not enough shifts with the required personnel to complete the work in the order in which it needs to be done.
4. Ship Condition: The condition of the boat will not allow a maintenance action to be executed. For example, access to a space may be required, but that space is only accessible when the boat is in dry dock.
5. Equipment Condition: The condition of a certain piece of equipment prevents a maintenance action from being executed. For example, a piece of equipment may need to be energized for maintenance, but the item is broken and awaiting repairs, so the maintenance will be deferred.

Some items would generally never be deferred. For instance, if an item would prevent the ship from getting underway unless it were executed, that job would be prioritized and completed before the refit could be certified as complete.

## 1.4 NAVSEA 00 Planning Summit

COMNAVSEA, Vice Admiral Thomas Moore, USN, convened a summit in early 2017 of stakeholders across the maintenance community to address systemic issues faced by the entire community. Specifically, the summit sought to improve the planning process as a way to positively impact the execution process. The summit generated a set of 28 actions to be executed by the maintenance community to improve the planning process and this thesis directly supports the first action item: "Identify improved strategies for execution of CMP requirements for… effectiveness and timeliness of assessments to support work package… and sequencing work." [2]

## 1.5 Thesis Statement

Section 1 details the background and motivation for this inquiry; the thesis consists of two objectives and is as follows:

> Deferring submarine maintenance actions can have large, negative impacts on availabilities by pushing off work today and incurring higher future costs, resulting in cost and schedule overruns. Through examination of the work deferment process and quantitative analysis of deferred maintenance items over multiple availabilities, the impact of these deferred maintenance actions can be determined. From this examination, a technical, risk-based model for deferment decision making can be generated to aid in future availability planning.

# Chapter 2

# Maintenance Action Deferrals

## 2.1 Data Source and Limits

Obtaining U.S. Navy submarine availability cost and maintenance data for academic research can be challenging even for the author, an active duty service member enrolled in a primarily active duty military program at a civilian institution with a long, robust history of collaborating with the Navy. Working with SUBMEPP and NAVSEA, the author was able to obtain refit data from TRF that showed which jobs were executed during which refits and which jobs were deferred and why. Although the reasons for deferment are captured, they are often too vague to analyze for root causes in any meaningful way. This lack of clarity is a common theme throughout this investigation and is discussed in detail in Section 5.3. Also from TRF, the author obtained cost and duration data related to those same refit periods, although access to this particular type of data was initially difficult, requiring several weeks and heroic efforts by some staff members at both TRF and SUBMEPP. These cross-organization barriers to data sharing and their impacts are discussed in depth in Section 5.

Although every ballistic missile submarine operates under the same nominal life cycle plan, the ships are not completely homogenous. Three decades of small variations in days at sea, season, patrol locations, and maintenance completion rates and timing have created a class of boats that are all unique. However, by fully opening the aperture to include all types of maintenance actions, the impact of these small variations between boats should be minimized. Furthermore, to ensure a valid comparison that eliminated as many external factors (personnel and processes) and variations as possible, the author limited the scope of the investigation to one repair facility, TRF King's Bay, and to only those refits executed on boats that had completed their midlife refueling overhaul. By limiting the scope of this inquiry to only those refits, the author ensured that all boats analyzed will be of similar age and in similar starting conditions, assuming that the boats exit their midlife refueling in generally excellent condition with all maintenance up to date and corrective repairs complete. The total time period for the data spans approximately ten years, covering a total of 50 refits both in the dry dock and pierside. A high-level summary of the data is shown in Table 1:

Table 1: Received Data for Analysis

| Boat | Number of Refits (Dry Dock / Pierside) |
|---|---|
| A | 7 / 18 |
| B | 4 / 11 |
| C | 2 / 4 |
| D | 1 / 3 |

## 2.2 Data Analysis

As discussed in Section 1.1, the data presented in this thesis has been anonymized, so the specific hulls, refit numbers, maintenance actions, and systems are not presented here. However, the insights garnered from the analyses remain valid and helped determine the impacts of deferred maintenance actions and shape the technical, risk-based deferment tool. The underlying assumption that drove the start of this analysis is that if a certain percentage of maintenance actions are unable to be completed during the scheduled duration of the current refit and are deferred to the next one, then that refit should have a much higher propensity for running beyond its scheduled duration. This section will dive into the data to determine the real impact deferred maintenance is having on the ballistic missile fleet. The percentages of deferred jobs per refit are shown in Figure 4 and Figure 5. Pierside refits contain on average 436 jobs, of which 11 are deferred, a rate of 2.5%; however, as Figure 4 shows, a significant amount of variability exists with the percentage of jobs deferred ranging from 0% to 10.9% with a standard deviation of 2.4 percentage points. The outcomes of these deferred maintenance actions are discussed later in this chapter.

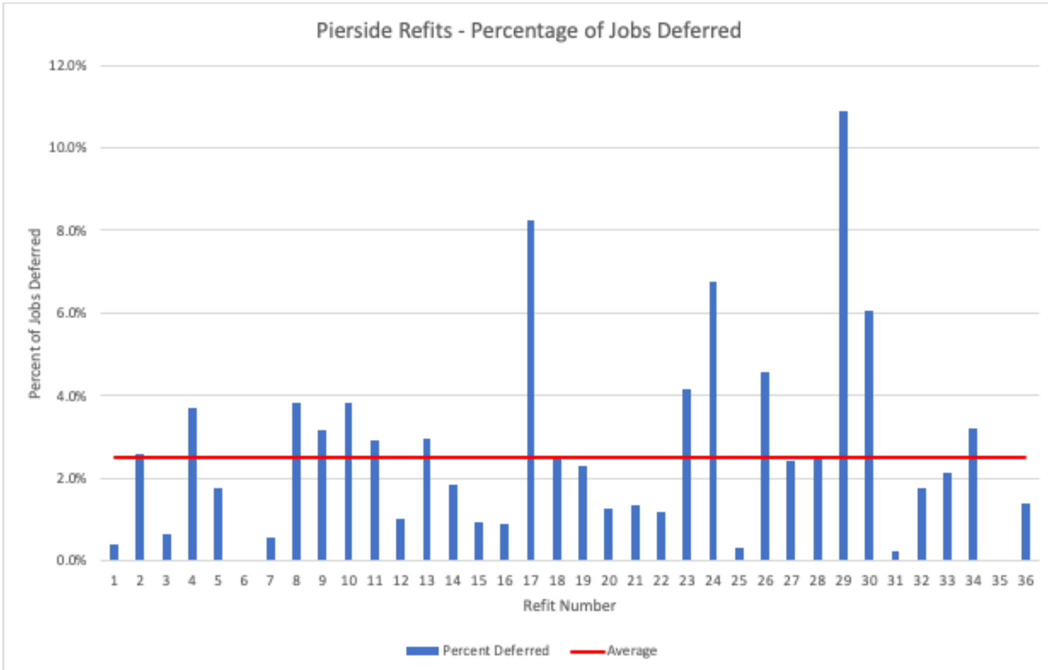

Figure 4: Pierside Refits - Percentage of Jobs Deferred

Dry dock refits are of a longer duration and scope, and therefore contain on average 803 jobs, of which 61 are deferred, a rate of 7.6%. Again, as shown in Figure 5, a high degree of variability exists with the percentage of jobs deferred ranging from 1.4% to 20.4% with a larger standard deviation of 5.2 percentage points. Although their standard deviation is much higher, their sample size is also much lower, which allows the extremes to have more significant impacts on the statistics.

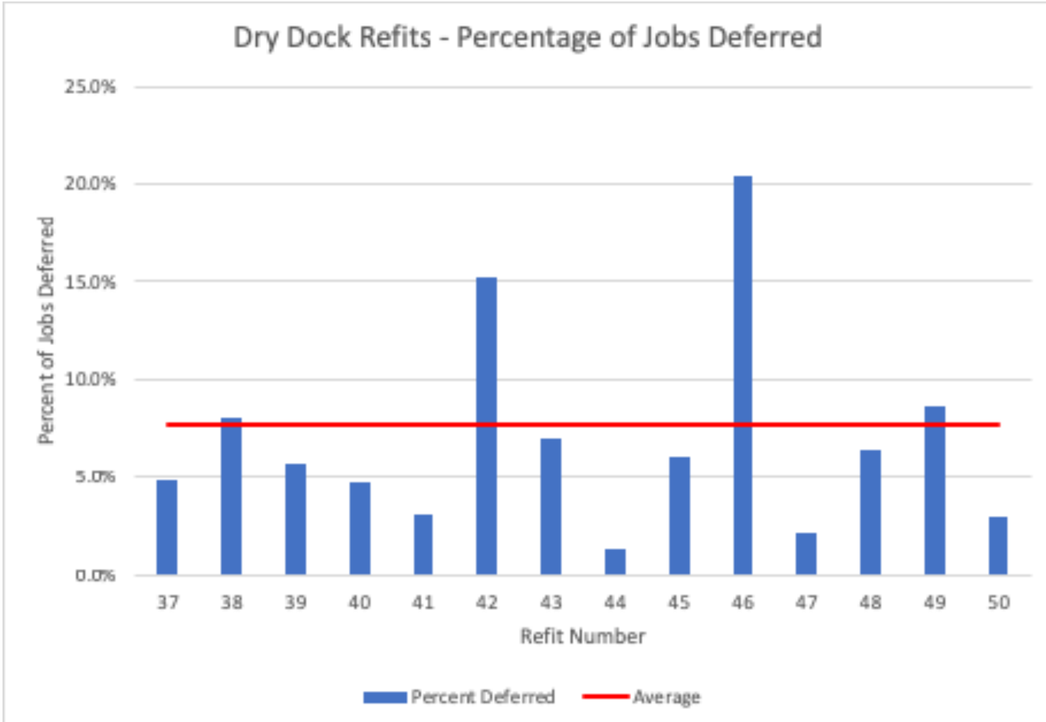


Figure 5: Dry Dock Refits - Percentage of Jobs Deferred

This higher rate of deferred jobs in dry dock refits is expected, as they contain nearly double the number of maintenance actions. Furthermore, these dry dock repair periods give the maintainers access to normally inaccessible areas, uncovering repairs that will need to be deferred to ensure a timely completion of the refit to make room for the next boat behind it in line; the cycle of patrol to refit must continue. Average deferral rates in the low to mid-single digit percentages do not initially seem like a high-risk activity, but the high variation yields several refits with deferral rates above 10% and as high as 20%, and these are initially the best candidates for potentially negative impacts. To understand these impacts, a comparison of deferred maintenance to cost and schedule is required.

## 2.3 Correlation with Cost and Schedule Data

To fully understand how deferred maintenance actions are impacting submarine availabilities, an analysis of deferral rates and how early or late refits are running gives the best understanding. Due to their vital national mission, high operational tempo, and small fleet size, time (measured in days early or late from the original scheduled refit duration) is the best test to determine the impacts of deferred maintenance actions on ballistic missile submarines. Any trend creating critical impacts will result in refits lasting longer than originally scheduled, and because each type of refit (dry dock and pierside) is scheduled for the same nominal length, any change from this length yields a valid, true comparison. Stated another way, schedule delays are the cost associated with negative impacts to ballistic missile submarine maintenance. Although a good argument can be made that a cost in dollars could also be utilized to conduct this analysis, time is a better argument for three reasons. First, cost and schedule are very closely correlated and any increase in time at the pier or in the dock will result in linearly increasing costs as the daily cost of services for the ship are constant for each location. Secondly, cost and schedule will always closely mirror one another unless a high material cost item is replaced, even though that item could have no impact on schedule, creating a divergence between the cost and schedule correlation. Finally, due to their mission, refits that run late are of far more importance than a similar increase in dollars spent on that refit.

The data discussed below came from several databases that track metrics such as expected duration, actual duration, and cost data. The most insightful data though, comes from the post-refit report that TRF provides to several organizations as a sort of immediate hot-wash that captures lessons learned, but also provides a narrative to explain any delays or schedule and cost overruns during the refit. Thankfully, SUBMEPP retains these reports electronically and they provide a wealth of insights into the way the refit was executed, the problems encountered (if any), which jobs were completed or deferred and why, and which jobs, inspections, or acts of nature impacted the duration.

How late or early refits ran is determined by the following formula for schedule delta, also referred to as just "delta" in this thesis:

$$Schedule\ Delta = Actual\ Duration - Scheduled\ Duration$$

The schedule delta for the all of the dry dock refits are shown in Figure 6. Although most went late by an average of nine days, extenuating circumstances impacted almost every refit that experienced delays. All of the refits with red stars above them went late due to items outside the control of TRF and totally unrelated to deferred maintenance. These outside influences include an oil spill in the dock that required an extensive two-week clean up and recovery period, a hurricane evacuation and recovery, significant alterations executed by outside entities, an international treaty inspection, and significant growth due to equipment failure during testing. Refit 46, which experienced the only significant (11 day) schedule delay not due to outside forces, ran late due to a delay in obtaining parts for some repairs that were identified late. In general, none of the dry dock refits experienced schedule delays due to poor execution or from items that TRF could reasonably control.

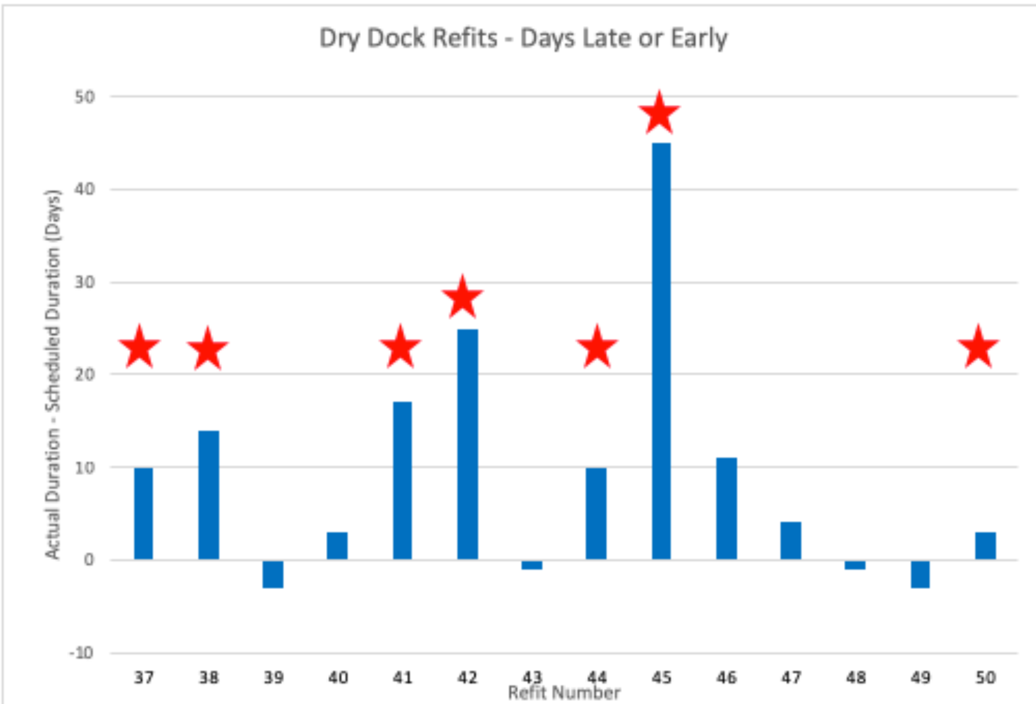

Figure 6: Dry Dock Refits - Days Late or Early (Schedule Delta)

Figure 7 shows the schedule delta for all pierside refits with an average of less than one day late across all 36 refits, an impressive record in the submarine maintenance community. Like the dry dock refits discussed above, the pierside refits that ran the latest were also impacted by some significant outside exigent circumstances including a hurricane, critical component failures identified late by the ship's crew, and another hurricane. The only two refits with any sort of significant schedule delay not due to an act of nature or some other extenuating circumstance are refits 19 and 21, both of which ran later than scheduled due to the late identification of required repairs, one as the ship was entering the refit and the other during testing near the end.

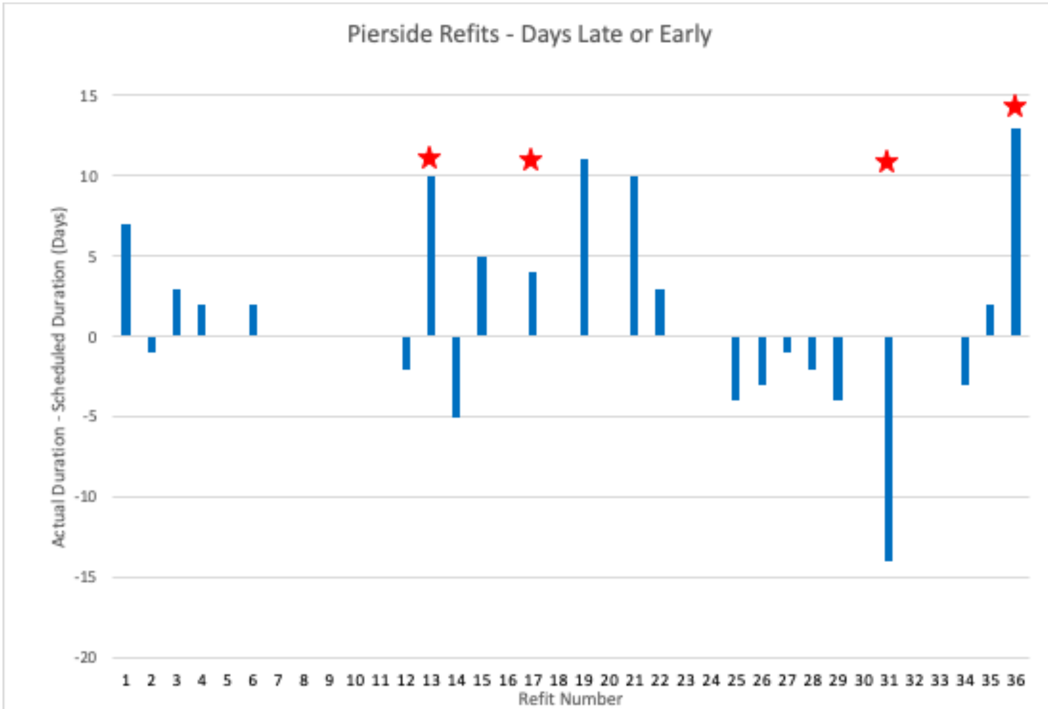

Figure 7: Pierside Refits - Days Late or Early (Schedule Delta)

In an attempt to find some deeper connections and more universal truths, a further comparison was made between deferred maintenance actions and refit durations in a time sequenced manner for four different boats as shown in Figures 8 through 11. This analysis enables a time-sequenced comparison on four specific boats (labeled A, B, C, and D for the purposes of this thesis, randomly assigned to anonymize the hulls) to show the flow of the ship from at sea to a refit and back again, tracking the impacts of deferred maintenance throughout a segment of the life of the hull. This kind of time-sequenced analysis can offer some of the best insights into how maintenance has impacted the ship over its life, but it is a tedious process. Compiling the data using multiple databases from different organizations that do not always work well with each other proved to be a longer process than anticipated, and is another example of the data barriers that exist across organizations preventing the sort of big data exercises and projects that are becoming more frequent in the corporate and academic sectors.

Figure 8 shows the deferred work rates and schedule delta for boat "A." No direct correlation between deferred maintenance rates and schedule delays can be drawn on this boat. Although there are several large increases in deferred maintenance rates on refits 46, 25, 29, and 31 (listed in chronological order as they were executed on this specific boat), there are no correspondingly late refits that were impacted by these deferrals. In fact, every refit directly following one with a high deferral rate on this boat, finished early or on-time, with an average finish of a half day early. For the refits that did experience significant schedule delays, these were due to acts of nature and international treaty requirements for inspections that themselves ran late. Even when diving into the execution of individual jobs, no previously deferred maintenance actions resulted in outsized cost and schedule impacts when those jobs were eventually executed. On boat "A," no correlation between deferred maintenance and schedule delays can be found, and there is even anecdotal evidence to suggest that deferring maintenance items the right way has positively impacted their record. During refit 33, an inspection noted some structural deterioration in an area outside the pressure hull, requiring some extensive welding, blasting, and painting to repair that would last nearly two weeks. The next refit (50) was scheduled to be a longer, dry dock refit, so the risk was assumed and the action was deferred, allowing refit 33 to finish on time. Although refit 50 did finish a few days late due to the extensive repairs, three days is preferable to two to three weeks had they executed the work in refit 33.

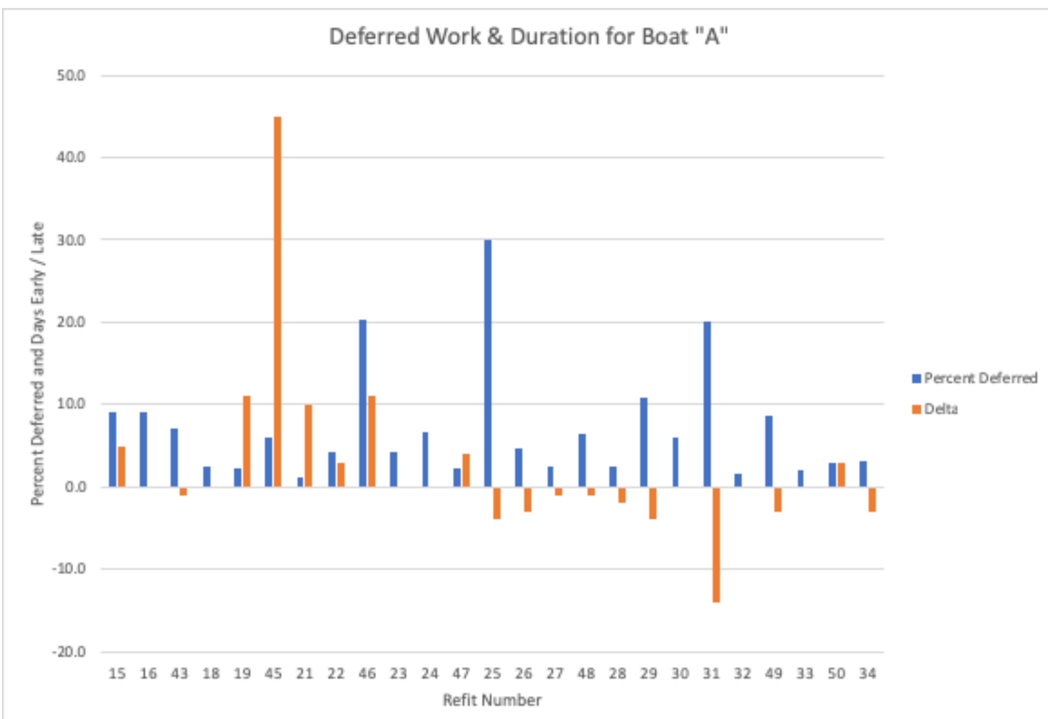


Figure 8: Deferred Work and Refit Durations for Boat "A"

Figure 9 shows the deferred work rates and schedule delta for boat "B." No direct correlation between deferred maintenance rates and schedule delays can be drawn on this boat. There was a large spike in deferral rates during refit 42, but all of the deferred items were absorbed into the next refit, number 17, which was late by four days, driven by component failures during testing that were on components not deferred from previous refits.

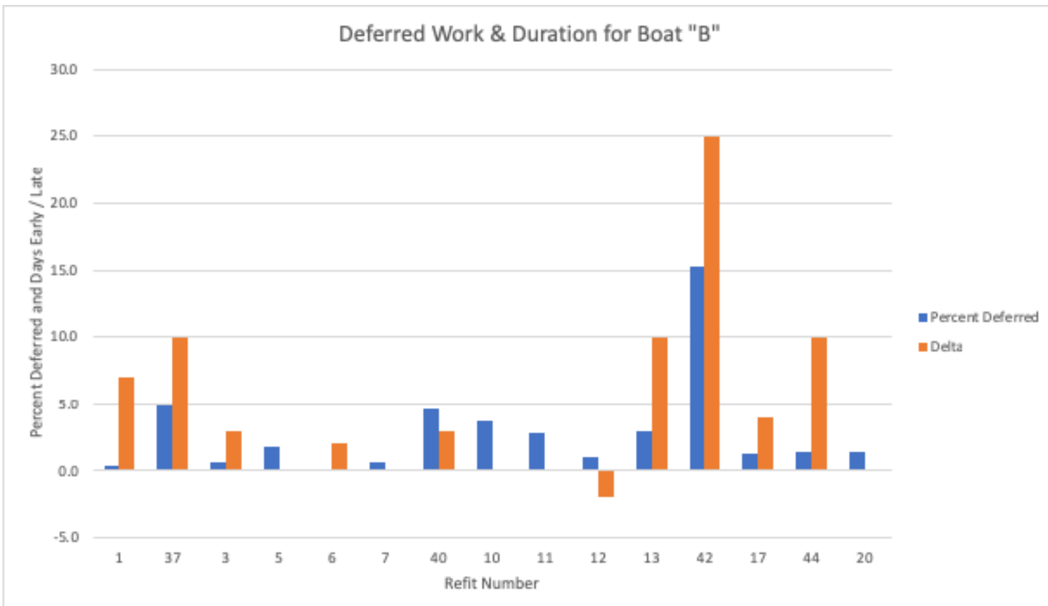

Figure 9: Deferred Work and Refit Durations for Boat "B"

Figure 10 shows the deferred work rates and schedule delta for boat "C." As before, no correlation between deferred maintenance and schedule delays exist for this ship either. Refit 39 had the largest deferral rate, and the following refit, 8, completed on time. Refit 41 is the only late refit for this boat during the timeframe of the analysis, and that is due to the emergency sortie of all boats for a hurricane and the subsequent clean up that cost the maintainers nearly three weeks of work after the sorties.

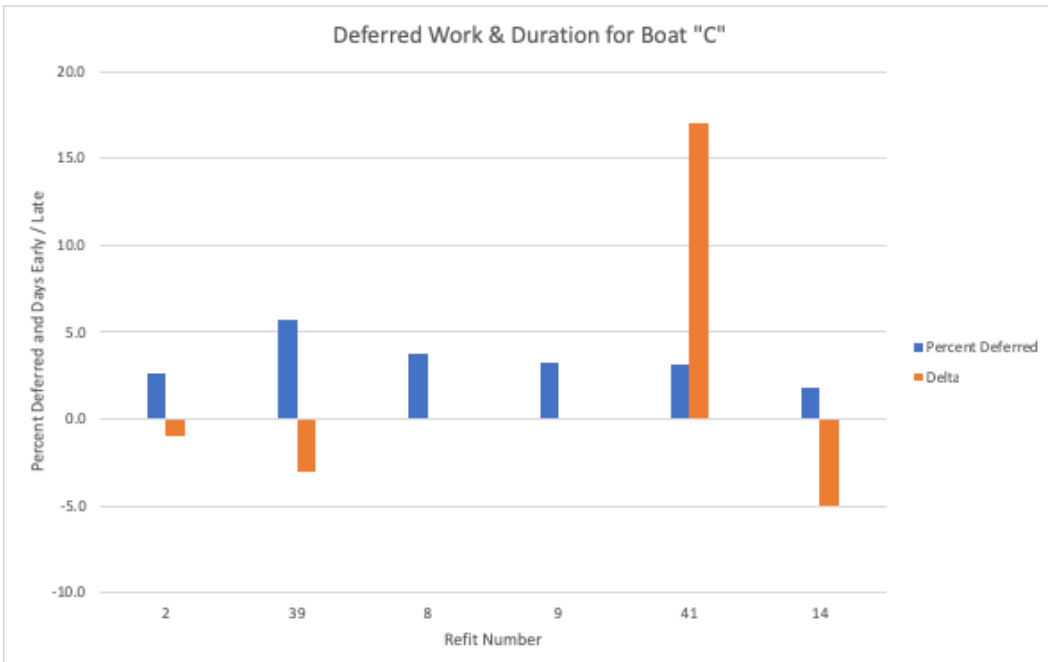

Figure 10: Deferred Work and Refit Durations for Boat "C"

Finally, Figure 11 shows the same deferment and duration data for boat “D.” As shown throughout this chapter, no correlation between deferred maintenance and refit schedule delays exist for boat “D” as well. Two of the late refits (4, 36) were late due to emergency sorties for hurricanes and the other, 38, was extended due to an oil spill in the dry dock that had to mitigated over the course of a few weeks. None of the maintenance that had been previously deferred exhibited any significant increase in duration or cost.

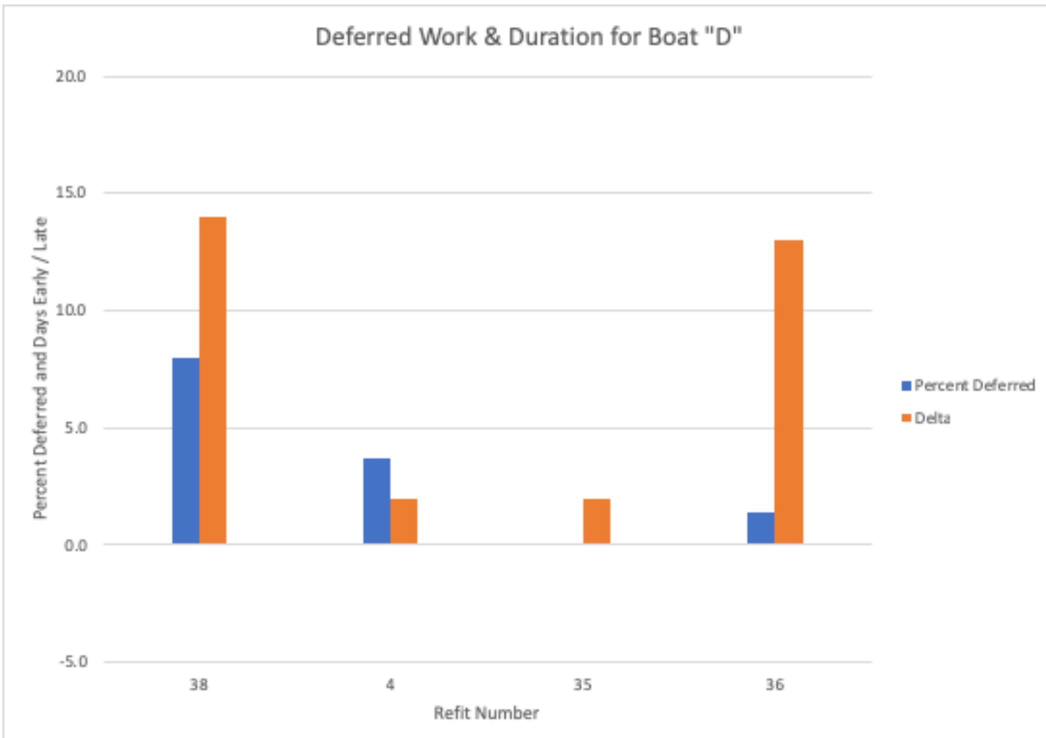

Figure 11: Deferred Work and Refit Durations for Boat "D"

## 2.4 Impacts of Deferred Maintenance Actions

As demonstrated throughout Section 2, deferred maintenance is not having a significant, negative impact on on-time or on-budget refits in at Trident Refit Facility King’s Bay. The amount of deferred maintenance actions, both in terms of number of jobs and as a percentage of total refit size have remained consistently low, at approximately 4.6%, and TRF is able to manage this level of deferred work with minimal impact to refit schedules. In fact, the majority of late refits are due to acts of nature or other elements outside of their control, generally unrelated to the maintenance they are executing.

Although the first objective of this thesis has proven unsuccessful, the insights gained from this investigation have allowed the author to explore some other avenues that were not originally a part of this thesis. Specifically, the author discovered multiple instances of deferred maintenance actions resulting in significant schedule savings in the current refit with a minimal impact on the refit in which the maintenance is eventually completed, building an initial argument for deferring maintenance as a way to positively impact schedules. This possibility has been investigated and incorporated into Section 3 and Section 5.

## 2.5 Future Considerations

The ballistic missile submarine fleet is aging, and the *Columbia* Class ballistic missile submarines to replace them will not be operational until 2032 at the earliest, so maintenance on the current class will continue for another 20 years. As they age and their material conditions deteriorate in ways that the community has not yet encountered, late and growth work (work added after all of the maintenance actions for that period have been scheduled) will increase, putting increased pressure on an already pressured community. Overtime and touch labor can alleviate some of these issues, but maintenance deferrals will rise as a way to relieve schedule pressure as the man-days required for corrective actions on aging boats increase, leading to material readiness and reliability issues within the ballistic missile fleet. A technical evaluation executed on the oldest ships could better inform decisions about the rest of the fleet as they age, giving maintenance brokers a technically sound, risk-based method to determine which jobs could be deferred with the least risk of future adverse effects. Further development of this technical, risk-based decision tool is discussed throughout Section 3.

# Chapter 3

# Deferment Tool Development

## 3.1 Current Deferment Process

The way maintenance organizations broker work is detailed in Section 1.3. Deferments generally can be classified into five categories: material, personnel, schedule, ship condition, and equipment condition. Under the current process for deciding to defer a maintenance action, nothing forces a technical assessment or risk analysis on the equipment in question. If it is not underway limiting, and a higher authority does not prohibit the maintenance action from being deferred, then the action can be deferred for the reasons outlined in Section 1. Best practices often generate an informal risk analysis by the maintenance brokers, but the process is not codified, so a formal process could provide some clarity and emphasis to the process.

## 3.2 Technical Risk Assessment

Availability sizes have outpaced the ability of maintenance facility workforces to accomplish them for many years, and the pressure to stay on schedule is intense across the fleet, with top level leadership and the national media paying particular attention to schedule and cost overruns. This pressure can lead to increased deferral rates that solve near term problems while generating unforeseen consequences in the future that often fall outside the purview of those who made the original deferment decisions, eliminating a feedback loop that would deter this kind of behavior. For example, if the intermediate maintenance facility in an area defers an item that is later absorbed by a depot level facility, the negative consequences from that deferral would have no realized negative impacts on the deferring activity, reinforcing the positive aspects of deferring maintenance actions to meet schedule demands. These small, positive-reinforcements over time can lead to an increase in deferrals exclusively to meet schedule demands, outside of the other, more valid reasons. The most critical issue with this current state, however, is that these decisions are made outside of any technical risk analysis of the potential impacts deferring the maintenance action will have on the equipment, the system, and the ship as a whole. The tradeoff between schedule and cost savings today are never evaluated against the exposure of the equipment and the ship to a risk level that may counter any savings enabled by the deferral. Section 3.3 outlines a technical, risk-based deferment decision tool (TRBDDT) that can be utilized to drive deferment decisions, or, at the very least, enable maintenance brokers to minimize the risk exposure by making the best possible decisions grounded in a technical understanding of the risks that they are incurring. Section 3.4 then takes this framework a step further, offering some ways in which the framework could be used to identify candidates for deferral to give some relief to the maintenance facilities.

## 3.3 Maintenance Action Deferment Risk Assessment

This section defines a framework for a technical risk-based deferment decision tool as a starting point for maintenance brokers to begin applying the framework in their work flows. Initially applied to intermediate level submarine maintenance, the tool could be generalized to many different industries and levels of maintenance. Some initial assumptions are required as a starting point for this analysis and are listed below:

1. The maintenance availability, for which deferrals are being considered, is expected to be overscheduled or, if already in execution, late work or growth items will push the availability late. In general, this tool is not intended to assess maintenance actions for which ship conditions cannot be met, nor for those missing parts, equipment, or narrowly trained personnel (such as a tiger team). If the jobs cannot be executed, extra time spent considering their risks are an inefficient use of resources and the organization's existing processes for deferring work should be utilized.
2. The candidate maintenance actions for deferral are not underway limiting items. This analysis is designed to relieve schedule pressure and deliver a ship that is fully operational and available for all tasking, not relegate an asset to the pier like USS BOISE.
3. The candidate maintenance actions for deferral are known well in advance of the start of the maintenance period and are able to be evaluated for deferral as the work package

is being populated. Or, if already in execution, late and growth work items could be considered for deferral. These late and growth work items will become more important as the ships age and equipment failures happen more frequently in ways not previously experienced.

4. The recent and relevant history of the candidate maintenance action, the affected equipment, and affected system should be included as a part of the maintenance decision.
5. Finally, the candidate maintenance actions should be of sufficient scope and duration (in man-hours or expected duration) that deferring them will have an appreciable, positive impact on the duration of the availability by freeing up resources to other work to be executed.

If these assumptions are satisfied, the maintenance broker can initiate an assessment using the technical, risk-based deferment decision tool. The TRBDDT frames the decision in the classical risk viewpoint of risk as a function of probability and consequence, and gives the maintenance broker a way to build a risk and consequence model in a timely manner so that the correct, technical decision can be made. The steps are as follows and they are discussed in detail throughout this section:

1. The equipment with the deferment candidate must be identified and a condition assessment executed, to include current physical condition from an up to date inspection.
2. A review of the equipment's relevant maintenance record must be completed, detailed down to the component level if applicable.
3. Consequences of applicable failure modes must be identified.
4. Probabilities of applicable failure modes must be identified.
5. The deterioration due to deferment must be identified (how much will the equipment be operated between now and its ultimate execution), as well as the applicable risks and consequences of that deterioration. These include both long-term and short-term consequences.

6. If desired, a list of possible alternative actions could be generated that could be executed instead of the deferment candidate. These alternative actions could be temporary fixes in place of the larger maintenance action to lower the assumed risk of deferring the candidate maintenance action.
7. Finally, a decision must be made to defer or execute the candidate maintenance action, using the risk generated by the probabilities and consequences discovered during this analysis.

Once the candidate maintenance actions are identified, the current condition of the equipment must be assessed. This assessment can be executed via ship checks or in conjunction with ship's force. Caution should be exercised such that the assessment of equipment condition does not offset the cost and schedule gains made by deferring the item. As more ships gain automated logging and monitoring systems, these condition evaluations can be done on a nearly continuous basis, and combined with historical data, a forecast of future risk of degradation could be generated. Although this condition assessment should be as quantitative as possible (i.e. plate thickness, operating condition based on bearing wear, temperature, and vibration data, etc.), experienced operators know their equipment best and it should be used to inform the condition assessment if desired. Furthermore, if this assessment reveals the equipment to be in immediate need of maintenance, then the TRBDDT process can be stopped and the maintenance executed.

The current condition assessment, as discussed above, is the first part of the process, but to completely understand the full condition of the equipment, the relevant maintenance history should be reviewed down to the applicable component level (i.e. if the shaft on a pump is to be worked, then the system, the pump, and the shaft itself should be assessed). A strong history of maintenance completed properly and on time should be weighed in favor of deferment, but a history of deferment or missed maintenance actions on the equipment should increase the probability of failure and weigh against deferring the candidate maintenance action.

After the condition assessment is complete, the failure modes of the equipment must be identified and their probabilities and consequences identified. The condition assessment, including both the current condition assessment and a historical investigation of the maintenance history, will inform the probabilities of different failure modes. Historical data (from SUBMEPP, TYCOM, or the maintenance facility itself) can also serve as a way to identify previous failures and the conditions that led to them, which can be used to better inform this analysis of failure modes. Along with the probabilities of different failure modes, the consequences of these failure modes should be identified and detailed as to their impact to both the ship and the maintenance facility servicing that ship. Impacts to the safe operation of the boat are the primary concern, but a failure due to deferment that resulted in the necessary replacement of that equipment could seriously impact the maintenance facility's ability to execute its mission as it devotes significant resources away from other projects to focus on this emerging, unplanned work. An improperly deferred maintenance item that later failed on mission could result in the loss of mission or the assumption of extreme costs to send a fly-away team of experts away from the maintenance facility to a ship on the other side of the globe.

Deferment of the maintenance action will permit the equipment to deteriorate over the period of time of the deferment, and the nature and severity of this deterioration should be anticipated. There could be both long-term and short-term impacts of this decision to defer: a maintenance action designed to be executed on a more frequent basis (such as a small component replacement) may help lengthen the time between larger actions, and deferment of a seemingly small action could result in a decreased lifespan at the equipment, not just component, level.

As a last step, if deferment is desired, a list of alternative maintenance actions could be generated to provide the maintenance brokers options to decrease the likelihood of potential failures. Although temporary measures are generally not desirable, if they can solve the problem temporarily and lower the probabilities of some of the risks, then they should at least be available as options for the maintenance team to evaluate.

Finally, once all of these analyses are complete, a Likert scale modeling system can be employed to provide a final risk score encompassing the likelihood and consequence of deferring maintenance action. The individual maintenance activities can establish their own thresholds and actions for each risk score, or the maintenance community as a whole can come to a consensus on an overall system. With this final risk score, a decision to defer or not can be made by the maintenance broker, in conjunction with the local chief engineer and technical warrant holders as required. The TRBDDT is shown as a flow chart in Figure 12.

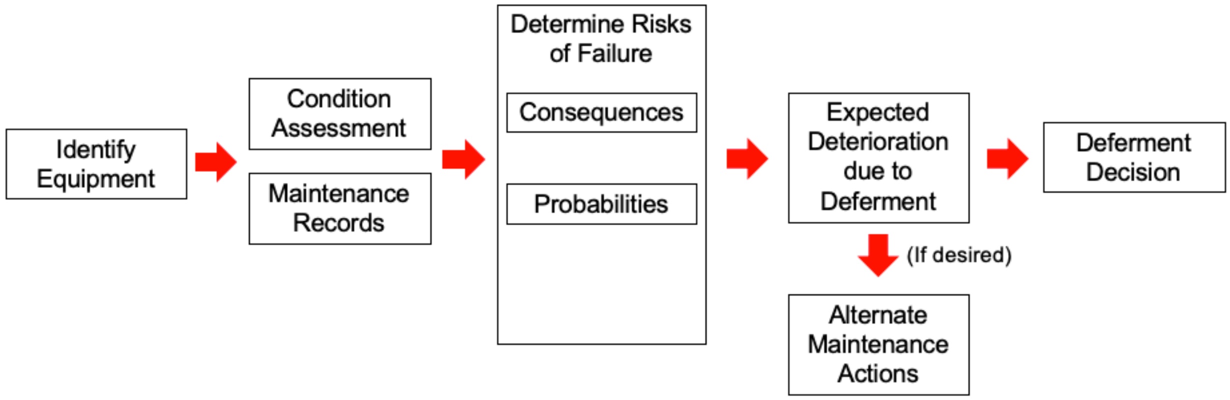


Figure 12: TRBDDT Flow Chart

## 3.4 Deferment as a Tool to Reduce Loading

The entire naval ship and submarine repair community, both public and private, has experienced years of schedule and cost overruns that have recently begun to receive attention at the highest levels of the military and government, as well as the national news media. Shipyards have too much work scheduled for accomplishment by too few people in too short a period of time, and the ships that execute these missions of vital, national importance need to get in and out of the yards in a timely manner and back to sea. A constrained fiscal environment and a thriving economy make finding and retaining a talented workforce within these maintenance facilities a serious challenge, and one that will take many years to resolve; skilled workers take many years to develop, and although recent hiring pushes across the maintenance community and NAVSEA enterprise have been successful, the workforce is still very young with an average of less than seven years of experience.

To alleviate some of the schedule pressure, this risk-based deferment decision tool could possibly be used to identify robust systems that would allow for increased maintenance deferrals at low risk levels. By identifying those maintenance actions on specific systems, the maintenance community could intentionally seek out low-risk deferment candidates and apply them across an entire fleet to reduce the workload. Nearly all proposals aimed at reducing the maintenance bow wave focus on more people, more money, more training, and doing more work than has ever been accomplished. This would be one of the few actions aimed at lowering the amount of work to be done, not at dramatically increasing the rate at which it is done. To really attack the bow wave and get the maintenance community back to even, increasing the rate and lowering the total amount could be a decisive victory.

## 3.5 Applications to Other Activities

Although this risk-based deferment decision tool was written with submarine maintenance in mind, the author believes it can be applied to any military or industrial activity engaged in heavy maintenance of complex, mechanical systems. Specifically, the application of technical, risk-based analysis to all scheduled maintenance could help decrease cost and schedule overruns, enabling short term gains while minimizing the risk of long-term negative impacts that can come from deferring maintenance without sound, technical rational behind it. One application of note, would be on the ballistic missile submarines themselves. As they age and move past their original intended lifespans and into their now 42 year hull lives, a technical study of the required shift in maintenance focus areas could keep the expected increase in growth work due to equipment failures to a minimum.

# Chapter 4

# Deferment Tool Case Study

## 4.1 Superstructure Preservation

As discussed in Section 1.1, all U.S. Navy submarines are of a similar basic design: long, slender tubes designed for quiet and efficient operations with some differences depending on their primary intended mission. The most obvious difference between the ballistic missile and attack submarines is size: ballistic missile boats are nearly twice as long and displace nearly three times as much as an attack submarine. One of the defining differences between a modern ballistic missile submarine and an attack submarine is the topside superstructure (called the "turtleback") on a ballistic missile submarine. The turtleback extends from the sail, aft, nearly the entire length of the boat and consists mainly of steel structural elements to support the missile tubes. The turtleback (as shown in Figure 13) is a free-flood area when the ship is at sea, constantly exposed to seawater as it flows in and out along its entire length along with the salt ions that cause rust and other material degradation.


Figure 13: Ballistic Missile Submarine Superstructure ("Turtleback")

To ensure a high degree of material readiness, parts of this topside superstructure are periodically inspected to ensure a high degree of material readiness. When spots of bare metal or degraded paint are discovered during these inspections, the problem areas are spot corrected, or, an entire section may be sandblasted and painted to reestablish the protective barrier between the sea and the steel, like the hull of any metal ship in the world.

In 1998 the United States Navy, after a long, technical investigation, decided to extend the life of the ballistic missile submarines from 30 out to 42 years, and some analysts predict that they may even be extended beyond that if there are any delays to the *Columbia* Class. This life extension allows this turtleback area to spend even longer exposed to the elements, resulting in deterioration not expected during the initial design of the ship. During one pierside refit, some of this enhanced deterioration was discovered during an inspection of the turtleback, resulting in the need for surface preparation and preservation, a task that would last a few weeks due to the prep and cure timelines, pushing the refit past its end date by 10 to 15 days. Due to this possible long schedule delay, the maintenance organization decided to defer the maintenance action until the next dry dock refit using a technical, risk-based analysis to drive their decision making. Section 4.2 examines their decision making analysis and the resulting outcome as a case study of how the

TRBDDT can be utilized to make the best, most well-informed decision possible with the information available.

## 4.2 Technical Risk Assessment

Although not codified, the maintenance brokering team completed an analytical process to decide to defer the maintenance action, in this case, the repair of the topside superstructure. The deferment candidate was identified and an assessment of the current condition was completed, including a review of the applicable previous inspections and repairs. The result of the condition assessment revealed enough material that the probability of failure was deemed low, even when considering the anticipated deterioration due to not executing the repairs immediately. Possible alternative actions were considered, but none were utilized, as they did not appreciably lower the probabilities of possible failure modes.

After completing the technical risk assessment, as developed in Section 3.3, TRF and the technical warrant holders decided that the risk of deferring the repairs was low and accepted the risk.

## 4.3 Outcome and Impact

When the work was finally executed, the dry dock refit was completed on time, because the emergent work was able to be planned and resourced properly. The decision to defer the maintenance was based on a sound, technical evaluation of the current condition, the possible degradation throughout the delay, and the risks associated with that delay both to the ship and to the maintenance facility. The decision to defer ultimately avoided a 15 day delay during one refit and did not result in any delay in the refit where it was actually executed, presenting an excellent case study for how the TRBDDT can be used to manage maintenance deferral decisions.

# Chapter 5

# Conclusions and Recommendations

## 5.1 Conclusions

> "Deferring submarine maintenance actions can have large, negative impacts on availabilities by pushing off work today and incurring higher future costs, resulting in cost and schedule overruns. Through examination of the work deferment process and quantitative analysis of deferred maintenance items over multiple availabilities, the impact of these deferred maintenance actions can be determined…"

This first thesis objective was executed successfully, but with some surprising results. A quantitative analysis of deferred maintenance items over multiple refits was successfully executed, and the impact of these deferred maintenance actions was determined; however, the results ran contrary to the author's and the maintenance community's expectations.

Deferred maintenance actions on ballistic missile submarines at TRF are not having a large, negative impact on future availabilities, and the steady, low percentage of deferrals are readily absorbed within the next possible refit period. Instead of being a source of work planning practices that could be improved, their processes helped inform the risk-based decision model contained within Section 3. This thesis provides a model for a risk-based technical deferment process that is being successfully implemented at TRF, even if part of it exists mostly as a part of the "tribal knowledge" that is so prevalent throughout the maintenance community.

> "…From this examination, a technical, risk-based model for deferment decision making can be generated to aid in future availability planning."

This objective was highly successful. Section 3.3 presented a risk-based technical deferment process that could be applied across the Department of Defense or any heavy industrial activity engaged in maintenance. This objective was also carried a step further into considering the possible positive effects of deferring work. Deferments are generally viewed within the maintenance community as a failure of the work planning and execution processes, but with the nearly impossible bow wave of future work due to the inability to accomplish previous work, unique solutions need to be identified and pursued.

## 5.2 Future Work

Three possible pieces of future work could use this thesis as a starting basis. First, a more in-depth look at maintenance deferrals across O, I, and D level facilities could greatly improve the robustness of the model and account for differences across the fleet. Opening the aperture from a focus solely on ballistic missile submarines in one port to a more robust look at the entire fleet would allow for more general conclusions. An in depth look at the conventional surface fleet could prove especially useful since they often experience the brunt of maintenance deferrals. While submarines investigate how to minimize deferring individual maintenance actions, surface ships can often have entire maintenance periods deferred, something the submarine force would never consider.

Secondly, as proposed in Section 3.4, deferment could be used as a tool to reduce the size of upcoming maintenance periods due to a load that is beyond the capability of the maintenance activity. To assist a strained maintenance activity, a technical assessment of which items would be the ideal candidates for deferment could pay immediate dividends. As a starting point, one thesis could look into whether deferring O and I level work into a ship's upcoming D level availability result in real savings, or if the increased deteriorations, due to longer time intervals between maintenance actions, negatively impact the D level availabilities. This investigation could also scale up to determine which maintenance in the "bow wave" that the major public yards are facing could be deferred after in depth, technical evaluations.

Finally, as discussed in Section 5.3, a robust thesis should dive deep into the problems of data robustness and availability within the submarine maintenance community. The exponential growth of data science and the use of "big data" to solve large, complex problems has revolutionized large swaths of the private sector, but its integration into the public sector has lagged considerably. To begin to leverage these new tools in meaningful ways though, the submarine maintenance community and the Navy in general will need to generate better data from which deeper insights can be deducted. Frequently during the analysis of the data for this thesis, the author attempted to locate other, more granular data to try some different approaches, but the data was either not captured, only locally held, not retained for later analysis, or not formatted for analysis in the author's tools.

## 5.3 Recommendations

One of the most eye-opening realizations made by the author during his work on this subject is how stove-piped the various groups that perform analysis on maintenance have become. NAVSEA 04X and SUBMEPP tend to focus on major depot level availabilities where the most public and costly delays and overruns occur. The actual maintenance facilities, deeply engaged in the day to day operations of ship and submarine repair, lack the bandwidth, personnel, expertise, equipment, and tools to devote more than cursory efforts to studies that are not directly impacting the work currently or soon to be in execution. The squadrons focus on O and I level maintenance, with most efforts centering on the ships and submarines that are the closest to deploying or actively heading out to sea. Overall, there is little cross-level and cross-community efforts to gather and analyze data in one central location with the latest tools and the right personnel with unencumbered access to all of the available data. While attending several thesis preparation and planning meetings at SUBMEPP, multiple ideas were suggested and found to be viable and interesting theses with high potential impacts; however, the roadblocks to completion of many ideas were significant and frustrating. Access to all available data, even for SUBMEPP employees, is not a given and the juvenile need to hold on to certain data and not share it among the rest of the community is startling and prevents real progress from being made. Although there are many efforts by dedicated members of the maintenance community to improve its operations, the dispersed nature of these efforts and the lack of one central authority leads to duplication of efforts or labors that do not have the full power and results that they could. The community needs to make the right investments and set the proper policies to remove these roadblocks and unleash these dedicated personnel to tackle larger systemic issues.

In order to make serious strides towards one center of data excellence that can analyze massive amounts of data with the right personnel, budget, and tools to continuously analyze and improve the maintenance community, the author offers the following suggestions:

1. The current disparate attempts to improve the submarine maintenance community often do not have a central authority behind it, preventing the right people from getting the right data at the right time. Therefore, one central authority should be established as the center of excellence for submarine maintenance data analysis, across O, I, and D levels. SUBMEPP is the best place for this centralized effort to begin, and expanding their analysis divisions and giving it full authority as the center of excellence would be the best first step towards making real impacts. They are blessed with dedicated personnel who want to make improvements, and endowing them with all the authority possible would create a meaningful impact.
2. To truly become a center of excellence in data analysis, SUBMEPP needs full, unfettered access to all data from all maintenance levels. Although this requirement would appear sorely obvious even to the most casual outside observer, the lack of access to various forms of data from maintenance monitoring teams, squadrons, and other organizations within the submarine maintenance community is a real challenge. Data ownership is often unclear and some organizations are hesitant to share data with other organizations, even though they all support the same navy maintenance team. These issues could be overcome by giving SUBMEPP the authority it needs to obtain all the desired data at all times.
3. Aside from access to all available data, improving the quantity and quality of the available data would give the newly invigorated center of data excellence at SUBMEPP a much more robust set of raw materials with which to work. A myriad of possible thesis topics exists within this realm, and SUBMEPP should work with the MIT Naval Construction and Engineering Program to further these efforts. Several SUBMEPP personnel already have a solid list of desires for both improvements to current data and additional items which they would like to see. These include:
    a. Increased granularity and more details across the maintenance spectrum. For example: creating various check boxes and a remarks section so that a maintainer

can more completely describe the results of a clean and inspect, instead of just recording the item as "satisfactory."

b. Receiving the data as close to the time it was recorded as possible. Often, SUBMEPP employees must wait months to have access and when they do receive it, they must "mine for gold" because the quality is not where they would like it.

c. Unification of all navy maintenance data within one repository that is available to the SUBMEPP data center of excellence at all times.

d. Access to component and system operational data from the ship's logs. Some newer ships are including more automated data collection within the equipment itself as industrial controllers mature and get smarter over time, but this data is not readily available to SUBMEPP. Modern industries often use equipment run times and frequencies to inform maintenance plans, and the navy could benefit from this if the data were made available. An effort is in place to make this data available, but with no results yet.

e. The number of times a maintenance item was missed or deferred at all levels and the reasons why. This group is of particular interest to the author, as he had to dig this out of many different places and people to compile this thesis. This data could be correlated to maintenance failures to better refine and target maintenance actions on commonly missed items and systems.

4. The Navy does not have a large group of data scientists with advanced degrees and familiarity with machine learning, deep learning, and artificial intelligence. Efforts should be made to identify which fields and specialties would provide the most impact and then target data scientists with graduate degrees in those areas for hiring. A small team of highly qualified data scientists should be given the proper resources, authority, and access to data and turned loose on several big data problems, and they should immediately pay big dividends.
5. Finally, in order to execute data analytics at a high level with meaningful results, the Navy needs to invest in the right IT infrastructure so that these data scientists with access to robust data can analyze and produce the deep insights that will pay dividends in the end. All of this work is worthless if it does not save time, money, and effort and allow the navy maintenance community to "do more with less;" that is, to reduce the maintenance

backlogs and get more ships back out to sea faster, safely, and ready to fight. This IT infrastructure challenge is larger than just purchasing ever more powerful computers and server farms to do the data crunching. Security will play a huge role in this effort, and innovative solutions will be required to bring classified and unclassified data together to find the real relationships that are driving modern maintenance problems.

Although discussed above, the author would like to call special attention to the need for better data within the maintenance community. Even with all of the data available and fully analyzed, it is impossible to tell the full story of a piece of equipment across the entire maintenance spectrum. Often the data would show a maintenance action had been deferred or missed, but getting to the reason why is frequently impossible from what the data shows. Conversations and a good bit of "tribal knowledge" can lead to improved clarity, but collective memory is short and not useful for a large undertaking across thousands of maintenance actions. Increased granularity within the maintenance community, across all levels, would go a long way towards improving the types of questions that can be asked, and therefore, the impact of the answers from the analysis of the data. Identifying the right types of data and specific improvements to currently available data would make an excellent and immediately actionable thesis topic.

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