Naval Submarine Maintenance: An Examination of Areas of Potential Availability Execution Risk

by

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B.S. Civil Engineering, Worcester Polytechnic Institute, 2014

Submitted to the Department of Mechanical Engineering and the System Design & Management Program in partial fulfillment of the requirements for the degrees of

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Abstract

In the growing 'Great Power Competition' of the 21st century, the US Navy has faced near-peer competition that it has not experienced in several decades. This competition has ultimately resulted in increased operational strains on the submarine fleet which have in turn trickled down to affect the nuclear submarine maintenance enterprise. Despite the recognition of that strain, problems continue to persist that are yielding significant ramifications on overall submarine fleet readiness. The urgency to consistently complete maintenance availabilities on time in order to provide combatant commanders with the submarine assets they need, when they need them, has become a primary concern of the fleet.

The goal of this thesis is to explore potential areas of execution risk within the submarine maintenance enterprise. It is clear that the US Navy possesses a strong incentive to better understand ways in which submarine availability durations can be minimized and execution risk can be better managed throughout the lifecycle of an asset. In support of that incentive, this thesis first looks to examine the current state of the submarine maintenance enterprise, including an understanding of the initiatives currently being undertaken to improve performance. Second, the thesis looks to analyze additional ways in which more efficient submarine maintenance processes can be realized, through the lens of a flexible hose case study involving a comprehensive lifecycle analysis and service life evaluation. In doing so, the thesis investigates supply chain composition, as well as the history flexible hose employment and service life policy by way of extensive literature review and stakeholder analysis. Additionally, flexible hose replacement data is quantitatively analyzed to ascertain expected service life and understand the cost savings and benefits that may be achieved by extending flexible hose service life to achieve parity with non-nuclear surface ships.

The results of this thesis highlight the existence of a number of potential risk areas that can be extrapolated to the enterprise as a whole. Inadequate and incomplete maintenance data structures, sub-optimal maintenance scheduling policies, and lack of employment of innovative technology all threaten to exacerbate the ongoing issues exhibited by the enterprise. However, they also present an opportunity for the Navy to adopt new processes and improve the efficiency of submarine maintenance in the decades to come.

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Acronyms

3M Maintenance and Material Management

ACN Advance Change Notice

ASN(RD&A) Assistant Secretary of the Navy for Research Development & Acquisition

ASTM American Society for Testing and Materials

AWP Availability Work Package

BCG Boston Consulting Group

C2 Command & Control

CASREP Casualty Report

CBM Conditions Based Maintenance

CMP Class Maintenance Plan

CNO Chief of Naval Operations

CSMP Current Ship's Maintenance Project

CW Chill Water

CWP Cumbersome Work Practice

DBPM Driver-Based Performance Management

DFS Departure From Specification

DLA Defense Logisitics Agency

DoD Department of Defense

DSRA Docking Selected Restricted Availability

EAFW Electronic Auxiliary Fresh Water Cooling

FMA Fleet Maintenance Activities

FYDP Future Years Defense Program

GAO Government Accountability Office

GCC Group Component Code

IEM Inactive Equipment Maintenance

IMA Intermediate Maintenance Activities

IMP Intermediate Maintenance Periods

ISEA In-Service Engineering Activities

ISIC Immediate Superior in Command

JCN Job Control Number

LMA Last Maintenace Action

LOS Length of Service

M&SWP Maintenance & Ship Work Planning

MAC Maintenance Action Code

MIL-SPEC Military Specification

MPA Maintenance Planning Activities

MRC Maintenance Requirement Cards

NAVSEA Naval Sea Systems Command

NIIN National Item Identification Numbers

NNPI Naval Nuclear Propulsion Information

NNSY Norfolk Naval Shipyard

NSN National Stock Number

NSS-SY Naval Sustainment Systems - Shipyard

NSTM Naval Ships Technical Manual

NSWC Naval Surface Warfare Center

OEM Original Equipment Manufacturer

OFRP Optimized Fleet Response Plan

P2P Performance to Plan

P2P-SY Performance to Plan - Shipyard

PHNS Pearl Harbor Naval Shipyard

PMS Planned Maintenance System

PNSY Portsmouth Naval Shipyard

PPM Predictive Performance Models

PSA Post Shakedown Availability

PSNS Puget Sound Naval Shipyard

QPD Qualified Product Database

QPL Qualified Product List

RCM Reliability Centered Maintenance

SAE Society of Automotive Engineers

SBIR Small Business Innovation Research

SEA 05Z NAVSEA

SIOP Shipyard Infrastructure Optimization Program

SQL Structured Query Language

SUBMEPP Submarine Maintenance Engineering Planning and Procurement

SURFMEPP Surface Maintenance Engineering Planning Program

TBM Time Based Maintenance

TED-010 Technical Manual for Piping Devices and Flexible Hose Assemblies

TRL Technology Readiness Level

TYCOM Type Commander

VCNO Vice Chief of Naval Operations

WISP Work Integration and Scheduling Program

Chapter 1

Thesis Introduction

1.1 Motivations

In the growing 'Great Power Competition' of the 21^{st} century, the US Navy has faced near-peer competition from Russia and China that it has not experienced in several decades. This competition has ultimately resulted in increased operational strains on the fleet which have in turn trickled down to affect the nuclear submarine maintenance enterprise. The urgency to consistently complete maintenance availabilities on time in order to provide combatant commanders with the submarine assets they need, when they need them, is becoming more prevalent as the 21^{st} century progresses.

Nuclear submarines are one of the more, if not the most, important assets in the US Navy's arsenal of warships. These platforms are capable of extended and independent operations across a wide array of mission sets including Strategic Deterrence, Anti-Surface Warfare, Anti-Submarine Warfare and Intelligence, Surveillance, and Reconnaissance. Unfortunately, it is evident that Navy is struggling to keep pace with the need for operational submarines. Inasmuch, the maintenance delays affecting Naval nuclear submarines are no longer just matters of simple scheduling improvements or cost overruns, but that of national security as well.

Despite the recognition of strain on the maintenance enterprise, problems continue to persist that are yielding significant ramifications on overall submarine fleet readiness. Increased operational needs, personnel and supply chain shortages and poor maintenance planning processes have resulted in Naval submarines incurring over 10,000 days of idle time due to delays resulting from maintenance backlogs in the last decade alone [23]. This is not lost on the current Chief of Naval Operations (CNO), Admiral Michael Gilday, who expressed overall dismay at the current state of of the Naval maintenance enterprise in 2019:

> "We are getting 35 to 40 percent of our ships out of maintenance on time... That's unacceptable. I can't sustain the fleet I have with that kind of track record." [17]

Even more pressing, the current U.S. Navy attack submarine force inventory is at a decade low, sitting at only 47 operational SSNs today, a result of submarine decommissioning and new deliveries running behind schedule [13]. Couple this with the current maintenance challenges the submarine force is enduring, and a recipe for drastically diminished submarine fleet readiness ensues. In FY21 alone, an equivalent of 3.5 submarines were lost due to repair periods runner longer than planned [13].

All of the circumstances outlined above prompted the ideas for this thesis, as well as their timeliness and value. Further, the author's own experiences as a submarine officer in the maintenance enterprise, as well as his anticipated career trajectory in the submarine maintenance community, provided further motivation to pursue this topic. It is clear that the US Navy possesses a strong incentive to better understand ways in which submarine availability durations can be minimized and execution risk can be better managed throughout the lifecycle of an asset. In support of that incentive, the primary motivation for this thesis is two-fold: First, this thesis looks to examine the current state of the submarine maintenance enterprise holistically, including an understanding of the structures and processes that comprise its makeup, as well as the initiatives currently being undertaken to improve performance. Second, the thesis looks to analyze additional ways in which more efficient submarine maintenance processes can be realized, through the lens of a case study proposed by Submarine Maintenance Engineering Planning and Procurement (SUBMEPP).

1.2 Objectives

The Naval Sea Systems Command (NAVSEA) responsible for class maintenance planning, availability planning, record keeping, and material planning for submarines is SUBMEPP. In support of NAVSEA's Campaign Plan 3.0, SUBMEPP is looking to optimize maintenance and material planning strategies to reduce availability execution risk at the Navy's public shipyards. Specifically, SUBMEPP is interested in analyzing how they can improve the scheduling and execution of intermediate level preventative maintenance requirements, and how extending preventive maintenance requirements may impact availability execution, component reliability, as well as schedule and costs.

In concert with support from SUBMEPP, this thesis aims to conduct research and analysis on submarine flexible hoses (flexhoses). Flexhoses are used aboard US Navy ships for many applications, including piping for various fluids, such as freshwater, seawater, and lubrication oil. Recently, the Navy updated the critical flexhose replacement periodicity for all non-nuclear surface ships from 12 to 20 years. SUBMEPP is interested in understanding whether there is adequate information and data to demonstrate that critical flexible hose replacement periodicity aboard submarines can also be extended beyond the current 12-year requirement. As such, maintenance records pertaining to critical flexhoses provided by SUBMEPP will be analyzed to understand failure rates associated with these components. In addition, data-centric analyses and a lifecycle evaluation will be completed for these components to determine the benefits that an extension in periodicity would yield for the submarine maintenance community.

This effort will serve as an opportunity to demonstrate ways in which data analytics and innovative, flexible solutions can be implemented in the conduct of submarine maintenance availabilities to help drive process improvement and potentially reduce growing maintenance backlogs. In that endeavor, the primary objectives of this thesis are to:

1. Understand the current state of Naval nuclear submarine maintenance, to include current system structure, processes, and issues the maintenance community is currently facing.

2. Examine current submarine maintenance initiatives in order to gain a better understanding of where the goals of this study might support or align with the goals of the examined initiatives.

3. Aggregate large amounts of component-level, historical data to determine if sufficient evidence exists to make risk-based extensions to the periodicity for replacement of critical flexible hoses on board Naval nuclear submarines.

4. Perform a lifecycle evaluation of flexible hoses to understand potential performance improvements that can be realized as well as areas where flexible hose maintenance execution risk may be mitigated.

5. Examine general problem areas in intermediate level maintenance processes and determine what, if any, conclusions can be drawn with respect to innovative, technological solutions. Understand how these solutions could drive process improvements and potentially be adapted to other components and systems on board the submarine.

1.3 Scope

The scope of this thesis focuses on Naval nuclear submarine maintenance. While some data is referenced regarding aircraft carriers and/or non-nuclear surface ships, the results and insights obtained should only be considered relevant to the nuclear submarine maintenance enterprise. There are multiple reasons for this. First, the data and information examined is limited solely to the submarine maintenance community. Additionally, other similar studies have already been completed which focused specifically on non-nuclear and nuclear surface ship data, and the intent of the author was to avoid completing overlapping analyses. Also, the conditions, requirements, and processes imposed on submarine maintenance are different from other Naval communities, and in most cases more strict. As a result, it would be difficult to adapt findings across the Naval enterprise as a whole. Ultimately, no conclusions should be drawn for the non-nuclear surface ship and aircraft carrier maintenance enterprises as a result of this study.

The literature review section of the thesis examines nuclear submarine maintenance from a more holistic perspective, examining all levels of submarine maintenance, as well as Planned Maintenance System (PMS). Given the time constraints and limited access to data from private shipyards, only public maintenance activity data is examined. The thesis also draws upon the authors own experiences as a submarine officer at sea, as well as within a shipyard environment, and leverages the personal connections made during his career.

The case study section of the thesis is limited in scope to the execution of intermediate level submarine maintenance requirements, and more specifically, requirements pertaining to Navy synthetic rubber flexhoses as defined in the Technical Manual for Piping Devices and Flexible Hose Assemblies (TED-010). Data spanning across all public shipyards and Intermediate Maintenance Activities (IMA) was used for both the data-centric analysis and lifecycle evaluation. Additionally, relevant stakeholders in the flexhose domain were consulted to inform the study and help draw actionable insights.

This thesis was conducted in coordination with SUBMEPP and utilizes Naval Nuclear Propulsion Information (NNPI), which if discussed too specifically, would be sensitive to national security. As a result, some of the raw data pertinent to the analysis were omitted from the final document in order to permit its public release. This thesis is unclassified.

Chapter 2

Submarine Maintenance Background

The goal of this chapter is to provide relevant background information pertaining to the conduct of nuclear submarine maintenance. This will include an examination of the system structure (or levels) that comprise the submarine maintenance enterprise, the processes that dictate how submarine maintenance is accomplished, and a breakdown of the major issues that are currently plaguing the submarine maintenance community. A thoughtful literature review of this background information provides the context and insight necessary to proceed with a comprehensive case study within the nuclear submarine maintenance domain.

2.1 Overview of Submarine Maintenance

The submarine maintenance enterprise is a vast and complex system, involving thousands of personnel from dozens of organizations spanning the public and private sectors. The execution of submarine maintenance is a combined effort involving these organizations to plan, budget for, and complete required lifecycle maintenance. The Navy categorizes submarine (and surface ship) maintenance according to three levels:

organizational (O-Level), intermediate (I-Level) and depot (D-Level). These levels describe the scale and complexity of repair required, as well as the entities typically responsible for performing the maintenance actions. OPNAVINST 4700.7M, Maintenance Policy for Ships, provides official definitions for each of these levels, which are outlined below [33]:

- **Organizational-Level Maintenance**: "The lowest maintenance echelon. Organizational level maintenance consists of all maintenance actions within the capability and resources provided to the organization who routinely oversees equipment operation (e.g., ship's force). It is the first defense against allowing small defects to become major material problems, which could impact ship operations and mission capability."
  - O-Level work is performed by a submarine crew on a continuing basis, and some examples include lubricating equipment, cleaning filters, and inspecting electical cabinets [25].
- **Intermediate-Level Maintenance**: "Maintenance that requires a higher skill, capability, or capacity than organizational-level maintenance. Intermediate-level maintenance is normally accomplished by centralized repair facility personnel such as a Navy fleet maintenance activities, submarine refit and support facilities, RMCs, and battle group or other intermediate maintenance activities."
  - I-Level maintenance is work considered beyond the scope of what ship's force is capable of, and is instead accomplished by personnel assigned to an IMA. There are IMA's located at every major homeport for submarines. Examples of I-Level work include maintenance items that require specialized training and/or equipment, such as removing a rudder ram for inspection, ultrasonic testing, or replacing a flexhose [25].
- **Depot-Level Maintenance**: "The highest maintenance echelon. Depot-level

maintenance consists of maintenance tasks that focus on repair, fabrication, manufacture, assembly, overhaul, modification, refurbishment, rebuilding, test, analysis, design, upgrade, painting, assemblies, subassemblies, software, components, or end items that require specialized facilities, tooling, support equipment, personnel with higher technical skill, or processes beyond the scope of the IMA."

- D-Level maintenance is the highest level of submarine maintenance work, and is performed by personnel assigned to one of the nations four public, nuclear capable shipyards. It often requires a submarine to be in drydock, and examples include refueling the reactor, large hull cuts, and the overhaul of major valves. [25].

The emphasis of the case study conducted as part of this thesis work will be on I-level repair, as the components being studied (flexhoses) are required to be replaced by IMA's due to their inherent complexity. Now that an understanding of the system structure of the submarine maintenance enterprise has been established, the following section will briefly describe the processes employed by the Navy and submarine force for maintenance management.

2.2 Submarine Maintenance Management

A naval nuclear submarine requires extensive maintenance support throughout its lifecycle. Planning, executing, and evaluating maintenance of submarines is an arduous task that occurs on a number of different levels, and is often juxtaposed with balancing cost and risk associated with those actions. As a result, there are a number of strategies the Navy has employed over the years to determine when and how maintenance should occur. The major strategies and processes employed are discussed in further detail below.

2.2.1 Class Maintenance Planning

Each class of submarine possesses its own, unique Class Maintenance Plan (CMP) that is strategically managed throughout its lifecycle. The CMP is the principal document for executing the approved maintenance program for all ships in a class. It describes all planned maintenance actions at each level, directs when they occur, and outlines all maintenance support requirements, including material condition assessment requirements, approved modernization and shipyard routines. It may also include standard repairs based on commonly expected assessment results [33]. Lifecycle planning activities, such as SUBMEPP, are in charge of managing these CMPs and ensuring that all submarines implement them as written.

In general, all submarines go through various phases in their lifecycle (e.g. training, deployment and maintenance). The maintenance phase is split between I-level (pierside) and D-level (drydock) periods, which are referred to as "availabilities" for fast attack submarines, and "refits" for ballistic missile submarines. There are no specific time periods dedicated to O-level maintenance, as this type of maintenance occurs continuously thoughout the life of the ship. A typical submarine hull will last 40+ years, and so during its lifetime will undergo multiple availability or refit periods. Depending on the maintenance that is required and the temporal point in the submarine's lifecycle, different types of availabities may be necessary. These are outlined further in [33].

2.2.2 Planned Maintenance System

O-level maintenance is managed through the Navy's PMS as part of its Maintenance and Material Management (3M) program [27]. PMS stipulates all hourly, daily, weekly, monthly etc. maintenance that is required to be performed on board a submarine by the crew. The 3M system provides policy in support of the maintenance performed, with an objective to "maintain equipment within design specifications through preventive maintenance and to identify and correct potential problems before the equipment or system becomes inoperable" [27].

Preventative maintenance items are typically scheduled based upon factors such as service life and conditions based monitoring. Sailors aboard submarines are trained to maintain equipment in such a manner as to ensure the maximum amount of readiness and safety while conducting normal operations. However, for PMS that falls beyond the capability of ship's force, careful planning is required to ensure requisite I-level or D-level work is accomplished at the cadence required throughout the life of the submarine by the appropriate activities, during the appropriate refit or availability. Lastly, it's also important to note that PMS can occur in port or at sea, dependent upon the operational conditions required to perform the maintenance.

2.2.3 Reactive Maintenance

Reactive maintenance is performed for items that are expected to run to failure or those items that fail in an unplanned or unscheduled manner. Run to failure is often the planned maintenance strategy for items that have little readiness or safety impact [11]. As such, reactive maintenance usually costs less than other strategies because there is little need for additional maintenance actions prior to failure. That said, reactive maintenance is only preferred in low-cost, low-risk environments, since failure could occur at inconvenient times during an operational cycle and consequences of failure are not intended to be managed.

2.2.4 Proactive Maintenance

Proactive maintenance attempts to prevent failure by increasing safety and reliability on critical components. Condition based maintenance, scheduled discard (replacement) and scheduled restoration maintenance tasks are all examples of proactive tasks. These tasks are accomplished on a scheduled interval and intend to manage consequences of a failure occurring. This type of strategy requires an investment in technology, resources, data, personnel and knowledge-based capabilities in order to improve the reliability and maintenance effectiveness of components [11]. CMPs administer proactive requirements across all levels of maintenance.

Time-Based Maintenance

Time Based Maintenance (TBM) is the typical application of proactive maintenance, usually in the form of scheduled restoration (e.g. periodic cleaning, inspecting, lubricating of a component regardless of condition) or scheduled discard tasks (e.g. periodic, time-based replacement of component regardless of condition). These tasks are time-directed in order to mitigate likely periodicity failures for specific components. Most PMS items have time-based periodicities, including flexhoses [11]. Time-based periodicities are typically based on operating age, which is a measure of how long a system, asset, or component has been in service. Operating age can be measured in many units, such as calendar time, operating hours, miles, or cycles [11]. Advantages of this type of strategy include mitigating the risk associated with known failure of a system or component at specific operating intervals. However, a clear disadvantage is that unnecessary resources may be allocated to conduct TBM tasks prior to degraded performance or failure. This is especially relevant if a component has not been operating in accordance with its normal operational profile during the period of time quantified by the TBM task.

Condition Based Maintenance

Conditions Based Maintenance (CBM) comprises another subset of PMS requirements aboard nuclear submarines, however they are not employed nearly as frequently. In order to conduct CBM, the total and real-time health of a component is monitored according to a pre-determined routine to identify signs of impending failure. Numerous inspection techniques such as human senses, sophisticated monitoring equipment, or continuous monitoring by sensors applied directly to the equipment may be employed in the implementation of CBM. Examples include visual or non-destructive testing of pipe walls, vibration monitoring and analysis of pumps, taking oil samples, and measuring brake pads [11].

By conducting on-condition monitoring, engineers can identify when CBM tasks might be required based on evidence of need. This approach has some obvious advantages over time based maintenance, including preventing resources from being allocated to replace equipment prior to degraded performance or failure, which inherently leads to savings in the form of cost and man-hours [25]. Conversely, a submarine's schedule must permit enough flexibility to accommodate CBM tasks, since these tasks are not planned around lifecycle planning milestones (e.g. minor or major availabilities). For these reasons, O-level and I-level maintenance items are much more conducive to a CBM approach.

While CBM remains the Navy's primary approach to maintenance today, it prescribes what is known as Reliability Centered Maintenance (RCM) to determine what failure management strategies should be applied to ensure a system or component achieves the desired levels of safety, reliability, environmental soundness and optional readiness [11]. The Department of Defense (DoD) approved RCM process includes the identification of the following items in sequence for a given process: functions, functional failures, failure modes, failure effects, failure consequences, maintenance tasks and intervals, and other logical actions [11]. After the preceding RCM analysis has been accomplished, the resulting outputs can be implemented. Output forms include developing new maintenance tasks, redesigning hardware, modifying operating and maintenance processes and procedures, and incorporating results into long term maintenance plans [11]. In this way, RCM is able to utilize a systems engineering approach to ensure optimal failure management strategies. Additionally, by encompassing the application of RCM, CBM enables maintenance managers to attain desired levels of system and equipment readiness in the most cost-effective manner [11].

2.3 Recent Submarine Force Maintenance Issues

Over much of the last decade, the US Navy has continued to face persistent and substantial maintenance issues within its submarine community. Reports from national media about these issues have been rampant, and have highlighted the lack of readiness in the submarine force as a whole. This is important for a number of reasons. First and foremost, the US Navy's near 70 submarines comprise about one quarter of the total fleet for the US Navy. As with all naval ships, Navy doctrine dictates several periods of required maintenance over their lifetime in order to maintain adequate performance for the crew. As the maintenance periods of these immensely expensive submarines become delayed and overrun their intended completion dates (often times on the order of months, and sometimes years), they are left to sit idle pier side or in a dry dock, costing the Navy hundreds of millions of dollars in the process. In addition to the extreme costs associated with these delays, they also drastically affect the schedule and periodicity at which the Navy's fleet of submarines operate. In many cases, submarines have had their deployments shortened or cancelled entirely. As a result, operating submarines are forced to pick up the slack and fill the gaps in the cycle, often overburdening crews and leading to reduced morale and crew performance.

Before understanding what solutions might exist to combat submarine maintenance woes, it is imperative to understand the direct and indirect root causes behind them. The goal of this section is to gain a better understanding of the current maintenance issues that are plaguing the submarine community, and more importantly, why they are occurring. A comprehensive literature review follows, examining analyses from the Government Accountability Offices. The author will gather insight from these sources, as well as national media, in an attempt to establish a foundation for the current state of submarine maintenance, as well as identify possible points of intervention for potential solutions.

2.3.1 Literature Review

After conducting multiple studies over the last decade, the Government Accountability Office (GAO) found that the Navy has been hard pressed to begin or complete the majority of its submarine maintenance periods on time. In fact, data collected for the fiscal years ranging from 2008 to 2018 identified that attack submarines in particular totaled over 10,363 days of unplanned idle time resulting from delays getting into or out of the shipyard. Of those 10,363 days, more than 82% were attributed to delays in depot level maintenance [23]. In that same time period, the GAO estimated that the Navy spent more than $1.5 billion (FY2018) to support these attack submarines that provided no operational capability for the fleet. In general, it was found that "attack submarines maintenance delays are getting longer and idle time is increasing", an ominous reality for the submarine community [23].

The USS BOISE provided the most glaring example of these delays. She was scheduled to enter the shipyard in 2013 for an extended maintenance period to perform periodic hull examination and testing. This testing is required to conduct normal at sea operations and certify the boat to dive beneath the ocean surface. However, the Navy delayed the start of the maintenance due to more pressing workload issues and delays of dozens of submarine maintenance periods across all four of its public shipyards. In 2016, after waiting for more than three years to conduct her required hull inspection and maintenance, the BOISE lapsed on its dive certification and was decertified to conduct normal at-sea operations, and at that point tied to the pier. She then sat idle for an additional 3 years until 2019, nearly 6 years after she was originally scheduled to start the required maintenance [40].

Furthermore, NAVSEA data suggests that most shipyard maintenance is completed late. From 2015-2019, the Navy's four shipyards completed 75 percent of maintenance periods late for aircraft carriers and submarines, totaling 7,424 days of maintenance delays [20]. On average, submarines have experienced average maintenance delays of 225 days compared to only 113 days for aircraft carriers [20]. Shipyard officials attribute the difference in submarine delay magnitude to both the priority to which some submarines have maintenance performed, as well as factors relevant to the scale of the submarines and their crews [20]. For example, Navy guidance dictates that ballistic missile submarines receive the highest priority of resources available to perform maintenance while in a shipyard environment, followed by aircraft carriers, and then attack submarines. Also, given the compact nature of submarines, there is much less space available to conduct the aforementioned maintenance. As such, all maintenance must be highly organized and completed in lock step. Any disruptions in the process outlined can lead to significant delays in the maintenance period. Lastly, the size of the aircraft carrier crew relative to a submarine is far greater. The more crew a ship has, the more personnel who can contribute to work being performed during a maintenance period. At only about 150 crew per boat, submarines don't have the added flexibility as it pertains to man power. Most recently, in February 2020, the Navy projected that most submarine maintenance periods already in progress or those planning to begin maintenance prior to fiscal year 2021, would be completed later than initially intended [20].

Performance of Intermediate Maintenance Periods

I-level maintenance, or work conducted while a ship is pierside and still capable of getting underway within 96 hours, constitutes a significant amount of the maintenance performed on a submarine during its lifecycle. Specifically, the Navy schedules Intermediate Maintenance Periods (IMP)s for submarines every 3 to 5 months, with durations ranging anywhere from 21-35 days. In their 2022 report, the GAO noted that from 2015-2020, the submarine maintenance community completed 46% of its IMPs late, totaling 2,525 days of maintenance delay [37]. Additionally, it was noted that submarine IMPs averaged anywhere from 8-22 days late during the same time period. As part of their findings, the GAO identified four primary challenges affecting the performance of IMPs for submarines, which are outlined in the figure below:

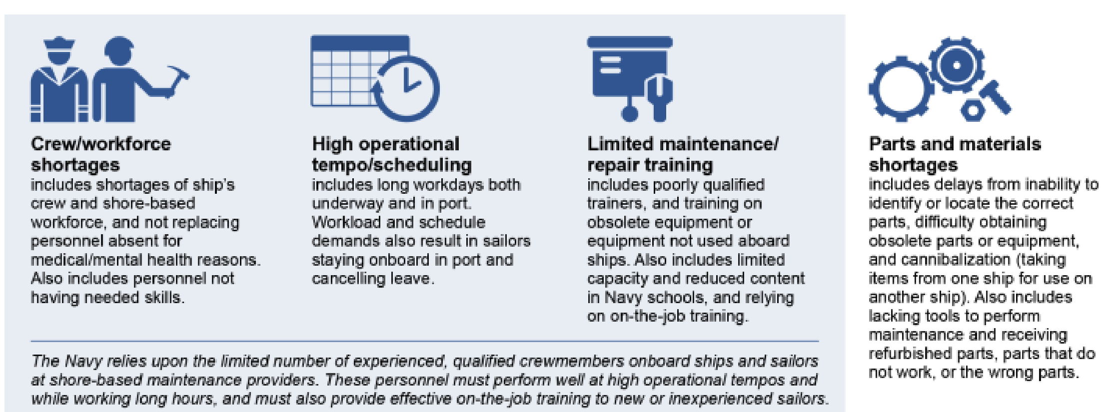

Figure 2-1: Challenges Affecting the Performance of Intermediate Maintenance Periods [37]

Further, the report went on to iterate that the Navy lacks complete and reliable data to adequately monitor IMPs. In most cases, the Navy collected only limited reliable or incomplete data for IMPs, and did not actually analyze it or derive any actionable insights from it [37]. For example, the Navy provided a spreadsheet to the GAO listing some causes for late completions of IMPs during some years, but not others. Additionally, many of the causes provided were vague and did not provide enough granularity to develop actionable insights.

It was clear from the research that there are a number of issues affecting the successful performance of I-level submarine maintenance, and that the Navy is still working on ways to mitigate the risk exposure it currently has in this domain. Addressing the challenges outlined above will certainly help better position the Navy to improve performance of its IMPs and increase overall availability of submarines assets for vital training and operations.

Performance of Depot Maintenance Periods

There were an abundance of issues identified throughout the literature review process as to why the Navy has experienced significant delays in D-level submarine maintenance. In general, the GAO has attempted to further segregate these issues into three distinct categories for analysis: Acquisition, Operations, and Maintenance [21]. In addition, it was noted that many of the systemic issues devolved within these categories are interrelated [21]. For example, providing ships to the fleet with defects leads to a faster decline in overall ship condition and material readiness. In turn, these declining conditions can lead to increased time spent in a maintenance environment, which can lead to changes in operational schedules for the fleet as whole in order to accommodate these extended maintenance availabilities. Ultimately, significant schedule and cost over runs develop and impose a ripple effect across the fleet. The figure below captures some of the major issues as seen from the lens of the GAO in each of the aforementioned categories. A summarization of the problems facing each category follows:

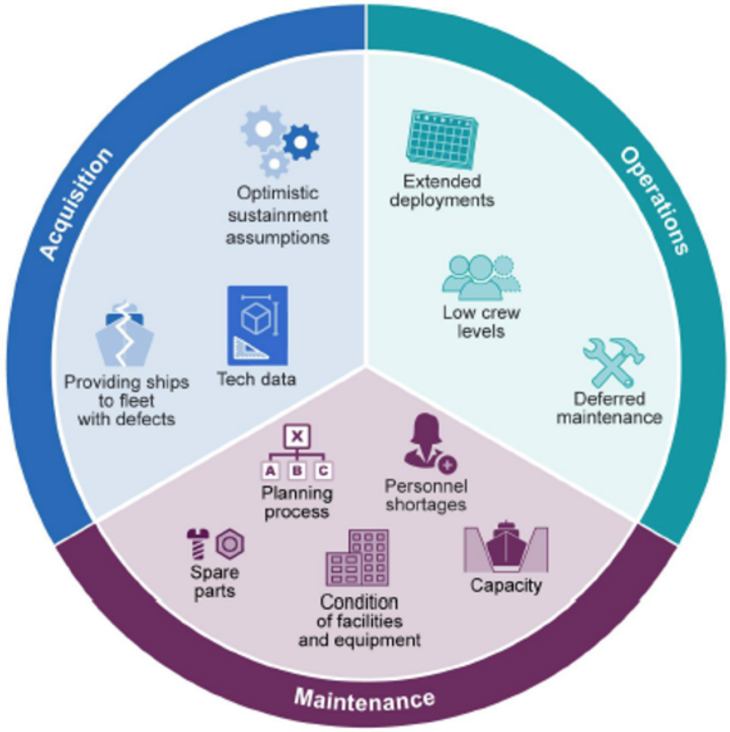

Figure 2-2: Issues Plaguing the Submarine Maintenance Community [21]

1. **Acquisition**

   (a) *Optimistic Sustainment Assumptions*: Long-term sustainment costs can be affected by decisions made early in the acquisitions process. In fact, it is estimated that nearly 80% of a program's operating and support costs are fixed once ship requirements are set and design begins [21]. As such, the decisions made during the acquisitions phase have far-reaching effects on the maintenance strategies used throughout the lifecycle of a submarine. If these decisions aren't carefully thought out, issues will inevitably arise down the road.

   (b) *Technical data*: The decision to either acquire or not acquire rights to technical data regarding a submarine component or system can have positive or negative implications on the Navy's ability to not only sustain associated systems, but also competitively procure parts or services for those systems.

(c) *Providing Submarines to the Fleet with Known Defects*: Providing submarines to the fleet with known defects not only reduces the ability of the submarine to conduct its mission set, but also increases the likelihood of extended maintenance availabilities and cost over runs in order to rectify the issue.

2. **Operations**

(a) *Low Crew Levels*: Crew levels aboard fast attack submarines have gradually decreased since the turn of century. The GAO reported that the decision to reduce crew sizes between 2003 and 2012 left crews overburdened and contributed to more minor organizational or intermediate level maintenance being deferred to depot level maintenance as the effects of the deferment compounded. As a result, the increases in maintenance costs associated with these deferments actually outweighed the savings achieved through the reduction of personnel [21].

(b) *Extended Deployments*: It is no surprise that extended deployments lead to more operational wear and tear on a submarine. The extended time at sea has lead to declining ship conditions across the fleet upon arrival to the shipyards, and has increased the amount of time the submarines have spent in any given maintenance availability [21]. Extended deployments also result in ships not arriving to their maintenance period on time, which can have downstream effects on other submarines maintenance schedules.

(c) *Deferred Maintenance*: As mentioned previously, maintenance that is deferred has the potential to increase in severity and develop into more costly issues that must be addressed at the depot level. This requires new work for the shipyard, as the degraded ship needs additional maintenance to achieve an acceptable level of readiness. Deferred maintenance often occurs as a result of required operational tempo or lack of personnel capacity to conduct the work.

3. **Maintenance**

(a) *Dry Dock Availability*: The effects of dry dock capacity on the operational tempo of the submarine fleet cannot be understated. Depot level maintenance requires the use of a dry dock. Across the Navy's four public shipyards, dry dock capacity has been continuously limited [23] and in 2019, a GAO study revealed that naval shipyards won't be able to support nearly a third of the maintenance periods that aircraft carriers and submarines will require through 2040 [21]. Any delay in an attack submarine maintenance period while in dry dock restricts the use of that dry dock for extended periods of time. These delays ultimately interfere with the future maintenance of other vessels, and restrict the ability of the shipyard to conduct necessary repairs to its facilities.

(b) *Maintenance Planning Process/Unplanned Work*: The Navy does not always adhere to its own planning process. Missing planning milestones can have a significant effect on maintenance delays. This is typically caused by the necessity for high operational tempo, scheduling difficulties and personnel shortages, among others [21]. Unfortunately, these issues usually lead to discovering unplanned work after maintenance has begun, and the necessity to modify the schedule with additional time added in due to contracting or waiting for parts. The GAO found that unplanned work contributed most significantly to the delays observed in submarine maintenance periods [20].

(c) *Personnel Shortages*: The GAO reports that the Navy has exhibited a variety of self-described workforce challenges at its public shipyards, including hiring personnel in a timely manner and providing skilled workers required for the maintenance involved with a nuclear-powered submarine [21]. In fact, a report from 2018 identified that nearly 30% of the Portsmouth Naval Shipyards "skilled workforce" had fewer than 5 years of experience

[21]. Lack of capacity, capability, prioritization, and inconsistent shipyard and contract performance inevitably contribute to the delays seen in submarine maintenance availabilities.

(d) *Condition of Facilities*: Poor condition of shipyards facilities and equipment plays a significant role in the ability for submarines to come through a maintenance availability on time. In general, the average condition of shipyard facilities is poor, and much of the equipment is past its expected service life [21]. These issues directly affect the depot's ability to conduct work, and can lead to increased delays and higher maintenance costs. Furthermore, the Navy does not currently track when facility problems lead to maintenance delays [21].

(e) *Spare Parts*: Supply chain and material issues for submarine parts are additional areas of major concern causing ripple effects across the submarine fleet. Many submarines are designed with "life-of-ship" parts or components. However, these life-of-ship parts are only lasting 25-50 percent of the life of the ship, and the shipyard and Navy are left scrambling trying to procure parts that are not in the supply system or have significant lead times. This leads to major backlogs in the supply chain and has serious effects on maintenance planning. In addition, this issue includes not being able to find the right spare parts or materials required for the job, lack of cannibalization opportunities from other boats, and lack of order history to warrant necessary inventory levels [20].

(f) *Information Technology Infrastructure*: Software without predictive capabilities, obsolete systems, lack of processing power, inability of systems to communicate with each other, and lack of technology in controlled areas comprise this maintenance factor [21]. All of the issues mentioned have both direct and indirect effects on the ability of a maintenance period to be completed in a timely manner.

2.4 Summary

The findings from the GAO reports that have been synthesized pose significant consequences if not addressed. While the Navy has taken steps to address some of these issues (discussed further in Chapter 3), it is evident that it risks negatively affecting submarine fleet readiness and operational availability even more than it already has if it doesn't find ways to consider the performance of maintenance availability periods in its strategic planning and related long-term initiatives.

Most importantly, without establishing and implementing formal procedures to collect and analyze meaningful data, the Navy does not have the ability to track and monitor the performance of its maintenance availability periods (both I-level and D-level alike). This inherently acts to limit the Navy's ability to provide effective oversight of maintenance for its submarines, as well as implement measures that may help improve performance of availability periods over the coming decade(s). The next chapter will examine some of the major initiatives currently taking place to address the issues facing the submarine maintenance community. It will also look to identify opportunities where the goals of study align with and perhaps support examined initiatives.

Chapter 3

Current Submarine Maintenance Initiatives

Before proceeding with a case study that supports the goals of this thesis, its imperative to first understand where this study fits into the landscape of submarine maintenance process improvement, holistically. The problems that were discussed in the previous chapter have spawned a slew of process improvement initiatives over the last decade, including the Optimized Fleet Response Plan (OFRP), the Shipyard Infrastructure Optimization Program (SIOP), Naval Sustainment Systems - Shipyard (NSS-SY) and Performance to Plan (P2P). The following chapter examines these initiatives in detail in order to gain a better understanding of where the goals of this study might support or align with the goals of the examined initiatives. In this manner, the basis and support for a case study regarding submarine maintenance process improvement can be derived.

3.1 Optimized Fleet Response Plan

With the turn of the 21st century, the US Navy has experienced an unprecedented demand by combatant commanders around the globe for its forces. This has resulted in an extremely high operational tempo for individual units and strike groups alike, and has been especially difficult on submarine forces [13]. The increased operational tempo has led to longer and more unpredictable deployment periods for sailors, and in parallel, has strained the industrial base that supports ship repair and maintenance for these assets [36]. As ship deployment periods have lengthened, declining ship conditions and material readiness have followed, and industrial bases have struggled to keep up with the resulting maintenance backlog. The ripple effects of these maintenance backlogs are significant. Ships are spending more time waiting to get into the shipyard in order to perform the required maintenance[1], while poor ship conditions have necessitated increases in the duration of time that ships are actually undergoing maintenance, which ultimately compresses the useful time available in the asset schedule to conduct training and operations [36]. To address these issues and changes in the evolving global landscape, Navy officials introduced and began implementing the OFRP in November of 2014.

The OFRP is described as an "optimized process to ensure continuous availability for manned, maintained, equipped, and trained Navy forces capable of surging forward on short notice while also maintaining long-term sustainability of the force" [34]. The overall goal of the OFRP is to maximize employability while preserving maintenance and modernization, and restoring operational and personal tempos to acceptable levels. At its onset, Navy officials touted the plan as a way to drive costs down by "increasing predictability" for the public shipyards that maintain nuclear submarines as well as better understanding of the potential impacts of schedule changes. They intended to achieve this by creating optimized schedules for each of their assets, including the different submarine classes, based on technical and engineering requirements [36]. In this way, lifecycle schedules could be developed that allowed sufficient time to accomplish needed maintenance tasks and ensure that platforms can reach their expected service lives.

[1]Between 2008 and 2018, attack submarines incurred 10,363 days of idle time and maintenance delays as a result of getting into and out of shipyards [20]

3.1.1 Basics of the OFRP

The OFRP can be considered an operational framework consisting of five phases: Maintenance, Basic, Integrated, Advanced and Sustainment. Per [34], it was designed to optimize the return on training and maintenance investments, maintain sailor quality of service, and ensure units and forces are certified in defined, progressive levels of employable and deployable capability. The start of an OFRP cycle coincides with the beginning of a maintenance phase, and ends with the beginning of the next maintenance phase. Additionally, the length of a cycle for a particular force element varies based on the strategic goals for that element and the pre-determined OFRP goals. However, no OFRP cycle is designed to last longer than 36 months. Furthermore, the integration of a building block approach within a given OFRP cycle is designed to assure increases in readiness through each phase in order to achieve a level of readiness commensurate with the capabilities required for deployment certification [34]. With respect to the maintenance and modernization of nuclear submarines, the OFRP is designed to promote cycle lengths that support maintenance and training, as well as create stable and predictable maintenance plans with accompanying modernization efforts that support warfighting integration and interoperability. Figure 3-1 below provides a visual description of each of the five phases of the OFRP:

3.1.2 Maintenance Phase Struggles

As explained in the previous section, the OFRP was initially developed as a way to maximize employability of the US Navy's assets in order to meet standing presence requirements and mission around the world. It was designed to achieve this through a system of tiered readiness (see figure 3-1). However, OFRP was also designed at a time when Navy assets, and submarines in particular, were deploying for lengths well beyond their intended periodicity [19]. The excess use over multiple decades contributed to rapidly deteriorating conditions and put wear on hulls that they were not designed to sustain. As a result, when these ships went in for maintenance, there were many more issues than were originally expected. To make matters worse,

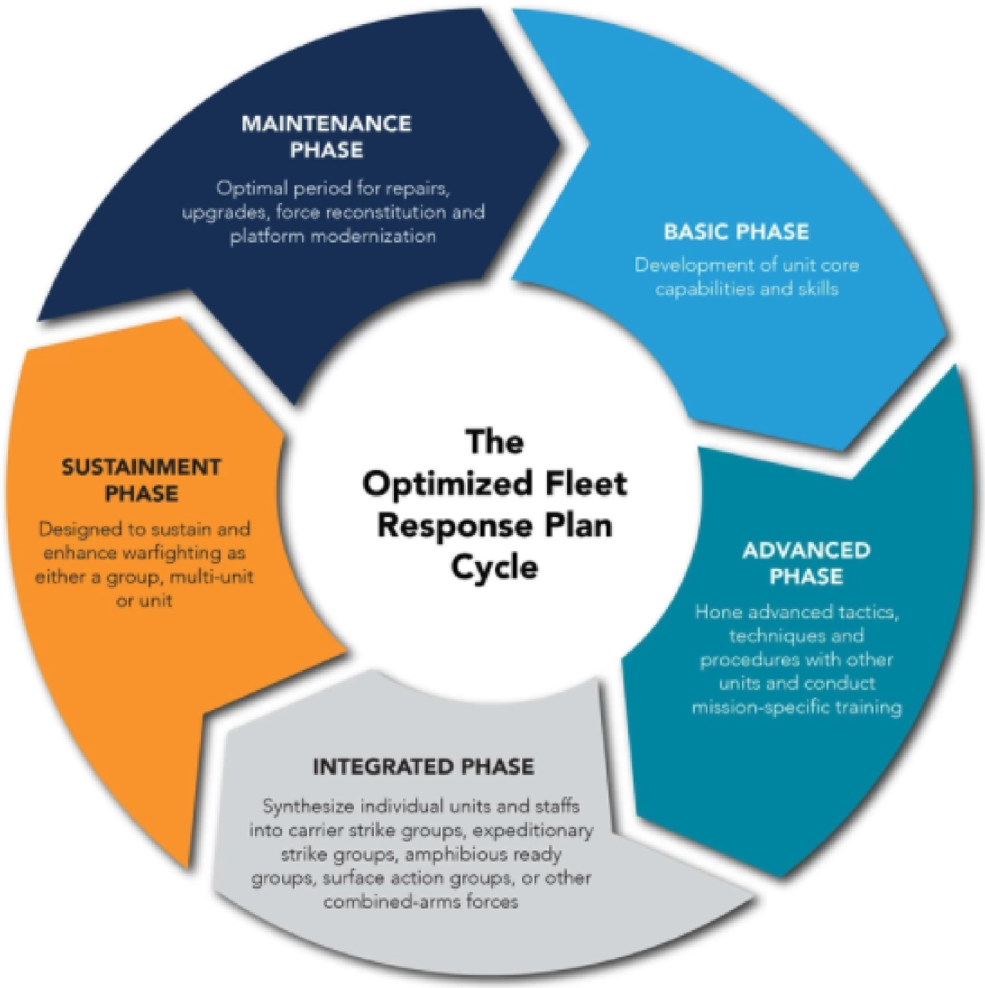

Figure 3-1: Phases of the OFRP [36]

defense funding cuts also diminished maintenance budgets [18]. This led to waves of retirements, work stoppages, and furloughs that hit the public shipyards that maintain nuclear submarines especially hard. Shipyards became understaffed, maintenance took longer to perform, and maintenance availabilities began to pile up. In fact, a GAO report from 2019 found that only 25 percent of all submarine maintenance periods from 2015-2019 were completed on time [23].

It is important to note that one of the key assumptions made by the Navy when developing the OFRP was that shipyards would complete maintenance on time [36].

If this assumption isn't realized, than the Navy is very much at risk of not achieving its employability and sustainability goals. A key aspect of this assumption includes being able to accurately define the requirements for an availability prior to the onset of the project. This has not happened, and shipyards have experienced anywhere from 17 to 34 percent in growth work during its submarine availabilities over the last 10 years [36]. In addition to compounding growth work, workforce inexperience, aging infrastructure and competing priorities between assets have all contributed to an overloaded maintenance phase that has undermined the Navy's OFRP since its inception in 2014.

The fact that the maintenance phase has consistently been a linchpin in the OFRP is not lost on senior Navy officials. However, some officials have argued that it's important to also acknowledge the key drivers contributing to a strained OFRP, and examine solutions to mitigate those drivers. Capt. David Wroe, U.S. Fleet Forces Command's deputy of fleet readiness, shared a similar sentiment in 2020:

> "OFRP provides the construct to best assess and optimize readiness production — down to a unit level — taking into account all the various competing factors to produce Navy readiness...Bottom line: OFRP helps mitigate fundamental points of friction, such as shipyard capacity and manning gaps at sea — but in itself doesn't solve key degraders like depot level maintenance delays and extensions" [18].

The GAO noted that Navy officials are well aware of the risks associated with the implementation of the OFRP and the challenges faced by public shipyards in completing nuclear submarine maintenance on time. To address these risks, Navy officials have worked continuously over the last decade to refine OFRP schedules and institute changes that mitigate the issues outlined above [36]. Ultimately, if the Navy can find ways to streamline modernization processes and get assets out of the shipyard on time, champions of OFRP believe it is the most viable option moving forward. At the Fleet Maintenance and Modernization symposium in 2020, Fleet Forces Command

Admiral Chris Grady expressed the importance of solving the maintenance problem as it pertains to OFRP:

> "My bottom line here is that, as a process, OFRP works. If we are looking where to improve upon it, each of these studies came to the same conclusion: the biggest inhibitor to fleet readiness is maintenance and modernization performance in the shipyards. We simply must get better." [18]

3.2 Shipyard Infrastructure Optimization Program

The Navy's submarine maintenance processes are not solely to blame for the observed maintenance delays and backlogs over the last decade. The Navy's four public shipyards - Norfolk Naval Shipyard (NNSY), Portsmouth Naval Shipyard (PNSY), Puget Sound Naval Shipyard (PSNS), Pearl Harbor Naval Shipyard (PHNS) - are all vital in the Navy's ongoing effort to maintain fleet readiness and supporting ongoing operations for nuclear powered submarines. Inasmuch, the condition these facilities are in, as well as the condition of the equipment that support operations at these facilities, directly effect shipyard throughput and the efficiency in which submarines can get back to normal, at-sea operations. After World War II, naval shipyards largely moved away from new construction and focused mainly on maintaining the fleet. As a result, less emphasis was put on sustaining these facilities and many closed as a result, leaving the Navy with the four public shipyards mentioned above [16]. The remaining public shipyards range in age from 109 to 250 years old, and were originally designed to build wind and steam powered ships [24]. Given their rapidly deteriorating conditions and outdated infrastructure, today's public shipyards are not efficiently equipped to repair today's modern nuclear-powered submarines [22].

In an effort to understand the performance of the nation's public shipyards, the GAO conducted multiple studies from 2017-2019 to examine the state of public shipyard facilities, capital equipment, and the Navy's capital investment plans to address growing shipyard challenges. Analysis of Navy shipyard data found that the overall physical conditions of the shipyards remain very poor. Most alarming, Navy data showed that the cost of backlogged restoration and maintenance projects at shipyards had grown by 41% over 5 years, totaling nearly $4.86 billion dollars, and that the average age of shipyard capital equipment now exceeds its useful life [24]. These issues have compounded over the last two decades, and are at least partly to blame for the growing backlog of submarine maintenance and the Navy's inability to meet submarine readiness goals. From the same GAO report, it was estimated that between fiscal years 2000 and 2016, inadequate facilities and equipment led to maintenance delays that contributed to more than 12,500 lost operational days for submarines (over 34 years) [24].

The Navy has acknowledged a history of under-investment in shipyard restoration and modernization needs[2], and in the last few years has taken steps to address the aforementioned concerns that continue to worsen. In 2018, a framework known as the SIOP was introduced as means to address critical deficiencies at the public shipyards and recapitalize infrastructure[3]

3.2.1 SIOP Overview

In 2018, NAVSEA presented a plan to congress in recognition of the fact that the four public shipyards need substantial recapitilization and reconfiguration in order to improve the timely return of submarines back to the fleet following maintenance and modernization. The SIOP was described as a "comprehensive, 20-year, $25-billion effort to modernize infrastructure" at the shipyards by addressing three major facets: dry docks ($8 billion), facilities ($14 billion), and capital equipment ($3 billion) (see figure 3-2) [8]. The program is a joint effort between NAVSEA, Naval Facilities Engineering Command (NAVFAC) and Commander, Navy Installations Command (CNIC).

[2] Department of the Navy, Report to Congress on Investment Plan for the Modernization of Naval Shipyards (April 2013)

[3] SECNAV Report to Congress 12 Feb 2018, "The Shipyard the Nation Needs"

Implementing the SIOP will be a complex process conducted over many years in order to redesign workflows and build in enough capacity to meet the future needs of the Navy's submarine force projections. The SIOP is intended to be conducted in three phases [8], as outlined below:

1. **Phase I:** Consisted of an architectural and engineering study that identified courses of action for shipyard infrastructure configuration and modernization to support current and future maintenance processes and methods. The overall objective of this phase was to develop a virtual, unconstrained optimization of the nations public shipyards in order to improve process flow and production efficiencies. The first phase was submitted to Congress in February 2018.

2. **Phase II:** This phase will culminate in final optimized infrastructure plans (including area development plans (ADP)) for each shipyard and will incorporate dry dock capital equipment investment plans. Simulation and modeling will be utilized to conduct detailed industrial engineering analysis in order to develop optimized processes that ensure execution of each shipyards workload and performance requirements. The second phase is already in progress and was scheduled to be complete by the end of FY 20.

3. **Phase III:** The final phase will look to prioritize, develop and execute individual projects identified during phase II, and will modernize public shipyard capital equipment to include use of new technologies that are more adaptable and flexible. The goal is to improve shipyard efficiency, reduce costs, and meet future capabilities to support on-time delivery of ships and submarines back to the fleet. Phase three is not expected to be completed until 2035-2040.

3.2.2 Issues with Implementing the SIOP

Although still in its nascent stages, the SIOP is believed to be years behind schedule [15]. For example, the digital models of the public shipyards that were expected to be completed in phase II by the end of FY 20 have yet to materialize. At the end of

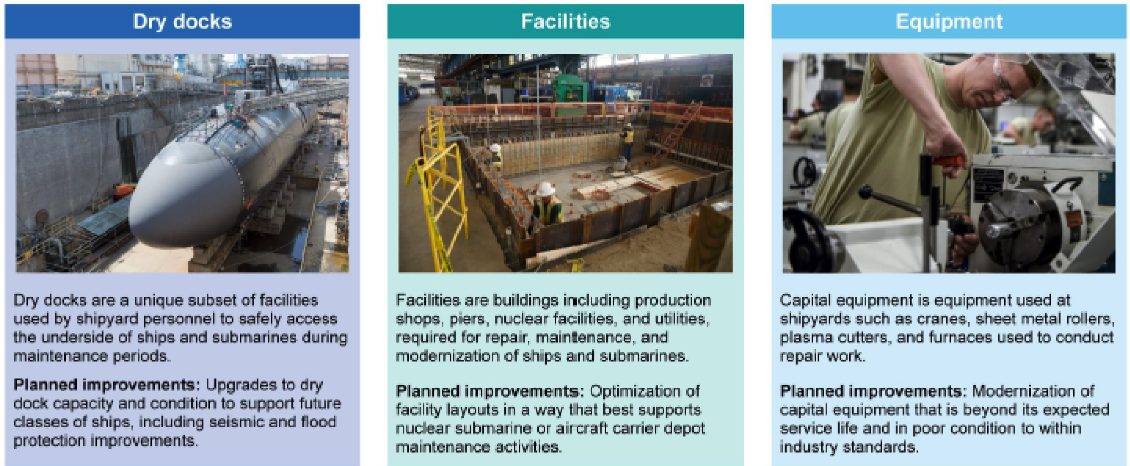

Figure 3-2: Major Areas for Improvement Identified in SIOP [22]

2020, only the PHNS model had been completed. All others are still being generated, despite the Navy's assurance that the "digital twins" would be up and running by the beginning of FY 22 [15]. These models are vital to the foundation of SIOP, as they will inform all the projects that are pursued in phase III.

Furthermore, a GAO report from 2019 highlighted multiple areas in which the Navy fell short in developing its SIOP. First and foremost, the plan failed to utilize best practices in generating its initial cost estimate of $25 billion, including document key assumptions, account for inflation, and address risks that together could add billions to the ultimate cost of the SIOP [22]. This has resulted in requesting inadequate resources from congress to address mounting shipyard deficiencies. Furthermore, when the SIOP was first proposed, the Navy created a program office (PMS 555) to oversee all program management operations. This program office includes representatives from NAVSEA, NAVFAC and CNIC. However, the Navy failed to adequately define the role of shipyard officials in the implementation of SIOP. This has created concerns and confusions among shipyard officials, and led to inefficient and sometimes duplicative efforts in enacting implementation activities [22]. Even minor delays resulting from these overlaps in effort could have substantial effects on submarine maintenance availabilities and lead to additional critical submarine maintenance being deferred.

The ramifications resulting from the issues discussed previously are not insignificant and should be noted. For example, anticipated workload for PNSY beyond 2021 creates a significant challenge as it exceeds available dry dock capacity. It is expected that Dry Dock 1 at PNSY will lose capability to support Los Angeles-class submarines by the end of 2021. The anticipated workload for Virginia-class submarines is expected to exceed PNSY's capacity beginning in 2025 [8]. The delays incurred by the poor planning and implementation of the SIOP further exacerbate the operational strain at PNSY and the other public shipyards. Couple these delays with unexpected work generated for the shipyards stemming from incidents such as the collision by USS CONNECTICUT[4], and what results is an overburdened shipyard ecosystem that struggles to meet submarine readiness goals.

3.3 Naval Sustainment Systems - Shipyard

NSS-SY is a recently developed business and process improvement initiative that aims to solve the Navy's highly complex problem of delivering aircraft carriers and submarines back to the fleet on time, all the time. This effort spans across all four public shipyards, and focuses on optimizing public shipyard maintenance operations all the way down to the deck plate level. Where the SIOP focuses on physical upgrades to the nation's public shipyards, NSS-SY intends to focus on the necessary procedural and operational updates for ships that are undergoing maintenance availabilities in order to maximize overall workforce productivity [6]. Overall, the initiative aims to improve shipyard performance by increasing throughput, reducing ship maintenance costs, and shortening durations for ship maintenance availabilities in order to increase operational availability and deliver readiness to Fleet combatant commanders, with a North star of every availability on-time by 2023 and a 27% maintenance duration reduction by 2026 to meet fleet needs [28].

NSS-SY is a joint collaboration between Navy leaders, shipyard experts and commer-

[4]The USS Connecticut collided with a sea mount on October 2nd, 2021 and is currently awaiting repairs from a submarine tender [14]

cial business process consultants at Boston Consulting Group (BCG), and is modeled after the successful efforts of NSS-Aviation[5]. The Navy's goal is to integrate leading private industry and government best practices with robust requirements tied to the planning and execution of submarine maintenance availabilities [30]. Inasmuch, NSS-SY's overarching goals are to ensure the maintenance and production workforce have access to the tools, equipment, material and information that is needed in order to execute maintenance in the most efficient manner possible, while also eliminating or mitigating barriers that might delay the on-time delivery of submarine assets back to the fleet [30].

Implementing the ecosystems developed as a result of NSS-SY will also require effective alignment and leveraging of other public shipyard change management efforts, including OFRP, SIOP, and Performance to Plan - Shipyard (P2P-SY). Understanding how these efforts can work in concert and compliment each other simultaneously is key to achieving a transformation structure that is both feasible and scalable across the submarine maintenance enterprise.

The following sections review the high level phases and tasks associated with the NSS-SY effort, as well as some initial results stemming from these efforts.

3.3.1 NSS-SY Scope

The shipyard assessments being conducted by BCG as part of the NSS-SY initiative focus on uncovering and designing solutions in five major functional areas. These functional areas were identified by Navy leadership as the key drivers for delays in maintenance availabilities across all four public shipyards [28]:

1. **Waterfront and Inside Shop Production:** Involves the assessment of major performance drivers, and potential solutions for delay, work stoppage, and rework at the deck plate worker level.

[5]NSS-Aviation is a collaborative effort between BCG and the Navy's Fleet Readiness Center to achieve more mission capable F/A-18 E/F Super Hornets and EA-18G Growlers in the aviation depot [6]

2. **Planning, Scheduling and Resourcing:** Involves the assessment of adequacy of planning, schedule development, and maintenance and resource management.

3. **Material Management and Supply Support:** Involves the assessment of current material management organization, process and performance.

4. **Engineering and Technical:** Involves the assessment of engineering organization processes and their technical response time to reduce delays or increase reliability.

5. **Execution Project Management:** Involves the assessment of existing project management structure, execution priority management, and processes to reduce delays.

The NSS-SY effort is considered an "enterprise-wide" transformation. As such, it will require a three-phase implementation approach, along with corresponding tasks for each phase to ensure adequate vertical integration across public shipyards. Phase I will consist of designing, implementing, and scaling a productivity and scheduling transformation system across the public shipyards. Phase II will build upon phase I and further include schedule and resource optimization tactics. Lastly, phase III will identify, implement, and scale system-level transformation innovations and resolutions to systemic issues [28]. The tasks that support these phases of improvement are outlined below:

1. *Task 1 (Phase 1):* Design and implementation of a productivity and scheduling transformation system across public shipyards, NAVSEA and support activities.

2. *Task 2 (Phase 1):* Scaling of the productivity and transformation system across the public shipyards.

3. *Task 3 (Phase 2):* Design and implementation of a planning system that includes schedule and resource optimization.

4. *Task 4 (Phase 2):* Scaling of the planning system from task 3 and transition to complete government driven execution of the transformation system.

5. *Task 5 (Phase 3):* Identify and implement system level transformation innovations and resolutions to systemic issues. Continue transition of complete government driven execution of planning system.

6. *Task 6 (Phase 3):* Assess the productivity and schedule transformation system and the planning system.

7. *Task 7 (Phase 3):* Implement recommendations for each system discussed above and complete transition of the NSS-SY transformation system to government led execution.

Currently ongoing, task 1 is arguably the most important task in the NSS-SY effort, as it will set up the core transformational governance structure that will be implemented and monitored and eventually drive lasting change across all public shipyards. In that task effort, BCG and Navy leaders are looking to understand how best to utilize advanced analytics to identify and prioritize submarine maintenance process improvements. This is a key theme of this thesis that will be explored further in chapter 4.

A complete timeline of the phased approach can be seen in figure 3-3. As discussed previously, one of the primary objectives of the NSS-SY is to improve both shop and project performance. In the pursuit of that objective, NSS-SY aims to execute shop-level performance improvement across all production shops that achieve a minimum double turn-around time and increase machine utilization rate by at least 90%. Additionally, it aims to achieve an 80% reduction in maintenance delays by the end of task 2, and 100% reduction in maintenance delays by the end of task 4 [28]. Lastly, understanding the return on investment (ROI) for these tasks, as well as achieved and projected savings is integral to the NSS-SY's ultimate adoption and scalability.

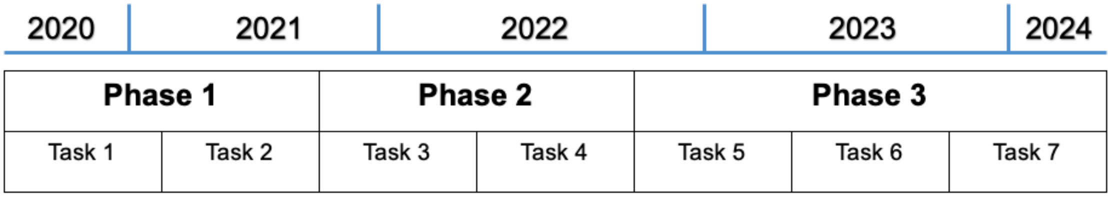

Figure 3-3: NSS-SY Phased Approach Timeline [28]

3.3.2 NSS-SY Initial Results

As mentioned previously, the NSS-SY initiative was established in late 2020, and initial pilot projects began being tested at the onset of 2021. Each of the four public shipyards identified an on-going submarine availability to use as a test platform for various process improvements identified by NSS-SY in real time [30]. The pilot projects were not chosen at random, and were designed to build consistency across the four shipyards, capture any measure of performance improvement, and understand areas where proposed initiatives might not be working [5]. The four pilot projects chosen were the USS MISSISSIPPI at PHNS, USS LOUISIANA at PSNS, USS VIRGINIA at PNSY, and the USS PASADENA at NNSY [30]. A synopsis of the initial findings from each pilot project follows:

- **USS MISSISSIPPI:** The production team was able to avoid more than 100 days of potential delay using NSS-SY's new escalation and resolution format, a concept used to rapidly resolve obstacles with off-yard decision makers. The idea behind this format is to drive new behaviors by Navy leadership, including focusing on the most important issues first and removing barriers that would inhibit the on-time completion of work items [30].

- **USS LOUISIANA:** Attempted to capture lessons learned from previous availabilities and increase testing certifications in order to streamline current and future work through a new NSS-SY effort called a "sprint". Resulted in record test performance rates compared to all previous SSBN CNO availabilities [30].

- **USS VIRGINIA:** The maintenance team piloted tools and process changes to increase the visibility of production barriers and provide simplified tracking of issues that were driving maintenance delays. New daily and weekly production meeting structures were utilized to align priorities, support teams and connect leadership in and out of the shipyard that were shown to improve material readiness and yield a positive impact on the efficiency of the availability [30].

- **USS PASADENA:** Similar to USS VIRGINIA, the project team implemented a new daily production meeting structure spearheaded by NSS-SY that focuses on driving solutions and rapid identification and resolution of issues that drive delays in the availability. Aiding in this effort are new Zone Manager goal trackers that set daily and weekly goals and track progress continuously in order to identify any issues before they have larger ramifications [30].

NAVSEA Commander, Vice Admiral Bill Galinis, recently remarked that NSS-SY is a critical component in the Public Shipyard Improvement Plan, and that the keys to success for the initiative rely only on a few primary ingredients: A sense of urgency, a willingness to challenge established modes of thinking, and ensuring quick and visible change where possible in matters of maintenance [5]. His overall goal for NSS-SY is to provide opportunities for waterfront teams to be more effective and efficient in their day-to-day operations, and create process improvements that are transferable across all four public shipyards so that all may benefit. Availability turnaround efforts, inside shop transformations, engineering tracking and reporting, and material tracking reform will lay the groundwork for the larger transformational effort, and serve as the driving tenets for NSS-SY [28]. This thesis looks to support the "engineering tracking and reporting" tenet directly, and the "availability turnaround efforts" tenet indirectly.

3.4 Performance to Plan

During the fall of 2018, the Navy began an initiative to improve the readiness of its surface ship, aviation and submarine assets, called P2P. The initiative designated NAVSEA to improve performance of submarine maintenance, among others, in private and public shipyards [23]. At its core, P2P includes the proposed development of analytically based metrics to measure various aspects of shipyard maintenance that could eventually support the development of potential solutions that would address any issues found in the process. In this way, NAVSEA and shipyard leadership can better understand factors that contribute to maintenance delays and make more informed decisions to address them. The following sections review the background, key principles and major outputs of P2P, as well as current efforts related to P2P-Shipyards and submarine maintenance.

3.4.1 P2P Background

In the face of the growing great power competition at the rise of the 21st century, the Navy began to pour tremendous amounts of resources into improving mission performance and fleet readiness. However, increased resources and funding was seldom translating to better performance, as exhibited by the Naval Aviation Enterprise[6]. The Navy's fleet of ships, including its submarines, were experiencing similar issues over the past decade leading up to the fall of 2018. As discussed in previous sections, maintenance was taking much longer to complete than expected, and backlogged work leading to budgetary shortfalls occurred much more frequently. This led to senior Navy officials searching for new and improved ways to do business in the maintenance community.

In 2018, senior Navy leadership engaged with executives from fortune 500 companies

[6]Starting in 2005, the Navy began to bolster its inventory of F/A-18 aircraft, however the number of mission capable aircraft remained stagnant, and a large number of the Navy's fleet of aircraft remained idle in hangers waiting for maintenance to be completed. In 2018, the Secretary of Defense directed a a full review and rectification of the ongoing issue and a minimum of 80% mission capable rate by the end of FY 2019.

to understand best practices currently being utilized in the private sector, and what opportunities existed for the Navy to apply those practices in the areas of concern mentioned above. From these conversations, P2P was established [26]. The intent of P2P is to leverage industry proven "driver-based performance management" and advanced analytics to help bring transparency, accountability, accelerated learning and data-driven decision making to the Navy [26]. P2P created a new school of thought for the Navy when it came to driving process improvement: directed focus on high-leverage performance improvement opportunities that directly impact mission performance outcomes. To do this, the Navy desires to create a culture that balances institutional experience with data. The overall goal of P2P is to use data, analytics and leadership insights to characterize performance gaps, identify barriers and develop solutions that provide real and measureable results.

Navy leadership believes that through the use of actionable data, real process improvement can occur. Early P2P pilot efforts in the Naval Aviation Enterprise and the Surface Ship Enterprise served as proof of concept for those beliefs, and displayed how data-informed decision making can transform understanding and yield tangible results [26]. These early efforts also helped the Navy recognize the value of the P2P program, and the need to continue to scale the program to all levels of the fleet, including the submarine maintenance community. Presently, there are eleven P2P efforts ongoing across the US Navy.

3.4.2 P2P Core Tenets and Principles

The P2P approach intends to focus senior leadership's attention on a prioritized set of metrics that matter, rather than the myriad of metrics that don't necessarily reflect the real performance level or health of the organization. The metrics should closely align to strategic objectives, and leverage data analytics to understand cause-and-effect relationships between the different metrics and provide actionable insights for leaders to act upon [26]. More specifically, P2P is designed intentionally to shift focus to outcomes rather than activities, and making decisions based on output metrics (e.g. throughput, operational availability), rather than input metrics (e.g. dollars, labor).

The overall approach for P2P is founded upon four core tenets that characterize the organizational and cultural changes that define the Navy's performance objectives [26]:

- **Transparency** – Improve leadership understanding of key information, "embrace the red" to solve key issues through teaming
- **Accountability**– Empower a single individual who is accountable and responsible for achieving clearly defined strategic outcomes and elevating performance barriers to a senior-level forum
- **Accelerated Learning** – Learn from predictive models and levers to close performance gaps, and drive this knowledge across the Navy to create continuous performance improvement
- **Data-Driven Decisions** – Base decisions on a balance of data and experience versus intuition, with timely, accurate, and credible information available to decision-makers

In addition to these tenets, P2P leverages three key principles to develop data-driven performance plans. These principles are integral to effective implementation of P2P efforts across various the various domains of the fleet, and are explained in further detail below [26].

1. **Command & Control (C2) Alignment**. This helps drive clarity about what leader is ultimately accountable for measured performance outcomes, and then helps support this leader with appropriate resources. Supported Commanders are accountable for executing performance plans that improve key strategic outcomes. Supporting Commanders, whose success is measured by improvements in the Supported Commander's metrics, are integral in determining what re-

sources are needed to aid the Supported Commander.

2. **Driver-Based Performance Management (DBPM) & Predictive Performance Models (PPM)**. DBPM is a structured approach that focuses on identifying the outcomes an organization wants, and the "drivers" that have a quantifiable, cause-and-effect impact on those outcomes. In this manner, organizations can develop a structured model of performance, or a "Driver Tree", that focuses leaderships attention on metrics that matter. Once the outcome metrics (Tier 1) are identified, the driver tree's cascading structure allows for further breakdown of key "driver" metrics (Tier 2, 3, 4). Of note, an outcome metric can have multiple driver metrics. The figure below provides an example of what an initial driver tree output might look like.

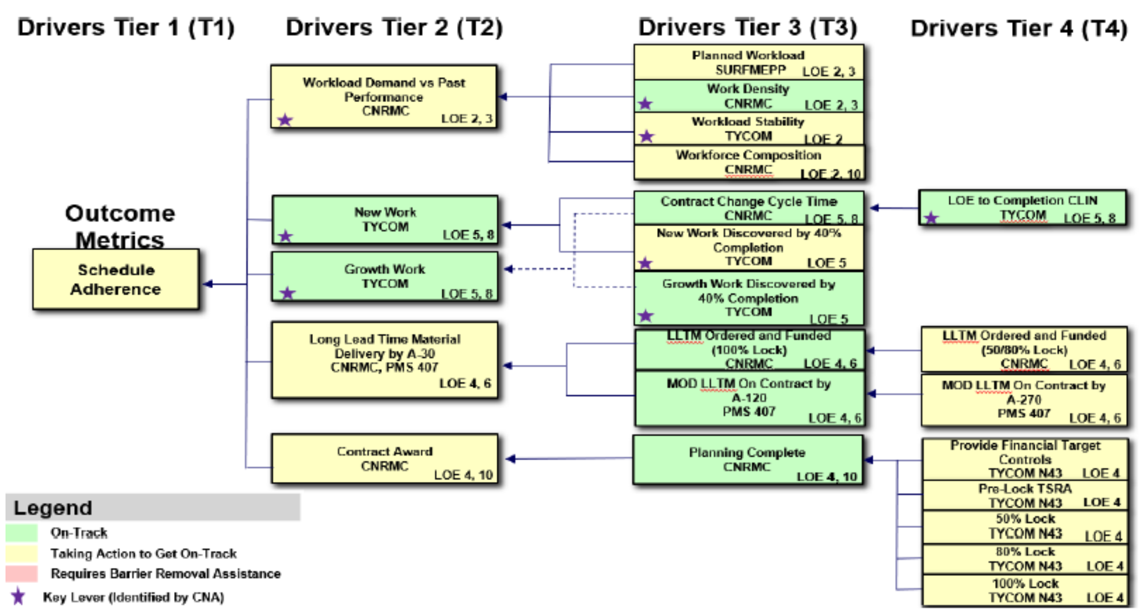

Figure 3-4: Example of a Driver Tree - Surface Warfare Enterprise [26]

PPM utilizes historical data to develop a forecast of future performance based on existing process capabilities. Data scientists from the Center for Naval Analyses use the historical data for each driver tree outcome/driver metric to develop a predictive model that can forecast future performance. The analytics model that is developed can offer prescriptive insight, by identifying the highest leverage drivers to swarm. Inasmuch, performance "levers" are indicated that can be pulled to adjust driver performance and achieve targeted outcomes. PPM is an iterative process that evolves over time, which allows for continued incorporation of new, lower-tier drivers and the identification of new, high-impact drivers. Together, DBPM and PPM integrate leading indicators of performance to identify the highest leverage drivers and predict Tier 1 outcome performance improvement that accrues from Tier 2/3 driver improvement.

3. **Barrier Removal Leadership Forum**. These are forums where P2P leaders present their forward-looking, data-driven performance forecast. Through the use of a standardized format and templated briefs, leaders are able to focus on key performance drivers and leadership actions required for a strategic area of concern. Furthermore, barriers that may be constraining or suppressing performance drivers are discussed, and also swarmed if data indicates high leverage opportunities to improve. These forums should be convened regularly, at a minimum on a quarterly basis.

It is important to also understand that P2P is only intended to show where the problems are in an organization, not tell the organization how to fix them. Organizational leaders are responsible for pulling "levers", or actions that can be taken to positively affect drivers. In some cases, leadership intervention may be required to pull levers, which is where Barrier Removal Forums become important.

3.4.3 P2P Outputs

P2P efforts are designed to lead to 3 key outputs to help leadership make informed decisions: Driver Trees, Data Dictionary's, and Metric Graphs and Scorecards [26].

As discussed in previous sections, the driver tree is a schematic that's intended to summarize the scope of a P2P initiative, as well as the associated outcome metrics and drivers. Drivers are arranged in a hierarchical manner to help highlight cause-and-effect relationships. It's understood that driver trees may change over time as organizational learning takes place, but significant changes should be discussed and agreed upon at the barrier removal forums [26].

The data dictionary serves as a catalog of the supporting data for all the drivers listed in a driver tree. For each driver, the data dictionary will capture information such as the associated tier, metric name, definition, data owner, data source, data status, the path forward, and any correlation to other drivers. The data dictionary should be comprehensive, and continuously updated as driver trees evolve [26].

The P2P metric graphs and scorecards (shown in figure 3-5), help provide a snapshot of performance for all outcome metrics and drivers. The score card will capture a variety of information, including:

- **Metric name**: The agreed upon nomenclature for the metric.

- **Value Delta**: The difference between the value at the last Forum and the current value

- **Historical Best**: The historical best observed value (i.e, historically, the recorded "best" the metric has ever performed—can be high or low depending on the driver tree strategic objective)

- **Baseline**: The value at the first Forum.

- **Prior P2P Forum**: The value at the previous Forum.

- **Plan for Current Quarter**: The previously projected value at current quarter-end.

- **Forecast for Next Quarter**: The projected value at the next Forum.

- **Goal**: The target or optimal value.

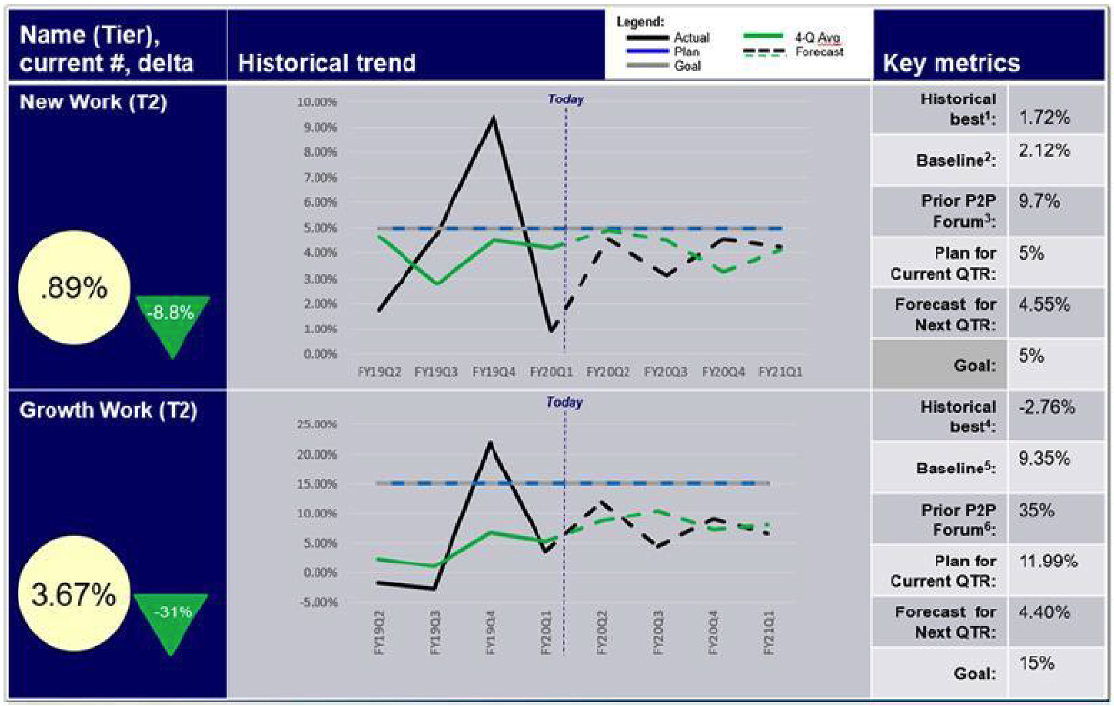

Figure 3-5: Metric Score Card Example [26]

By highlighting a preponderance of data in these scorecards, and reviewing them on a frequent basis, a more robust trend analysis can occur. Additionally, as these scorecards cascade to lower levels of the organization, specific metrics and drivers can be targeted and actionable insights result.

3.4.4 P2P - Shipyards

At the onset of the P2P effort, Navy senior leadership developed a governance approach, referred to as Echelon I, reserved for efforts that are most critical and significant to the US Navy. Echelon I efforts work in concert with dedicated resources, such as Process and Analytics teams who assist in applying DBPM and PPM methodologies, and are required to hold quarterly forums co-led by the Vice Chief of Naval Operations (VCNO) and the Assistant Secretary of the Navy for Research Development & Acquisition (ASN(RD&A)). There are currently 7 Echelon I strategic focus areas spanning a number of domains across the Navy fleet, including shipyards. Specifically, the shipyard effort focuses on public shipyard capacity and throughput for maintenance availabilities, and what can be done to help reduce the durations of those availabities [26]. In order to help define the scope and understand the underlying issues that comprise the focus of the shipyards effort, as well as make recommendations to improve processes, NAVSEA hired Boston Consulting Group (BCG) and developed a joint effort with them leveraging P2P initiatives, known as NSS-SY.

Integrated with BCG and NSS-SY, the P2P-Shipyards team utilizes data and develops and employs algorithms and models that can help reduce the amount of delays observed in the submarine maintenance community. As a "North Star", they want to achieve all availabilities on time completion by 2023, and reduce the total duration of availabilities from current values as much as 36% by 2026 [28]. This helps ensure that the fleet has enough boats and ships to meet the OFRP, submarine response plan and other fleet tasking. It also ensures that we will not have to send another submarine to a private shipyard in order to conduct its maintenance availability. This is important because private shipyards have proven that they struggle to complete submarine maintenance availabilities, and typically lack the skill and knowledge required to complete them efficiently.

Given these goals, the outcome metric senior leadership is focusing on is the number of days late for a scheduled availability. By interrogating forecasting and planning efforts, as well as execution efficiency for planned schedules, the team can begin to identify what the most impactful driver metrics are that lead to increased days late. Once those metrics are identified, BCG and NSS-SY work with the P2P team to perform root cause analysis and develop countermeasures to help alleviate those issues and ultimately help reduce the number of days an availability is late.

In August of 2020, the GAO released a report regarding shipyard P2P efforts. The report highlighted some glaring issues with the program, including the lack of developed metrics that could improve the understanding of the causes of maintenance delays, as well as actionable goals, milestones and monitoring processes associated with those developed metrics to address weaknesses [23]. NAVSEA also recognized that their transformation efforts were not generating results fast enough, and in the summer of 2021, proposed a restructuring of the P2P shipyard effort that leveraged additional Navy and institutional expertise. This restructuring included the formation of guiding pillars, with flag level officers (supporting commanders) assigned to each as oversight and in charge of delivering results for each of their respective pillars. The different pillars comprising the shipyard strategic focus area are defined below:

- *Engineering* - "Engineer out" mandays from Availability Work Package and develop methods and standards to improve predictability.
- *Planning* - Decrease unplanned work starting with planning milestones and inline to rotatables.
- *Materials* - Increase material availability to enable nonstop execution starting with end-to-end supply chain visibility.
- *Inside Shops* - Accelerate turnaround time for shop components through work center transformations.
- *Waterfront* - Improve on time starts, throughput, and production performance.
- *Shipyard Resourcing* - Improve manning to plan and focus on trade talent development and workforce allocation.
- *Fleet Operations* - Improve coordination between fleet and shipyard, focus on project and ships force integration
- *Infrastructure* - Reduce degraded industrial plant equipment impact on production
- *Information Technology* - Improve IT interoperability across the enterprise; standardize supporting systems

Furthermore, specifically defined metrics and targets were developed for each pillar to help drive accountability within each of the domains. These recommended target metrics, in conjunction with planned courses of action and sequences of sub elements, are designed to help achieve individual duration reduction targets for each pillar. In this way, pillar targets are grounded in tangible and specific days saved for each availability, which ultimately contributes to the North Star targets across the shipyard enterprise discussed above. A breakdown of each of the pillars, their owners and associated duration reduction targets can be seen in the figure 3-6:

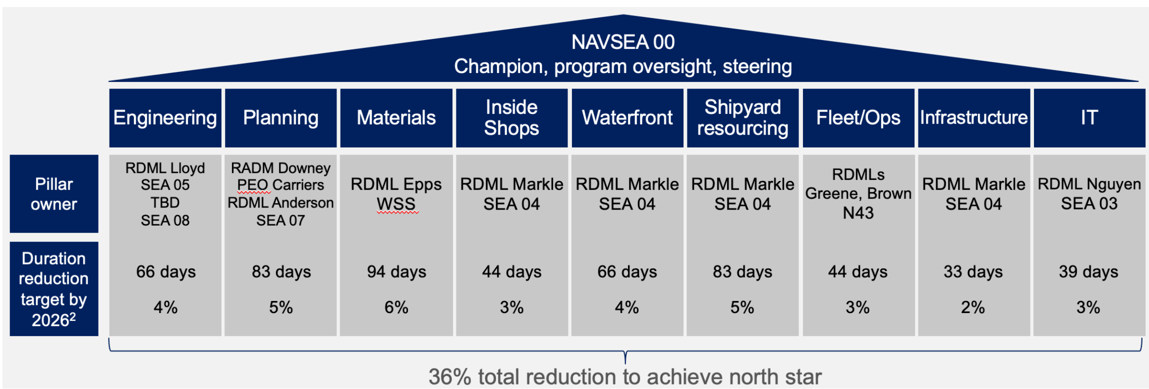

Figure 3-6: P2P-Shipyards Pillar Domains [26]

3.5 Summary

It is abundantly clear that the Navy has invested a considerable amount of time and money into efforts that are designed to help drive submarine maintenance process improvement. While the benefits of those efforts have yet to be fully realized, it is obvious that all of the initiatives share three primary goals:

1. Reduce submarine maintenance availability durations
2. Reduce submarine maintenance availability execution risk
3. Increase operational availability of the submarine fleet

As was highlighted in this chapter, each of these initiatives have faced their own unique challenges, and in some cases fallen short of their originally intended goals. This thesis does not purport to address all the issues outlined in the previous chapters (e.g. operational tempo, budgeting, manning, facilities, infrastructure, etc.) however, the need to improve availability planning and execution, by any any means, is apparent. It is evident that there are opportunities for the work conducted in this thesis to support some or all of the goals outlined above. Specifically, the preceding literature review generated a notable observation:

> **The submarine engineering maintenance enterprise is not currently providing solutions to reduce availability duration by challenging technical requirements and leveraging actionable data and innovative technology in order to measurably reduce job durations or frequency.**

With this realization in mind, the need for an example of a study central to the submarine maintenance domain that aggressively scrutinizes technical requirements, leverages actionable data and lifecycle performance to draw insights, and explores innovative technological solutions to improve overall maintenance execution is prudent. The next chapter will review the essential background and context necessary to conduct such a study involving submarine flexhoses.

Chapter 4

Flexible Hose Case Study - Background

This chapter seeks to address multiple goals. First, it will provide the essential background information, definitions and stakeholders needed in order to proceed with a robust, data-driven analysis and lifecycle evaluation. Second, it will provide the context necessary to understand why submarine flexible hoses were chosen as the focal point for this study.

4.1 Flexible Hoses: What are they?

The Navy has employed hoses on submarines for many years, dating all the way back to the World War II era Gato Class submarines. Although it is somewhat difficult to pinpoint the first shipboard application of hoses on submarines, it is generally accepted that nascent flexible hose technology consisted of hand sewn leather hoses used for both the discharge of bilge water overboard and for fire fighting [4]. In either case, these hoses would have been hand-pump operated and incapable of high pressure or high capacity. Suffice to say, today's flexible hose technology has dramatically improved since World War II, necessitated by the genesis of contemporary mechanical systems with elevated pressure and temperature requirements. Inasmuch, the hose industry was able to break away from costly, hand-built hoses and keep pace with evolving shipboard technology with the introduction of mechanical weaving, spiraling and braiding machinery to develop the contemporary flexible hoses examined in this study.

The Navy's TED-010 defines a hose as "a flexible conduit of circular cross-section used for the transfer of fluid media. Hoses usually consist of an inner element (tube), a reinforcement element (carcass), and an outer element (cover)" [9]. Flexible hoses (flexhoses) have many different applications for shipboard use, but the primary applications, as defined in the TED-010, are outlined below [9]:

1. To connect moving parts of shipboard equipment. Flexible hose assemblies are use in a variety of applications to provide a necessary flexible link between resiliently mounted machinery and rigidly mounted pipe.

2. To connect equipment to system piping or other equipment between stanchion or floating decks. Flexible hose assemblies can provide a flexible link between two pieces of machinery or decking which move relative to each other.

3. To absorb the movements of resiliently mounted equipment under normal operating conditions, as well as under extreme conditions of shock and vibration.

4. For their noise attenuating properties. Noise attenuation is paramount on submarines.

There are also many different types of flexible hoses, characterized by the material used for the construction of the hose itself. While the majority of shipboard hoses are composed of synthetic rubber, there are other alternative material hoses used on board surface ships and submarines, including polytetrafluoroethylene (PTFE), other thermoplastic hoses, and metal. In order to satisfy the needs of the various fluid media, temperature and pressure used in shipboard piping systems, the Navy utilizes many sizes and styles of hoses [4]. Selection of the most satisfactory hose for a given function depends upon hose material compatibility with the system fluid, performance, and endurance characteristics, which widely vary across different hose types.

The pictures below show a typical hose configuration, as defined in the TED-010, as well as a rendering of the structural elements of a typical Military Specification (MIL-SPEC) hose used aboard surface ships and submarines.

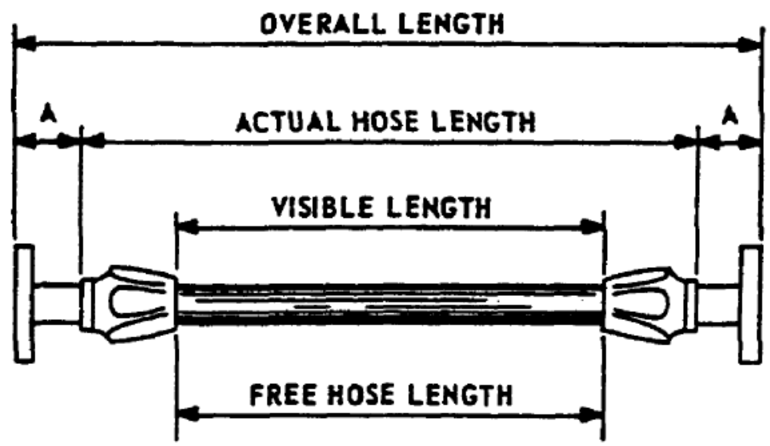

Figure 4-1: Typical Single Hose Configuration [9]

Figure 4-2: Structural Composition of a Typical MIL-SPEC flexible Hose Assembly provided by Eaton Aeroquip [2]

4.2 TED-010 Flexible Hose

The TED-010 is the single, primary technical directive employed by sailors on both surface ships and submarines to conduct shipboard flexible hose maintenance. It covers the requirements for selection, fabrication, inspection, testing, installation and replacement of flexible hose assemblies.

TED-010 compliant flexible hoses form the basis of examination for this case study. In this context, TED-010 compliant hoses refer to new construction, synthetic rubber flexhoses that are permanently installed in shipboard piping systems. As such, this case study does not address service hoses (e.g. firefighting hose, etc.), temporary hoses, or stowed hoses not in use. Further, some shipboard equipment is supplied with Original Equipment Manufacturer (OEM) or commercial hoses that are integral to the proper functionality of that specific piece of equipment. Those hoses are subject to unique manufacturer specifications and are not considered TED-010 compliant or included for examination in this case study. Lastly, although alternative material hoses are utilized on board in various applications, they are considered non-compliant with respect to TED-010 since these materials do not have a limited service life compared to synthetic rubber flex hoses. Therefore, alternative material hoses are also not included for examination in this case study.

The TED-010 provides the following additional definitions that will help facilitate follow-on discussion [9]:

Flexible Hose Assembly: A length of hose with an end fitting attached to each end.

End Fitting: A device attached to the ends of each hose to facilitate the connection of the hose assembly to a piping system.

Synthetic Rubber: Synthesized polymers that have physical properties similar to or superior to that of natural rubber (i.e. neoprene, butyl rubber, nitrile, fluorocarbon, etc.)

MIL-SPEC: In the area of flexible hose assemblies, the Navy uses commercial hose styles with specific controls, or military specifications, to help achieve interoperability, interchangeability, and commonality between products of qualified suppliers. These specifications detail the processes, materials, qualification and testing requirements required for Navy shipboard flexhoses.

Shelf Life: The shelf life of a hose is the time period from the date of manufacture to the date of installation in its intended system.

Service Life: The service life of a hose begins at the service start date, or the date when it is installed in the system for its intended purpose, or as agreed upon contractually for new acquisition. The service life ends upon failure of the hose assembly, or removal from the system dictated by criticality or PMS requirements.

4.3 Flexible Hose Criticality

The criticality of a synthetic rubber flexhose assembly refers to a designation indicating the end use of the flexhose in a shipboard environment [9]. A synthetic rubber flex hose assembly is designated as "critical" when it supports an essential or hazardous service and whose disruption of operation would jeopardize vessel operations and/or human and system health. Rubber hoses that exhibit any of the following six criteria are designated as critical flexhoses [9]:

- *Mission Essential*: Where failure of hose assembly would jeopardize ship's mission. Hose assemblies whose failure would impact the availability of propulsion power, and are not redundant, are considered mission critical.

- *Ship Safety*: Where failure of hose assembly would impact systems related to ship safety, including loss of redundancy.

- *Hazardous Fluid*: Where failure of hose assembly would release system fluid that could cause injury to personnel or damage equipment.

- *Hazardous Pressure*: Where system design pressure is greater than 1000 psig for gas or greater than 500 psig for liquid.

- *Collateral Damage*: Where leakage or rupture of hose assembly would cause damage to equipment.

- *Repair Capability*: Where hose replacement is beyond ship's force capability.

Due to the inherent mechanical and structural properties of synthetic rubber flexhoses, they tend to naturally degrade over time as they are exposed to prevailing shipboard piping system conditions. As a result, rubber flexhoses that are designed as "critical" by the TED-010 are subject to maximum allowable service lives to ensure proper operation throughout the life of the hose [9]. These critical hoses must be replaced when the flexhose reaches the service life allowance, as dictated by the shipboard PMS and TED-010 requirements.

Rubber hoses that are designated as "non-critical" do not have a maximum allowable service life, and are considered satisfactory for the life of the ship, dependent upon successful inspections and operations as designated by PMS requirements. Corollary to these non-critical rubber hose requirements, Metal, PTFE, and other thermoplastic hoses are not considered to "significantly degrade" over their typical life span in a shipboard piping system when properly selected, installed, used, and maintained in accordance with manufacturer and government requirements [9]. It then follows that these hoses also do not have limited service lives, and the terms critical and non-critical are reserved only for synthetic rubber hoses.

It should be noted, however, that the rubber hoses deemed as "critical" and "non-critical" are the exact same hoses with respect to their chemical and structural makeup (dictated by MIL-SPEC requirements), and in many cases, non-critical hoses experience very close to or the same environmental and system piping conditions as their critical counterparts. The only difference in two types of hoses is their end use as it pertains to the criteria outlined above.

4.4 Surface Ship vs. Submarine Service Life Requirements for Critical Flexible Hoses

The service life of rubber flexhose assemblies is determined only by the criticality designation it is assigned for the application which it is installed in. In most cases, the critical/non-critical hose list for a given vessel is developed by the design yard or maintenance facility, and the list is ultimately approved by NAVSEA (SEA 05Z). The following service life requirements are imposed for TED-010 compliant rubber flexhoses [9]:

Submarines and Aircraft Carriers: The service life of critical flexhose assemblies is a maximum of 12 years (144 months).

Surface Ships: The service life of critical flexhose assemblies is a maximum of 20 years (240 months)[1].

Non-Critical Hoses: All rubber flexhoses determined to be non-critical do not have a maximum service life. These hoses shall be replaced only when they fail in service or fail periodic inspections as required by PMS.

4.5 Goals and Motivation for a Flexible Hose Case Study

As stated at the onset, a secondary objective of this chapter is to provide the context necessary to understand why submarine flexhoses were chosen for this case study analysis. The evolution of this thesis spawned from the pursuit of alternative, data-driven methods to drive process improvement within the submarine maintenance community in order to reduce availability execution risk and durations. Flexhose maintenance practices provide an excellent opportunity to explore alternative methods to achieve

[1]It should be noted that the hoses used on surface ships and submarines are the same physical hose, both chemically and structurally, as stipulated in the MIL-SPEC for the given shipboard application

these goals.

In order to understand the motivation behind choosing the topic for this case study, it is prudent to first understand the goals of the case study. This case study seeks to understand whether there is adequate information and data to demonstrate that critical flex hose service lives, onboard current and future submarine classes, can be extended beyond their current 12-year maximum requirement, as directed by the TED-010. Additionally, the case study also seeks to understand the current state of the submarine maintenance enterprise as it pertains to flexhoses, and what limitations (if any) exist that would prohibit the primary goal from being achieved or from realizing more flexible and efficient flexhose maintenance operations holistically. The methods used to achieve these goals will consist of a robust, data-driven analysis and lifecycle evaluation.

The motivations for utilizing flexhoses as a vessel to achieve the goals stated above are abundant, and outlined for further review:

1. Flexhoses are ubiquitous on submarines, integrated into almost every piping system spread across the hull. Further, there are a vast amount of flexhoses on any given class of submarine (outlined in the table below)[2]. Together, these two realizations necessitate the existence of a large volume of data that can be utilized and examined .for the purposes of this case study. A greater volume of data yields a number of benefits, including better segmentation, more features and dimensions to explore, and more detailed results.

2. The precedent for extending the service life of critical flexhoses has been previously established by the Navy[3]. Moreover, additional analyses were performed by NAVSEA in 2018 to establish the technical position for service life of rubber

[2]Numbers in table should be considered approximate. Actual numbers vary based on specific hull and system configurations, as well as ship alterations that occur over the course of a submarine's lifecycle

[3]Critical flexhose service life extension programs were undertaken in 1993 and 2006 for submarines and non-nuclear surface ships, ultimately resulting in the current standards for service life outlined in TED-010 today [NAVSEA, personal communication, January 2022]

Submarine Class	Critical Hoses	Non-Critical Hoses	Total
21	263	437	700
688	181	491	672
726	431	250	681
774	161	312	473

Table 4.1: Flexible Hose Quantities Onboard US Navy Submarines

flexhoses in the Navy. These analyses were primarily qualitative in nature and focused mainly on non-nuclear, surface ship data. In July 2021, reference [9] was released and officially changed the service life of critical, TED-010 flexhoses from 12 to 20 years for non-nuclear surface ships. As previously discussed, these are the same hoses that are used on submarines, but the critical service life of submarine flexhoses remains at 12 years. The reasons for this are complex, and are explained in greater detail in follow on chapters. However, a logical question remains, why isn't there parity between surface ship and submarine flexhose service lives? Thus, an opportunity was created to investigate in the form of a data-driven, quantitatively focused case study and lifecycle evaluation.

3. SUBMEPP serves as the primary sponsor for this thesis topic, and through multiple discussions with senior leadership there, this topic was identified specifically as something they desired to get a more definitive answer on. SUBMEPP is always looking for new ways to optimize maintenance and material planning strategies to reduce availability execution risk at Naval shipyards. An area they have been focused on recently is how they can improve the scheduling and execution of intermediate level preventative maintenance requirements, and how extending those requirements might impact availability execution, component reliability, and overall costs. It was clear that the sponsor and author's goals were aligned appropriately to pursue this topic further in the form of a case study.

4. Lastly, although this case study topic focuses specifically on flexhoses, the au-

thor and sponsor are hopeful that results drawn from both the data and lifecycle analyses transcend flexhoses. In this way, similar methods can be applied to other components touching Hydraulic, Mechanical and Electrical (HME) systems across current and future submarine classes in order to potentially achieve similar results and help optimize IMA operations.

4.6 Stakeholders

The Navy's submarine maintenance enterprise is vast and complex. As a prerequisite to conducting any type of data-based or lifecycle analyses pertaining to flexhose maintenance, it's important to have a keen understanding of the stakeholders involved as well as the leading technical authorities for policies and procedures. Each of the stakeholders listed below plays an integral role in the establishment, implementation and oversight of flexhose policy. As such, individual (and sometimes multiple) representatives from each entity were consulted and leveraged to gain insight regarding flexhose maintenance practices and inform the methods and processes utilized in the following case study analysis. For the sake of privacy, names of interviewees were not included in this study, only the parent organizations they are affiliated with.

- SUBMEPP
- NAVSEA (SEA 05Z)
- NAVSEA (SEA 05U)
- Naval Surface Warfare Center (NSWC) Corona
- NSWC Philadelphia
- In-Service Engineering Activities (ISEA)
- Fleet Maintenance Activities (FMA)
- Danfoss Inc. (formerly Eaton Aeroquip)
- Hydrasearch Company (LLC)

4.7 Summary

The preceding sections have outlined the background, definitions, and stakeholders relevant to flexhose maintenance practices. They have also established the motivations for choosing flexhoses as the central topic of this case study in order to address the overarching goals of this thesis. The next chapters will present the data-driven analysis and lifecycle evaluation in their entirety, including the assumptions, current state, methods and results obtained from each. Most importantly, the proceeding chapters will examine the submarine flexhose maintenance domain holistically, and attempt to build an understanding of any inefficiencies that may exist therein, so that credible solutions may be elucidated.

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Chapter 5

Flexible Hose Case Study - Lifecycle Analysis

This chapter seeks to examine the submarine flexhose lifecycle holistically in order to better understand the policies and processes that govern the flexhose domain. In doing so, the author will attempt to garner insights pertaining to any areas where execution risk for flexhose maintenance may be elevated. Additionally, the case will be made that a robust, data-driven analysis is warranted in order to ensure that all variables are being taken into consideration by maintenance planners when deriving flexhose service life policy. The proceeding chapter is a synthesis of both literature review conducted by the author, as well as personal communication between the author and relevant flexhose stakeholders throughout the course of this study.

5.1 MIL-SPEC Flexhose Background

There are a multitude of different fluid, pressure and temperature combinations inherent to submarine piping systems. In order to accommodate these variations, the Navy utilizes a variety of styles and sizes of synthetic rubber hose. The requirements for the majority of these hoses are outlined in two corresponding MIL-SPEC's, MIL-

DTL-24135 and MIL-DTL-24136. In addition, the requirements for flexhose fittings are outlined in MIL-DTL-24787. The importance of MIL-SPEC when it comes to flexhose requirements cannot be understated and is worth reviewing further.

In general, the synthetic rubber hose MIL-SPEC informs the shipbuilder or operator what flexhoses and/or fittings are approved for use onboard ships in the US Navy, as well as what applications specific hoses can be utilized in [4]. Up until the 1960's, there was very little guidance in the fleet regarding the use of flexible hose assemblies. However, the advantages flexhoses offered in shipboard applications was evident and their use was becoming more ubiquitous, especially on submarines. As a result of the obvious advantages, in the early 1960's the Bureau of Ships developed a policy regarding the use of flexhoses in the Navy. In a series of tests, the Bureau of Ships examined a variety of flexhose piping devices, and issued approval letters for those hoses that passed the test program [4]. Those approval letters were ultimately revised and reissued as the original MIL-SPECs which laid out the requirements for hoses and fittings used as flexible hose assemblies aboard Navy ships [4]. Since the original specifications were released, multiple revisions have occurred. Most recently, revision C to MIL-DTL-24135 and MIL-DTL-24136 were released on September 24th, 2020[1].

MIL-SPECs are significant for a number of reasons. Most importantly, the specifications detail the construction, inspection, materials, qualification[2] and testing requirements for any flexhose that is used onboard a submarine [4]. In most cases, these requirements are much more extensive compared to commercial flexhoses. By subjecting all hoses to the same requirements, the Navy is able to achieve an adequate level of interoperability and interchangeability between products from qualified suppliers. This allows them to use hoses and fittings from different manufacturers in the same application onboard any vessel, which drastically reduces the difficulty in integrat-

[1]All MIL-SPEC standards can be found at the following link: quicksearch.dla.mil

[2]Qualification requirements refers to the fact that potential suppliers must test their products to the requirements of the specification and have a letter from NAVSEA approving the product based upon the test report, so that it may be listed on the Qualified Product List (QPL) [4]

ing flexhoses on already complex submarine piping systems. Furthermore, the Navy works with manufacturers to derive their own MIL-SPECs for a given component. By doing this, the Navy accepts total ownership over the specification, and is willing to assume the risk associated with that specification because they have complete oversight of the design and testing requirements imposed in any given specification. In the case of submarine flexhoses, SEA 05Z maintains all MIL-SPECs and works with qualified manufacturers to amend or update specifications when necessary [SEA 05Z, Personal Communication, January 6$^{\text{th}}$, 2022]

Today, MIL-SPECs are written in specification sheet format. The parent specification (e.g. MIL-DTL-24135) provides all the general construction, inspection, and testing requirements for that type of flexhose. Each underlying specification sheet (e.g. MIL-DTL-24135/1, also referred to as a "slant sheet") provides specific values for those tests covered by the specification sheet. Each slant sheet covers a range of hose sizes, depending on the specification [4]. Use of this format makes it easier to include new hose constructions as they are approved, especially as flexhose technology develops that may be of particular advantage to the Navy. This is because no changes to the basic specification would be required, only an additional specification sheet.

5.1.1 MIL-DTL-24135 Flexhoses

MIL-DTL-24135 hoses are constructed out of synthetic rubber, and contain metal wire for the reinforcement layer. The wire can be braided or spiraled, depending on the hose style [32]. Applications for these hoses include water, oil, high pressure air, hydraulic and lubrication systems. MIL-DTL-24135 contains 8 separate slant sheets which generally represent all the small bore flexhoses used on submarines [32]. Table 5.1 was adapted from the MIL-SPEC and summarizes the MIL-DTL-24135 flexhose parameters.

Specification	Size Range (in.)	Compatibility
24135/1	1/4 to 2	Oil, Water, Air
24135/2	3/8 to 1	Oil, Water, Air
24135/4	2.5 to 4	Oil, Water, Air
24135/5	1/4 to 2	Air
24135/9	1/2 to 2	Oil
24135/10	1/4 to 3	Oil, Water, Air
24135/12	1/4 to 2.5	Oil, Air
24135/13	1/4 to 2	Oil, Air

Table 5.1: MIL-DTL-24135 Hose Parameters [32]

5.1.2 MIL-DTL-24136 Flexhoses

MIL-DTL-24136 Hose are constructed using neoprene compounds and/or copolymer butadiene. These hose contain synthetic fiber for the reinforcement layer. The synthetic fiber can be braided or spiralzed, depending on the hose style [32]. Applications for these hoses include water, oil and gas systems. MIL-DTL-24136 contains 4 separate slant sheets, which generally represents both small and large bore flexhoses used on submarines [32]. Table 5.2 was adapted from the MIL-SPEC and summarizes MIL-DTL-24136 flexhose parameters.

Specification	Size Range (in.)	Compatibility
24136/1	5 to 12	Gas, Oil, Water, Air
24136/2	1/4 to 2	Oil, Water, Air
24136/3	1/4 to 2	Oil, Water, Air
24136/4	2.5 to 4	Oil, Water, Air

Table 5.2: MIL-DTL-24136 Hose Parameters [32]

5.1.3 MIL-SPEC Flexhose Usage and Requirements

Navy policy for flexhose assemblies is to buy bulk hose and reusable fittings. The primary reason for this is that shipboard installations of flexhose assemblies seldom use standard lengths since piping systems are complex and often circuitous [4]. Additionally, the NiCu alloy used for most fittings is expensive, so reuse of these materials is cost-effective [4].

Given the aforementioned policy, all hoses of the same type and size are stocked under a single National Stock Number (NSN), regardless of the manufacturer. For example, the MIL-DTL-24135/1 hose in the 2 inch size is stocked under the NSN 4720-00-288-9865. The Qualified Product Database (QPD) lists the NSN for each general specification and its corresponding slant sheet and size, as well as the approved manufacturers for that unique specification. This is helpful for a number of reasons, including when querying for specific flexhose related jobs (discussed further in Chapter 6).

It is important to also note that although testing requirements may vary from specification-to-specification for a given MIL-SPEC slant sheet, shelf life and service life requirements do not change concurrently. These requirements are stipulated for all flexhoses in the TED-010, regardless of the unique MIL-SPEC. The only time these requirements change are when directed by NAVSEA.

5.2 Supply Chain

As a result of the extensive requirements associated with MIL-SPEC flexhoses, the supply chain for those flexhoses is relatively limited in terms of scope, and is confined to a small amount of primary stakeholders. As such, it is prudent to review these entities in order to understand where supply chain risk may exist for the US Navy and SUBMEPP, as well as to begin to discern ways in which that risk can mitigated. The following sections discuss the two primary suppliers of Navy flexhoses, Danfoss Inc. and Hydrasearch Company, their relationship with the Navy and the flexhose domain, and common problems observed by both suppliers within the flexhose ecosystem. Information for the proceeding sections was gathered from remote interviews conducted with representatives from Hydrasearch and Danfoss[3].

5.2.1 Danfoss Inc. (EATON Aeroquip)

Danfoss Inc. and their marine military department have a long and successful relationship with the Navy, however the genesis of that relationship did not begin with Danfoss. Aeroquip was the original manufacturer of all flexhoses for the US Navy, dating back over 40 years ago. They worked hand-in-hand with the Navy to develop the original MIL-SPECs and supply the first contemporary flexhoses. Aeroquip was eventually purchased by Eaton at the turn of the 21st century, and operated under them for eighteen years. In August of 2021, Danfoss Inc. purchased Eaton, and the company today operates under that new name. However, the marine military line of products still uses the Aeroquip name today as a result of the years of brand recognition and loyalty built with its customers while in the Aeroquip time period.

Danfoss is primarily a hose manufacturer, but they also sell some fittings that conform to MIL-DTL-24787. Their "bread-and-butter" products for Navy are small bore flexhoses, however they are listed on the QPL for all MIL-DTL-24135 slant sheets, as well as 3 of the 4 MIL-DTL-24136 slant sheets. They manufacture their small bore hoses in house, at hose plants in North Carolina and Arkansas, and purchase large bore hoses (5 inches and greater) directly from suppliers. They also don't perform any metal manufacturing for hose fittings in house, instead purchasing from suppliers for their final hose assemblies. In addition to manufacturing, Danfoss also conducts all required MIL-SPEC testing of its flexhoses internally prior to shipping to its distributors.

At the onset of their relationship, Danfoss and the Navy possessed a direct, 1-to-1 relationship. Inasmuch, Danfoss would sell raw flexhose materials and/or full assemblies directly to the Navy on a consistent basis. However, in the last two decades their business direction has shifted substantially, and today most of their MIL-SPEC

[3]Interviews were conducted with representatives from Hydrasearch and Danfoss on January 14th and 17th, 2022, respectively.

hoses ultimately end up in the Navy's hands through third-party distributors. In fact, in the last 4 years combined, Danfoss has only filled about twenty specific contracts directly with the Navy. Instead, Danfoss provides both bulk materials and full assemblies to certified distributors. These are distributors that are specific to their marine military business who must possess a certain level of knowledge and expertise in order to sell Danfoss' flexhose products.

A simplified graphic depiction of the Danfoss flexhose supply chain can be found in figure 5-1.

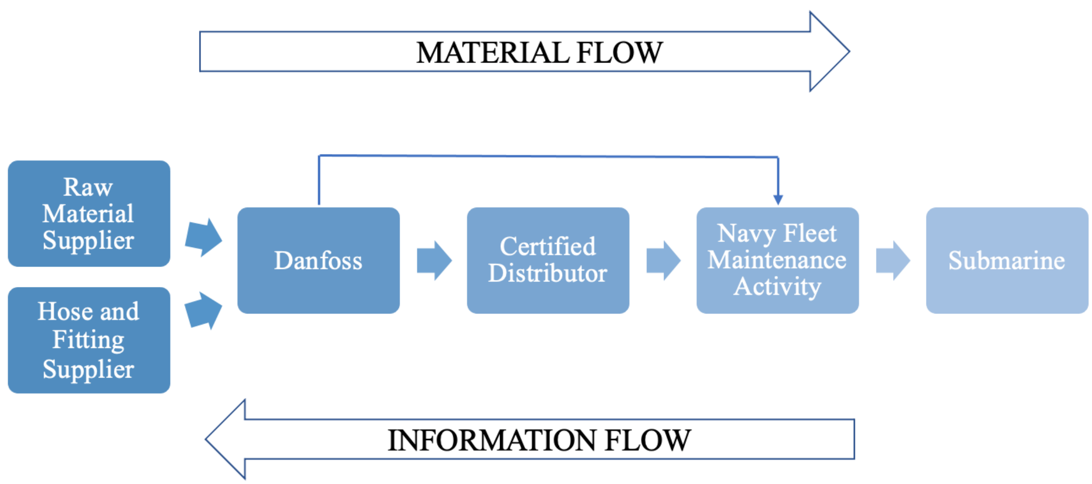

Figure 5-1: Danfoss Flexhose Supply Chain

5.2.2 Hydrasearch Company (LLC)

As with Danfoss, Hydrasearch Company has held a relationship with the Navy and its flexhose domain for the last forty years. However, their relationship with the Navy flexhose domain was established subsequent to Aeroquip's relationship. Hydrasearch is also a smaller operation than Danfoss. As a result, they have a much more limited relationship with the Navy compared to their peer, instead focusing on unique solutions that Aeroquip doesn't specialize in, such as large bore hoses and end fittings.

Hydrasearch outsources all manufacturing of MIL-SPEC hoses that they provide to the Navy, however they do own multiple foundry's that allow them to produce associated MIL-SPEC hose end fittings in house. Their primary products for the Navy are the large bore hose (MIL-DTL-24136/1) and the associated end fittings (MIL-DTL-24787), but they are also listed on the QPL for the MIL-DTL-24136/4 specification. Since they don't manufacture the hoses internally, Hydrasearch works closely with its suppliers to qualify them for the entire build, testing, and processing of their MIL-SPEC hoses. Currently, their supplier is Salem Republic Rubber Company out of Salem, Ohio.

In terms of product delivery, Hydrasearch provides both bulk material and complete flexhose assemblies to the Navy through two different avenues. The first avenue (and the preferred method) is direct-to-consumer sales. Utilizing this method, Hydrasearch provides bulk material or complete assemblies to Naval fleet maintenance activities. In this way, Hydrasearch can more easily control quality and pricing for the Navy. In the second method, third-parties called "system integrators" source materials from Hydrasearch, and ultimately provide those complete flexhose assemblies to the Navy. In contrast to distributors, who solely act as a provider of a manufacturer's product to a consumer, system integrators source raw material from manufacturers and combine them internally, providing final product solutions to the customer. This has both benefits and drawbacks, which are discussed in further detail in a later section.

A simplified graphic depiction of the Hydrasearch flexhose supply chain can be found in figure 5-2.

5.2.3 Danfoss and Hydrasearch Relationship

As the two primary manufacturers of the Navy's flexhose supply, an understanding of the relationship dynamic between Hydrasearch and Danfoss is imperative. It was noted that NAVSEA was "amazed and impressed" regarding the relationship between the two entities, and specifically how well they compliment each other in providing the Navy's supply of flexhoses [NAVSEA, personal communication, January 2022].

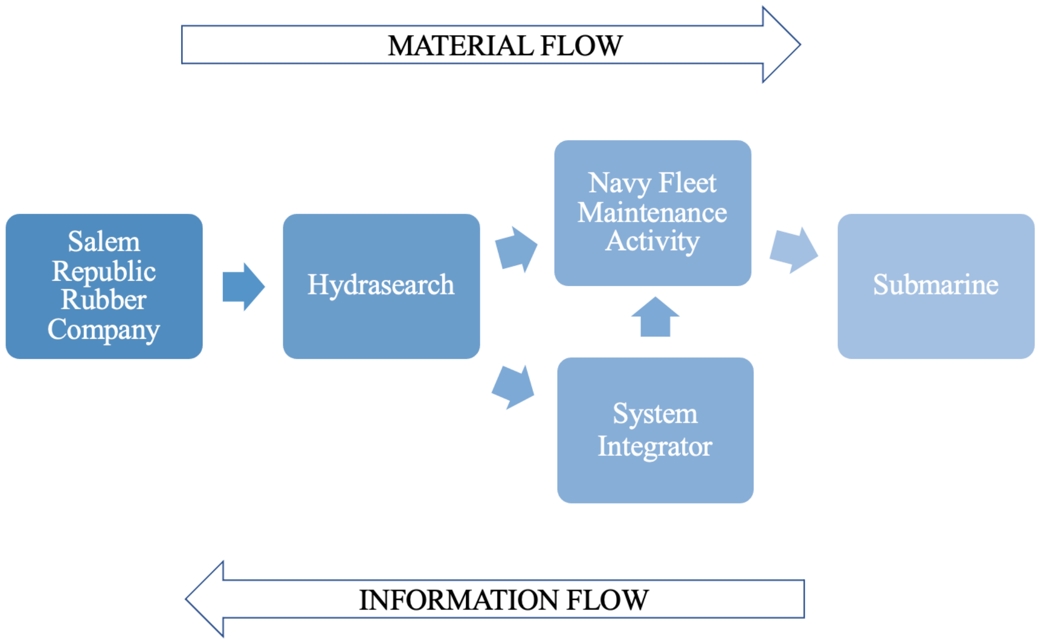

Figure 5-2: Hydrasearch Flexhose Supply Chain

Both companies expressed similar sentiments as well.

Hydrasearch explained that they have a direct relationship with Danfoss, and communicate with them on a consistent basis regarding Navy MIL-SPEC flexhoses and the manufacturing of hose assembly components. It's important to understand that the original MIL-SPEC for Navy flexhoses was written based upon Aeroquip components. As a result, Hydrasearch has had to communicate extensively with Danfoss to "put together the missing pieces" when it comes to MIL-SPEC flexhoses. Also, while they acknowledged that they both have independent customer bases and expectations for the products they provide, they're also still able to work together to improve the Naval flexhose domain holistically. For example, they noted that they recently worked with both Danfoss and NAVSEA 05Z to revise the MIL-DTL-24787 specification in such a way that was advantageous for both companies strategic objectives.

Similar to Hydrasearch, Danfoss noted the advantages of sustaining a strong working relationship with the other. They acknowledged that Hydrasearch is able to provide some components, such as large bore hoses and hose end fittings, that Danfoss is not capable of manufacturing in house. As such, a relationship is advantageous in order to ultimately provide complete flexhose assemblies for the Navy. Further, they also recognize that Hydrasearch has a smaller operation, and relies on them at times to provide certain hoses that their supplier isn't capable of manufacturing. While Danfoss did note some minor pain points in the relationship, they ultimately continue to foster strong ties to Hydrasearch with regards to system knowledge sharing and integration of components.

5.2.4 Identified Supply Chain Risks

Following discussions with both of the primary suppliers of the Navy's flexhoses, it was clear that there some common issues internal to both supply chains. These issues, if not addressed, incur significant associated risk for the submarine flexhose supply chain system and it's relevant stakeholders. Four primary issues were identified and are summarized below:

1. **Limited Raw Material Suppliers**: Both Danfoss and Hydrasearch expressed concern regarding the lack of raw material suppliers for MIL-SPEC flexhoses, as well as their ability to keep up with demand for commercial and MIL-SPEC raw hose materials. Both companies noted strains in their respective supply chains over the last two years, and in some cases it was clear that the same supply chain pressures were affecting both companies concurrently. For example, until 2020 both Danfoss and Hydrasearch were sourcing from the same raw hose material supplier overseas for their large bore hoses. That supplier shut their doors in 2020, and left each company scrambling to try and fill the gap. While Hydrasearch was able to find an alternative supplier, they are still looking to shore up that leg of the supply chain, and Danfoss has yet to find an alternative supplier. When supply chain issues such as this affect both of the primary suppliers of Naval flexhoses, inherent ripple effects will ultimately trickle down to the Navy's submarines, making it difficult to find inventory to replace certain MIL-SPEC hoses when required.

2. **Reduced Quality Amongst Third-Party Distributors**: It was clear that both companies were very confident in their quality control processes and have experienced little to no issues in terms of providing the Navy true-to-specification flexhoses and flexhose assemblies. However, the same could not be said for the quality of products provided to the Navy through third-party distributors or system integrators. Both companies noted that they have observed recurring issues with build quality and attention to detail amongst third-party distributors. This most often stems from the fact that these third-party distributors are typically smaller companies with much less expertise regarding the assembly and testing of MIL-SPEC flexhoses. Hydrasearch also noted that most of the time, they are unable to compete with these smaller businesses for flexhose contracts, due to the DoD's policies regarding requirements to award government contracts to small or disadvantaged businesses[4]. As a result, the quality control issues become hard to control once the product leaves their warehouse.

3. **Restrictive and Cost-Prohibitive MIL-SPEC Requirements**: As mentioned in the previous section, MIL-SPEC flexhoses have extensive testing, qualification and inspection requirements compared to commercial flexhoses. In most cases, this requires companies like Danfoss and Hydrasearch to hire additional employees to both interpret the requirements the right way and implement the associated MIL-SPEC requirements successfully. This results in inflated costs for suppliers, which acts to deter them from DoD flexhose contracts and push them towards commercial contracts that are much more lucrative and require significantly less leg work to fulfill. Hydrasearch noted that they have had significant trouble finding an additional supplier for the MIL-DTL-24136/1 flexhose specification simply because it "doesn't fit the business model" due to low return on investment. Both companies suggested that they have recently observed more suppliers getting away from selling to MIL-SPEC requirements and instead shifting to less restrictive flexhose requirements, such

[4]According the Office of Small Business Programs, 23% of the total value of all prime contract spending for the DoD is required to be awarded to eligible small businesses [31]

as the American Society for Testing and Materials (ASTM), simply because the profit margin is significantly more worthwhile.

4. **Difficulty in Implementing New Technology**: It was expressed by both companies that the restrictive MIL-SPEC requirements makes it difficult to implement any new technology into the flexhose supply chain. Newly engineered materials, additive manufacturing techniques and self-monitoring flexhoses are all innovations in the pipeline that could eventually lead to significantly longer service life applications for Naval flexhoses. To this point these innovations are cost-prohibitive, partly due to aforementioned MIL-SPEC ecosystem in place. However, both companies are optimistic that as the Technology Readiness Level (TRL) matures and material availability increases, they will be able to work with the Navy to amend the MIL-SPEC to allow for newer flexhose innovations to be integrated into the supply chain.

5.3 General Flexhose Lifecycle

A typical submarine flexhose lifecycle is defined in the TED-010 as "the accumulation of the events the hose endures from the time of manufacturing until the end of life, including all storage and usage" [9]. For the purposes of this study, a flexhose lifecycle includes testing, shelf life, service life and ultimately, replacement. An understanding of the processes involved in these different phases, as well as how the requirements imposed therein have evolved over the last sixty years, will aid in illuminating possible areas of execution risk internal to the flexhose lifecycle. What follows is a deep dive into each of these different lifecycle phases, derived from a combination of literature review and interviews and/or personal correspondence with stakeholders from SUBMEPP, Fleet Maintenance Activities and NAVSEA 05Z[5].

[5]Interviews and personal correspondence with representatives from each of these organizations occurred continuously during the months spanning from December 2021 through February 2022.

5.3.1 Testing

Pre-Delivery Testing

Naval flexhoses are required to undergo significant and extensive testing prior to being certified for installation on submarines. Some of the required tests are conducted by the raw material supplier, however most are conducted by the manufacturer (e.g. Hydrasearch and Danfoss), and a few are even conducted by Naval fleet maintenance activities, depending on if a hose is being reassembled or replaced. In most cases, testing that has been completed for a particular hose is documented on the ID tag attached to the hose upon delivery. However, it was noted by Danfoss that they have observed instances of repeat testing being performed at the ship level as a result of inadequate documentation of previous testing certifications. This is an area they feel can be exploited in terms of cost and time savings within the flexhose lifecycle, assuming standardized testing practices can be implemented across the flexhose domain.

The parent MIL-SPECs for submarine flexhoses provide a comprehensive list of required testing that must occur prior to delivery to FMAs. A brief synopsis of the major tests is provided below.

- **Proof Pressure**: Hoses are filled with water, oil or hydraulic fluid and internal pressure is raised to 200% of rated working pressure for 1 to 5 minutes. Evidence of leakage, rupture, or deformation constitutes failure [32] .

- **Stability (Dimensional Change)**: Completed in concert with the proof test, hoses are marked within a half inch of the junction of the hose and end fitting. After proof pressure is reached, the distance between the hose junction and the mark is remeasured and verified within required specification [32].

- **Impulse Pressure**: Hose assemblies are subjected to a peak pressure impulse rate of 30-80 cycles per minute for a predetermined number of cycles while bent to a required bend radii. Evidence of failure is examined for as in the proof pressure test [32].

- **Burst Pressure**: Similar to proof pressure test, hose is filled with applicable fluid medium and internal pressure is raised to 400% of the maximum working pressure. Evidence of failure is examined for as in the proof pressure test [32].

- **Vacuum**: Hose samples are tested under vacuum pressure of a minimum of 28 inches of Mercury for at least 30 seconds. Again, evidence of failure is examined for [32].

- **Cold Temperature Flexibility**: Hose assemblies are cold-temperature tested while filled with fluid at temperatures of -40 degrees F for note less than 24 hours. At the conclusion of the required time period, hoses are verified to attain minimum bend radii requirements at the cold temperature [32].

- **Adhesion**: Adequate adhesion of tube and cover to the reinforcement layers shall be verified while supporting minimum required weight for at least 3 minutes [32].

- **Flammability**: Flame spread and fire resistance testing are conducted in accordance with ASTM and Society of Automotive Engineers (SAE) standards and validated to be in conformance [32].

Post Service Life Testing

In addition to pre-delivery testing, the subject of post service life testing was also highlighted as a potential area of opportunity where the Navy currently falls short. Representatives at NAVSEA conceded that the Navy still has much to learn regarding how flexhoses behave throughout their service life, considering the wide variety of factors at play for any given flexhose (e.g. parent platform, system operating parameters, surrounding environmental conditions, active fluid media, geographic location in the submarine hull, etc.). They also discussed that, despite the immense opportunity presented by examining flexhoses onboard decommissioning submarines, retired flexhoses that are still intact are seldom analyzed regarding their structural integrity and material behavior. To date, no comprehensive test program has been conducted on aging flexhoses to determine what kind of performance is being obtained, what actually constitutes a failure and how we can extend expected flexhose service life.

NAVSEA attributed the primary reason for lack of post service life testing to fiscal budgetary limitations. Unfortunately, the money is not available to conduct scientific research on components that are being scrapped. They also lack the resources and manpower to implement any such kind of test program. As a result, the responsibility (and associated costs) to perform such testing most often falls to OEMs, who farm the work out to commercial laboratories. There are only a select amount of laboratories who can perform the type of testing required for MIL-SPEC hoses, and its infrequent that NAVSEA is provided any results for MIL-SPEC specific hoses.

It is abundantly clear that, given the wide variety of flexhose types and operational conditions exhibited onboard a submarine, the lack of post service life testing for submarine flexhoses is concerning. Without access to concrete data and facts stemming from rigorous test programs, it would be difficult to make any decisions related to PMS requirements or maintenance availability planning, let alone those decisions pertaining specifically to the flexhose domain.

5.3.2 Shelf Life

The shelf life of a hose was previously defined in section 4.2. Shelf life requirements are implemented for Naval flexhoses for age control based on the premise that elastomers are age sensitive. Physical properties or form changes can occur with exposure to certain elements (e.g. Ultra-violet light, temperature, solvents, etc.) [4]. As such, age control allows for reasonable period of time that the flexhose is expected to maintain its full structural integrity. Methods such as protective material and storage controls can act to minimize exposure of a hose to degrading environmental conditions and decrease the rate at which a material might degrade over time [4]. For submarine applications, bulk rubber hose or hose assemblies that are within tolerance of their basic shelf life requirements may be used directly from storage without any additional testing besides proof testing. The current shelf life for TED-010 hose assemblies is 10 years for both MIL-DTL-24135 and MIL-DTL-24136 flexhoses [9].

Shelf Life Requirements Over the Years

Up until 2008, TED-010 flexible hoses had a basic shelf life of 6 years, which could be extended up to an additional four years at two year intervals, following successful completion of hydrostatic testing [9]. However, this required the packages that contained the flexhoses to be opened in order to test the flexhoses that were being stored. Opening packages of shelf-life controlled items, other than for immediate use, is discouraged since the impact that has on the service life for the remaining products in the container is unknown [7]. Further, the cost associated with the testing required to extend the shelf life of the flexhoses likely outweighs the cost of the flexhoses themselves, which goes directly against the primary reasons for implementing a shelf life program [7]. Understanding this realization, NAVSEA extended the basic shelf life of all flexhoses to 10 years with revision 3 of TED-010 in 2008 [9]. This was also in line with both the commercial industry and DoD shelf life program requirements regarding the storage of flexible rubber hose [7]. It was also noted by Hydrasearch that they implement additional shelf life requirements that necessitates they deliver hoses to the Navy that have at least 85% of their total shelf life remaining, which ensures the hose is fairly new upon delivery to FMAs.

Other Shelf Life Considerations

By conforming to commercial and DoD shelf life program requirements for flexhoses, NAVSEA assumes there is reasonable assurance that a shelf life compliant item will be received by the Navy [7]. However, it's also acknowledged that submarines have complex availability schedules as well as varying demand signals for flexhoses needed to support the in-service fleet. Inasmuch, the TED-010 was written to provide some lee-way to allow for ordering of larger volumes of product in order to ensure that flexhose is available when needed and is affordable [7]. In the case of submarine availabilities, it follows that it wouldn't be logistically feasible to construct and install all required hose assemblies in an immediate time frame once a bulk flexhose package is opened, especially from a cost and man-hours perspective. Extended shelf lives enable some additional flexibility for bulk orders and are designed to mitigate those limitations.

That said, it's evident that the need to maintain readily available local supplies to support deployable submarines outweighs the logistical limitations (e.g. cost, time, etc.) associated with ordering and receiving products solely on an on-demand basis. Despite that realization and the changes made to shelf life requirements in support of it, representatives from FMAs expressed that one of their bigger concerns remains that in some cases they don't have enough inventory on hand to complete the flexhose replacements they are tasked with in a given availability. Specifically, it was noted that a more consistent and larger inventory of individual flexhose assembly components would help reduce delays at the availability level regarding flexhose maintenance. As a result, FMAs are relegated to deal with extended lead times within the flexhose supply chain, which has been exacerbated by the supply chain woes exhibited across the globe over the last two years.

5.3.3 Service Life

The service life of a flexhose was previously defined in section 4.2. The examination of service life requirements for TED-010, synthetic rubber flexhoses also comprises the foundation of this study. As such, an in depth review of how these requirements have changed over the years and why those decisions were made is warranted. It is the author's belief that context from historical decisions have the capability of informing future decisions, when examined appropriately in the bounds of a study such as this one. The proceeding sections attempt to capture the necessary information to show that additional study in the form of robust data analysis is prudent in the flexhose service life domain.

5.3.4 A Brief History of Flexhose Service Life Requirements

It was previously outlined in section 4.4 that the service life of TED-010, critical flexhoses on submarines is a maximum of 12 years, and a maximum of 20 years on non-nuclear surface ships. Additionally, non-critical flexhoses do not have a maximum service life, and may be installed for the life of either the submarine or surface ship. However, this was not always the case, and in fact the requirements have been updated and revised a number of different times dating all the way back to the 1970's. The timeline below attempts to highlight the major changes that have occurred over the years, as well as any underlying reasons for those changes:

- **Pre-1960's**: Prior to 1959, there was little to no guidance for the fleet regarding a codified Navy policy for the treatment of flexhose assemblies [29]. Failures to several submarine hoses in the 1956-1958 time frame, coupled with the genesis of the SSN 594 Permit class (which used an abundance of flexible hose assemblies), prompted a program called "Project Pressure". In this program, many types of flexhoses and connections were inspected, tested and certified for use on US Navy submarines [29]. The final results of Project Pressure were a series of letters to submarine type commanders, which together formulated a basic policy for the treatment of rubber flexible hose assemblies on submarines. The policy included replacement criteria, which directed replacement of all flexible hoses at a maximum periodicity of 5.5 years (66 months) [29].

- **1963**: The aforementioned letters were combined and issued as BUSHIPS Instruction 9480.65. It was primarily aimed at the submarine world since submarines used most, if not all, of the hoses during this period [29].

- **1963-1973**: During this 10 year period, the surface Navy began to realize the benefits of employing flexible hoses on board their ships [29]. In recognition of increased surface ship use, the BUSHIPS Instruction was rewritten and issued as NAVSHIPS NOTE 9480 in 1973, and was applicable to all Navy vessels. The maximum service life remained unchanged for all hoses at 5.5 years [29].

- **1973-1983**: Throughout this next 10 year period, various hoses were removed from ships and examined and tested. The results of these examinations and tests showed that many hoses could be left in service for far longer than the 5.5 years that was being mandated at the time [29]. Following these results, the NAVSHIPS NOTE was revised to reflect several major changes. First, ship systems were categorized into "critical" and "non-critical". Second, flexhoses in systems that were critical maintained their 5.5 year periodicity. However, flexhoses in non-critical systems were given a new 12 year maximum replacement periodicity [29]. The updated service life guidance was codified in a new publication, the first volume of the NAVSEA Technical Directive, TED-010, which was released in 1983 [29].

- **1983-1993**: From 1983-1993, the surface Navy voiced many complaints regarding the application of criticality and the feeling that non-critical hoses were being replaced too often. Their argument was that, to that point, there was no record of repeated hose failures, and the current service life criteria was too conservative [10]. In November 1993, NAVSEA 03Y initiated a flexhose service life extension program. Shortly after, Revision 1 of the TED-010 was released in 1993 which permitted an allowance of an additional 6 months to the maximum service life of critical flexhoses, if necessary for operational schedule flexibility [1].

- **1995-1997**: In November 1995, Advance Change Notice (ACN) 2/A to revision 1 of the TED-010 was released which increased the service life of critical flexhoses from 6 to 7 years (84 months). Non-critical hoses remained at 12 years [1]. Following further evaluation, ACN 3/A to revision 2 of the TED-010 was released in December 1997. This was a significant ACN for multiple reasons. First, the ACN established a CBM program for non-critical hoses, meaning that non-critical flexhoses no longer had a maximum replacement periodicity, and instead would only be required to be replaced based upon failed inspections [1]. Second, the maximum service life for critical hoses was extended from 7 years to

12 years (144 months) [1]. Lastly, definitions of criticality and criteria for criticality were updated to be more in line with contemporary flexhose technology and vessel construction [1].

- **2006**: The surface fleet implemented a new critical flexhose life extension program in 2006 to extend the service life of critical flexhoses on surface ships from 12 to 20 years [NAVSEA, personal communication, January 2022]. Concurrently, via PMS, the entire surface community was directed to implement 20 year critical flexhose change outs (raised from 12 years), with risk mitigations in place (see section 5.3.6) [7].

- **2019**: NAVSEA implemented revision 7 of the TED-010 in November 2019. This revision officially codified the current guidance of a maximum of 20 years service life for non-nuclear surface ship critical flexhoses, and 12 years for submarine critical flexhoses. Non-critical service life remained as required by CBM for both communities [7][9].

5.3.5 Reliability Centered Maintenance Service Life Requirements

There are some exceptions to the service life guidance outlined previously. Some flexhose service lives have been established based upon RCM analysis. Inasmuch, critical flexhoses exposed to harsh environments or operating conditions have more stringent maximum service lives corresponding to system specific failure analysis data. For example, there are three snorkel system hoses specific to 688 class submarines that have prescribed maximum service lives of 66 months. These snorkel hoses are external to the pressure hull, which exposes them to harsh environmental conditions, and they also undergo routine pressurization cycles. Together, these conditions have shown to limit the viable service lives of these hoses and system engineers accounted for that limitation in the development of the CMP by limiting their maximum service life. Also, if hose service life requirements are defined in system specifications, PMS, Naval

Ships Technical Manual (NSTM) or other system documents, those requirements take precedence. For example, any rubber flexhose that is subjected to vacuum service and which is immersed in bilge water during any normal operation shall have a maximum service life of only 6 years (72 months) [9].

5.3.6 Service Life Extension Efforts

The service life requirements of flexhoses have been challenged and examined multiple times over the course of the last 30 years. The following sections attempt to briefly summarize those initiatives. It's imperative to understand what work regarding flexhose service life has been done in the past, in order to avoid overlapping efforts in the conduct of this study.

NAVSEA 03Y Flexhose Service Life Extension Program (1993-1997)

The early and mid 1990's represented a period of heavy scrutiny and evaluation of flexhose service life requirements, and in 1993, Cumbersome Work Practice (CWP) action CWP-104 was initiated for both critical and non-critical flexhose assembly service life requirements for cost savings and work reduction benefits [7]. In the Navy, there is a NAVSEA sponsored group who manages CWP investigations. Topics of interest are brought to the CWP team's attention in order to keep track of them, get the right people in place to manage them, and ultimately take appropriate action [NAVSEA, personal communication, January 2022]. Flexhoses were a topic of particular interest at that time.

As a result, in November 1993, NAVSEA 03Y (now NAVSEA 05Z) initiated a flexhose service life extension program using CG-60 and CG-61 as test platforms to reduce cumbersome work practices and provide cost avoidance. In addition, NAVSEA also collected data on some submarine flexhoses removed from SSN's 673, 689 and 700 [1]. As part of their test program, the team reviewed replacement data of flexhoses for the previous 5 years, completed inspections of flexhoses on the various vessels, and conducted destructive testing on hoses removed from those vessels. In total, 21 hoses were examined from submarines, and 37 hoses were tested from CG-60 and CG-61. The results of the tests confirmed that none of the hoses were catastrophically failing when conducting proof or burst tests, even at older ages (15+ years old) [1]. In addition, in the conduct of these tests, it was shown that only the fittings were leaking upon raising pressure to burst pressure [1].

Ultimately, the service life extension program that began in 1993 culminated in multiple changes to service life and criticality requirements for both critical and non-critical flexhoses from 1995 to 1997. Those changes were outlined previously in section 5.3.4.

Surface Fleet Critical Flexhose Life Extension Program (2006)

For surface ships, the cumbersome work practices study that began in the 1990's regarding flexhose service life requirements continued into the 2000s. In 2006, the surface community was granted permission to conduct testing to support implementation of a service life extension program in an effort to extend the replacement periodicity of critical flexhoses beyond 12 years [NAVSEA, personal communication, January 2022]. The target of the critical hose extension program was to achieve a service life of 20 years for all surface ship critical hoses [NAVSEA, personal communication, January 2022].

The rationale behind the effort consisted of numerous arguments. First, stakeholders posited that extension beyond 12 years was medium risk, since there were no reported critical hose failures during the 12 year service life [7]. Second, feedback from port engineers indicated that critical hose assemblies being replaced at the 12 year periodicity were still passing annual PMS inspections and in good condition [7]. Third, critical flexhose replacements that required a Departure From Specification (DFS)[6] because of operational commitments and were deferred for multiple years were still

[6] Departure from Specification messages are requests used in the Navy to obtain permission for temporary departures from a component's specification. In the case of critical flexhoses, if a particular submarine had operational commitments that prevented it from being in port to conduct its required 12 year replacement, a DFS would be submitted to the Type Commander (TYCOM) for approval to defer the required maintenance [39]

in good condition and passed the annual PMS inspection when replaced [NAVSEA, personal communication, January 2022].

Multiple test ships were chosen to participate in the extension program. These ships were directed to remove and replace 10% of their oldest hoses for laboratory testing and inspection, and conduct semi-annual vice annual inspections on all critical flexhoses [7]. Through the use of PMS, which takes precedence over TED-010 requirements, all surface ships were directed to discontinue planning for critical flexhose change outs under 20 years old while the service life extension program was ongoing [NAVSEA, personal communication, January 2022]. This meant the entire surface Navy was now using a 20 year service life requirement for it's critical flexhoses, beginning in 2006. The 20 year service life was implemented contingent upon two things: 1) ship's force was required to generate a critical flexhose list and provide annual updates about that list, and 2) ship's force was directed to complete semi-annual inspections for flexhose assemblies greater than 12 years old [7].

There were multiple attempts to obtain hoses from the surface community in 2006 and 2008, however, the test program team noted that there were difficulties in obtaining those samples [7]. Additionally, the testing that was conducted illuminated the "inherent inability to analytically predict end of useful life with testing" [7]. Ultimately, the Navy accepted the risk of extending non-nuclear surface ship critical flexhose service life to 20 years, with the risk mitigations outlined above in place [7]. The change was not captured in the TED-010 at that time.

NAVSEA 05Z Review of Flexhose Shelf and Service Life Requirements (2018)

As a result of the lapse in time between the CWP efforts of the early 2000's to today, it was acknowledged that there were likely an abundance of hose assemblies reached their 20 year service life. This prompted NAVSEA 05Z to conduct their own review of flexhose service life requirements in 2018 in order to establish an official position on the changes that the surface community implemented via PMS [7].

NAVSEA examined about 4,700 2-kilo records, as well as DFS records. A 2-kilo is the principal means used to document material deficiencies and completed maintenance actions on board Naval vessels [39]. In this context, 2-kilo's are utilized by ship's force to indicate that replacement is required for critical hoses that exceed or are about to exceed service life requirements, or indicate replacement is needed for critical or non-critical hoses that fail inspection criterion. The 2-kilo records that were examined represented all MIL-DTL-24135 and MIL-DTL-24136 flexhoses that were captured across the Navy, spanning from 2005-2018 and [NAVSEA, personal communication, January 2022]. Of note, the 2-kilo records do not indicate whether or not replacement occurred, they are simply ship's force documentation of the component of interest and why replacement is required. There was also no review of the time between replacements for critical or non-critical flexhoses.

In their review, NAVSEA was primarily focused on two things, number of failures and severity of failures (i.e. catastrophic failure vs. out of specification paint covering) [NAVSEA, personal communication, January 2022]. Further, they only assessed records spanning the time periods of 2005-2008 and 2016-2018. The reason for this was two fold. First, the review was prompted based on the extension of non-nuclear surface ships critical flexhoses to 20 years, which to that point in 2018, hadn't yet been officially codified in the TED-010. Second, these times made sense chronologically, as 2005 was the year when the surface fleet service life extension program was first recommended, and 2018 was the latest data could be pulled, given the time period of the review [NAVSEA, personal communication, January 2022]. It should also be noted that the primary focus of this examination was on non-nuclear surface fleet flexhose data. While some nuclear platform data was reviewed, it wasn't at the forefront, and there were no noticeable changes in the the 2-kilo/DFS information [NAVSEA, personal communication, January 2022].

Upon their assessment, NAVSEA noted a 50% decrease in the total number of 2-kilo's, with half of that reduction stemming from the change in service life, and the other half due to changes in procedures for hose identifications tags [7]. They also noted inconsistency in the 2-kilo data, and in many cases, the general lack of information provided. This made it tough to tell whether or not a hose failed, or why a hose required replacement. For example, some entries might just say "hose replacement required", with no indication given as to why, or some entries might be non-existent regarding why the 2-kilo was submitted. The lack of standardization in the 2-kilo data was a point of frustration [NAVSEA, personal communication, January 2022]. Ultimately, NAVSEA concluded that the 20 year service life for non-nuclear surface ship critical flexhoses was acceptable, and the corresponding change was implemented in the TED-010 in 2019 [7].

5.3.7 Replacement of Flexhoses

At the end of their service life, flexhoses are required to be replaced. Critical and non-critical flexhose replacements are incorporated into a submarine's CMP. The CMP incorporates PMRs that mandate the replacement of critical flexhoses at their maximum service life periodicity, and replacement of non-critical flexhoses that have failed inspection [SUBMEPP, personal communication, January 2022]. Once a PMR is called out for a flexhose replacement, SUBMEPP is able to track that replacement and update in their Maintenance & Ship Work Planning (M&SWP) application (explained in further detail in Chapter 6). In theory, this process is designed so that SUBMEPP can ensure repeat work is not performed on flexhoses once a submarine comes in for an extended availability. In this way, flexhoses are not included in an Availability Work Package (AWP) needlessly.

Flexhose replacements are considered I-level maintenance. This means that ship's force doesn't actually perform the physical manufacturing of new flexhose assemblies. Instead, an IMA (or depot level repair activity if desired[7]) will conduct the maintenance on behalf of the ship [SUBMEPP, personal communication, January 2022]. Additionally, the processes employed by FMA's to replace flexhoses do not change based on criticality of the hose. The general process for replacement is as

[7] Flexhoses will occasionally be replaced during depot level availabilities, if replacement periodicity aligns with depot availability scheduling (explained in further detail in section 5.4)

follows:

1. Ship's force will fill out a 2-kilo indicating replacement is required.

2. The 2-kilo is entered into the Current Ship's Maintenance Project (CSMP). The CSMP is the primary repository of information concerning the material condition of the activity [39]. In this context, the CSMP contains all the 2-Kilo's ship's force submits regarding required replacement of flexhoses, either due to periodicity or failed inspections.

3. Once a submarine is able to, all 2-kilo's get uploaded from the CSMP to the IMA via the Immediate Superior in Command (ISIC) [SUBMEPP, personal communication, January 2022].

4. When the submarine is in port, the IMA will send personnel to examine the flexhose that needs to be replaced. They will ensure everything is adequate to perform the replacement, and then ship's force will isolate the flexhose, uninstall it and bring it to the respective shop for replacement [Fleet Maintenance Activity, personal communication, January 2022].

5. A new flexhose assembly is built to the exact same specifications as the one being replaced. Fittings are removed from the old hose and inspected. If there are no issues with the inspection, fittings are reused whenever possible. New hose material will be picked up from the applicable storage area and cut to specification for the required flexhose assembly [Fleet Maintenance Activity, personal communication, January 2022].

6. The shop cleans, inspects and proof tests the newly formed flexhose assembly. Assuming all inspections and testings are satisfactory, the assembly is delivered back to ship's force, who will reinstall the new assembly and tag it with all the required information per the applicable maintenance requirement [Fleet Maintenance Activity, personal communication, January 2022].

There are a few other important facts to understand regarding replacement of flexhoses. First, ship's force does not possess the capability on board to replace a flexhose assembly. Special tools and supporting equipment are required to manufacture a complete flexhose assembly. This means that if a hose fails while on deployment, sailors will take one of three actions. If it's non-critical and can be isolated easily, they will isolate it. If degraded operation is possible and poses no risk to the crew or surrounding systems, operation will continue. Otherwise, if a hose is critical and continued operation is required, sailors will "improvise and try and find a way to make it work" in the short term [SUBMEPP, personal communication, January 2022]. Concurrently, a Casualty Report (CASREP) will be flown off hull with the requisite 2-kilo information so that the shore based IMA can manufacture a new assembly and deliver it back to ship's force at sea for replacement.

Additionally, just because a critical hose has lapsed its maximum required service life periodicity does not mean the hose can no longer be used. In most cases, operations will continue for the hose that has exceeded its maximum service life, as long as there is no degradation to performance for the hose. Formal documentation of the service life violation, including a 2-kilo and DFS request to a submarine's ISIC, will occur in most cases [SUBMEPP, personal communication, January 2022]. However due to the variability of submarine schedules and timing considerations regarding I-level availability planning, it is common for critical flexhose replacements to exceed the current 12 year required cadence. The extent to which this type of situation occurs is not well known, including how far beyond the maximum service life these replacements are occurring. This provides opportunity for additional investigation with regards to service life requirements.

5.3.8 Observed Failure Modes

Given the extent to which service life requirements have been examined, it follows that there has been a significant effort over the years to better understand what actually constitutes a flexhose failure, and what the primary failure modes of flexhoses actually are. Failure of the rubber flexhose itself can constitute a number of different conditions, including nicks, leaks, bulges, blistering, bubbling, cracking and delamination of the hose material [9]. Failure can occur differently for every type of flexhose, and should be reexamined on a hose-to-hose basis.

There has been ample research conducted over the years regarding the primary failure modes of flexhoses. Upon completing the testing conducted as part of the flexhose service life extension program in the 1990's, it was noted that the primary failure mode for hoses that were tested was "leakage at the fittings, which is both containable and not detrimental to a ship's operational or personnel safety", and not catastrophic failure [1]. Additionally, the test program team expressed that the replacement data and test results did not indicate a correlation between failure frequency or mode of failure and length of service [1].

Although the test data used to derive the conclusions above was limited, the results are significant and align with much of the anecdotal insights provided by relevant stakeholders. Representatives from NAVSEA noted that flexhoses can "last the life of the ship", some of which are 35+ years old [NAVSEA, personal communication, January 2022]. This is known because when ships are inactivated, there are some originally installed flexhoses still on the ship. Representatives from FMA's relayed a similar sentiment: "If a hose is installed properly, and there's not much deflection or adverse environmental conditions, we have seen non-critical hoses that are 20-25 years old that still look and perform like their brand new...all depends on the environment it's subjected to, and if it's exposed to conditions that cause it to age prematurely" [Fleet Maintenance Activity, personal communication, January 2022].

From literature review and personal correspondence, it is generally accepted amongst all flexhose stakeholders that MIL-SPEC hoses are robust. This is evident given the sheer volume of flexhoses installed across the submarine and surface communities coupled with the fact that there are very few instances of documented catastrophic failure [NAVSEA, personal communication, January 2022]. Notwithstanding that idea, flexhose compounds are organic and will eventually degrade. The overarching question remains: When is that expected to occur for any given flexhose?

The answer is not straight forward, and changes based on a multitude of different circumstances. For these reasons, primary manufacturers of Navy flexhose (e.g. Danfoss and Hydrasearch) avoid giving any data whatsoever on service life estimates for MIL-SPEC hoses. This is due mainly to the fact they don't want to be held accountable to predicted service life performance when a hose inevitably fails prior to that expected life span. They also aren't intimately familiar with all the different service conditions that a hose may be exposed to on a submarine. For these reasons, it's imperative that alternative methods are explored to try and get closer to answering that sixty year old question.

5.4 Integrating Flexhose Maintenance into the Submarine Lifecycle

5.4.1 I-Level Availability Planning

As was mentioned in previous sections, flexhose maintenance is considered I-level maintenance work. As such, if a flexhose is due for replacement, the normal process for scheduling the replacement during an I-level availability is as follows [SUBMEPP, personal communication, January 2022]:

1. Ship's force submits a 2-kilo into the CSMP. If a replacement is not needed immediately, its expected to occur at the next scheduled I-level availability.

2. Replacement requests are submitted to IMA's via the ISIC. In this way, the ISIC acts as a broker between the ship and the IMA for flexhose replacement jobs. Typically, jobs are submitted to the ISIC at least 90 days prior to the beginning of an I-level availability to ensure adequate time for planning

3. A work division conference is held prior to the start of the I-level availability to

determine what jobs can be completed during said availability. It is here that flexhose replacements would be incorporated for completion in the AWP.

4. Flexhose replacements occur during the next scheduled I-level availability. Additionally, the PMR for the replacement is called out in order to reset the date for the next planned replacement at the SUBMEPP level. This updates the CMP and ensures that I-level work is not needlessly considered during D-level availabilities.

5.4.2 D-Level Availability Planning

Although flexhose maintenance is not considered depot level work, there is still a possibility that flexhose replacements will occur during D-level availabilities. There are scenarios where some flexhose replacements are required to be performed during the same time that a D-level availability is scheduled, or where not all replacements could be accomplished during an I-level availability. In these cases, critical flexhoses will only be added to the AWP for D-level availabilities when the TYCOM and the FMA determine they can't be accomplished before or after the availability [SUBMEPP, personal communication, February 2022].

For replacements that occur during D-level availabilities, the TYCOM and ISIC will review the 4.13 index of the AWP, which is a comprehensive listing of all the I-level work that comes due within 6 months of the planned completion date of the next depot availability. This is designed to help TYCOM's understand what I-level work will become due and promote optimal managing and scheduling of the AWP. The TYCOM and ISIC will ultimately make the determination to add some (or all) of those items into the AWP for accomplishment [SUBMEPP, personal communication, February 2022].

In some cases, the ISIC and TYCOM may make the decision to task the FMA to accomplish a concurrent I-level availability in order to complete I-level requirements (such as flexhose replacements), as was the case during SSN 760's recent Docking

Selected Restricted Availability (DSRA). Not all depot availabilities have concurrent I-level availabilities, and it typically depends on a number of factors, including how well the ISIC and FMA schedule and accomplish I-level work before the depot availability, or even the existing relationship between the particular TYCOM and FMA. At any rate, most depot availabilities get the I-level work screened into the AWP at least 12 months prior to the availability start date [SUBMEPP, personal communication, February 2022].

5.4.3 Submarine Lifecycle Maintenance Considerations

When determining appropriate service life requirements for submarine flexhoses, its important to consider the implications for the overall submarine lifecycle. In general, most submarines have a projected service life of greater than 3 decades [25]. After the submarine is built and commissioned, it undergoes sea trials and a Post Shakedown Availability (PSA). At this point, a submarine is considered operational and begins its deployment cycle. Deployment cycles are assumed to be nominally 18 months long, and include training, certifications, maintenance, and about six-month deployments [25]. Various maintenance periods are scheduled throughout a submarines service life, some of which are less intrusive I-level availabilities, and some of which are major D-level availabilities. Once a submarine has completed its service life and all of its respective availabilities, it is decommissioned and inactivated. In some cases, usable components might be re-purposed and distributed to other submarines in the fleet [25]. A generic submarine lifecycle is shown in figure 5-3.

It is advantageous for maintenance planners to understand a submarine's lifecycle for a number of different reasons, but most importantly, to understand how availability scheduling can coincide and compliment specific maintenance items. This is especially true for high volume components, such as flexhoses, whose service life requirements may necessitate replacements in large batches. This requires a concerted and coordinated effort by availability planners in order to ensure timely completion of large volumes of specific maintenance items. One way to accomplish this is to align service

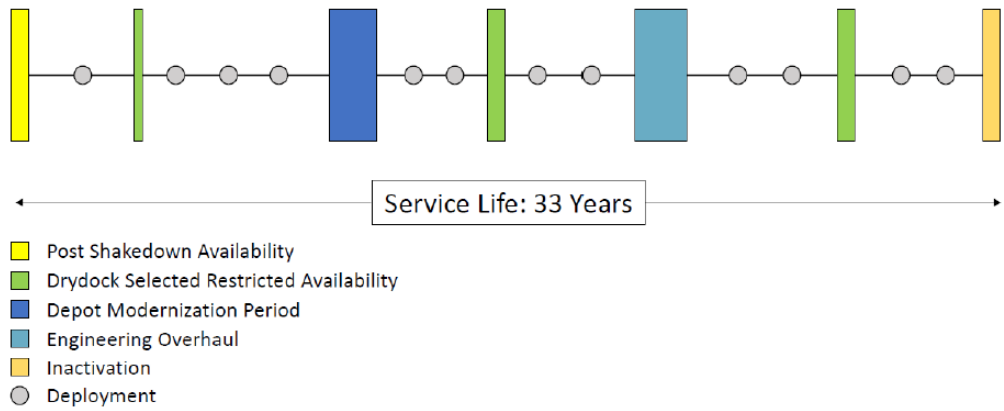

Figure 5-3: Generic Submarine Lifecycle [25]

life requirements with availability schedules.

One of the primary reasons that critical submarine flexhoses remains at 12 years is due to maintenance availability time frames. NAVSEA 05Z acknowledges that a 12 year service life coincides with major availability periods for some submarines (e.g. Los Angeles and Virginia Class). This makes the replacement of a large number of hose assemblies both feasible and cost effective [NAVSEA, personal communication, January 2022]. Additionally, in order to replace a flexhose, you have to remove it from the system. This requires isolating it and/or shutting down the system or part of the system entirely to perform the work. This can be operationally intrusive on smaller platforms, like submarines, that don't have as many redundant hoses built into their systems [NAVSEA, personal communication, February 2022]. During availability periods, systems are inherently shutdown while the submarine is in a non-operational status. This creates opportunity to perform a large volume of replacements at once, and in theory is much more efficient.

The rationale provided above is logical as long as availability schedules remain constant from class-to-class, which may not be the case in the future. Additionally, it disregards the fact that flexhose maintenance is inherently designed to be performed at the intermediate level, and there are smaller I-level availabilities or "refit" periods that occur for some submarine classes (e.g. the Ohio class). Lastly, by assuming that all flexhose replacements will occur during major availabilities, the burden to perform those replacements now falls on the AWP for a given D-level availability, which may already be packed full with other pertinent maintenance items. This fact does not lend itself well to a community who is actively trying to reduce its availability durations.

5.5 Summary

The preceding chapter has generated a number of important insights for the author, some of which have already been captured in prior sections. Most significantly, the submarine flexhose domain is comprised of an intricate and complex system, with relevant stakeholders spread throughout the maintenance enterprise. Additionally, vast amounts of time and money have been spent examining, evaluating and updating policies regarding flexhose requirements. At this juncture, it is evident why SUBMEPP has a continued and vested interested in the topic.

It can be inferred from this chapter's analysis that the policy regarding critical flexhose service life requirements on submarines is one that is primarily based on risk tolerance. NAVSEA 08 and the submarine community have a long and storied history of adopting a "risk averse" stance when developing and implementing their policies and mandates. Couple this with the inherent complexity and dangers associated with the submarine mission, and what results is a very low risk tolerance and stringent maintenance policies. In most cases, zero failures, or very, very close to zero failures, is the only acceptable answer for the nuclear community. In contrast, surface ships have a much higher risk tolerance. Their philosophical approach to flexhose maintenance can be characterized as "fix when fail". They are not as concerned about hose failures and how those may affect the mission. This is clear in their actions, by choosing to use PMS to extend their critical service life requirements to 20 years.

That said, the author submits that technical directives like the TED-010 must not remain static, otherwise they risk becoming useless over the years. Such documents should remain abreast of contemporary technology and account for the changes that are occurring both at the deck plate and the fleet level. It is also fair to say that there has not been any rash of failures to submarine flexhose assemblies because of the robust maintenance philosophy that has evolved over the last sixty years.

However, there has been a multitude of changes to the maintenance philosophy for flexhose assemblies, and the topic of flexhose service life has been highly scrutinized and challenged in both the Naval submarine and surface communities for decades. The desire to mitigate cumbersome work practices, reduce availability man-hours and achieve availability cost savings have remained the primary driving factors for continued evaluation of flexhose service life policy. As was highlighted in section 5.3.6, while multiple extension efforts and service life reviews have been conducted over the years, none have focused on the length of time critical and non-critical hoses are actually lasting based on robust, quantitative replacement data. Further, none have exclusively focused on submarine flexhoses, which are inherently exposed to different operational conditions compared to a surface vessel. Inasmuch, additional data analysis pertaining to flexhose replacement frequency is warranted to ensure that all variables are considered when developing flexhose service life policy for both current and future submarine classes.

Chapter 6

Flexible Hose Case Study - Service Life Evaluation

It was identified in the previous chapter that, despite multiple flexhose service life extension studies occurring over the previous thirty years, no studies have exclusively focused on the length of time critical and non-critical submarine flexhoses are actually lasting in service and what kind of associated cost savings can be realized by extending their service life. Additionally, it is clear that there has been a lack of parity between surface ships and submarines regarding the extent to which technical flexhose requirements, such as service life, have been examined and challenged over the years. This illuminates an obvious gap that can be filled in the form of a robust analysis of flexhose replacement frequency data. The following chapter will describe the data mining, data cleaning, and data processing methods used to collect and analyze available flexhose replacement data. Ultimately, results are obtained and utilized to draw additional insights and conclusions regarding submarine flexhose service life policy.

6.1 Flexhose Data Mining

The first step in the data evaluation process involved collecting data that was relevant to the study, or the "right data". Data pertaining to Naval submarine maintenance is hosted on a variety of different software systems and programs, and sometimes relevant data may even be spread across multiple software infrastructures or programs. There are also various security requirements involved in extracting and handling much of the data that comes out of the submarine maintenance enterprise system. This can make it time consuming and/or difficult to collect the representative data that one needs for follow-on analysis. For this study, submarine flexhose replacement data, consisting of replacement frequency and cost, formed the underlying foundation. As such, it was important to understand what resources were available internal to the submarine maintenance enterprise that could provide some or all of the pertinent information required for the study. By working with personnel from SUBMEPP, the author was able to ascertain what data resources were available and how they could be exploited for the purposes of this study.

6.1.1 Maintenance and Ship Work Planning (M&SWP) Data

The primary data resource for this study was the Navy's M&SWP application. M&SWP is the core business application for class maintenance planning for the three Navy Maintenance Planning Activities (MPA), including SUBMEPP. M&SWP houses and maintains the CMP for all Navy combatants, submarines, surface ships and aircraft carriers [SUBMEPP, personal communication, February 2022]. The CMP consists of thousands of planned maintenance requirements per ship class paired with accurate ships configuration, ship's lifecycle availability schedule and complex scheduling logic. This allows MPAs to produce an AWP and project lifecycle maintenance cost for the Future Years Defense Program (FYDP) and over a ship's lifecycle. M&SWP also records all I and D level maintenance accomplishments, which allows SUBMEPP to maintain an accurate maintenance schedule. M&SWP contains millions of component maintenance requirements and directly supports availability planning efforts, material readiness and expected service life while helping minimize total ownership costs [SUBMEPP, personal communication, February 2022].

Since flexhose replacements are PMRs part of the CMP and considered I level maintenance, the M&SWP application tracks all accomplishments. As such, it can be queried to extract all records pertaining to flexhose replacements occurring in the submarine community. This includes replacements conducted at every I level and D level maintenance facility within the submarine enterprise, across every submarine class, dating back to 1980.

It's important to note that M&SWP houses all I and D level maintenance accomplishments, not just accomplishments related to flexhose replacements. Additionally, one maintenance record can be comprised of over 150 different data elements pertaining to that individual record. As such, additional processing was required to capture maintenance solely related to flexhoses. Unfortunately, there is no simple "click of a mouse" that outputs that specific data. Instead, data elements unique to flexhose maintenance needed to be filtered so that the raw data being examined consisted only of flexhose maintenance items.

One of the data elements internal to M&SWP is the Group Component Code (GCC). This is a six character alphanumeric code that corresponds to a high level description of what component a given maintenance action is being performed on (e.g. "Pump", "Ball Valve", "Lagging", etc.) [SUBMEPP, personal communication, February 2022]. Hoses utilized in the submarine community have their own unique GCC which was utilized to query for all hose specific maintenance accomplishments in M&SWP. This resulted in 197,779 records for examination, and provided the starting point for data cleaning and examination processes. The records were exported to a Microsoft Excel® workbook for external processing.

6.1.2 Work Integration and Scheduling Program (WISP) Data

The WISP is a Structured Query Language (SQL) based platform used by the New London IMA to manage all execution maintenance and improve the scheduling and coordination of jobs and work tasks for their I-level maintenance. Specifically, WISP provides accurate data on the expenditures of resources and material, work flow variances, and process inefficiencies to support continuous process improvement and their concomitant cost savings [SUBMEPP, personal communication, March 2022]. WISP was used for this study to collect data related to the cost and man-hours associated with specific flexhose replacement jobs. Flexhose specific data was queried for by searching the WISP database for jobs that contained flexhose National Item Identification Numbers (NIIN). Flexhose NIINs were obtained from the QPL for the two flexhose MIL-SPECs listed on the Defense Logisitics Agency (DLA) quick search website. If a particular job contained a flexhose NIIN, it was added to a database that was eventually exported to a Microsoft Excel® workbook for external processing.

It should be noted that New London only represents 1 of 7 total submarine IMA activities across the country. However, following consultation with SUBMEPP, it was determined that New London's execution maintenance data was the most accurate and complete data available for the purposes of this analysis. Further, the flexhose replacement data obtained from the New London's WISP should not diverge much, if at all, from the other IMA's across the country. For these reasons, it was deemed acceptable to continue with the analysis using only New London IMA replacement data.

6.2 Data Cleaning

The second step in the data evaluation process required cleaning of the data to the point that it was in an interpretable and manageable condition for the analysis required for this study. While data from WISP was in adequate pre-existing condition and did not require additional cleaning, the same could not be said for data from

M&SWP. The following sections review the raw state of the M&SWP data as well as the filters that were required to clean the data to an adequate level.

6.2.1 Raw State of M&SWP Data

It was outlined in the previous section how the GCC was used to query for all hose related maintenance records. An important distinction in that sentence are the words "all hose related records". The GCC provides a means to capture all records pertaining to a particular component, not just "replacements". That means that the records in the initial raw database consisted of other maintenance items as well (e.g. clean and inspect, hydrostatic testing, calibration, repair, replace, etc.). Furthermore, the GCC that was used to query for the initial records pertains to any type of hose used in the submarine community. As was alluded to in Chapter 4, there are many different types of hoses employed by the Navy, not just synthetic rubber flexhoses. This study concentrates specifically on the service life of synthetic rubber flexhoses.

Beyond these pressing issues, the Excel® workbook that was initially extracted from the larger M&SWP database was very dense and consisted of over 150 different elements for each individual record. Many of these elements were considered esoteric, and didn't have any relevance to the study at hand. There was also very little organization within the data elements that were included, and most elements were labeled in such a manner that required additional investigation from the author and/or SUBMEPP representatives in order to determine what an element abbreviation meant or what a particular element was describing or used for. Needless to say, there was a steep learning curve associated with the initial raw M&SWP data file and extensive data cleaning was required to ultimately ascertain insightful results.

6.2.2 M&SWP Data Filters

The raw state of the initial M&SWP file necessitated the use of an abundance of filters to remove records that were inapplicable or unusable for this study. Those filters are described in detail below:

- **Duplicate Records**: For reasons beyond the scope of this study, M&SWP contains duplicate records of many of it's maintenance accomplishments. The major data elements used to differentiate records in this study were the submarine platform number, the flexhose being replaced on that platform, the system that specific flexhose came from on the platform, and the actual completion date of the maintenance action. Using these four elements, duplicate records could be filtered from the Excel® workbook to ensure the same maintenance action wasn't being captured multiple times during follow-on processing.

- **Completion Last Maintenace Action (LMA) Date**: Completion LMA data is the primary data element of concern in this study, and integral to the studies accomplishment. It represents the date that an individual maintenance action was completed, and can be used to reconcile the maintenance life cycle for a given flexhose on a given submarine platform. However, upon inspection it was clear that there issues with some records regarding completion LMA dates. Some records had dates years in the future, some had dates in the past that were impossible (i.e. a Virginia class record having a completion LMA data in 1997, when the first Virginia class boat didn't commission until 2003), and some records were missing dates entirely. Unfortunately, any of these issues rendered a given record unusable, and needed to be filtered from the database.

- **Hose Type**: There were multiple types of hoses that were not applicable to the scope of this study, but were found in the raw MSWP Excel® file. Examples included metal, teflon, thermoplastic, polytetrafluoroethylene (PTFE), OEM and stowed hoses. Unfortunately, M&SWP did not contain any material codes to filter these records out. However it did contain a maintenance requirement description element, which was essentially a plain text description of the work being conducted for that maintenance record. These descriptions also provided the required granularity to ascertain the type of hose being replaced, and could be used to filter out inapplicable records.

- **Maintenance Action Code**: It was previously mentioned that the raw database consisted of not only flexhose replacement records, but any maintenance action records pertaining to flexhoses. In order to remove inapplicable records from the analysis, a data element called the Maintenance Action Code (MAC) was utilized. The MAC is a 4 character alphanumeric code that corresponds to the "maintenance action" a given maintenance requirement requires to be performed [SUBMEPP, personal communication, February 2022]. "Replace", "Repair" and "Clean and Inspect" are some examples of these actions. In addition, there may be multiple MACs that correspond to one maintenance action. The author was able to work with SUBMEPP to decipher which MACs were applicable so that only replacement records for synthetic rubber flexhoses remained.

- **Platform Type**: For consistency purposes, only active submarine class records were examined in this study (e.g. 21, 688, 726 and 774 classes). However, in addition to active submarine flexhose records, M&SWP also contained flexhose records from submarine classes that have been completely decommissioned, as well as training facility prototypes. Retired platforms were assessed to provide very little relevant data for the purposes of this study and training platforms are not exposed to the same operational conditions as active submarines. For these reasons, they were also excluded from the cleaned Excel® file.

- **Planned Periodicity**: Another data element of importance to this study is the planned periodicity for a given record. This details how often any maintenance action is required to be completed, and is based on requirements outlined for the PMR in the CWP. The planned periodicity is useful for a number of reasons, which will be explained in further detail in later sections. For the purposes of data cleaning, it can be used to discriminate between flexhose replacement records. Specifically, this study is focused on records that conform to current TED-010 service requirements (e.g. 12 year replacements for critical TED-010 hoses, and no requirement for non-critical TED-010 hoses). Any other service life identified in the MSWP database is either derived from RCM requirements or pertains to other equipment. Both are outside the scope of this study and were filtered out.

Table 6.1 summarizes the amount of records removed and the cumulative records remaining in the database after each filter was applied to the database.

Filter	Records Removed	Cumulative Records Remaining
Duplicate Records	137,175	60,604
Completion LMA Date	6,553	54,051
Hose Type	2,153	51,898
Maintenance Action Code	4,238	47,660
Planned Periodicity	1,193	46,467
Platform Type	429	46,038

Table 6.1: Data Cleaning Filters and Corresponding Record Removal

6.3 Data Processing

Upon cleaning the data, additional processing was required in order to transform the data into a state that was readily interpretable and capable of being analyzed for the purposes of this study. The following sections discuss the methodologies that were employed in Excel® and MATLAB® to achieve that state. Additional assumptions and limitations regarding the data examination are also outlined.

6.3.1 Assumptions

The usefulness of the results of this study is largely a function of the quality of the data that was supplied as the input. As such, assumptions were necessary in order to conduct the follow-on study, and those assumptions are outlined below.

1. **The data examined is both accurate and complete.** It is assumed that the data extracted from the M&SWP and WISP databases fully captures all flexhose replacements that have occurred in the submarine community, and information contained therein is accurate, including completion LMA dates and

associated costs.

2. **Service life times are independent.** There are likely many covariates that are of interest to the Navy when analyzing flexhose replacement data. Most of those are beyond the scope of this study, and distinguishing idiosyncrasies from hull-to-hull are not considered in the evaluation of service life.

3. **TED-010 service life policy was implemented correctly on every hull.** As outlined in Chapter 5, flexhose service life policy has changed over the years. It is assumed that policy regarding flexhose service life requirements was enacted on every submarine, for every flexhose, at the date the new policy was promulgated.

4. **All flexhoses that have been replaced are currently still installed.** Unless a submarine has been decommissioned, it is assumed that every flexhose that has been replaced on a given submarine is still installed as of the date of analysis, March 9th, 2022.

5. **Ship alterations that have affected a given flexhose are accounted for.** It is assumed that any ship alteration that has affected or modified flexhoses, across all submarine classes, is accounted for in the M&SWP data (i.e. naming conventions are consistent for a given hull number throughout the life of the flexhose).

6.3.2 Limitations

There are some inherent limitations associated with this study that must be highlighted prior to conducting any type of analysis. Those limitations are outlined below.

- **Criticality Determination**: One of the primary independent variables in this study is the criticality of the flexhose being examined. Criticality determines service life requirements, and thus is directly related to the length of service for a given flexhose. Unfortunately, M&SWP does not directly provide criticality information for its flexhose records. However, it does provide "Planned Periodicity" and "Situational Periodicity" information, which are indications of the periodicity requirements for a given flexhose. Together, both of these data elements can indirectly imply the criticality of a given component, based on the service life requirements outlined in section 4.4. The details of this are explained further in section 6.3.3. Nonetheless, the only way to directly determine criticality of a given flexhose is to examine every flexhose drawing for every submarine in each class, as well as applicable Maintenance Requirement Cards (MRC), and individually identify criticality on a component-by-component basis. This was impossible given the time constraints of the project, and so criticality was indirectly inferred.

- **Flexhose Operational Time**: As was outlined in Chapter 5, submarine lifecycles require multiple maintenance availabilities throughout their duration, and these availabilities can last anywhere from 1 to 3 years typically. During availabilities, it is common (and often required), to shut entire systems down so that maintenance can be performed by personnel in a safe manner. When this occurs, the components that comprise that system are put into an Inactive Equipment Maintenance (IEM) status, including flexhoses. What this means is that the components are in a non-operational status, and no longer enduring the typical operational conditions that system imposes. The effect this has on the overall service life of a flexhose is unknown, and outside the scope of this study. As such, this examination of exhibited service life for flexhoses does not take into consideration how often or how long a given flexhose is non-operational during its lifetime. To take non-operational time into account would require reconciling the lifecycle of every single submarine with the given M&SWP data, which would take significant time and effort beyond the abilities of the author given the time constraints of this project. For these reasons, operational status is not considered when determining the service life of any flexhose.

- **Lack of Failure Data**: The author's original ambitions for this study consisted of performing a survivability analysis of flexhoses, similar to the methodology outlined in [25]. However, after receiving the data, it soon became clear that M&SWP lacked the necessary granularity to perform higher fidelity analysis. Specifically, despite over 150 elements of data per record, there was no element that indicated the cause for replacement (e.g. periodicity, failure, scheduling, etc.). Further, even if there were an element that identified the cause, chapter 5 served to illuminate the fact that there are multiple types of failures for flexhoses, and most often, catastrophic failure of the hose itself is not the primary mechanism of failure. While some failure information is available via information provided from CSMP records, it was noted by NAVSEA in chapter 5 that those records are highly subjective based on the person inputting the information, and most often lack the detail required to make any sort of practical engineering assessment. Additionally, some CSMP records either don't highlight the actual hose that requires replacement or use one CSMP entry to cover multiple hoses. Ultimately, it would be near impossible to reconcile CSMP records with M&SWP records, given the sheer volume of records and the lack of granularity in the data sources. It would also require many assumptions to be made that very likely would not be near enough accurate to make sound engineering conclusions. For these reasons, the cause for replacement, including failure, is not considered in this analysis.

6.3.3 Methodology

The overall goal of this analysis is to understand the frequency with which critical and non-critical TED-010 flexhoses are being replaced in the Navy based on replacement records extracted from the M&SWP database. As highlighted in the previous section, the criticality of a component was not provided by the mined data. Additionally, while M&SWP records do provide the dates of replacement for flexhoses, they do not provide the service life of the flexhose at the time of the replacement. This requires additional reconciling between records that consist of the same submarine hull, flexhose system, and flexhose component. The analytical tools Excel® and MATLAB® were utilized to help derive the required information. Those processes and logic are described in detail in the following subsections.

Criticality

Criticality of a flexhose replacement record was determined using two data elements, "Situational Periodicity" and "Planned Periodicity (In Months)". At this point, it has been clearly defined that on submarines, TED-010 non-critical flexhoses have no prescribed service life requirement. Instead, non-critical flexhoses adhere to CBM. As such, non-critical flexhoses are only replaced if they are degraded to a concerning point or have failed, based on inspections that occur every 24 months. For this reason, non-critical flexhoses fall under the situational maintenance category, and would be marked with an "R" in the "Situational Periodicity" element within M&SWP. "R" stands for "As Required".

Critical TED-010 flexhoses are required to be replaced every 144 months. As was mentioned in section 5.3.5, there are some flexhoses that have more restrictive service life requirements (e.g. 66 or 84 months), based upon RCM analysis. Those flexhoses don't conform to normal TED-010 requirements and were disregarded from the study. However, it can be inferred that any records with a "Planned Periodicity" of 144 months are critical.

Using nested IF functions in Excel®, criticality for each record was determined in accordance with the logic depicted in figure 6-1 below.

Planned Periodicity

The data extracted from the M&SWP database spans all the way back to 1980. It was previously highlighted in Chapter 5 that the policy for flexhose service life has evolved over the years, with significant changes coming in 1995 and 1997. It was also evident upon examination of the extracted data that these requirements were retroactively updated in the M&SWP database. This means that if a flexhose has a current

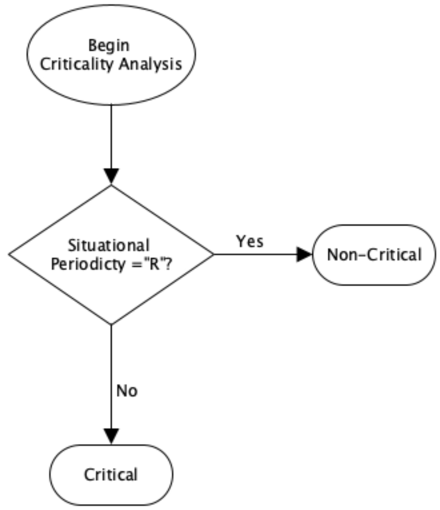

Figure 6-1: Criticality Determination Logic

periodicity of 144 months, all instances of replacement for that specific flexhose also had a periodicity of 144 months, even if they occurred prior to 1997.

Using nested IF/AND functions in Excel®, the required periodicity for the time period the replacement occurred in was applied in accordance with the logic depicted in figure 6-2. In this way, service life comparisons to required periodicity in follow-on analysis could yield more accurate results.

Service Life Determination

The primary output of this study is the service life, or age, of a flexhose upon replacement. As previously stated, M&SWP does not indicate age of a component at replacement. The only information provided is the date of the replacement for a given flexhose. Along those same lines, the extracted data does not account for the current age of any flexhose. For example, if the last replacement for a specific flexhose on SSBN 741 was identified as January 5th, 2010, there is no record to account for the current age of that hose (i.e. 12 years). Inasmuch, the current age of any flexhose installed on a submarine must be captured in a service life analysis in order to ensure the utmost accuracy when drawing conclisions regarding service life.

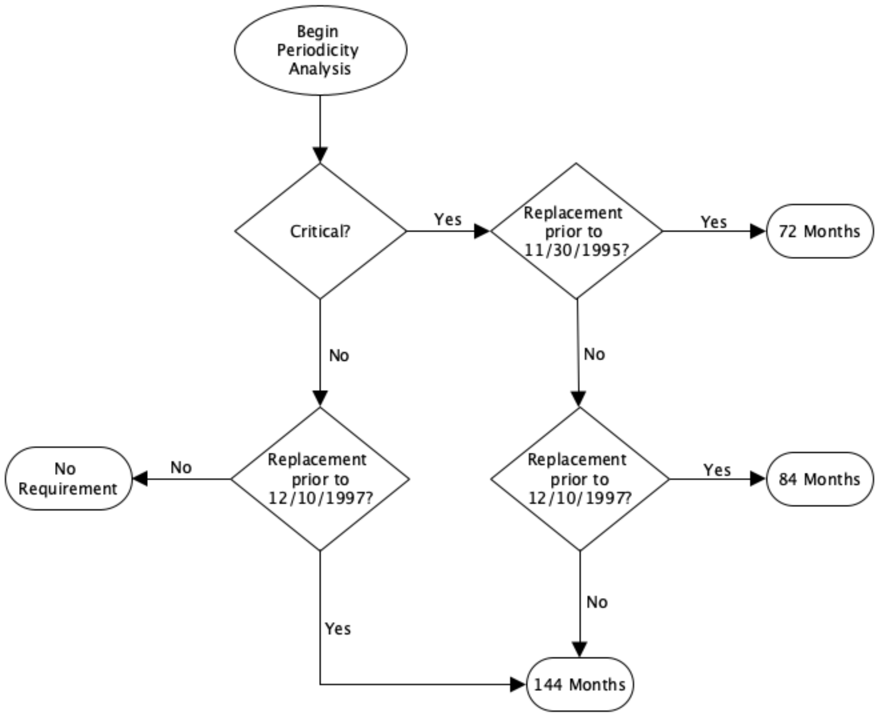

Figure 6-2: Required Periodicity Determination Logic

The first step in the overall service life determination process involved capturing the current age of installed flexhoses. This required incorporating additional replacement records into the data file, with a new "Completion LMA" date corresponding to the date of analysis, March 9th, 2002. This was accomplished by copying the last chronologically unique instance of a flexhose replacement (based on the hull number, flexhose system, flexhose component, and completion LMA date), and updating the completion LMA date for that new "last" record to the date of the analysis. For submarines that have been decommissioned, the decommissioning date was imported into Excel® and was used for the date of the last record. In this way, the periodicity and criticality of a given flexhose were assumed to remain the same, and analysis for the current age of the component could follow. MATLAB® was used to perform these operations.

Following the addition of the new "last" records, reconciling of unique combinations of hull number, flexhose system, and flexhose component could begin. This required first creating three new data elements: "Occurrence", "Occurrence Note" and "Length of

Service". Occurrence is the order of occurrence for a replacement record belonging to a unique flexhose combination. For example, if there was a flexhose on SSBN 741 that was replaced 3 times over the course of its life, in 1995, 2003, and 2012, the 1995 replacement "Occurrence" would be labeled as "1", 2003 labeled as "2", and 2012 labeled as "3". This was a necessary first step in order to later determine the length of service. Occurrence note was generated in order to identify the first and last records for a unique flexhose combination. Using the same example, the 1995 replacement was labeled as "first" and the additional record that was added in for the date of analysis (March 9, 2022 since 741 is not decommissioned) was labeled as "last". This is important for a number of reasons, but most significantly it helps with filtering when conducting follow-on analysis, especially since first records don't have any age associated with them and instead start the clock on a lifecycle. Length of Service (LOS) is simply the time that has elapsed from one replacement occurrence to the next for a unique flexhose combination.

Once all unique flexhose combinations were reconciled and sorted in order of occurrence, a MATLAB® script was generated to determine the LOS between each flexhose replacement, for every unique combination of hull number, flexhose system, and flexhose component. The full MATLAB® script can be found in Appendix A. Upon determining the value associated with occurrence, occurrence note, and LOS for every unique record, a new data file was exported to Excel® for follow-on processing and analysis using Excel® embedded pivot tables. The logic implemented for the service life calculation is depicted in figure 6-3.

Deviation from Periodicity

The final step in the data processing phase was to determine the deviation from required periodicity for each individual record. Deviation helps gain a better understanding of the magnitude of critical service life deviation from the required periodicity, as well as trends that may be occurring with regards to critical flexhose replacements. Inherently, there is no deviation associated with non-critical records.

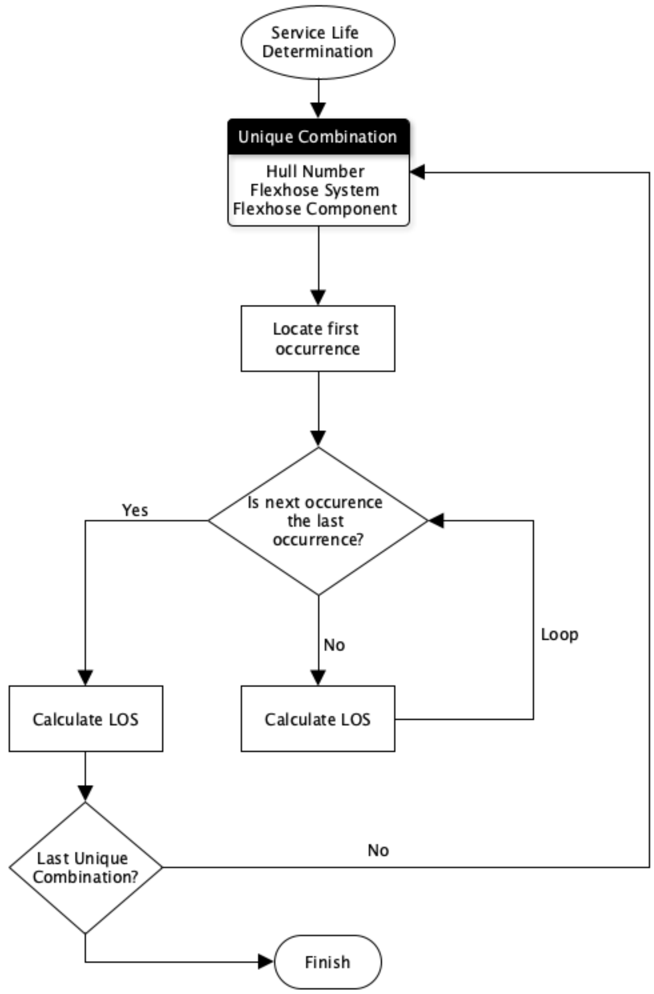

Figure 6-3: Service Life Determination Logic

Critical record deviation from planed periodicity was determined utilizing the following equation: Deviation = LOS - Planned Periodicity.

6.4 Results

The following sections will review the results obtained from the analysis methodology that has been previously outlined. A holistic baseline of the data is provided first in an effort to adequately identify both the bounds of the data, as well as to ensure the data is portrayed in the most accurate manner possible. Results are then broken down by criticality, submarine class and flexhose parent system in order to identify any additional trends. Lastly, a brief cost analysis is provided and compared to historical assumptions for greater fidelity.

6.4.1 Baseline

Following all data cleaning and processing, 46,038 replacement records remained for review. The MATLAB® program generated an additional 26,498 "last" records, which accounted for the LOS of all flexhoses currently installed on submarines (as of the date of analysis), as well as the final LOS for flexhoses on submarines that were decommissioned prior to the date of analysis. In total, 72,536 flexhose records were available for review by the author. Of that total, 26,498 were labeled as "first" records. These records do not have an associated LOS, and were simply used to start the clock on the first LOS that was determined for a unique flexhose on a given submarine. A summary of these statistics are provided in table 6.2 below, including the total amount of records that have observable LOS pursuant to this analysis.

Record Type	Amount
First	26,498
Middle (Any)	19,540
Last	26,498
Total Records	72,536
Total Observable LOS	**46,038**
Critical	**32,181**
Non-Critical	**13,857**

Table 6.2: Flexhose Replacement Record Types and Counts

In total, the flexhose replacement data covers records from 92 different submarines, spread across the four active submarine classes (21, 688, 726 and 774). Of those 92 submarines, 24 were decommissioned prior to the date of this analysis. Further, 11 submarine's records were not provided in the original M&SWP data, challenging the assumption that the data was complete and accurate. The records that weren't provided consisted solely of decommissioned, 688 (LOS ANGELES) class submarines.

726 (OHIO) class submarines comprised nearly 50% of the total data. A percentage breakdown of the different submarine classes replacement records can be seen in figure 6-4

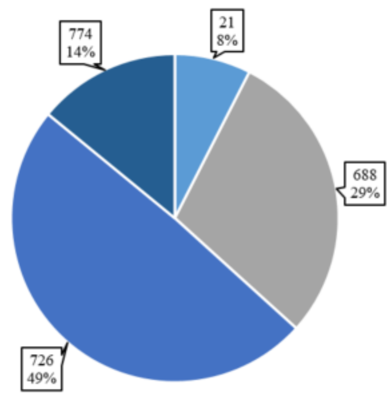

Figure 6-4: Percentage Breakdown of Replacement Records by Submarine Class

Table 6-5 provides a count of replacement records by criticality. The difference in magnitude is consistent with the submarine community's philosophy of replacing critical flexhoses more frequently, with critical flexhoses comprising 64% of all replacement records in M&SWP.

Criticality	Count
C	46,244
NC	26,292

Figure 6-5: Flexhose Replacement Record Frequency by Criticality

In addition to spanning four different submarine classes, the replacement records represent flexhoses internal to 100 different submarine systems. The system that incurs replacements most often is Electronic Auxiliary Fresh Water Cooling (EAFW) on the 726 class, with a total of 7651 replacement records. The Chill Water (CW) system on the 688 class had the least amount of replacements, with 4 total.

Lastly, it was noted in Chapter 5 that a major flexhose service life extension program took place between 1993 and 1997 that resulted in critical flexhoses being extended to

144 months for their required periodicity, and non-critical flexhoses were only required to be replaced upon a failed inspection. As such, it was prudent for the author to understand the volume and fidelity of data before and after the new guidance was implemented in the TED-010.

The cleaned and processed M&SWP data file contained 13,951 records occurring prior to December 10th, 1997, and 58,585 records that occurred after the same date. Additionally, all of the 11 submarines whose records were missing from the original file were commissioned prior to 1983, and have since been decommissioned. Further, more than half of those submarines were decommissioned prior to contemporary flexhose service life guidance being implemented in December 1997. Following consultation from NAVSEA and SUBMEPP regarding lack of record availability prior to 1998, coupled with conflicting service life guidance, the decision was made to partition the data further into different time periods. Replacements occurring prior to 1998 were separated from replacements occurring since 1998. In this way, a more accurate representation of how flexhoses are performing with respect to contemporary service life guidance could be solicited.

6.4.2 By Criticality

As a first step, figure 6-6 can be used to visualize the spread of the data in terms of LOS. As can be seen in the figure, the data approximates a slightly skewed normal distribution, with the bulk of the records falling somewhere between 9 and 15 years old. The histogram also illuminates the existence of about 286 records which are greater than 30 years old, and can likely be considered outliers. All but six of these records are non-critical hoses, so it is reasonable to assume these hoses could potentially have an LOS equivalent to what the record is indicating. However, the critical hoses in these outliers are likely indicating such a high LOS due to a missing record, and thus were removed from the analysis.

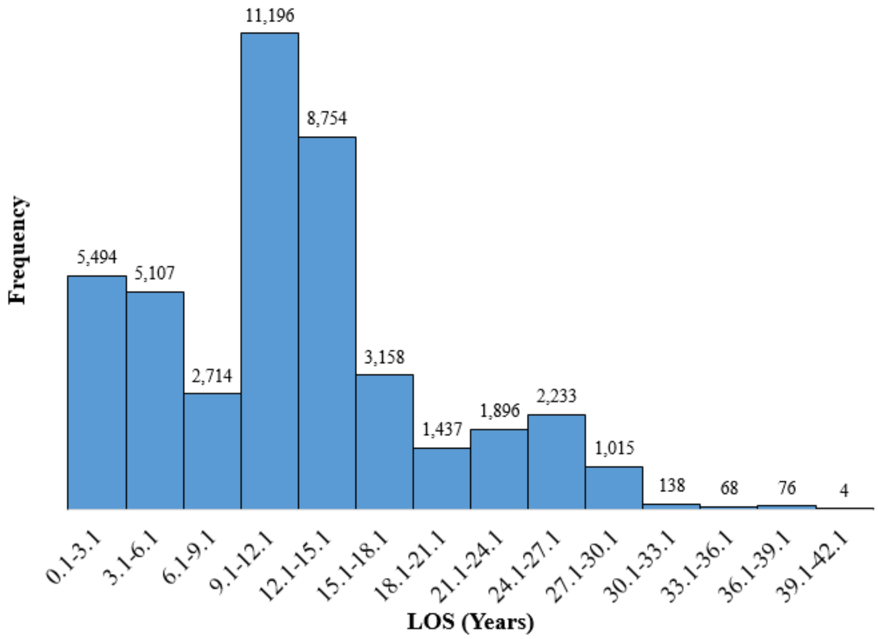

Figure 6-6: Frequency Histogram for Observable LOS Records (In Years)

Table 6.3 provides a summary of the average and standard deviation of LOS in both months and years, broken down by criticality for all records with an observable LOS. In this context, standard deviation is simply a measure of how widely the values of LOS vary from the average. It can be seen from the table that average LOS for critical flexhoses is about 2 years less than the current prescribed length, and average LOS for non-critical hoses hovers slightly above 16 years old.

	Average of LOS (Months)	Average of LOS (Years)	StdDev of LOS (Months)	StdDev of LOS (Years)
C	119.38	9.95	61.87	5.16
NC	194.43	16.20	104.96	8.75
Average	**141.66**	**11.80**	**84.49**	**7.04**

Table 6.3: Average and Standard Deviation LOS by Criticality

One can further break down the average LOS as a function of time, for both critical and non-critical flexhoses. Figure 6-7 utilizes a dual line chart to demonstrate how the average LOS has changed each year since 1998 for TED-010 hoses. Of note, non-critical LOS lagged critical LOS for nearly 18 years after the new service life requirements were promulgated at the end of 1997. A spike in non-critical LOS is then exhibited starting in 2017, approximately 20 years later. It follows that many of the non-critical hoses were likely replaced during the transition period or shortly thereafter (based on availability schedules) to keep things clean and easier to manage in the future. As such, the spike that's exhibited in the graphic is indicative of the likely true service life of Naval flexhoses.

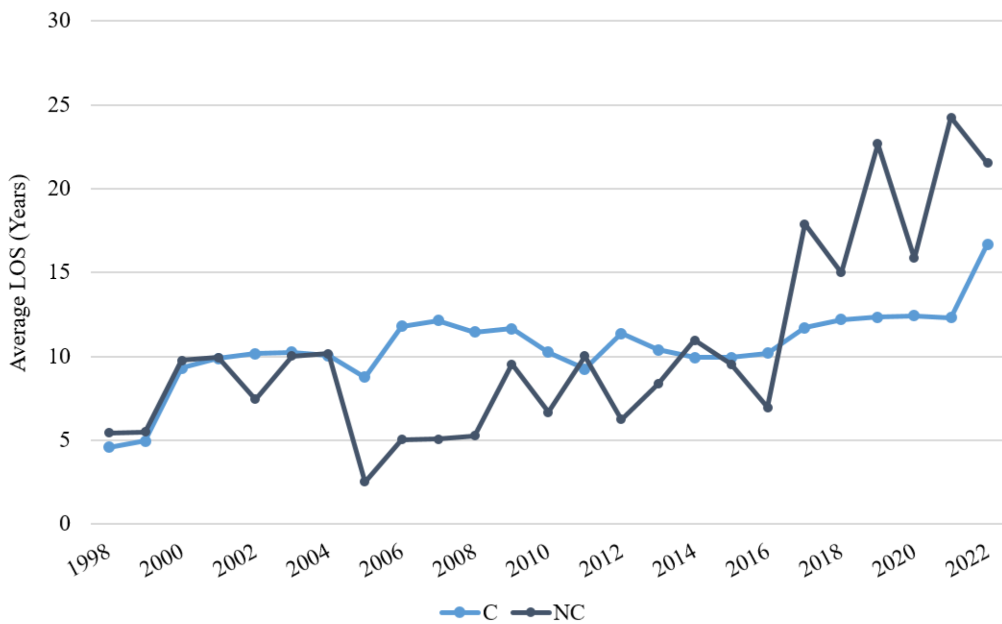

Figure 6-7: Average LOS as a function of Criticality Over Time

It was noted during the analysis that there are a number of censored records. In this case, censored records refer to flexhoses that are currently installed as of the date of the analysis, and whose age is less than 12 years old. These flexhoses have not been installed long enough on their respective submarines to determine if they would last for the prescribed service life (or longer in the case of non-critical flexhoses). In fact, there are 12,367 total records that meet this criteria when considering replacements that occurred after 1997. These types of records inherently bring the average LOS down. To satisfy academic curiosity, the censored records were filtered out, and the preceding analysis was re-ran. Summary statistics are provided in table 6.4. Average LOS for critical flexhoses increases by about two years, and by about 4 years for non-critical flexhoses.

	Average of LOS (Months)	Average of LOS (Years)	StdDev of LOS (Months)	StdDev of LOS (Years)
C	143.32	11.94	52.46	4.37
NC	241.26	20.11	82.00	6.83
Average	**172.61**	**14.38**	**77.14**	**6.43**

Table 6.4: Average and Standard Deviation of LOS by Criticality (Censored Records Removed)

Figure 6-8 depicts the general types of deviation behavior exhibited by the critical replacement records. "Over" refers to the total amount of critical records with LOS greater than planned periodicity, while "under" refers to the total amount of critical records with LOS less than planned periodicity. Overall, the average over-run for critical records was determined to be 2.59 years, while the average under-run was determined to be -4.89 years.

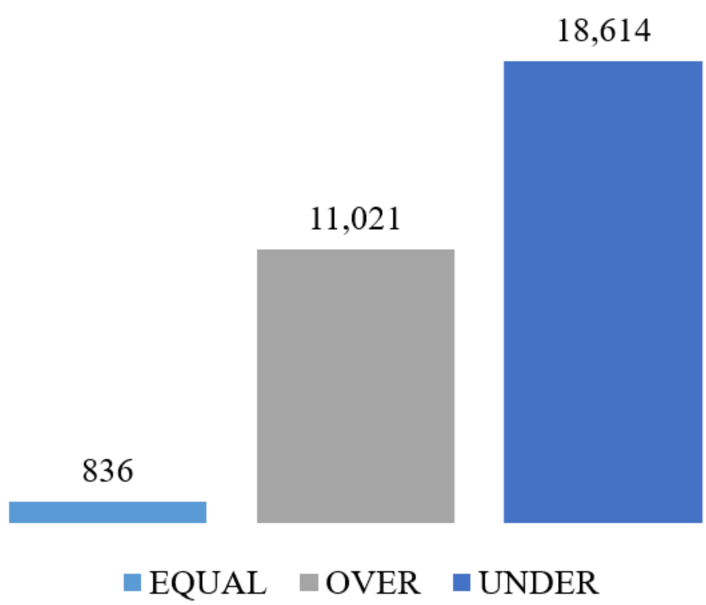

Figure 6-8: Summary of Deviation Behavior for Critical Flexhose Replacements

After removing censored records, the same graph can be reproduced, as seen in figure 6-9. In this case, the average over-run for critical replacements remains the same, but the average under-run decreases to -3.03 years.

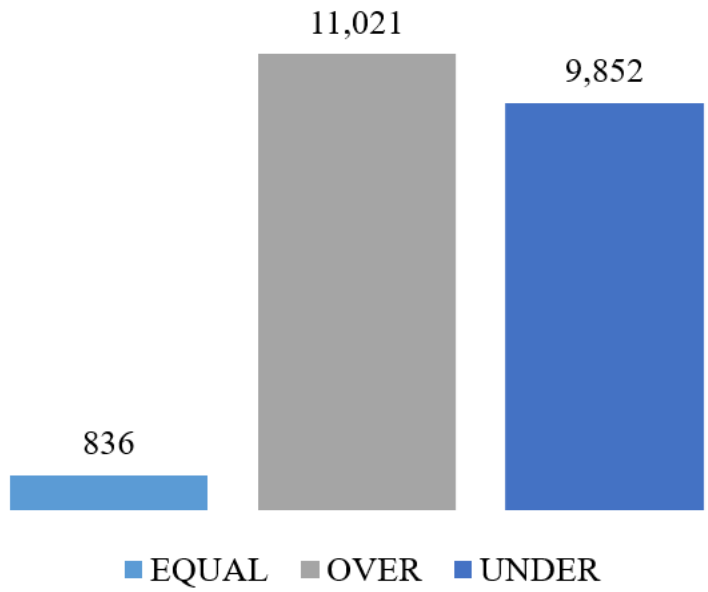

Figure 6-9: Summary of Deviation Behavior for Critical Flexhose Replacements (Censored Records Removed)

More interesting, over 21% of critical records with observable LOS have a deviation greater than 1 year, and over 15% have a deviation greater than 2 years. Additionally, there were approximately 1200 critical records spread across 64 different hulls with deviations greater than 6 years, or 50% beyond the required periodicity for replacement. While this is hypothetically possible, it is unlikely that so many critical flexhoses would lapse required periodicity by such a large magnitude, and further challenges the assumption that the records are complete and accurate. A summary of deviation statistics for critical records is provided in table 6.5

6.4.3 By Submarine Class and Hull Number

Figure 6-10 is a graphic depiction of the average LOS for critical and non-critical flexhoses, partitioned by submarine class.

Deviation	Percentage of
>+1 year	21.8%
>+2 years	15.3%
>+3 years	9.9%
>+4 years	6.9%
>+5 years	5.5%
<-1 year	16.6%
<-2 years	11.6%
<-3 years	10.5%
<-4 years	9.9%
<-5 years	8.8%

Table 6.5: Summary of Deviation Statistics (Censored Records Removed)

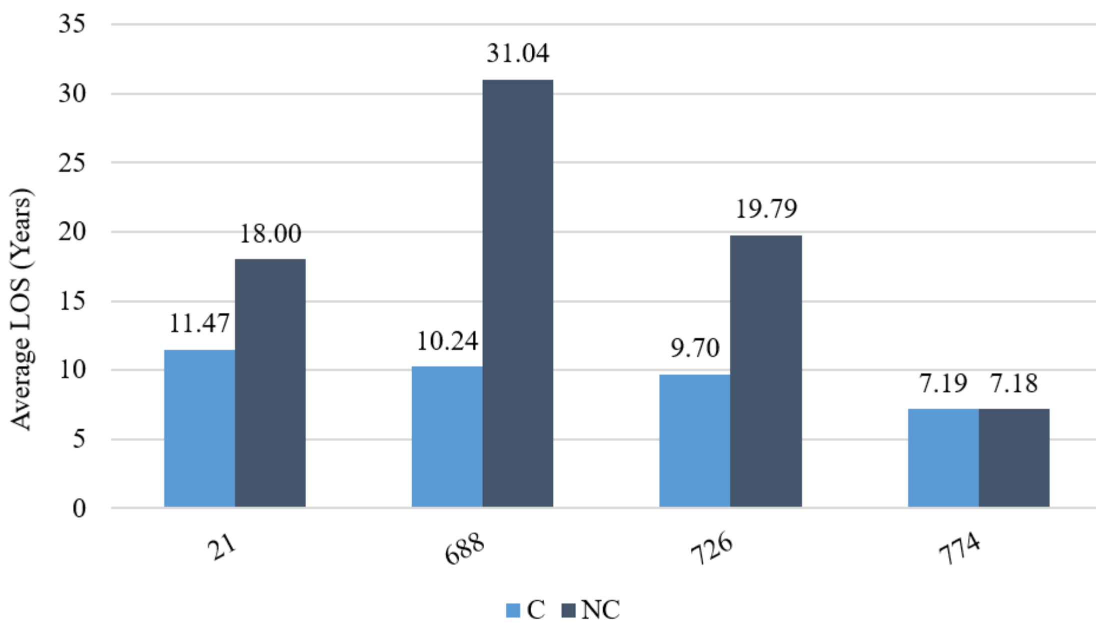

Figure 6-10: Average LOS for Critical and Non-Critical Flexhoses by Submarine Class

There are a few notable insights and trends that can be ascertained from the bar chart. First, 774 (VIRGINIA) class submarines have significantly lower average LOS values compared to their other class counterparts. This makes sense, given that the first 774 class submarine wasn't commissioned until 2004, and there are less than 20 currently in service. Drilling deeper in the data illuminates further key findings:

- The first non-critical 774 flexhoses were not replaced until 2016, 12 years after they were first installed on the Virginia.

- From 2019-2021, the average critical and non-critical LOS were both 13.1 years, demonstrating and up tick in LOS as 774's accumulate more data and become older.

Additional key insights comes by way of examining the running average LOS of 726 and 688 class submarines, who provide 78% of observable LOS data. Figure 6-11 displays a clear trend of increasing LOS from 1998 to present day for 726 class submarines, amongst both critical and non-critical flexhoses. Again, the spike observed starting in 2017 for non-critical hoses is indicative of true service life being reached by non-critical flexhoses, given the elapsed time since the last service life policy change for those hoses.

Figure 6-12 helps elucidate the first key shortcoming of the data analysis methodology employed. As was mentioned in previous sections, criticality was indirectly inferred from the "Planned Periodicity" data element. It can be seen in the graph that non-critical replacements were not recorded for 688 submarines until 2017. After investigating further, it was discovered that there were only about 75 non-critical records total out of about 21,000 replacement records for 688 submarines. This is obviously inaccurate and the result of incorrect record keeping by external maintenance activities. This likely indicates a systemic issue relative to the way 688 flexhose replacements are tracked and recorded by the submarine maintenance enterprise as a whole. It was also verified that no other class contained a similarly disproportionate ratio compared to the total ratio outlined in section 6.4.1.

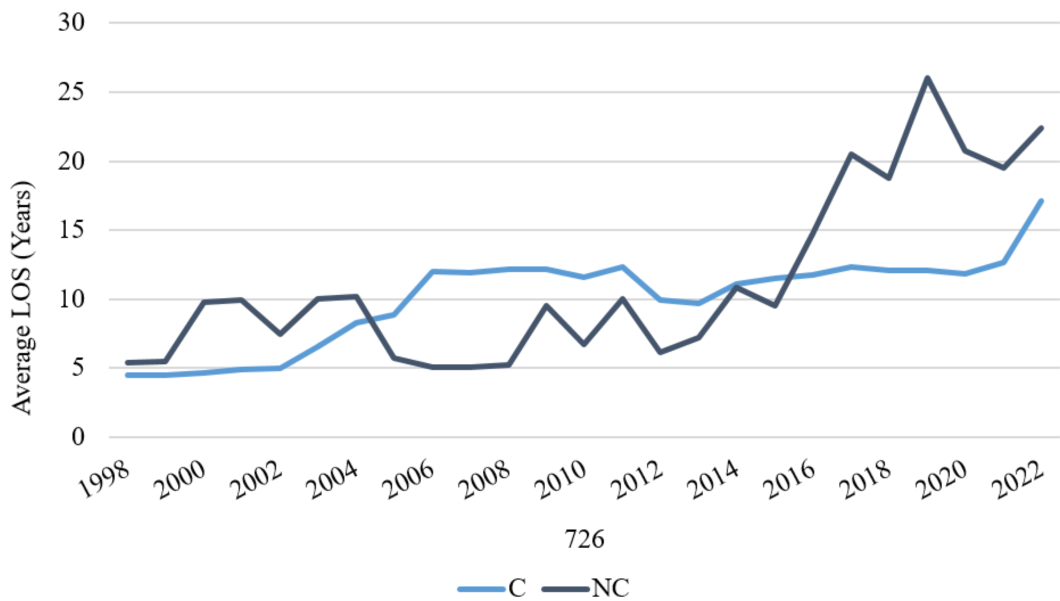

Figure 6-11: Running Average LOS for 726 Class Submarines by Criticality

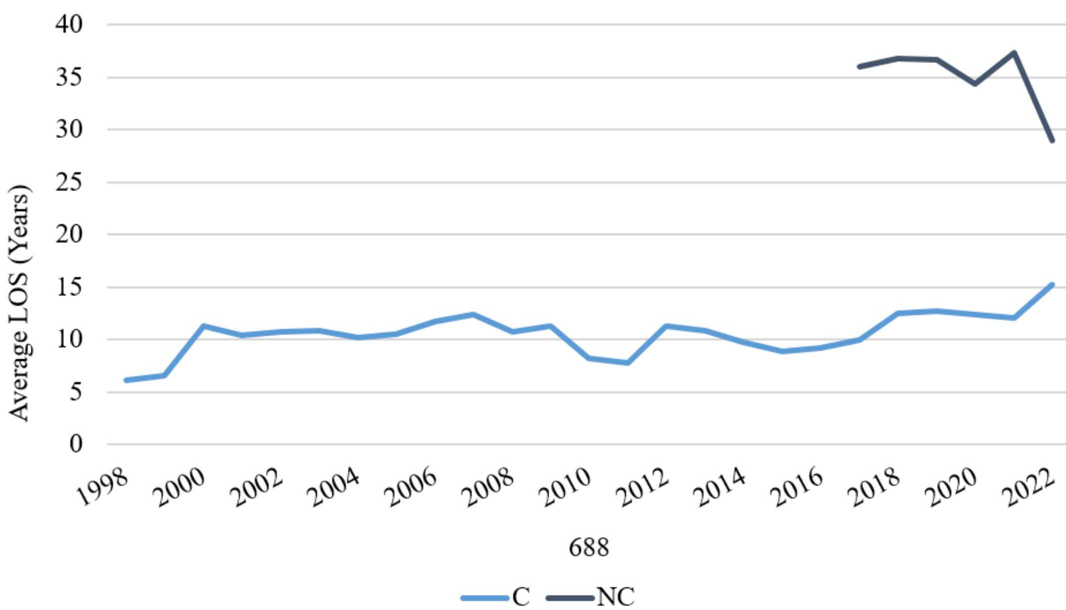

Figure 6-12: Running Average LOS for 688 Class Submarines by Criticality

That said, the running average of all 688 flexhose replacements can instead be tracked and plotted, as seen in figure 6-13. A clear upward trend in LOS can be observed from 1998 to present day, further indicating expected service life beyond 12 years.

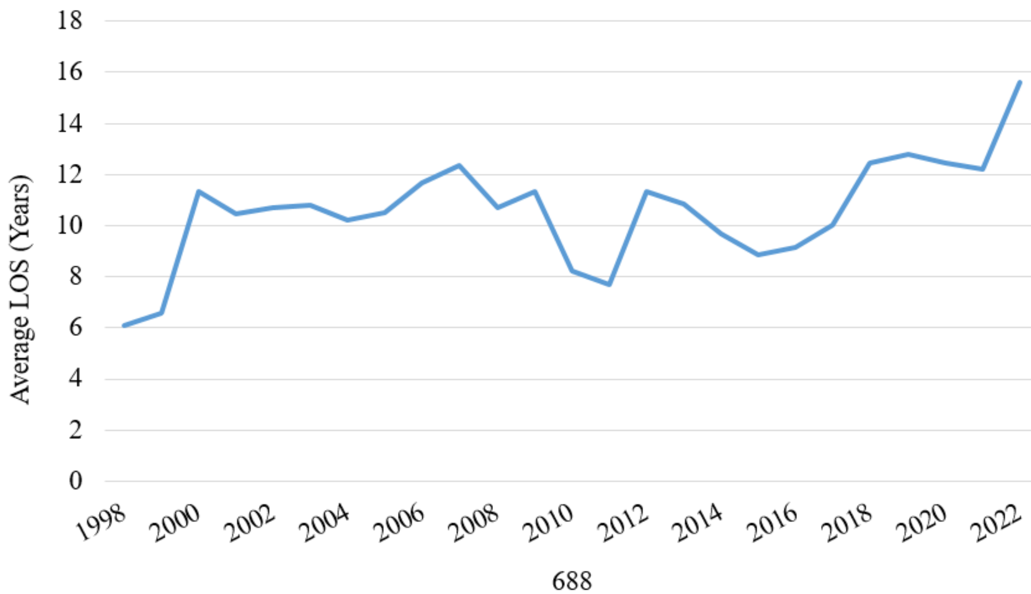

Figure 6-13: Running Total Average LOS for 688 Class Submarines

An attempt was made to also understand the variability of average LOS from hull-to-hull. Table 6.6 is a summary of the maximum, minimum, and range of average LOS across all hull numbers, by criticality, that were represented in the data. It follows that the minimum LOS for both categories of TED-010 hoses are exhibited on newer 774 class hull numbers.

	Critical		Non-Critical	
	Value	**Hull**	**Value**	**Hull**
Maximum Average LOS (Years)	18.07	22	24.83	730
Minimum Average LOS (Years)	1.16	785	0.42	783
Range	16.90		24.42	

Table 6.6: Summary of Variation in Average LOS Across Different Hulls

The local maximum for critical flexhoses occurs on a 21 (SEAWOLF) class submarine, at over 18 years LOS. Further data interrogation for 21 class submarines is provided in table 6.7. The table highlights the fact that all 3 vessels in the class have an average critical LOS of greater than 12 years, and 2 of the 3 have an average non-critical LOS of over 20 years. These higher trends may be due in part to the alternative mission sets this class of submarines perform relative to other classes, as their demanding schedules may prevent them from accomplishing routine maintenance at required intervals.

	Critical		Non-Critical	
	Average LOS (Years)	StdDev LOS (Years)	Average LOS (Years)	StdDev LOS (Years)
21	15.61	5.21	21.68	2.09
22	18.07	2.79	20.90	1.26
23	12.42	6.51	16.08	3.70
Average	**15.17**	**5.69**	**19.33**	**3.67**

Table 6.7: Summary of Average LOS Statistics for 21 Class Submarines

Lastly, the maximum non-critical LOS on a 726 class submarine is in line with the trends highlighted earlier in this section. 726 submarines comprise nearly half the available data for analysis. Additionally, older submarines, such as the 730, have been around long enough to demonstrate extended viability with regards to service life of their non-critical flexhoses. Further interrogation of 726 data revealed that the lowest average LOS amongst the non-critical hoses of each hull in the class was 18.31 years. The average LOS for all 18 hulls in the class was 20.67 years, with a standard deviation of 5.89 years.

6.4.4 By Parent System

A breakdown of the number of different flexhose parent systems represented for each class in the data is provided in table 6.8.

Class	# of Systems
21	34
688	14
726	33
774	23
Total	**104**

Table 6.8: Number of Flexhose Systems Per Class

Table 6.9 represents an attempt to map the spread of average LOS across all systems within each class. From class-to-class, minimum average LOS does not change a significant amount. However, maximum average LOS is much greater on 21 and 726 class submarines than it is on 688 and 774. This makes sense for 774, given the younger overall age of the class. The lower average for 688 submarines is likely due in large to the discrepancy in criticality labeling for that particular class, highlighted above.

	21	System	688	System	726	System	774	System
Maximum Average LOS	20.22	Atmosphere Analyzing	13.30	Reverse Osmosis	25.23	Missile Dehumid. & Drying	13.75	Chill Water
Minimum Average LOS	11.13	Internal Launchers	10.75	Main Propulsion Turbines	9.75	Stern Diving Hydraulics	8.7	Trim & Drain
Range	9.09		2.55		15.48		5.05	

Table 6.9: Summary of Variation in Average LOS Across Different Flexhose Systems by Hull

Further interrogation of the parent system data yielded some notable insights. First, there was apparent frequency variability within each class from system-to-system. Some systems had as little as 3 total records captured, while some had in the thousands. Further, the nomenclature used for the same system varied from class-to-class. For example, the 726 class labeled their chill water system "Cooling Water (Chill Water)(CW)", while the 774 class labeled it "Cool Water (Chill Water System)(CW)". These type of inconsistencies prevent similar systems on different classes from being aggregated with the use of pivot tables. Additionally, there was no clear trend with regards to parent systems that consistently have the oldest or youngest flexhoses, from class-to-class. As can be seen in the table above, there was no crossover among system types for the global maximum and minimum average values.

Lastly, for systems that had both critical and non-critical hoses represented in the data, the author was interested to understand the spread in average LOS amongst those respective hoses internal to a single system. The average LOS was determined for each type of hose, and the spread was calculated by subtracting the average critical LOS from the average non-critical LOS for each system. Table 6.10 summarizes the those findings. Most significantly, the average system spread with regards to average LOS by criticality was +6 years. This finding is in line with the insights generated earlier on in the chapter.

	Value	System
Maximum System Spread (Years)	18.76	Missile Heating and Cooling
Minium System Spread (Years)	0.02	Main Propulsion Lube Oil
Average System Spread (Years)	6.26	

Table 6.10: Summary Statistics for the Spread of Average LOS Amongst Flexhose Systems with Regards to Criticality

6.4.5 Estimated Savings for the Submarine Maintenance Enterprise

A secondary goal of this study consisted of understanding the magnitude of savings, in terms of man-hours and cost, that could be realized by extending the service life of critical flexhoses from 12 years to 20 years. To accomplish this, data obtained from New London's WISP database was utilized in order to determine estimated average cost and man-hour values per flexhose replacement job across the submarine maintenance enterprise. Using these values in tandem with M&SWP critical flexhose replacement frequency data, a final estimated per annum savings was obtained based on the average number of critical replacements that have taken place over the last 5 years.

There were a total of 277 flexhose replacement jobs (as identified by unique Job Control Number (JCN)[1]) that occurred at the New London IMA from 2010 to 2021. The average cost for each replacement was determined to be $3442. However, this number represents all the material required for a flexhose replacement job, not just just the flexhose itself. For example, additional materials such as adapters, end fittings, clamps, connectors, sockets and bolts may also be required for a given flexhose replacement. As was highlighted in chapter 5, many replacements involve reusing the fittings that were previously installed. This can drastically vary the costs associated with a JCN.

[1]The JCN is used to identify a unique maintenance action and to relate all of the parts used when an activity reports a maintenance action. It also links all associated reporting of said maintenance action [27].

To mitigate the variability associated with different jobs, only the hose material itself was considered in the total cost per job calculation. Using just the hose material associated with a unique JCN, the average cost per replacement was determined to be $840. Additionally, each flexhose replacement averaged around 18.21 man-hours over the same time period. It should be noted here that in 2001, the flexhose CWP team estimated that a savings of $523/hose could be realized with reused fittings [NAVSEA, personal correspondence, January 2022]. This translates to $842.35 in FY 2022 dollars, almost exactly the same as was empirically determined from WISP data. This should be considered a testament to the fidelity of the New London execution data.

Once average cost and man-hours per job were determined, M&SWP was examined to calculate the average number of critical replacements per year in the submarine community. From 2016-2021, about 1398 critical replacements occurred per year. Assuming service life of critical hoses is extended by 66% (from 12 years to 20 years), cost savings would be:

$$\frac{20\,\text{years - }12\,\text{years}}{20\,\text{years}} * \frac{1398\,\text{hoses}}{\text{year}} * \frac{\$840}{\text{hose}} = \mathbf{\$469{,}728/year}$$

Similarly, man-hour savings would be:

$$\frac{20\,\text{years - }12\,\text{years}}{20\,\text{years}} * \frac{1398\,\text{jobs}}{\text{year}} * \frac{18.21\,\text{man-hours}}{\text{job}} = \mathbf{10{,}183\,man\text{-}hours/year}$$

A full proof of the calculations above can be found in Appendix B. While this is only a basic estimation of savings and doesn't take into consideration some obvious externalities (e.g. cost of labor, rework, maintenance level, etc.), it does provide a conservative approximation of the magnitude of savings that might be realized by implementing extended critical service life policy across the submarine fleet. For example, over the course of the next 5 years, the Navy could potentially save over $2.3 million in material costs alone, and over 50,000 man-hours. It is likely that these type of savings in the flexhose domain would translate to higher efficiencies in other parts of the submarine maintenance enterprise.

Chapter 7

Conclusions and Recommendations

A number of insights relevant to the submarine flexhose domain were garnered from the analysis conducted in the previous two chapters. This final chapter attempts to capture those insights, and more broadly, understand the implications as well as potential next steps. The following sections summarize the primary maintenance execution risks that have been identified throughout the course of this project, highlight some potential opportunities for improvement in those various areas, and review final thoughts and areas for continued work towards overall submarine maintenance process improvement.

7.1 Summary of Potential Maintenance Execution Risks

A summary of areas of potential maintenance execution risk are succinctly captured below so that relevant stakeholders may begin to make progress towards potential mitigation actions.

1. **Overly Conservative Time-Based Maintenance Planning.** While the author asserts that follow-on validation should be performed, the results of these

analyses indicate that critical flexhoses are likely being replaced too frequently, and additional cost and man-hours savings can be realized by considering extension of their maximum service life to 20 years, in line with non-nuclear surface ships. In general, a lack of higher fidelity, data-centric engineering analyses on submarine components, such as flexhoses, ensures that over-burdensome, time-based maintenance requirements continue to prevail and that fleet readiness will continue to be adversely affected.

2. **Lack of Complete and Reliable Data.** Throughout the course of literature review, stakeholder analysis, and data evaluation, it was clear that a recurring theme in the submarine maintenance enterprise is a lack of actionable data. Actionable data implies that the data is complete and accurate, to a point that policy decisions can be informed. Concurrently, the enterprise also seems to lack clear and concise supporting policies regarding the collection and analyzing of data pertaining to the performance of maintenance, especially IMA maintenance. Specifically, data required to inform flexhose policy decisions is decentralized and disorganized, and in some cases, incomplete or inaccurate. This hindered the completion of the project and necessitated several assumptions and extra steps to reach the point that conclusions could be drawn.

3. **Supply Chain Challenges.** It is evident that the Navy is not excluded from the organizations affected by global supply chain woes over the last few years. Chapter 5 outlined a number of supply chain related challenges for flexhoses which likely permeate throughout the enterprise. Limited raw material sourcing options, reduced quality from third-party distributors, restrictive and cost-prohibitive MIL-SPEC requirements, and lack of innovative technology all threaten to exacerbate flexhose related maintenance issues. Failure to address these issues will impinge on maintenance efforts short-term, and likely affect submarine fleet readiness long-term.

4. **Inadequate Intermediate Maintenance Prioritization in Strategic Plan-**

ning. The literature review of current maintenance initiatives across the fleet, as well as the follow on flexhose domain analyses, yielded an interesting observation: The lack of prioritization of I-level maintenance. While most initiatives outline at length the need to improve CNO or D-level maintenance periods and the methods to get there, none really focus on I-level maintenance, or the ramifications that policy decisions regarding the former have on I-level maintenance. Inasmuch, it's possible that I-level maintenance periods are not being leveraged and optimized to their fullest extent. By not including the performance of intermediate maintenance periods in its lifecycle and strategic planning efforts, the enterprise risks negatively affecting overall submarine fleet readiness, and may continue to incur unacceptable maintenance delays.

7.2 Recommendations for Improvement

There are some clear cut areas where the Navy can improve its maintenance processes and perhaps integrate new technology to help optimize current flexhose maintenance operations and mitigate the risks outlined above. Some high level recommendations and areas for further analysis and exploration regarding submarine flexhoses are provided in the following subsections. It's worth noting that the areas of improvement outlined here might also be applied to components beyond the flexhose domain throughout the submarine's system architecture.

7.2.1 Integrated and Standardized Maintenance Data Structures

This thesis only explored a select few of the many data structures and programs utilized by the submarine maintenance enterprise to track, schedule and perform maintenance. From that analysis, it was clear that both the quality of data that is captured and the integration of systems that house the data is severely limited and likely handicapping the enterprise's ability to achieve efficient operations. In order to achieve any of the goals set forth in initiatives such as NSS-SY, P2P-Shipyards, and SIOP, the "right and complete data" must be there, ready to be utilized. Further, that data needs to be cleaned, organized, and accessible in centralized databases. To do this, the submarine community needs to overhaul the way it collects and analyzes maintenance data.

Multiple stakeholders involved in the flexhose domain expressed an overwhelming desire for more streamlined and standardized maintenance deficiency reporting systems on board submarines. Right now, systems like the CSMP are highly subjective and the quality of the data pulled from the system depends on the person who input it and their willingness to capture enough detail. Standardized systems that are customized and tailored for the type of component being reported on would help achieve a level of granularity and overall data quality that would allow associated engineers and planners to make informed decisions regarding that component's maintenance policy.

In the case of flexhoses, the ability to accurately capture criticality, possible failure modes, reason for replacement, and replacement history of a specific flexhose component in one centralized location would eliminate much of the uncertainty regarding the actual expected service life of the component (something M&SWP currently falls short of). Beyond that, consolidation of maintenance data across the fleet should be a priority. In order to obtain all the data required to perform a robust analysis of flexhose service life and likely failure modes, at least 5 different data sources across 7 executing activities would need to be parsed and reconciled. This is an immense undertaking for one person, and inherently acts as an impediment to any progress that might be made in amending policy in the future to realize potential savings.

Not only will consolidation of data into centralized systems recoup countless manhours for the Navy, but it will enable the identification of class or fleet wide issues that might be occurring with specific maintenance components. Currently, maintenance deficiency reporting is tracked separately from maintenance accomplishments for a particular component (including flexhoses). One system that combines the two would be revolutionary for maintenance planners. Given the advent of the multitude of maintenance initiatives over the last decade, the time is ripe for the enterprise to leverage data as a strategic asset and embrace a "DevOps" approach by laying the groundwork for deployment of integrated and standardized maintenance data structures.

7.2.2 Flexible Scheduling of Replacements

Critical, TED-010 flexhoses on submarines are currently replaced on a 12-year cadence cycle. This is due in large part to the alignment of large batches of replacements with depot level availabilities for submarines. It must be remembered, however, that submarine flexhoses are considered I-level maintenance items, which means that the intent of the PMR in the CMP is for these replacements to occur during I-level availabilities, not D-level. It was previously outlined in chapter 5 how this type of planning could negatively impact an AWP for a submarine. Given that fact, a more flexible approach to scheduling these replacements could be adopted if their service lives were to be extended out to 20 years.

Upon extending the service life of their critical flexhoses to 20 years, the Surface Maintenance Engineering Planning Program (SURFMEPP) adopted a maintenance philosophy for flexhoses that allowed them to break down their critical replacements into smaller batches. In this way, surface ships were given the flexibility to perform replacements during in-port periods over an extended period of time, at the 15, 18 and 20 year periods of flexhose service life [NAVSEA, personal communication, January 2022]. As long as all flexhoses are replaced before or at the 20 year mark, they are considered to be in compliance with the service life replacement policy. Adopting an approach such as this for submarines would enable operational flexibility and limit required dependence on D-level executing activities.

There is ample opportunity to implement a replacement strategy such as this on current and future submarine classes, such as the COLUMBIA. Currently, IMPs occur every 3 to 5 months for submarines and last anywhere from 3 to 5 weeks [37]. Assuming that future assets like COLUMBIA adopt a similar I-level maintenance strategy, it is not unreasonable to expect the CMP to allocate small batches of a submarine's overall flexhose inventory to successive IMPs over the course of 3 to 5 years. While the details of planning these replacements around other necessary I-level work would need to be further investigated and de-conflicted, the benefits of this more "agile" scheduling methodology could ultimately lead to less congested IMPs and shorter overall durations. It would also ensure that we are extracting optimum value from our IMPs and relieve some of the burden on D-level maintenance activities.

7.2.3 Employment of Innovative Technology

While it has gained in importance, how flexhose maintenance is currently conducted has remained relatively unchanged over the last 60 years. Additionally, the materials and parts used have also remained stagnant, in conformance with MIL-SPEC requirements. New and innovative technology exists today that, if studied and invested in further, could provide unparalleled benefits for the flexhose domain and help indirectly improve intermediate level maintenance processes.

In-Situ Machinery Condition Analysis and Remote Monitoring Systems

The previous section spoke about the conservative nature of time-based maintenance for flexhoses. Additionally, applying a flat CBM approach to flexhoses would prove inconsistent for a number of reasons, including the unpredictably and difficulty of assessing failures later in life, and the tendency of flexhoses to fail from the inside, providing little or no indication outside the hose wall that failure may be occurring. One solution to these issues for critical flexhoses is the incorporation of hose condition monitoring (or self-monitoring) hose systems that detect failure-related events and provide advance notification to a maintenance manager when a hose may be nearing the end of it's useful life. Danfoss has developed such a system with their LifeSense® hose technology [3].

According to Danfoss, the LifeSense® system is based on the idea that certain properties of hose change as the hose approaches failure [3]. By periodically comparing samples of these properties to a baseline, highly reliable indicators of hose failure can be obtained [3]. For example, in hoses that have metal wire braid, continuous electrical signals can be sent from the fitting that can monitor the resistance at certain points along the length of the hose. If a change in resistance is observed, its indicative of failure at that point. Failure indications can then be sent to remote monitoring stations that interpret the data and alert operators if a hose is compromised [3]. In this way, system downtime, replacement costs, and environmental and collateral damage can be mitigated with on-going, real-time monitoring of the flexhoses.

Incorporation of this technology on Naval submarines would require further analysis and investment by the maintenance enterprise. Additionally, this type of technology is not currently approved in either flexhose MIL-SPEC. Manufacturers like Danfoss would need to work with NAVSEA to revise the MIL-SPECs to allow for platform integration in the future. There are examples of similar technology already being incorporated on non-nuclear surface ships, such as the Integrated Condition Assessment System (ICAS) on Machinery Control System-equipped ships[1] [38]. Incorporation of such systems would eventually allow for the widespread adoption of RCM methodologies and eliminate waste in lifecycle chains for components such as flexhoses.

Life of Ship Flexhose Technology

The topic of innovative flexhose technology has been one explored in the past by the submarine community. In December 2012, the Advanced Submarine Systems Development (SEA073R) team submitted a Small Business Innovation Research (SBIR) program[2] request to "develop an affordable flexible hose that lasts the average life of a ship" [12]. The SBIR request also necessitated that the new hose be comparable or better in affordability to current synthetic rubber hoses and meet current MIL-SPEC

[1]ICAS monitors sensor data from various pieces of engineering equipment and can send the information off hull for relevant stakeholder analysis [38]

[2]SBIR is a three phase program established by Congress in 1982 to strengthen the role of innovative small business concerns in federally-funded research and development initiatives[35]

requirements for the Navy's flexhoses and fittings [12]. Unfortunately, the SBIR request was never able to get off the ground. Only one company (Creare LLC out of New Hampshire) was approved for phase II, and their proposal was later rejected in 2014 [Creare, personal communication, January 2022]. That said, there is no indication from any POCs that the submarine community or the Navy ever followed up with the request, and thus no further action was taken.

Creare's solution is one example of technology that could be refined further with additional investments in research and development by the Naval submarine maintenance enterprise. It is also likely that enhancements to existing flexhose technology have been achieved since 2014. Employing such technology in the future could virtually eliminate the need for continuous flexhose replacements on-board submarines. Additionally, given that flexhoses exist in such large quantities on any given submarine platform, the benefits in terms of cost and man-hour savings are exponential. It would be prudent for the Navy to reconsider its initial SBIR request, and ascertain the extent to which contemporary flexhose TRLs might meet their initial objectives. Again, employment of such technology would require a revision to the current MIL-SPECs.

Additive Manufacturing

The analysis conducted in chapter 5 revealed some pertinent supply chain issues, including raw material sourcing and extended lead times for flexhose material not in stock at Naval supply depots. It is inevitable that, despite the resourcefulness of shipyard repair shops and novel maintenance tools, flexhose assemblies will fail, and the timing may or may not compound effects on the overall conduct of a given maintenance availability. One possible remedy for these type of concerns is 3D printing of flexhose parts (otherwise known as additive manufacturing).

The technical maturity of additive manufacturing technology has vastly improved over the last decade and has shown elevated viability for both technical and fragile systems. For example, on surface ships the Navy has already utilized 3D-printed parts in some if its systems, including the strainer for the high-pressure steam system on aircraft carriers [38]. While this is largely seen as a convenient peacetime capability, it could become especially critical during war time when the Navy's supply chains could possibly become under attack. Another use case to consider is emergency replacements. There may be scenarios where a submarine is only in port for two days and requires a rapid critical flexhose replacement. The ability to print that material in the shops at the IMA instead of relying on adequate supply chain lead times or cannibalizing from another boat in order to get underway is invaluable.

Representatives from Danfoss and Hydrasearch both expressed that, despite their desires to get to a point where 3D printing is the norm vice the exception, it is currently cost prohibitive due to the intricate structure and varying materials associated with flexhoses. With regards to flexhose assemblies, a great starting point for this technology would be flexhose fittings, which are typically homogeneous in their structure and also are the source of the most grief related to flexhose failures and material lead times. The ability to print these fittings on demand by an executing activity would significantly reduce the delays incurred by unexpected flexhose failures and even planned replacements. Eventually, once technology improves to the requisite level, flexhoses themselves could also be 3D-printed. At any rate, all submarine maintenance executing activities should be equipped with additive manufacturing technology and should be trained in the equipment's use. Beyond this, MIL-SPECs would need to be reevaluated to allow for alternative material composition for fittings.

7.3 Areas for Future Work

While there are potential benefits that may be realized by improving flexhose maintenance efficiency, it is also clear that flexhoses are just one component that is routinely maintained on Naval submarines. In all likelihood, flexhoses are not the biggest cost drivers with regards to maintenance and system availability. Inasmuch, it is reasonable to assume that there are other components similar to flexhoses (e.g. pumps, valves, sensors, etc.), for which the observations made in this study may also apply.

While it was outside the scope of this project, a potential area for future work might involve investigating similar components and/or systems and understanding how they may be grouped into larger classes. In doing so, the methodologies used in this study can be applied to larger classes of systems, and it can begin to be understood what classes are the biggest drivers of maintenance cost and system availability. Work such as this also has the potential to illuminate components and/or systems where this studies findings are not applicable. At any rate, having the ability to readily explore the maintenance history of a multitude of components and establish more cost-effective and time-efficient maintenance policies for those components could have significant positive ramifications for the submarine maintenance enterprise.

7.4 Closing Thoughts

The challenge of keeping ships at sea and maintaining them is both fiscally and strategically urgent. In the growing "Great Power" competition, operational tempo shows no signs of letting up, and the Navy's adversaries will continue to gain ground if their readiness continues to lag as a result of maintenance shortcomings. The maintenance backlog currently exhibited by the submarine fleet is a real threat that warrants increased attention in the form of studies such as the one conducted here.

Regarding critical flexhose replacement periodicity, this thesis has demonstrated the potential for utilizing historical data and lifecycle assessment methods to challenge existing service life periodicities and identify replacement periodicity shifts that might improve overall maintenance efficiency. It's further posited that by accumulating similar shifts in periodicity to appropriate, data-validated lengths for components across the submarine ecosystem, benefits may be rendered in the form of availability cost and man-hour savings and improved system availability. Together, these benefits could result in shorter availability durations.

It should also be remembered that changes to the maintenance philosophy of submarine flexhoses should be made only after careful consideration of all the factors that affect such changes. Safety to ships force and and the ship itself are of prime importance. Detailed engineering analysis to prove the validity of any proposed change is paramount. Also, any proposed changes must have the concurrence of all interested NAVSEA codes.

Ultimately, the positive effects that may be realized as a result of ideas or changes proposed in this thesis (or any of the current maintenance initiatives for that matter) will not happen over night. Consistent incremental improvements are necessary in order to one day fully achieve the Navy's long-term strategic maintenance objectives. It is the author's hope that this project sheds some light on the potential to realize those incremental gains both in the submarine flexhose domain, and the overall Naval submarine maintenance enterprise.

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Appendix A

MATLAB® Script

Contents


```
% Matthew Valcourt
% MIT, 2022
% Flexhose Service Life Determination Tool
```

Clear Old Runs

```
clc; %clears all the text from the command window before running a command
clear; %removes all variables from workspace, releasing them from system memory
```

Import Data

```
%The file name should be manually updated based on which data are being studied
rawdata = readtable('CUI_NF_FlexHoseMaintenanceMSWP_Cleaned3.xlsx');
rawdata = sortrows(rawdata,[6 7 8 11]);
newdata = rawdata;
```

Set Dates for Analysis

```
%Can Hardcode a date here vice always using the current date
date = datestr(now, 'mm/dd/yyyy');
date_c1 = datestr([1997,12,10,0,0,0], 'mm/dd/yyyy');
date_c2 = datestr([1995,11,30,0,0,0], 'mm/dd/yyyy');
```

Determine Location of Last Unique Entries

```
[C2, ia2, ic2] = unique(rawdata(:,6:8), 'rows', 'last');
ia2 = ia2';
```

Additional Records and Data Processing

```
%For loop to add in extra entries to represent last records
for i = 1:length(ia2)
    newrow = rawdata(ia2(i),:);
    if isequal(newrow.DECOM, {'Y'})
        newrow.COMPLETION_LMA_DATE = newrow.DECOMDATE;
        %If loop to set new Periodicity based on criciticality
        if isequal(newrow.CRITICALITY, {'C'})
            %If loop to compare DECOMDATE to Criticaility dates
            if newrow.DECOMDATE >= date_c1
                newrow.PLANNED_PERIODICITY_IN_MONTHS = 144;
            elseif newrow.DECOMDATE <= date_c1 && newrow.DECOMDATE >= date_c2
                newrow.PLANNED_PERIODICITY_IN_MONTHS = 84;
            elseif newrow.DECOMDATE <= date_c2
                newrow.PLANNED_PERIODICITY_IN_MONTHS = 72;
            end
        %Else Part of the loop to set new periodicity for non-critical
        else
            if newrow.DECOMDATE >= date_c1
                newrow.PLANNED_PERIODICITY_IN_MONTHS = NaN;
            else
                newrow.PLANNED_PERIODICITY_IN_MONTHS = 144;
            end
        end
    else
        newrow.COMPLETION_LMA_DATE = date;
        %If loop to set new Periodicity based on criciticality
        if isequal(newrow.CRITICALITY, {'C'})
            newrow.PLANNED_PERIODICITY_IN_MONTHS = 144;
        else
            newrow.PLANNED_PERIODICITY_IN_MONTHS = NaN;
        end
    end
    newdata = [newdata;newrow];
end
```

```
clear i
```

Add in columns for new information

```
add_info = table('Size', [size(newdata,1),3], 'VariableTypes', {'double','string','double'},'VariableNames', {'OCCURENCE' 'OCCURENCE_NOTE' 'LOS'});
newdata = [newdata, add_info];
```

Sort updated table by unique combos & dates, and identify Unique Entries

```
newdata = sortrows(newdata,[6 7 8 11]);
[C, ia, ic] = unique(newdata(:,6:8), 'rows');
ia = ia';
ic = ic';
```

Calendar Math

```
%For loop based on number of unique combinations of platform number, comp ID, and
%hardward system ID
for i = 1:length(ia)
    datecal = [];
    %For loop to find the dates assocaited with the multiple entries for
    %each unique combo
    for j = 1:size(newdata,1)
        if isequal(C.PLATFORM_NUMBER(i), newdata.PLATFORM_NUMBER(j)) && isequal(C.COMP_ID(i), newdata.COMP_ID(j)) && isequal(C.MR_HARDWARE_SYSTEM_OID(:
            datecal = [datecal, newdata.COMPLETION_LMA_DATE(j)];
        end
    end

    %Creation of Length of Service, Occurence, and Occurence Note vectors
    LOS = zeros(1, length(datecal));
    OCC = ones(1, length(datecal));
    OCCNOT = strings(1,length(datecal));

    %For Loop to calculate Length of Service, determine Occurrence, and
    %place appropriate First/Last notes
    for k = 1:length(datecal)
        if k == 1
            OCCNOT(k) = "First";
        elseif k == length(datecal)
            OCC(k) = k;
            LOS(k) = calmonths(between(datecal(k-1),datecal(k),'month'));
            OCCNOT(k) = "Last";
        else
            OCC(k) = k;
            LOS(k) = calmonths(between(datecal(k-1),datecal(k),'month'));
        end
    end


    %This ensures that the LOS/OCC/OCCNOT start from the beginning for each unique identifier
    subcount = 1;

    %For loop to place LOS/OCC/OCCNOT back into newdata table with
    %associated info
    for m = 1:size(newdata,1)
        if isequal(C.PLATFORM_NUMBER(i), newdata.PLATFORM_NUMBER(m)) && isequal(C.COMP_ID(i), newdata.COMP_ID(m)) && isequal(C.MR_HARDWARE_SYSTEM_OID(:
            newdata.LOS(m) = LOS(subcount);
            newdata.OCCURENCE(m) = OCC(subcount);
            newdata.OCCURENCE_NOTE(m) = OCCNOT(subcount);
            subcount = subcount + 1;
        end
    end

end
```

Final Excel sheet to Export

```
writetable(newdata,'CUI_NF_FlexHoseMaintenanceMSWP_Final.xlsx')
```

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Appendix B

Cost Savings Proof

$$\frac{\mathbf{20\ years - 12\ years}}{\mathbf{20\ years}} * \frac{\mathbf{1398\ hoses}}{\mathbf{year}} * \frac{\mathbf{\$840}}{\mathbf{hose}} = \mathbf{\$469,728/year}$$

<u>Proof:</u>

1. Old hose replacement rate $= \frac{16776\text{ hoses}}{12\text{ years}} = \frac{1398\text{ hoses}}{\text{year}}$

2. New hose replacement rate $= \frac{16776\text{ hoses}}{20\text{ years}} = \frac{839\text{ hoses}}{\text{year}} = \frac{12 * 1398\text{ hoses}}{20\text{ years}}$

3. Old cost = old hose replacement rate ∗ cost per hose $= \frac{1398\text{ hoses}}{\text{year}} * \frac{\$840}{\text{hose}} = \$1{,}174{,}320/\text{year}$

4. New cost = new hose replacement rate ∗ cost per hose $= \frac{12 * 1398\text{ hoses}}{20\text{ year}} * \frac{\$840}{\text{hose}} = \$704{,}592/\text{year}$

5. Cost saving = old cost − new cost $= \left(\frac{1398\text{ hoses}}{\text{year}} * \frac{\$840}{\text{hose}}\right) - \left(\frac{12 * 1398\text{ hoses}}{20\text{ year}} * \frac{\$840}{\text{hose}}\right)$

6. Factor out: $\left(\frac{1398\text{ hoses}}{\text{year}} * \frac{\$840}{\text{hose}}\right)$

7. Cost Savings $= \left(\frac{1398\text{ hoses}}{\text{year}} * \frac{\$840}{\text{hose}}\right) * \left(1 - \frac{12\text{ year}}{20\text{ year}}\right) = \left(\frac{20\text{years} - 12\text{ year}}{20\text{ year}}\right) * \left(\frac{1398\text{ hoses}}{\text{year}} * \frac{\$840}{\text{hose}}\right)$