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New Approaches to the Integration of Organizational Maintenance and Failure Data

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New Approaches to the Integration of Organizational Maintenance and Failure Data During Submarine Maintenance Planning

by

Aaron Paul Sponseller

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Naval Engineer and Master of Mechanical Engineering

at the

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Abstract

Planning for maintenance periods for U.S. Navy submarines is difficult due to schedule and cost constraints, operating cycles, and logistical concerns. Organizational maintenance and failure data is vital to understanding trends of failures among the various classes of submarines.

This thesis investigates the processes by which maintenance and failure data is collected, analyzed, and administered throughout the planning process. First, the relationship between organizational and depot level repair work is investigated with respect to how each level impacts the other. An original, multiple linear regression is used with little success to describe how maintenance completion rates affect failures of equipment; thus invalidating this process as beneficial. Additionally, an improvement in depot level completion of maintenance and how it affects equipment start-up is described. Next, the Navy's maintenance improvement process, known as Reliability Centered Maintenance (RCM), is reviewed in order to suggest improvements to their use of organizational data. This process utilizes a variety of experts in maintenance, and submarine operations and their knowledge can be better fused with data sources for greater planning efficiency. Finally, the data collection process, while electronic, is cumbersome for engineers to use effectively during their planning process. Higher quality content will allow engineers to better understand the root causes for failure which creates more informed planning for future maintenance periods.

Thesis Supervisor: Warren Seering
Title: Professor

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Chapter 1

Introduction

In 1746, Philip Stanhope, 4th Earl of Chesterfield, wrote a letter to his son. His intent was to teach his son about becoming a good person, and in the letter he states, "Whatever is worth doing at all, is worth doing well." His words apply to a variety of fields and certainly to the work done by the men and women who serve in and support the United States Navy. United States Navy ships and submarines were designed to navigate and operate in the open ocean whenever called upon. While not always underway and engaged in operations, maintenance becomes of utmost importance in order to deliver readiness.

1.1 Ship Maintenance

Most everyone who drives a car is familiar with the idea of equipment maintenance. Some people are able to perform smaller, more routine tasks like changing the engine oil, swapping out filters, and putting air in the tires. These tasks are designed to extend the life of major components which would fail sooner without any intervention. Larger and more complex tasks, such as replacing the transmission fluid, or even changing the brakes, are usually performed by trained service technicians at specific service centers. The automobile example, while simple, is effective in understanding the Navy's method for maintaining its ships, submarines, and aircraft.

The Navy utilizes a Maintenance and Ship Work Planning model in order to achieve combat readiness and safe operation of its assets. Figure 1-1 shows the base of the model as the class maintenance plan for each boat and its subsystems. Each subsystem and its main components, valves, pumps and motors, have maintenance items covered at three separate levels as described in the following sections. Each level, as in the automobile example, requires different resources and training.

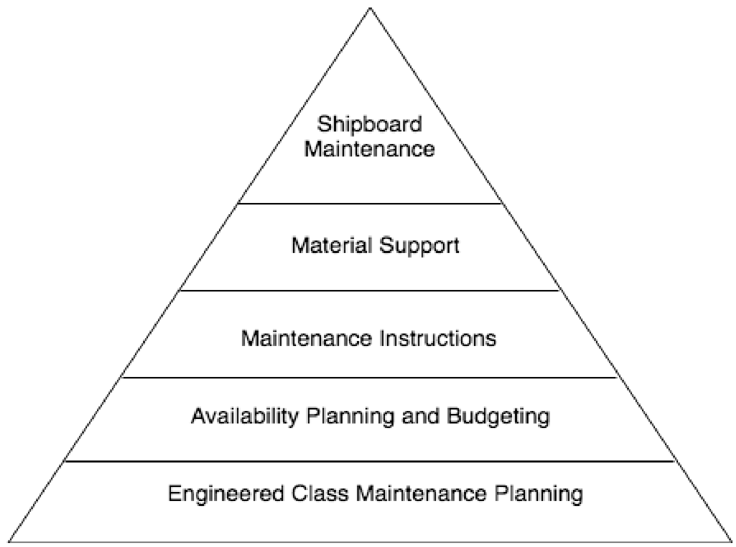

Figure 1-1: US Navy Maintenance Planning

1.1.1 Planned Maintenance System-Shipboard Maintenance

The organizational level maintenance is managed by the Navy's Planned Maintenance System (PMS)which governs all of the weekly, monthly, quarterly etc. maintenance that occurs onboard the submarine by her crew. The Maintenance and Material Management (3M) system provides policy in support of the PMS performed. On its objective, the 3M manual states

> The objective of the 3-M PMS is to maintain equipment within specifications through preventive maintenance, identifying and correcting potential problems before the equipment or system becomes inoperable. [4]

The sailors aboard each submarine are trained to maintain the equipment in order to provide the maximum amount of readiness and safety. This maintenance can occur in port or at sea depending on the conditions required.

1.1.2 Intermediate Maintenance Activities

Intermediate maintenance facilities perform higher level work during planned maintenance periods during a submarine's lifecycle. Prior to going on deployment, for example, submarines undergo maintenance periods in order to deliver a capable submarine to the area commander. Some of these repairs might require rigging out large pumps or opening, inspecting, and cleaning tanks. The results of these repairs and inspections help the boat in its current operational cycle and to inform the planning process for the depot or shipyard maintenance periods. These intermediate maintenance facilities are located at all of the major homeports for submarines including: Groton, CT, San Diego, CA, Bremerton, WA, Kings Bay, GA, Norfolk, VA and Pearl Harbor, HI.

1.1.3 Depot Level Maintenance

Depot level maintenance primarily occurs in the four public shipyards located in Kittery, ME, Portsmouth, VA, Pearl Harbor, HI, and Bremerton, WA. The schedules for these shipyards are planned months to years in advance for the many maintenance periods that the combined submarine fleet undergo. These shipyards have the ability to perform any maintenance conceivably required and then some. The scheduling for these yards can become disrupted when emergent repairs occur such as when the USS San Francisco ran into an underwater mountain range in 2005. Some of the jobs that occur in shipyards can last for weeks due to their complex nature. The nature of the work can either be corrective maintenance or modernization of existing systems.

1.2 Current US Navy Maintenance Environment

The four public shipyards are completing thousands of man days each year. In 2017, the NAVSEA community completed 48 Chief of Naval Operations Availabilities. [3] These maintenance periods can last anywhere from 60,000 to 300,000 man-days or more. And, the amount of maintenance for each submarine is only increasing. Figure

1-2 shows the maintenance and modernization requirements doubled over time for Virginia class submarines which only adds to the overloaded public yards. Addition-

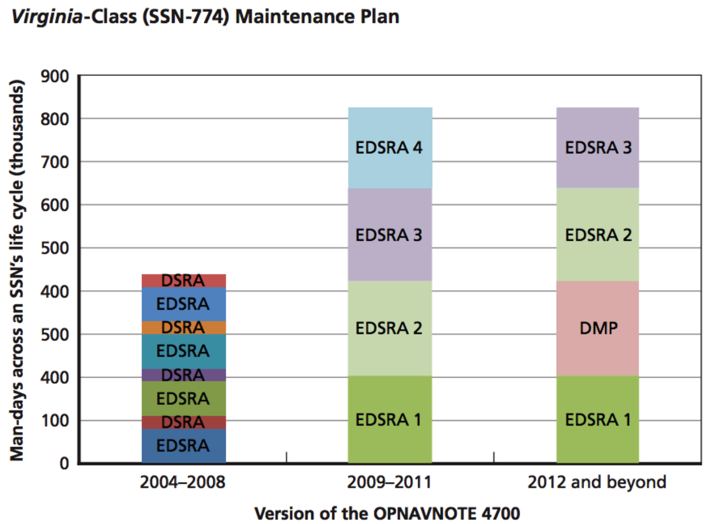

Figure 1-2: Progression of Maintenance Requirements
[14]

ally, one must only look to the news to see how the overloaded yards have affected submarine operations. An article from Breaking Defense states

> A massive maintenance backlog has idled 15 nuclear-powered attack submarines for a total of 177 months, and the Navy's plan to mitigate the problem is jeopardized by budget gridlock, two House Armed Services Committee staffers told Breaking Defense. That is almost 15 submarine-years, the equivalent of taking a boat from the 2018 budget and not adding it back until 2033. [11]

However, the Navy is seeking to address these issues and restore the fleet to a higher degree of readiness. Over the past three years, the Navy has increased its annual maintenance budget in order to increase throughput at its shipyards, and address the $3.5 billion of deferred maintenance at that time.

1.3 Thesis

The previous discussion of the current maintenance environment simply describes the motivation for this thesis. There are larger issues at stake that have led to the cited difficulties; however, those are beyond the scope of investigation and analysis presented here. Efficiencies at all levels of maintenance planning from shipyard scheduling to material support can lead to increases in readiness and decreases in cost. Thus, the case studies presented offer avenues worth pursuing in order to make more informed decisions for maintainers and planners from the operational to the fleet level.

Organizational maintenance and failure data can be used to a greater degree to yield more insights into submarine repair. Multiple linear regression performed on that data could better help engineers understand maintenance completion rates and that submarine's failure rate of components. Updating the Navy's methods for collecting and sorting data is necessary in order to make improvements to the planning process in the form of time and cost savings.

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Chapter 2

The Navy's Maintenance Strategy

2.1 Typical Maintenance Strategies

The Navy has always understood that a warship requires extensive maintenance support throughout its lifetime. Cost and risk are opposing sides when it comes to determining the right amount of maintenance that a boat or system needs. The Navy has turned to condition based maintenance in order to deliver a capable and sea-worthy vessel to fleet commanders.

CBM+ forms the backbone of the Navy's approach to performing maintenance. Several strategies exist to determine when maintenance should occur on a given asset. However, each strategy has its associated shortcomings and advantages that make it suitable for use.

2.1.1 Reactive Maintenance

This maintenance is the most basic strategy in order to fix items that fail and lose their functionality. Reactive maintenance may cost less than other approaches because there is little need for repeated maintenance actions prior to failure. However, the consequences of this maintenance can be large since the part has to fail prior to being fixed. Scheduling is also a concern since the failure will most likely not occur when it is convenient or with parts already on hand. Thus, reactive maintenance is only preferred in low cost and low risk environments. These instances could be as simple as a light bulb in a passageway aboard a boat or any other part that is cheaper to replace than maintain without any ramifications to safety. [7] A condensed version of comparison is included in Appendix A.

2.1.2 Pro-active Maintenance

Pro-active maintenance attempts to prevent failure which may increase safety and reliability on critical components. This approach requires an investment of time, technology, resources, and personnel. The vast majority of systems aboard naval vessels have pro-active maintenance administered via the Class Maintenance Plan across the depot, intermediate, and organizational levels.

Preventive maintenance is the typical version of pro-active maintenance which includes periodically cleaning, inspecting, lubricating, etc. in order to prevent failure. These tasks are usually time-directed in order to mitigate known failure time periods.

Predictive maintenance adds another level to preventive maintenance which requires a greater knowledge of the failure mechanisms. In order to be predictive, the total health of the part or system has to be understood entirely in order to know when a part will fail based on an inspection. For example, some Navy systems use vibration monitoring of pumps in order to detect damaged bearings. In order to schedule predictive maintenance, the engineer now takes the readings from the vibration monitoring and deliver a time-frame as to when failure will occur based on the results. This piece of information is crucial to operations and maintenance in order to know if a pump will operate for a period of time while the boat is needed.

2.2 Condition Based Maintenance Plus

The Navy has chosen to make pro-active maintenance their method of choice in order to maximize availability and safety. Department of Defense Instruction 4151.22 implements the requirement of Condition Based Maintenance Plus to all branches of service and the Condition Based Maintenance Plus Guidebook helps administer that implementation. The Guidebook states

> With more accurate predictions of impending failures (based on real-time condition data), coupled with more timely and effective repairs, moving toward CBM+ will result in dramatic savings, in time and money, and improved weapon system availability and performance. [7]

2.3 Condition vs. Time-Based

There has recently been a debate about the importance of condition based maintenance and whether or not it is saving time and money. Waiting to perform maintenance until the moment before it fails does theoretically save money because you get the most use out of a part. However, this type of maintenance requires a greater flexibility in scheduling because the failures do not always occur when they are convenient. Having maintenance occur in a pre-scheduled manner is still preventive in nature, but more predictable in terms of planning. Specifically with depot level repairs, predictability, in terms of scheduling and logistics, is important to smooth scheduling. Smooth scheduling allows for parts to be ordered in advance and the workload adequately managed which, in turn, reduces cost. From the 2017 Maintenance Planning Summit, Vice Admiral Moore states

> "Over the last 20 to 30 years we have tended to go more towards a condition-based maintenance approach, where ... we do not do maintenance in a time-directed basis. And that was done for good reason because it is, in time-directed you are spending a lot of money. But I think what we have seen over the last 20 to 30 years is the pendulum, as it often does, has maybe swung a little bit too far."[2]

In and of itself, this statement is pointing to the fact that perhaps having maintenance on a schedule is more beneficial and efficient than waiting until something breaks. However, there must be an assumed wear or failure rate for this process to be more effective than condition based maintenance. Because those failure profiles are not known inherently, condition based maintenance remains an effective tool. As stated previously, calculating the savings from time based maintenance with fixed maintenance periods is difficult, as compared to, the cost from not repairing equipment earlier than necessary and waiting until condition dictates.

Chapter 3

Understanding relationships between organizational maintenance and depot level repairs

3.1 The repair cycle

A submarine has a pre-determined amount of life based on how long certain components can operate safely. In order to maximize the effectiveness of a submarine, deployment opportunities are maximized with maintenance periods planned to minimize impact while maximizing capability.

However, organizational and intermediate maintenance are essential for reducing the overall impact of depot level repairs. Organizational maintenance occurs every day and quality work improves the overall process. Prior to deployment, intermediate level work accomplishes larger jobs that a submarine requires to be fully functional for its missions.

An example of work that traverses the entire maintenance spectrum could be pump maintenance. At the organizational level, sailors monitor and inspect pumps for uneven wear. During an intermediate level availability, workers might replace the brushes on the motor of a pump. Finally, during a depot level repair, the entire pump might be replaced.

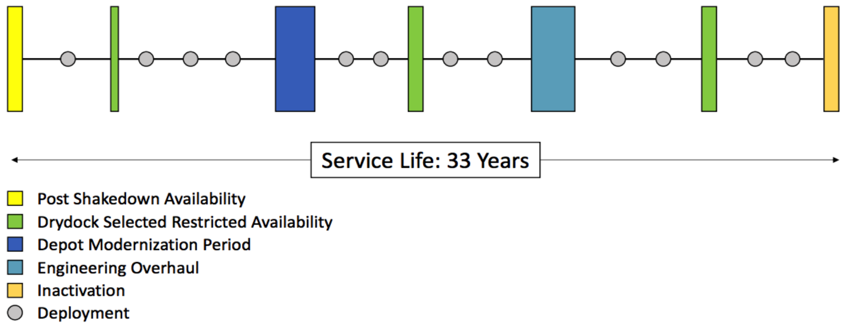

Figure 3-1: Typical Submarine Repair and Operational Cycle [6]

3.2 Taking credit for depot level repairs at the organizational level

3.2.1 Preparing for a depot level availability

The Baseline Project Management Plan describes the process for aligning all of the stakeholders involved with coordinating a submarine availability. The code at SUBMEPP issues an initial work package based on the class maintenance plan. After work discovery periods and additional meetings among stakeholders, a final work package is signed off. The maintenance entered into the final work package reflects recent corrective maintenance that requires depot level assets or long-term maintenance from the class plan. Once the submarine pulls into the drydock, the mechanical, electrical, and hydraulic systems are shut down and de-energized in preparation for the upcoming work.[1]

3.2.2 Inactive Equipment Maintenance(IEM) Status

After the submarine enters a drydock, there are significant changes to the status of each system aboard the boat. A system, for the purposes of this discussion, will be defined as an entire set of pumps, piping, components, etc. required to perform a specific physical purpose as part of the mechanical, electrical, or hydraulic requirements of the entire submarine. For example, the trim system moves water around the submarine for ballasting and other purposes and is accomplished by pumps, tanks, piping, etc.

Since the cause of a submarine drydocking is normally that of repair, and/or modernization, preservation and replacement of components is the nature of these repair periods. During that time, systems aboard the submarine may no longer be in a state to function properly, and without specific precautions, could become a hazard to personnel and other equipment. Therefore, these systems are placed in a state of lay-up or inactivation depending on their need or level of work to be done. While the system is in lay-up, there is a separate set of maintenance that occurs that is specifically delineated on the Maintenance Requirement Card(MRC).

3.2.3 Current State

The principle issue being addressed in this section derives from the re-activation of the system. This usually occurs at the end of the availability whenever the most invasive maintenance is complete and the focus turns to restoring the submarine to an operational status.

While the system has been in IEM, the "clock" or time from the last completion of a given annual, semi-annual, etc. maintenance continues to run. For example, a boat completes an annual maintenance requirement in January of 2014. The boat then enters the drydock in November of 2014 for an 18-month availability. The submarine will place systems in lay-up in accordance with the plan established prior to the start of the availability. That maintenance item would then be scheduled to occur in January of 2015 plus/minus 90 days.[4]However, the IEM status prevents the maintenance from occurring. Therefore, the maintenance will then re-populate in the scheduling program once the system returns its operational status.

Currently, there are several methods for dealing with this fact prior to the start of an availability. Obviously, the length of the drydocking impacts the importance of managing these maintenance items. In the previous example, the maintenance was completed in January of 2014. If the ship enters the drydock in February of 2014 and exits in December, this annual maintenance requirement is no longer an issue. This is the case as long as the annual maintenance described is not also part of the start-up maintenance.

Planning for this case is essential to mitigating the results of a large number of maintenance items populating the scheduling tool upon re-activation. This issue is exacerbated in longer availabilities because more systems are put into an inactive status and the duration is longer which gives a greater chance of not being able to complete the maintenance. Thus, at the end of the availability when time is sensitive and maintenance must be completed prior to critical testing, a plan to deal with this maintenance is important. A recent Virginia class submarine coming out of drydock faced delays up to a week for their post-work testing due to the bevy of maintenance that populated in the 3M scheduling tool. [16] A weekend spent doing the process described here put the schedule back on track to complete their testing.

There is also an issue with completing these maintenance items. Some of these items can, in and of themselves, be invasive which require a sailor to open up recently replaced equipment for no reason. An annual maintenance item that requires opening it up which could allow dirt and debris to enter the cavity, would be unnecessary on equipment. Not to mention, delicate equipment may suffer from a sailor's inexperience in the maintenance actions. It is recognized that poor maintenance techniques should not be an issue, but problems from this issue have occurred in the past.

There is a two-fold benefit, that from reduced scheduling pressure at critical junctures and minimized equipment maintenance on brand new equipment, could be realized from pre-availability planning. The organizational maintenance scheduling tool allows the user to take credit from work accomplished by a higher authority. Thus, any maintenance item performed by shipyard personnel can be used to sign-off for organizational maintenance. This authorization allows the ship to achieve the two-fold benefit as described above.

Currently, the two major ship planning programs do not communicate with each other as depicted in Figure 3-2. One of the primary reasons for this fact is the information architecture concerns associated with the two systems. Submarine computer servers have different classification levels due to the nature of submarine missions. Therefore, transferring data back-and-forth becomes difficult without upgrading the Maintenance and Shipwork Planning(MSWOP) program's classification. Thus, SKED data remains largely on the submarine without the ability to be analyzed, as will be discussed later on. When shipyard work is completed, there is no automatic entry into SKED that solves the issue previously described here.

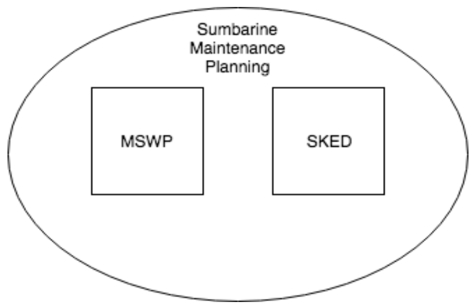

Figure 3-2: Relationship between SKED and MSWP

3.2.4 Future state

The future state then, naturally, allows for a process that enables these maintenance relationships to exist. A threefold approach is required in order to make these changes permanent.

First, a change in policy as written in the Baseline Project Management Plan is required. This document outlines the policies, timelines, and best practices for planning maintenance periods. It provides a framework for planning, but does not lay down all the requirements. However, it remains the ideal location for implementing this milestone. Figure 3-3 displays a representation of where the step could be added in the overall planning process.

Not all shipyard work goes according to plan when the jobs are written. Thus, even though the precedence relationships will be determined 10 months prior to the start (A-10) of the availability, the jobs will require review to ensure the work is completed as previously described. In short, the ship must confirm the work actually occurred

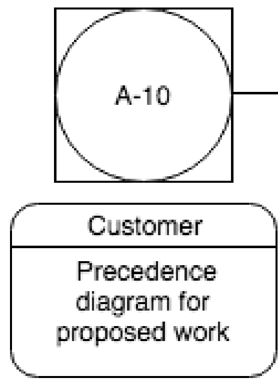

Figure 3-3: Representation of typical planning timeline with milestones

that would supersede their own organizational maintenance. Ideally, the division who owns the maintenance would review the shipyard job to verify the necessary steps took place.

Second, a series of training performed by the regional 3M representatives. In each of the fleet concentration areas, these individuals provide oversight and experience to the 3M supervisors aboard each boat. Usually, they are prior military with years of experience in managing their own workcenters.

Occasionally, they come down to the submarines to give training when asked. Specifically, when the new version of SKED, the 3M scheduling tool, was delivered to submarines, regional representatives gave training on the new features to crews. A one day water-front event would quickly instruct 3M supervisors in this process. A similar event would also be required at shipyard planning offices.

Third, a long-term solution that implements this process automatically would be most ideal. Combining Maintenance and Shipwork Planning and SKED would allow for a more holistic approach to understanding maintenance on an organizational level. Ideally, a shipyard worker would complete his assigned job and then, the supervisor would sign for completion in the Advanced Industrial Management(AIM) software that holds the project Gantt chart. AIM would then sync with the new MSWP/SKED tool that holds the entire maintenance plan in one place.

The concept described is rather straight forward and seems simple, but could save actual hours and days of delays at critical periods during major availabilities.

3.3 Is our organizational maintenance having an effect on failure rates and hence, depot level repairs?

After discussing efficiencies from the depot level down to the organizational level, we now seek to understand the interaction between organizational maintenance. After the Navy creates their class maintenance plan, there are many ways to describe its effectiveness. First, we can look at the availability, or A_o, and determine if our maintenance plan is meeting the requirement. Second, we can perform Reliability Centered Maintenance Seminars and sift through failure modes as the Navy currently does. There are countless other ways that the Navy can determine how "well" its maintenance is doing. In order to answer the specific question, "How is the completion of organizational maintenance affecting depot level repairs?", we look to a causal relationship established via a mathematical model.

3.3.1 Linear Regression

Simple Linear Regression

In order to model the relationship between two variables, we will use the linear regression. The linear regression seeks to understand how changing one variable, X, will cause another variable, Y, to change. The linear regression returns a slope, or effect, on Y from X as depicted in Figure 3-4.

The graph shows that for an increase in one unit on the X axis, the corresponding value of Y increases by β. One piece missing from this graph, is the fact that there is no error. The regression is derived from a sample or population, and thus we seek the "true" expression from this population. Naturally, we may not be able to describe the change in Y with 100% certainty. The full linear regression is divided into the population regression function, $\alpha + \beta X$, and the error term, e_i as discussed.[20] The error term holds all of the other factors or variables that may actually cause a change in Y not represented in the graph.

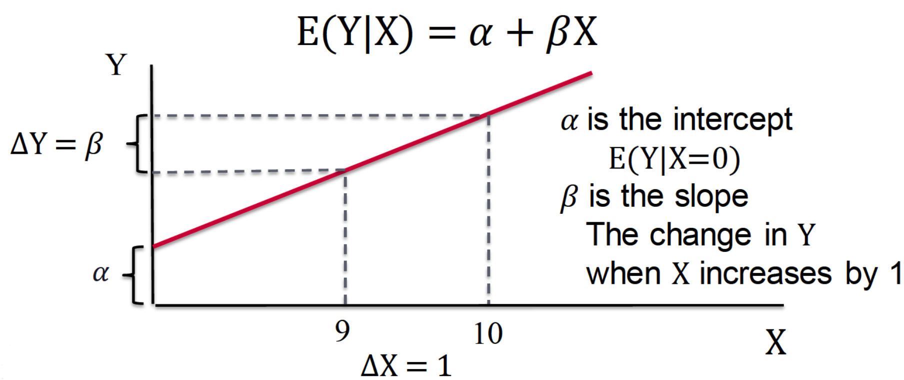

Figure 3-4: Relationship between X and Y[8]

An example is presented to help understand the concept. If we gather all the prices of various homes in a given area, we can graph the price and square footage as presented in Figure 3-5. A line of best fit, or regression line has been drawn with the equation included on top. The equation is interpreted as follows:

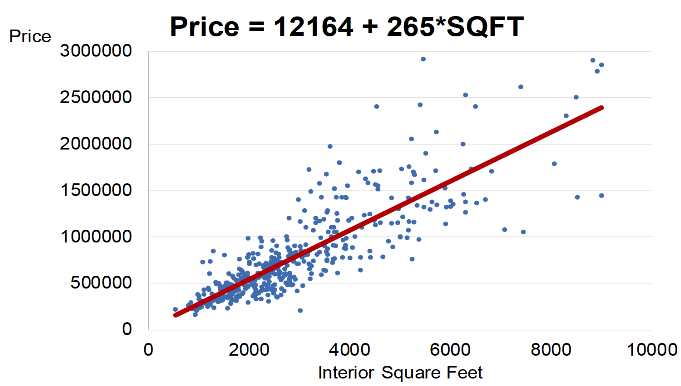

Figure 3-5: Relationship between Price and Square Footage[8]

$$Price = 12164 + 265 * SQFT$$

- If your house was 0 ft^2 then, theoretically, the price of the land is $12164
- If you enlarge your home by 1 ft^2, then the price of your home goes up by $265

One can imagine, that there is more to the story of home sales than just square footage. Home price can be affected by a myriad of factors and thus, this may not be the best model to price your home. In fact, if your home was approximately 6000 ft^2, there is a range of home price of $1.25 million. That is a significant amount to be off by if you solely relied on this calculation. Since you do believe there are more factors to home price, we will discuss multivariate regression or the use of several factors i.e. square footage, location, number of bathrooms, age of appliances, size of garage, etc. in determining the Y variable.

OLS Estimator

First, we must discuss how the actual slopes or coefficients are calculated in the linear regression. The Ordinary Least Squares estimator is the standard method to calculate α and β; several exist and are used depending on the type of data.

The main point of the OLS estimator is to have the line going through the data have the least amount of error from the sample of data. The sum of the squared error is used to determine how accurate the line is made. Figure 3-6 displays the derivation that allows the sample to give results for the population.

Choose $\hat{\alpha}$ and $\hat{\beta}$ to minimize:

$$\min \sum_{i=1}^{N} (\hat{\varepsilon}_i)^2 = \sum_{i=1}^{N} \{Y_i - (\hat{\alpha} + \hat{\beta} X_i)\}^2$$

$$\left(\sum_{i=1}^{N} \{Y_i - (\hat{\alpha} + \hat{\beta} X_i)\}^2\right)$$

$$\frac{d}{d\hat{\alpha}}\left(\sum_{i=1}^{N} \{Y_i - (\hat{\alpha} + \hat{\beta} X_i)\}^2\right) = 0$$

$$(-2) \sum_{i=1}^{N} \{Y_i - (\hat{\alpha} + \hat{\beta} X_i)\} = 0$$

$$\sum_{i=1}^{N} Y_i - \sum_{i=1}^{N} \hat{\alpha} - \sum_{i=1}^{N} \hat{\beta} X_i = 0$$

$$\sum_{i=1}^{N} Y_i - N\hat{\alpha} - \sum_{i=1}^{N} \hat{\beta} X_i = 0$$

$$\sum_{i=1}^{N} Y_i - \sum_{i=1}^{N} \hat{\beta} X_i = N\hat{\alpha}$$

$$\bar{Y} - \hat{\beta}\bar{X} = \hat{\alpha}$$

Figure 3-6: Selecting α and β [8]

Multivariate Regression

Most methods that require regression analysis have mitigating factors that must be accounted for. These other factors, or variables, must be included in order to make a factual causal statement.

Let us return to the housing price example with a simple scenario. What if we are trying to see how the location of a home affects its selling price. What information might we need about the home to make this assumption? If we map out home prices across the United States, we can assume they change depending on the location. Additionally, we can assume home prices change with the age of the house and the included features. These items we have just identified are the other variables that must be accounted for in order to answer our question. Choosing these variables is no simple matter and is the heart of having a causal relationship or just a correlation.

$$y = \alpha + \beta_1 D + \beta_2 X_1 + \beta_3 X_2 + \epsilon$$

$$Price = \alpha + \beta 1 Location + \beta 2 Bedrooms + \beta 3 Age + \beta 4 SquareFootage + \epsilon$$

The D variable is the variable that we are investigating and the X variables are the controls. We hold the X variables constant to allow for a change in Y to only be affected by a change in X. If we compare two homes with a similar number of bedrooms, we do not want to allow these other factors to impede our analysis.

3.3.2 Getting to Causality

In order to develop a causal model, there are several guidelines that should be followed. While there is not a specific method or recipe, the following guidelines allow for a logical approach in order to present a defensible model.[9]

Omitted Variables

When we sit down to consider a model, it may be difficult to think of every factor or variable that is involved with the question we are trying to answer. Should we put together a model that is missing a variable, those effects are then lost. Thus, the coefficients selected will not reflect the truth.

Let us relate back to our home price example. If we remove the "age" of the home, then the coefficients on the other variables will not actually be the truth.

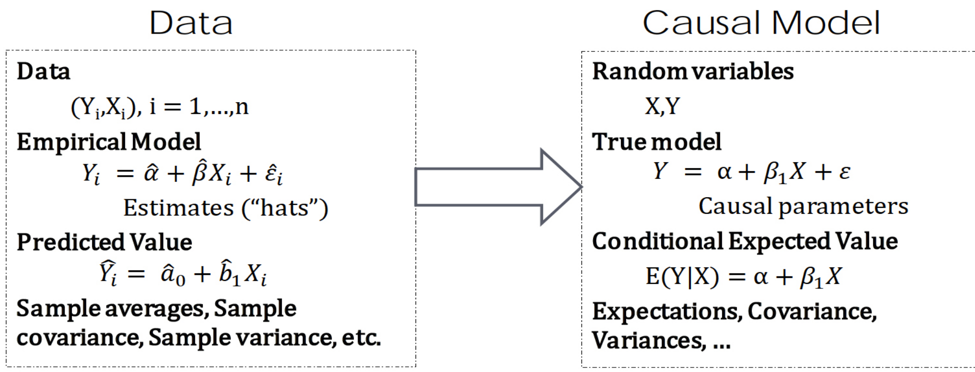

Figure 3-7: The development of a causal model[8]

What if true model is: $Y = \alpha + \beta_2 X_2 + \beta_3 X_3 + \varepsilon$,

$$E(\varepsilon | X_2, X_3) = 0$$

But we omit X_3 estimate: $Y = a + b_2 X_2 + u$

$$a = \alpha$$
$$b_2 = \beta_2$$
$$u = \beta_3 X_3 + \varepsilon$$

$$\widehat{b_2} = \frac{cov(X_2, Y)}{var(X_2)} \rightarrow \beta_2 + \beta_3 \gamma_{32}$$

Figure 3-8: Derivation of issue with omitting variables[8]

Over-controlling

On the other hand, it would be possible to include too many variables in our home price equation. At that point, the model is no longer causal and you are "over-fitting" the model. At this point, it may be possible to increase the "R-squared" without having a true model. The R-squared is a ranking that shows the amount to which a model follows the data. It may be possible to get a good model, but it will lack true out-of-sample predicting power. Figure B-1 in Appendix B shows how a model could be created using variables that correlate well, but are not causal.

Reverse Causality

When developing a model another cause of concern can be choosing independent and dependent variables incorrectly. In essence, the "y" variable may actually cause the "x" variable in some manner you did not anticipate. For example, let us observe the relationship between health and taking vitamins. We could develop a model to see whether or not taking vitamins(x) makes you healthy(y). However, those variables may be linked in another manner. Perhaps, people who are healthy are more likely to take vitamins anyways. Thus, your model is not truly causal.

Sample Bias

The final guideline for developing a causal model entails the sample selection. This focuses on ensuring the data is a true representation of the population. An easy example of this occurs in polling after elections. By only polling a specific subset of the total voter population, you may believe a candidate is being supported a certain amount, but in reality, that candidate has not fared well in other demographics.

3.3.3 The Making of a Model

The previous discussion on developing a causal model is important to understanding why the model presented is logical. The results of a logical model may or may not yield the insight one anticipated, but we know that the question was asked in the correct manner. Let us apply the previous discussion on getting to causality to that of submarine maintenance.

The question that we are trying to answer will be framed as follows: is the amount of maintenance performed by a crew affecting the amount of failures that are seen on a given system?[1] Now, we explore the independent variables that affect failures in a given system and any assumptions regarding our "y" and "x" variables.

Age of the component

A suitable proxy for the age of the component is the age of the submarine. Time since commissioning is easily identified for each submarine and used in this model.

[1] A system is defined as an electrical, mechanical, hydraulic, etc. combination of parts that perform a function. Examples of this would be the ventilation system with all of its fans, piping, or dampers. Another example may be the refrigeration system with its refrigerators, piping, refrigerant,etc.

Maintenance Completion

The model will use percentage of completion of all auxiliary division maintenance. This will be addressed further in Section 3.3.5.

Operation

All submariners who wear the dolphin pin have been trained to operate by procedure. Thus, irregularities that may arise in failure rates are not assumed to be derived from poor operating practices in and of themselves. Failures may take place during operation, but that operation is assumed to be within procedure.

Quality of the original part

The Navy has a vast supply network that it manages for its many parts and manufacturers. The Defense Contract Management Agency overseas the Navy's contracts and ensures that quality parts are delivered. This analysis assumes the agency is delivering

Length of Data Covered

The length of failure data varies for each submarine. There is no specific reason as to the amount of data held for each submarine and will be accounted for in its own "x" variable.

Reverse Causality

The question we are trying to answer assumes that a higher maintenance completion rate would cause less failures to happen. However, one could also imagine that more failures in a system would cause more maintenance to be performed. This issue is avoided by only using scheduled maintenance from the class maintenance plan in consideration. Thus, we are not looking at increased maintenance requirements from faulty parts.

Sample Bias

This analysis focuses on the Virginia class submarine and is taken from submarines with available data. The specific data used in this analysis is addressed in Section 3.3.5.

Class Maintenance Plan

The Class Maintenance Plan is assumed to be the required amount of maintenance that must be performed. The Class Maintenance Plan is derived from previous experience based on similar systems and thus must be assumed to be an adequate amount of maintenance for this analysis.

3.3.4 Understanding a Statistical Model

There are several factors to consider when looking at the results of a statistical model. The R-squared is often touted as the most important figure. In a causal model, the R-squared indicates how much of the variation you have captured. It is not necessary to know where 100% of the variation comes from. Even understanding 10% of a phenomenon can be useful. Correlative models seek a high R-squared, but that has little meaning if too many variables are added and you over-fit the phenomenon. Out-of-sample performance will be very low for an over-fit model as depicted in Figure 3-9.

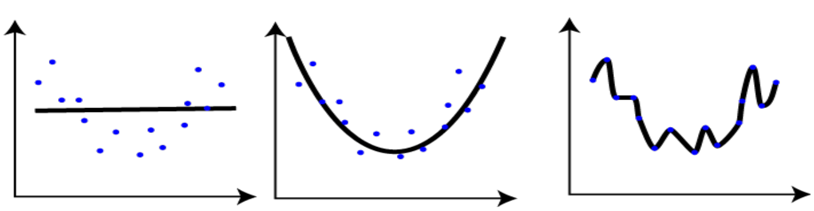

Figure 3-9: Examples of under-fit, balanced, and over-fit models [12]

A statistical model is best understood by the coefficients from the "x" variables and the P-value. The question being asked was whether or not maintenance performance affects failure rates and that coefficient holds the answer. If we see a coefficient that was anticipated, the P-value then dictates if it was statistically significant or just a fluke. A lower P-value indicates that there is a low probability our result was incorrect. We cannot, however, look at P-values and then determine if the corresponding independent variables are important. To be clear, an increase of one unit of the independent variable, creates an increase in the dependent variable by the amount of the coefficient.

Finally, the standard error gives a judgment as to the range that the coefficients cover. Failing to observe the standard error can be a mistake if the errors are so large that your results are less meaningful.

3.3.5 Data

The data included in this model comes from two sources for several submarines stationed in Pearl Harbor, Hawaii. The dependent variable, the number of failures, comes from 3M OARS which is the reporting tool for issues discovered by sailors. This database is easily queried for any system, time-frame, submarine, etc. The data is available for previous years which allows for analysis after the fact.

Submarine	Years of Continuous Data Coverage
A	2016-2017
B	2017-2018
C	2012-2014
D	2014-2015
E	2015-2016
F	2015-2017

The most difficult portion of the data to acquire was the maintenance completion rates for each submarine. As discussed, there is no directive, until previously, that requires maintenance completion data to be held for a given period of time past one year. Each home-port remains its own silo for organizational maintenance with little feedback or cohesion between them. Recommendations for this issue are addressed in Section 3.3.6.

The model used for this analysis takes the following form:

$$EquipmentFailures = \alpha + \beta_1 * A + \beta_2 * B + \beta_3 * C$$

$A =$ Submarine Age

$B =$ Weighted Average of Maintenance Completion

$C =$ Length of Failure Data

One portion of this equation that had not been discussed previously was adding in a factor to control for length of the failure data. Since we want to understand the effect of maintenance completion on reported failures, having different collection periods would prohibit this. If a submarine has 10% more failures, was that from having a collection period 10% longer or due to less maintenance performed? This factor helps ensure we are answering the correct question.

Sorting through what data was available yielded few submarines with consecutive months and years of organizational data. For submarines with only a month of missing data, an average of the preceding and following months was used. Of forty fast-attack submarines in service, only six held approximately 2 years of complete data. The failure data selected from 3M OARS was then selected for the following year after completion on the maintenance. This does not allow for long-term issues to appear which would only be possible with much larger databases of information and a much larger model to incorporate more factors.

3.3.6 Results

Simply put, the coefficient on maintenance completion does not support the initial hypothesis. A positive measurement draws the conclusion that increased amounts of maintenance raise the amount of failures reported. The issue is certainly complex and may not be easily solved through multi-variate regression. However, developing a model is still a worthwhile endeavor. A successful model may help define the point

Regression Statistics	
Multiple R	0.9919
R Squared	0.9839
Adjusted R Square	0.9598
Standard Error	73.37

Table 3.1: Regression Statistics

	Coefficients	Standard Error	t Stat	P-value
Intercept	-2041.9548	1547.0782	-1.3198	0.3177
Maintenance Completion	9.3297	2.2694	4.1110	0.0544
Age of Submarine	322.8690	83.5924	3.8624	0.0610
Length of Failure Data	0.0381	0.0470	0.8095	0.503

Table 3.2: Model Results

at which preventive maintenance makes more sense than proactive maintenance, or vice-versa. Possible obstacles are presented below.

Reverse Causality

As discussed previously, there may be an issue with whether or not a part needs more maintenance because it is faulty. Efforts to avoid this issue included choosing failure periods for a follow-on period of time, not during the exact same time the maintenance was recorded.

Causes of failure

There are an innumerable amount of failure modes. By selecting a maintenance period in the future, we are assuming that maintenance failures are all long term i.e. we ignore issues that occur at different intervals. Thus, the relationship between the years chosen for the maintenance and failure data assumes a simpler failure mode. Increasing the span between these periods would require a much more complex model to account for more variables.

Generalized Data

The difficulty in not having data available in a specific format leads to a generalized maintenance average for all of auxiliary division. Greater granularity may be available once more specific maintenance data is retained.

Chapter 4

Reliability Centered Maintenance(RCM)

4.1 What is RCM?

The history of maintenance practices is intertwined with the development of reliability centered maintenance. Prior to World War II, systems were not as complex and thus maintenance practices were simple. Things were only fixed when they wore out and failed, which is the reactive method as discussed in Section 2.1.1. World War II brought about large changes into the scope and complexity of machinery and equipment in all aspects of industry. Maintenance costs began to rise as did the number of failures. The Federal Aviation Administration took notice and formed a joint investigation into this issue. Their results are the first distribution of a maintenance planning product. The documents they introduced had large changes on the next generation of aircraft. Under maintenance practices of the time, the DC-8 has 339 items that require an overhaul. With the adoption of MSG-2, one of the documents introduced from the FAA study, the DC-10 aircraft has only seven items requiring overhaul.[5]

- 1950's - Larger number of failures in commercial aviation industry than previously seen

- 1960's - Industry and FAA reveal results of joint investigation MSG-1 and MSG-2 are introduced which prescribe reliability centered maintenance
- 1970's - Adopted by U.S. Navy
- 1980's - More industry adopts and develops standardized RCM

The next iteration of RCM occurred in the 1980's and 1990's as more industries adopted standardized maintenance practices and as computing power increased. This next generation of reliability centered maintenance delivered the methods that are still followed today.

Today, Reliability Centered Maintenance focuses on an approach that attempts to maintain the functionality of a given component. It is more than the act of developing a maintenance plan because it attempts to update and adjust the maintenance plan as new information arises. Six general steps for the RCM process are as follows:

- Functions - The desired capability of the system, how well it performs, and under what circumstances
- Functional Failures - The failed state of the system (e.g., the system falls outside the desired performance parameters)
- Failure Modes - The specific condition causing a functional failure
- Failure Effects - Description of what happens when each failure mode occurs, detailed enough to correctly evaluate the consequences of each
- Failure Consequences - The description of how the loss of function matters (e.g. safety, environmental, mission, or economics
- Maintenance Tasks - The description of applicable and effective tasks, if any, performed to predict or prevent failures and Intervals. [17]

Through this process, failure modes are analyzed in order to prescribe maintenance items that can mitigate these specific failures. Thus, changes can be made to a fleet of components in "real time" in order stem future issues.

4.1.1 Connection to CBM+

Condition Based Maintenance Plus remains the Navy's overarching approach to maintenance and this program specifically describes RCM as the best method to determine required maintenance for a given system. Some of the maintenance recommended by RCM might not be condition based maintenance. There are low cost and low risk systems that need only be replaced when the compenent no longer functions. Simple examples of this fact include filters or light bulbs. The CBM+ guidebook accurately describes the reason for applying RCM in the Navy. Additionally,

> If maintenance is ensuring that physical assets continue to do what their users want them to do; then, RCM is a way to determine what must be done to ensure that any asset continues to do what its users want it to do in its present operating context. [7]

Thus, the emphasis of RCM is on the complex, expensive, and important components necessary for safety and mission objectives.

4.2 RCM Seminar in Newport, RI

The Navy holds several RCM seminars a year throughout its fleet. Attendees at these seminars include military operators, maintenance personnel, and engineers. The events are facilitated by SUBMEPP personnel who have been trained in the RCM process and have extensive maintenance careers prior to their current positions.

During 3-7 December 2018, an RCM event was held in Newport, RI that covered sonar systems installed aboard Viriginia Class submarines. The event was broken down into segments where, roughly each day and a half covered a different sonar system. Attendees included personnel from as far as Hawaii and Washington state; the Navy ensured that individuals with a wide range of experience and expertise were present.

The functions, functional failures, and failure mode analysis were performed prior to the event. This portion of the RCM process had been completed on a previous occasion that these sonar systems had been discussed. This left the failure effects, consequences, and maintenance tasks portion still available for this group. The first portion held most of the failure data and had already been reviewed by SUBMEPP engineers.

The group relied on their experience to identify how each component failure affected overall system performance. These could be as basic as if a pump stopped working, it ceased providing flow, which caused the system to degrade and not serve its purpose. Then, the consequences focused on personnel safety, or mission performance degradation. The system that the team used to make these choices, had a built-in algorithm that determined whether or not preventive maintenance is required. The maintenance tasks step then goes to each component and each failure mode to determine what action will mitigate/prevent this failure.

The benefit from selecting a group of experienced individuals is their combined years of experience. These individuals have "seen" a variety of failures and repairs along the way, and hopefully they can draw on these experiences to provide meaningful recommendations to the maintenance required. However, we, as humans, are prone to certain cognitive biases that require recognition in order to avoid them and ensure we drawing on these years of experience correctly.

4.2.1 Cognitive Biases

When an individual draws upon memories and experiences, cognitive biases can alter these reflections and subsequent judgments. These biases affect everyone and are usually not recognized.

Negativity Bias

Unfortunately, it seems that negative events stick out in our minds more often than positive ones. If you've ever been late one time to pick your child up from practice, they will be quick to remember 10 years later. However, the many other times you were on time will fade from their memories. The same applies to remembering repairs and failure of systems. Recalling the one time that a failure occurred may have more weight than the many times a failure did not occur. Thus, the frequency of failure may become overestimated. [19]

Availability Heuristic

Another cognitive bias deals with how recent or how often an event occurred. Daniel Kahneman, who wrote the bestseller "Thinking: Fast and Slow" describes this characteristic. He states, "Thus, a person could estimate the numerosity of a class, the likelihood of an event, or the frequency of co-occurrences by assessing the ease with which the relevant mental operation of retrieval, construction, or association can be carried out."[13] Thus, years of experience possessed by the attendees becomes compressed and weighted by the brain subconsciously with the truth becoming altered.

Overconfidence Effect

The Journal of Economic Psychology states that "In its essence the overconfidence bias reflects the fact that the confidence that people have in their judgments does not match real accuracy of those judgments." These results have been confirmed repeatedly with professionals and ordinary citizens. We, as human beings, are not as correct in our judgments as we would like to think.[10]

4.2.2 Understanding the evidence

The previous discussion of cognitive bias does not reduce the need for assembling a group of experienced individuals. These men and women certainly have a lot to offer in creating a maintenance plan.

During our discussion throughout the day, several members of the team who came with extensive shipyard experience discussed how shipyard availabilities could have a negative effect on performance of systems. There are certain tanks aboard a submarine that are not frequently opened to atmosphere due to their location and purpose.

During a drydocking, these tanks are more easily accessed and thus preservation can occur. Some of these tanks have components that are outside the pressure hull, but have connections to inside the pressure hull. These external hull fittings can be delicate and if their integrity is lost, function is not preserved. These hull fittings are sometimes disassembled to allow for greater access to the tanks for preservation work. When the hull fittings are reassembled, if the software i.e. o-rings are not placed correctly, integrity would soon be lost.

The shipyard workers implied that because a large amount of preservation work occurs during a drydocking, there are an above average number of these failures soon after the boat returns to the water. This is insightful and is exactly the reason these individuals are gathered together. They are able to identify collective issues that are seen over time.

After gathering the data, however, this insight might not hold up as described. Virginia Class submarines have an availability immediately after delivery, and then another major drydocking a few years later. By compiling sonar failure data from submarines after they leave the drydock, we see in Figure 4-1 that this assumption is not supported.

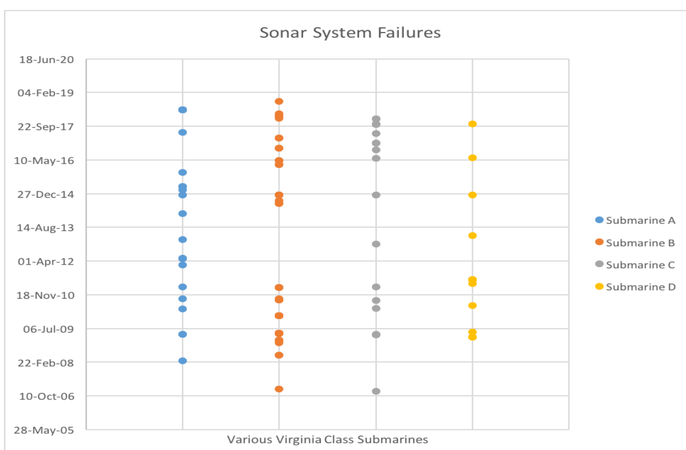

Figure 4-1: Investigation in Sonar Array Failures after Drydocking

It should be noted that work on these external hull fittings can occur outside of drydocking. However, this work would only occur if the failure was already known and the reason for entering the tanks is to fix these errors. Thus, other, undamaged external hull fittings would be disconnected during this type of emergent work.

Another example, while not as conclusive as the previous, illustrates a similar point. There is a maintenance item to test the emergency shutdown function of computer racks used for sonar processing. The maintenance is simple and involves starting up the system, pressing the emergency shutdown button, and verifying the proper shutdown occurs. At the conclusion, the computer servers are re-booted to ensure there were no ill effects from the emergency shutdown. The general consensus among the attendees was that conducting this maintenance annually was not necessary and in fact, created more problems than it solved. The discussion for this maintenance item included extending this item to biennially to reduce the chances for unnecessary wear and tear. Unfortunately, proving this assertion has been difficult as there is not a significant history of organizational maintenance data. It is a reasonable assumption to make about this maintenance item, but the evidence for proving or disproving this theory is not available.

These are only two small examples of how data and expertise could be combined during these meetings. One example is not enough to alter the entire method for conducting RCM seminars, but is a starting point for exploring new ways to add more insight from the available information.

4.3 Future State of Data Inclusion at RCM Events

To better align the use of expertise within the maintenance community, the use of maintenance history and failure data should be included throughout the selection process of maintenance tasks. This information is already used when selecting which topics the RCM seminars will cover.

The reasons for using this data to inform decisions during the event are to validate the insight gained among the attendees as discussed previously. This applies directly to selecting the failure rate which could be done with data, rather than intuition. It also applies to the discussion of how frequent a maintenance action should be performed as discussed previously.

4.3.1 Data Manager

The first method to directly apply the data would be to add an additional member to the SUBMEPP team that facilitates the RCM seminars. This member's responsibility would be to use 3M OARS, SKED, and any other maintenance data program to investigate worthwhile assertions made by the attendees. There are some issues that are perhaps too low of value, but there are larger systems where changes to the existing maintenance plan would have a big time or cost impact. While some questions do not have straight-forward answers, having the whole fleet's data available may allow for more efficient decision-making to occur.

Adding this position adds validity to the statements being made. Allowing the data to speak ensures the discussion remains objective and quantifiable. While the model in Section 3.3.5 did not follow our initial hypothesis, exploring is part of learning and understanding. The example given above about the external hull fittings was information readily available from a 3M OARS data pull.

4.3.2 Regression Difference

The other method for more data inclusion in the RCS process is a more rigorous analysis of the results made after an RCM event. Selected systems for the RCM process can only be accomplished every five years. The implementation of the changes can take time and thus, five years was chosen to allow for the changes to be seen in failure rates. One current method for knowing if RCM was effective was whether or not the system gets re-selected a few years after a previous event's completion. The process for choosing which systems to cover includes frequency of failure, cost to maintain, and fleet input.

A perfect statistical method to detect an increase or decrease in failures across the fleet remains the regression discontinuity design. Where natural changes occur involving a given variable, the effects can be determined mathematically and graphically. For example, Figure 4-2 gives a perfect graphical example showing the changes that occur in death rate at age 21. We see the large discontinuity in motor vehicle accidents that occur at age 21 and search for answers to why this occurs. By design, this graph already accounts for the various other variables that could be affecting the motor vehicle accident rates.

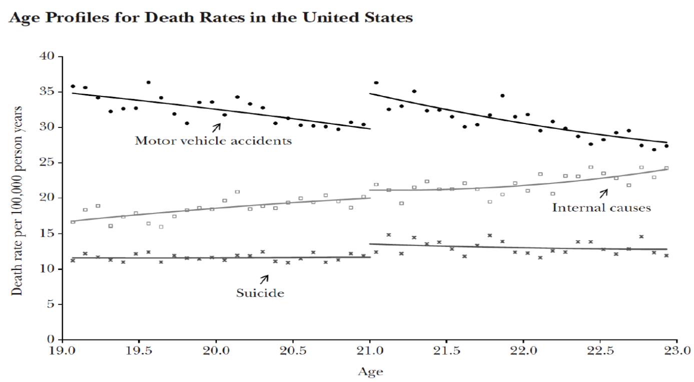

Figure 4-2: Example Regression Discontinuity Design

While all events might not have such a clear discontinuity, this method could highlight the changes that took place. The date at which the changes from an RCM event are implemented fleet wide would remain the target to observe a discontinuity. The results from the proposed discontinuity would be the total number or frequency of failures pre- and post- implementation. Observing this change would allow for better understanding of the efficiency of our RCM seminars and maintenance planning in general.

Current practices for archiving the seminars prevent this method from being implemented to test for RCM results. Identifying which specific maintenance practices that changed and which failures they were addressing is not currently feasible. Future seminars can produce a clear list of these changes to allow for future analysis to occur.

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Chapter 5

Data Quality Management in the Submarine Maintenance Community

5.1 Organizational Failure Reports

Chapter 3 of this thesis was an attempt to see what more can be done with organizational maintenance and failure data from the 3M system. Chapter 4 showed what the Navy is currently doing to optimize its maintenance strategy after reviewing organizational failure data. This chapter will discuss where this failure data used in Chapter 3 comes from and the changes that can be made to ensure future maintenance planning from this source is more fruitful.

5.1.1 Current Use

When there is an equipment failure aboard a Naval Submarine, the division submits an OPNAV 4790/2K Form to track the issue. This form gets logged into the Current Submarine Maintenance Project (CSMP) and tracked accordingly. The ship may make the repair after pulling an item from stock or broker the job with shore support. Additionally, the job may be deferred for a future dry-dock period if required. The Joint Fleet Maintenance Manual details the process for validating an OPNAV 4790/2K and verifying enough initial information is present for the job to be screened to an outside maintenance activity.

The OPNAV 4790/2K, as presented in Figure B-2, covers basic information about the job such as the ship name, component at fault, and the maintenance performed. The form is partially filled out once to inform the chain of command and maintenance personnel off-hull of the issue. After the repair is made, the comments section is filled in to further indicate the work that was performed. In Figure B-2, we see that the ship replaced the Klystron and both modulator switch tubes which is very clear from the notes.

After the work is complete, this 2K is then archived in the Open Architectural Retrieval System (3M OARS) for further use. The retrieval system is in place to allow logisticians, maintenance planners, and engineers to sift through the system looking at individual components or ships. Trends can be established for ordering parts for the supply system or faults in specific components. Special assignments such as validating pre-availability testing, service life extension, or risk assessments also use the database extensively.

Establishing these trends and understanding the status of a given component in the fleet is the whole reason for using this database. Therefore, it needs to be relied upon for its information and easily searchable. Unfortunately, both of these issues are in question. On average, only 66% of records are usable after performing a data query. The number one reason for this is the lack of detail associated with the post-maintenance completion. "Maintenance complete", "part replaced", or "2K for parts" are common occurrences which do not provide any detail to maintenance planners or engineers.

The lack of widespread use focuses on trust but also usability. The system is more advanced than using paper copies, but lacks the ability to be sorted adequately enough. Individuals have to pull hundreds or thousands of 2K's after searching for a specific parts number or submarine and then sort through each of them to comb through them. Engineers want to do less data management in order to focus on maintenance planning.

5.1.2 Ways to Improve

The quality of the information in the reports is something that can easily be fixed. It is tempting to say that the chain-of-command needs to do a better job in their review process. This is certainly true, but can only happen when these individuals are made aware of their importance.

Namely, a town-hall style meeting in each of the submarine concentration areas would introduce the necessary changes. These meetings already exist when Type Commanders come and visit a homeport. Having the Chief Petty Officers, Work Center Supervisors, and Department Heads understand how these are used will enable the quality of these reports to increase.

Submarine crews are well-versed in the art of writing high-quality maintenance reports. For equipment failure that has a serious impact to mission or safety, a casualty report (CASREP) is written following an OPNAV 4790/2K in order to request off-hull support. CASREPs have a large audience and thus, much more care is given in accurately identifying required information. Crews spend several hours in crafting a CASREP to a commanding officer's liking. Thus, applying a higher attention-to-detail on 2K reports is well within reach. However, the crew needs to understand that while a 2K does not generate as much response as a CASREP, the 2K is utilized by many different stakeholders and has great benefit.

The next avenue for improvement focuses on the accessibility of the OPNAV 4790/2K reports via 3M OARS. The 3M Manual describes the various fields and sections on the form and how to fill them out. However, additional fields are required in order to allow for better sorting and processing. Specifically, to prevent the need for engineers to screen 1/3 of the documents by hand. The following two changes would have a large impact on their ability to screen.

- Purpose Field- More options to delineate how 2K's are actually used in the fleet- only for parts, greater than quarterly maintenance, etc.

- Failure Modes- Allow for greater description of the reason for failure. These drop-down items can be tailored to specific APL's and follow the reasoning used in RCM Events. For example, a pump might not provide flow and the possible reason could be the impeller sheared off. Implementing this for all APL's would certainly take time, but the ground work is already there with the RCM tools in use.

Integration to Intermediate and Depot Level Repairs

When parts fail, the OPNAV 4790/2K and CASREP become the largest sources of equipment status available for stakeholders to perform trend analysis. Additional sources exist but are not tied into 3M OARS. Specifically, when the shipyard performs maintenance and "opens" systems for inspection, they record the status if the maintenance requirement has a form for this. However, this document is usually a scanned image and not searchable in an electronic database. Thus information can be gathered that better informs engineers when planning for future maintenance availabilities but remains cumbersome to use. Significant time savings could be achieved if the source were more easily accessed.

Discussing integration of organizational and depot level failures/repairs amounts to the creation of a database where information is available on parts for trend analysis. This could also be used as an electronic history of maintenance completion and failure data. Currently, information on maintenance and failure history exists in at least four different databases that do not interact. Getting a complete picture and history requires access to multiple archives with no tools to assist in creating a full picture. Maintenance planners lack a dashboard that gives fleet statistics on current issues nor ready access to all forms of maintenance data.

5.2 Current Efforts Towards Improvement

Naval Surface Warfare Center(NSWC) Corona leads the Navy in readiness assessment of key systems aboard submarines and surface ships. The warfare center can fuse information from various sources within the maintenance community to produce an overall operational availability of a system.

$$A_o = Uptime/OperationalCycle$$

There are requirements for what value each system must obtain in operational availability, but changes in this figure are not readily understood in actual operations. For example, seeing that a system is currently at 60% due to a failure in the supply system provides a quick way to see how the problem can be fixed. This low figure is readily understood as too low for safe and effective operations. However, when a system is at 85%, raising that figure by 2% is less tangible in terms of how much that actually affects submarine operations. Nevertheless, this concept and its ability to pinpoint where the maintenance or logistical support of a system is failing does provide the Navy with a great tool to maintain its assets.

Having NSWC Corona create this information for engineers is a step in the right direction for bringing the Navy's maintenance data to a higher state of use. There are other divisions, and agencies within the Navy who currently have more advanced uses of their maintenance data that the submarine maintenance community can tap into for support.

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Chapter 6

Conclusions

Organizational maintenance and failure data can be used to a greater degree to yield more insights into submarine repair...

This objective was moderately successful. The Navy has long used the RCM process in order to confirm and optimize its maintenance strategies. However, changes can be made to ensure that human insight is paired with and verified by data sources that are available. Changes to the program can ensure that decisions made by experienced operators and maintainers are on point and worthwhile.

....Multiple linear regression performed on that data could better help engineers understand maintenance completion rates and that submarine's failure rate of components.

This objective was not successful. With current data collection methods, the right data might not be retained from maintenance completion. Without proper specificity, the model is not insightful. However, requiring all submarines to retain completion rates could yield gains once there is a large enough data set.

...Updating the Navy's methods for collecting and sorting data is necessary in order to make improvements to the planning process in the form of time and cost savings.

This objective was successful. There are measurable and specific changes that can be made to existing materials that would benefit planners and engineers. The Navy needs to continue to invest in its Information Technology infrastructure with regards to the maintenance community in order to provide workers the best chance for accomplishing maintenance in a timely manner.

6.1 Further Work

With the rise of "big data" and machine learning, applying these techniques to the maintenance community could yield savings in time and money. These practices are becoming more readily used in many different industries helping businesses realize savings. Should the Navy pursue advanced data techniques, solutions already exist in the commercial industry for maintenance purposes.

For example, Microsoft Azure is a cloud-computing service that hosts and runs applications for business entities. They currently have in their portfolio, a section of business that runs predictive analytics for maintenance purposes. This departs from current practices in the Navy which are more descriptive in nature. The Azure Introduction Guide states:

> The goal of predictive maintenance is to optimize the balance between corrective and preventative maintenance, by enabling just in time replacement of components. This approach only replaces those components when they are close to a failure. By extending component lifespans (compared to preventive maintenance) and reducing unscheduled maintenance and labor costs (over corrective maintenance), businesses can gain cost savings and competitive advantages.[15]

There is certainly an optimal point for each system in terms of when maintenance should be performed which has to balance with current dry-dock timing.

Further studies into this topic include a possible roadmap for implementation into the Navy's current business practices. This thesis introduced the possibility of updating current data capture techniques, but with this technology a long verification process may be required. Projecting cost savings and schedule impact may be difficult to do for such a large shift in maintenance planning practices.

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Appendix A

Tables

Category	Maintenance Approaches			
	Reactive	Proactive		
	Run-to-fail	Preventive	Predictive	
Sub-Category	Fix when it breaks	Scheduled maintenance	Condition-based maint.-diagnostic	Condition-based maint.- prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance scheduled based on evidence of need	Maintenance need is projected as probable within mission time
How Scheduled	N/A	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	Forecasting of remaining equipment life based on actual stress loading
Kind of Prediction	None	None	On- and off-system, near-real-time trend analysis	On- and off-system, real-time trend analysis

Table A.1: Maintenance Approaches[7]

RCM Event	CBM+ Enabler
Functions	Provides analysis and decision support to help determine the life-cycle maintenance strategy to ensure achievement of required system performance. Provides technical data for a business case to determine optimal application of resources to perform selected maintenance tasks.
Functional Failures	Provides diagnostic tools to assess degree of system/component degradation. Tracks health and status of installed components.
Failure Modes	Uses sensor and data analysis technology to identify failure causes; collects, stores and communicates system condition and failure data.
Failure Effects	Uses automated tools and data manipulation software to produce diagnostic information on detected failures. Applies information from Interactive Electronic Technical Manuals to report, troubleshoot, test, and support documentation of failures.
Failure Consequences	Maintains platform hardware and software configuration. Provides data warehouse capability as a comprehensive database that includes condition trends, history, and transaction records from business processes.
Maintenance Tasks	Incorporates prognostic capabilities to help predict failure causes and timing. Embedded health management systems on each platform predict the remaining useful life of components based on failure predictors derived from composite condition analysis.

Table A.2: Ways that CBM+ assists the RCM process[7]

Appendix B

Figures

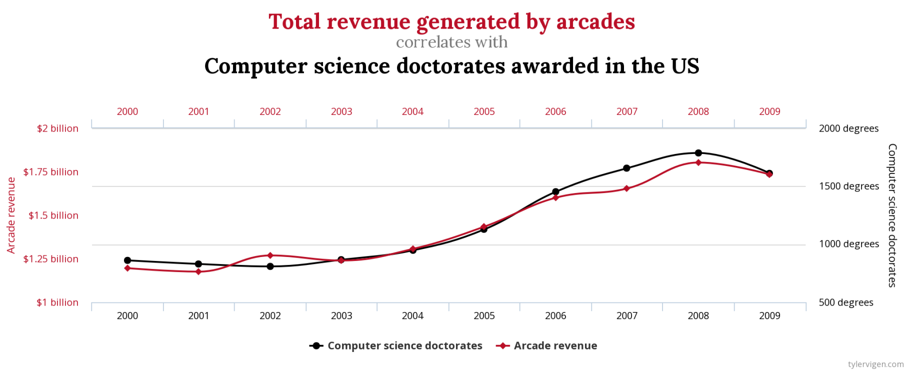
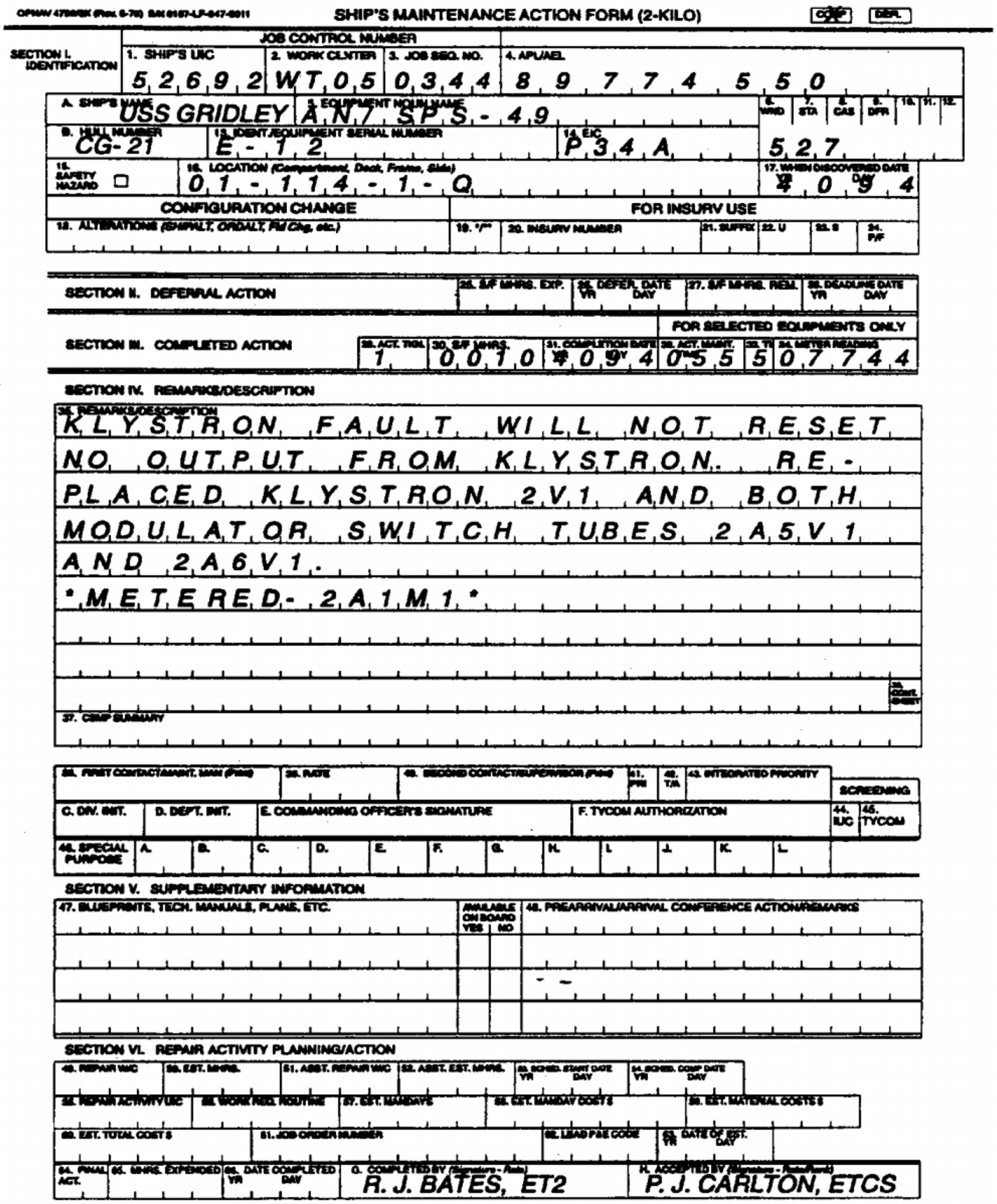


Figure B-1: Example Correlation with no Causal Support[18]


OPNAV 4790/2K (Rev. 6-78) S/N 0107-LF-047-6011

SHIP'S MAINTENANCE ACTION FORM (2-KILO)

SECTION I. IDENTIFICATION

JOB CONTROL NUMBER

1. SHIP'S UIC: 52692
2. WORK CENTER: WT05
3. JOB SEQ. NO.: 0344
4. APL/AEL: 8977 4550

A. SHIP'S NAME: USS GRIDLEY
5. EQUIPMENT NOUN NAME: AN/SPS-49

B. HULL NUMBER: CG-21
13. IDENT/EQUIPMENT SERIAL NUMBER: E-12
14. EIC: P34A
527

15. SAFETY HAZARD
16. LOCATION (Compartment, Deck, Frame, Side): 01-114-1-Q
17. WHEN DISCOVERED DATE: 4 094

CONFIGURATION CHANGE

18. ALTERATIONS (SHIPALT, ORDALT, Fld Chg, etc.)

FOR INSURV USE

19. "/" 20. INSURV NUMBER 21. SUFFIX 22. U 23. S 24. P/F

SECTION II. DEFERRAL ACTION

25. S/F MHRS. EXP. 26. DEFER. DATE YR DAY 27. S/F MHRS. REM. 28. DEADLINE DATE YR DAY

SECTION III. COMPLETED ACTION

FOR SELECTED EQUIPMENTS ONLY

29. ACT. TKN: 1
30. S/F MHRS.: 0010
31. COMPLETION DATE: 4 094
32. ACT. MAINT.: 055
33. TI: 5
34. METER READING: 07744

SECTION IV. REMARKS/DESCRIPTION

35. REMARKS/DESCRIPTION

KLYSTRON FAULT WILL NOT RESET
NO OUTPUT FROM KLYSTRON. RE-
PLACED KLYSTRON 2V1 AND BOTH
MODULATOR SWITCH TUBES 2A5V1
AND 2A6V1.
METERED - 2A1M1

36. CONT. SHEET

37. CSMP SUMMARY

38. FIRST CONTACT/MAINT. MAN (Print) 39. RATE 40. SECOND CONTACT/SUPERVISOR (Print) 41. PRI 42. T/A 43. INTEGRATED PRIORITY

SCREENING

C. DIV. INIT. D. DEPT. INIT. E. COMMANDING OFFICER'S SIGNATURE F. TYCOM AUTHORIZATION 44. IUC 45. TYCOM

46. SPECIAL PURPOSE A. B. C. D. E. F. G. H. I. J. K. L.

SECTION V. SUPPLEMENTARY INFORMATION

47. BLUEPRINTS, TECH. MANUALS, PLANS, ETC. AVAILABLE ON BOARD YES NO 48. PREARRIVAL/ARRIVAL CONFERENCE ACTION/REMARKS

SECTION VI. REPAIR ACTIVITY PLANNING/ACTION

49. REPAIR W/C 50. EST. MHRS. 51. ASST. REPAIR W/C 52. ASST. EST. MHRS. 53. SCHED. START DATE YR DAY 54. SCHED. COMP DATE YR DAY

55. REPAIR ACTIVITY UIC 56. WORK REQ. ROUTINE 57. EST. MANDAYS 58. EST. MANDAY COST $ 59. EST. MATERIAL COSTS $

60. EST. TOTAL COST $ 61. JOB ORDER NUMBER 62. LEAD P&E CODE 63. DATE OF EST. YR DAY

64. FINAL ACT. 65. MHRS. EXPENDED 66. DATE COMPLETED YR DAY

G. COMPLETED BY (Signature - Rate): R. J. BATES, ET2

H. ACCEPTED BY (Signature - Rate/Rank): P. J. CARLTON, ETCS

Figure B-2: Example OPNAV 4790/2K[4]

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