2022-06

HOW IMPROVED CORROSION CONTROL PRACTICES IN THE U.S. NAVY'S ARLEIGH BURKE CLASS DESTROYER ENGINEERING SPACES MIGHT ENHANCE SHIP EFFICIENCY WHILE OPERATING

Pratt, Justin R.

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/70724

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

HOW IMPROVED CORROSION CONTROL PRACTICES IN THE U.S. NAVY'S ARLEIGH BURKE CLASS DESTROYER ENGINEERING SPACES MIGHT ENHANCE SHIP EFFICIENCY WHILE OPERATING

by

Justin R. Pratt

June 2022

Thesis Advisor: Chad W. Seagren
Co-Advisor: Bryan J. Hudgens

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2022	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE HOW IMPROVED CORROSION CONTROL PRACTICES IN THE U.S. NAVY'S ARLEIGH BURKE CLASS DESTROYER ENGINEERING SPACES MIGHT ENHANCE SHIP EFFICIENCY WHILE OPERATING			**5. FUNDING NUMBERS**
6. AUTHOR(S) Justin R. Pratt			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This research attempted to answer how improved corrosion-control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces might enhance ship efficiency. It can be confidently stated that effective corrosion control in Arleigh Burke Destroyer engineering spaces clearly enhances ship efficiency. A semi-systematic review of the literature was used as a methodology. Data were mined using a Synthesis Matrix that isolated meta-narratives that were used later in a meta-analysis of the literature. The identified meta-narratives led to eleven emerging patterns. These patterns were condensed into six major themes and finally synthesized into two primary categories: corrosion control and ship efficiency. Although no causal relationships were proven, strong interrelationships were identified. The findings of this research recommend that in order to control corrosion and enhance ship efficiency, two strategies should be followed: 1) an implemented maintenance plan requiring training for the crew in techniques and knowledge acquisition that promote understanding of the science of corrosion and 2) decisions regarding materials selection, surface coatings, and corrosion control should be made with total ownership costs in mind, because for a ship to function efficiently it must be operational a majority of its work life.

14. SUBJECT TERMS Arleigh Burke Class Destroyer, DDG 51 class ship, corrosion, engineering space, U.S. NAVY, paint, defense, efficiency			**15. NUMBER OF PAGES** 85
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

HOW IMPROVED CORROSION CONTROL PRACTICES IN THE U.S. NAVY'S ARLEIGH BURKE CLASS DESTROYER ENGINEERING SPACES MIGHT ENHANCE SHIP EFFICIENCY WHILE OPERATING

Justin R. Pratt
Lieutenant, United States Navy
BAS, The Art Institute of Michigan, 2011

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PROGRAM MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
June 2022

Approved by: Chad W. Seagren
Advisor

Bryan J. Hudgens
Co-Advisor

Robert F. Mortlock
Academic Associate, Department of Defense Management

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This research attempted to answer how improved corrosion-control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces might enhance ship efficiency. It can be confidently stated that effective corrosion control in Arleigh Burke Destroyer engineering spaces clearly enhances ship efficiency. A semi-systematic review of the literature was used as a methodology. Data were mined using a Synthesis Matrix that isolated meta-narratives that were used later in a meta-analysis of the literature. The identified meta-narratives led to eleven emerging patterns. These patterns were condensed into six major themes and finally synthesized into two primary categories: corrosion control and ship efficiency. Although no causal relationships were proven, strong interrelationships were identified. The findings of this research recommend that in order to control corrosion and enhance ship efficiency, two strategies should be followed: 1) an implemented maintenance plan requiring training for the crew in techniques and knowledge acquisition that promote understanding of the science of corrosion and 2) decisions regarding materials selection, surface coatings, and corrosion control should be made with total ownership costs in mind, because for a ship to function efficiently it must be operational a majority of its work life.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

CBM	Condition Based Maintenance
CCD	Combat Craft Department
CCSE	Center for Corrosion Science and Engineering
CM	Corrective Maintenance
CPHM	Corrosion Prognostic Health Management
CS	Carbon Steel
DDG-51	Arleigh Burke Class Destroyer
EDMAP	Environmental Degradation Monitoring and Prognostics
FM	Facilities Management
LSM	Literature Synthesis Matrix
MIP	Maintenance Index Pages
MRC	Maintenance Requirement Cards
NRL	Naval Research Laboratory
NSLC	Naval Sea Logistics Center
NSWC	Naval Surface Warfare Center
OMT	Onboard Maintenance Training
ONR	Office of Naval Research
PM	Preventative Maintenance
PMS	Planned Maintenance System
PUR	Polyurethane
RH	Relative Humidity
SM	Synthesis Matrix
SS	Stainless Steel
SSRL	Semi Systematic Review of the Literature
TOC	Total Ownership Costs

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my advisors Chad Seagren and Bryan Hudgens for all their advice and support during my entire thesis process. I would like to thank my wife Hima and daughter Suri for their support and making sure that I did not stay in one spot for too long. I would also like to thank my pets Bubble and Big Ted for their company during late nights and for making sure I do not move from one spot.

Most of all, I would like to give a big thanks to my mom and especially dad, who continued to advise and push me through this process, making sure I finished this writing on time and never took a day off to call to see how my process was going.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

This research studies the environments of the main engineering spaces found on the U.S. Navy's DDG-51 Arleigh Burke Class Destroyer (DDG-51). It focuses upon corrosion, repair work and repair history between yard periods to identify problematic factors that may benefit from improved maintenance processes while underway. I experienced many difficulties with corrosion while on deployment working in such an environment which caused disruptions that effected the ship's performance and therefore also effected the performance of the fleet. Discussions with others lead me to believe that this is an issue on other ships as well.

A. BACKGROUND

While operating at sea, ships are exposed to a multitude of environmental conditions that create negative chemical reactions and physical stress. One of the most significant hazards to a ship at sea is corrosion. The management of corrosion is a challenge for ships' crews and keeping up with the inevitable force of corrosion is difficult, but necessary to ensure minimum vessel life cycle costs. "Effective corrosion control in hull structure is one of the most important features for the shipping industry to ensure reliability and minimize risk " (Mathiazhagan, 2011, p.1).

High maintenance costs often lead decision makers to defer expensive preventative maintenance for immediate savings today. This can result in breakdowns that could have been averted. In the short term, ships may complete their goals, but in the long term, deferring maintenance often leads to ships not reaching their expected service life, which increases the total ownership costs (TOC) of maintaining a fleet (Marais et al., 2013). This is what appears to be occurring now with the DDG-51 Arleigh Burke Destroyer: "Over the DDG-51 program lifetime more than 80% of maintenance performed has been corrective. This high reliance on corrective maintenance increases TOC" (Marias et al., 2013, p.804).

The Arleigh Burke Class Destroyer was developed as a surface combatant and comes with a set, initial procurement cost and programmed lifetime support cost. The ship has an all-steel hull, deckhouse and spaces within the hull that are primarily all steel; "the ship [also] employs a gas turbine propulsion system with Controllable Pitch Propellers similar to the CG 47 class" (Vandroff, 2013, p. 5). This huge investment requires manpower, maintenance and a plan for providing adequate surface area coverage for exposed steel. Corroded steel that needs to be replaced is about 10 times more expensive than using appropriate coatings and maintaining the coatings that protect it (Dunleavy, 2018).

B. RESEARCH OBJECTIVE

The overall objective of this research is to find an answer to the primary research question: How might improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces enhance ship efficiency while operating? Evidence suggests that several key elements relating to improved corrosion control practices do increase and enhance ship efficiency and fleet efficiency as well. Seven sub-questions used to explore current procedures the U.S. Navy employs in regard to corrosion control on an Arleigh Burke Destroyer, especially within main engineering spaces, validate this assertion. Comparisons as to how other marine organizations treat corrosion on their ships demonstrate the connection between preventative maintenance and corrective maintenance and how that effects the life cycle of U.S. Navy ships.

C. RESEARCH QUESTIONS

A primary research question and seven secondary research questions are used in this study to focus the research. They are listed below:

(1) Primary Research Question

How might improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces enhance ship efficiency?

(2) Secondary Research Sub-questions

1. Why is corrosion control necessary at sea?
2. What are the current corrosion control practices in Arleigh Burke engineering spaces?

3. Are current corrosion control practices in Arleigh Burke engineering spaces adequate?
4. What inhibitors are present that prevent adequate rust corrosion control?
5. Have surface paint materials effectiveness changed significantly over the past twenty years?
6. What factors influence corrosion control maintenance?
7. Do other maritime organizations prevent corrosion in their engineering spaces differently?

D. SUMMARY

An exhaustive review of the literature followed by an analytical look at the data retrieved, revealed that corrosion control and ship efficiency appear to be closely interrelated. Two key factors present themselves. Factor one includes the existence of an effective corrosion control maintenance plan that requires rigorous crew training, emphasizes preventative maintenance and follows guidelines supported by scientifically proven methods. Factor two includes the understanding that for a ship to function efficiently it must be operational a majority of its work life. When these factors are adhered to and decisions in regard to building materials selection, surface coatings and other corrosion control measures are made with an emphasis to keep ships in service for the longest amount of time possible, then effective corrosion control in Arleigh Burke Destroyer engineering spaces will clearly enhance efficiency when viewed over the total life of the ship.

E. SCOPE AND METHODOLOGY

This research project is an exploration encompassing three main areas; an overview of the current corrosion problem(s) in the U.S. Navy, a comparison of parallel industries and other Maritime Fleets and identification of best practices derived from all groups studied. This thesis provides the following:

- Analysis of current processes that the U.S. Navy utilizes in order to combat corrosion in in the DDG 51 main engineering spaces.

- Analysis of how much the U.S. Navy mitigates identified corrosion obstacles as compared to other maritime organizations.

- Analysis of previous studies as a basis for understanding and to provide strategies for moving forward.

- Recommendations for organizations for future preservation efforts.

The main thesis question for this research is a very complex question because corrosion control has been studied in many ways across many different disciplines. A Semi-Systematic Literature Review (SSLR) process is used as the methodology because the main problem, corrosion control, has been conceptualized in many studies from diverse points of view. A thorough description addressing this qualitative research method is provided in detail in Chapter II.

F. LIMITATIONS OF RESEARCH

I encountered a number of problems while completing this project. One was that I did not identify any specific literature or study on the subject of corrosion control in DDG-51 engineering spaces. I relied heavily upon online resources and was unable to pursue any data gathering in person since I was doing my degree through distance learning. A lack of time and resources limited the scope and depth of the research due to my active-duty status. My requests for data from the Navy department of records was not forth coming, so I was forced to only use published works. I have also served on a DDG-51 Arleigh Burke Class Destroyer, specifically in its engineering spaces, and have obtained technical knowledge and opinions regarding the working environment. To guard against any bias, every effort is made in this study to rely solely upon credible documentation and research and not personal experience. Finally, my research work was during the COVID pandemic where restrictions were high which further limited my capabilities to travel to obtain information.

G. ORGANIZATION OF THESIS

There are five chapters in this thesis. Chapter I is the introduction with the background, questions and current processes. Chapter II explicitly describes and defines the methodological approach used for this research. Chapter III reviews existing literature to aid in answering the overall thesis question and additional sub-questions. Chapter IV reports findings from the research reviewed. Chapter V provides conclusions and recommendations for future study.

THIS PAGE INTENTIONALLY LEFT BLANK

II. METHODOLOGY

A. INTRODUCTION

The main thesis question for this research is a complex question because corrosion control has been studied in many ways across many different disciplines. The research is divided into four areas to address this challenge. 1) Selection of an appropriate methodology which is determined to be a semi-systematic review of the literature; 2) A meta-analysis of selected, identified literature within that review; 3) Development of a tool that gathers and sorts the data for analysis; and 4) A final synthesis strategy to conceptualize the findings allowing for data backed recommendations.

A semi-systematic review of the literature (SSRL) is chosen as a methodology because it is designed to review multiple areas and disciplines. The thesis sub-questions presented in Chapter I establish common points among the varied sources reviewed. "The semi-systematic or narrative review approach is designed for topics that have been conceptualized differently and studied by various groups of researchers within diverse disciplines and that hinder a full systematic review process" (Snyder, 2019, p.335). I decided against a full systematic review as a methodological approach because it would be impossible to review every relevant article to the main thesis question. The semi-systematic review allows for identification and understanding of pertinent research traditions that relate to the main topic of this thesis as well as understand many sub-topics that lead to the discovery of unique themes (Wong et al., 2013). Snyder goes further and suggests that "a semi-systematic review approach could be a good strategy for example [to] map theoretical approaches or themes as well as identifying knowledge gaps within the literature" (2019, p. 334). This is exactly what this research sets out to do. Because the problem of my topic requires research conceptualized from diverse points of view, a (SSRL) process appears to fit the needs of this study best. Also, the (SSRL) process allows for the investigation and identification of themes and patterns that exist, especially when analyzing information from disparate, but interdisciplinary sources (Snyder, 2019). Once identified, these themes and patterns are more easily analyzed and assessed.

Figure 1 is a representation illustrating how the research is guided by the seven sub-questions, how they are arranged in this study and how they contribute information that overlaps and enhances understanding of the overall research question. The seven sub-questions purposefully cover a wide range of subjects that relate to the overall question in order to better answer it. With a broader understanding provided by the sub-questions, the main question is now better able to serve as a concise lens that allows for sifting and sorting through the relevant data that will be mined and coded.

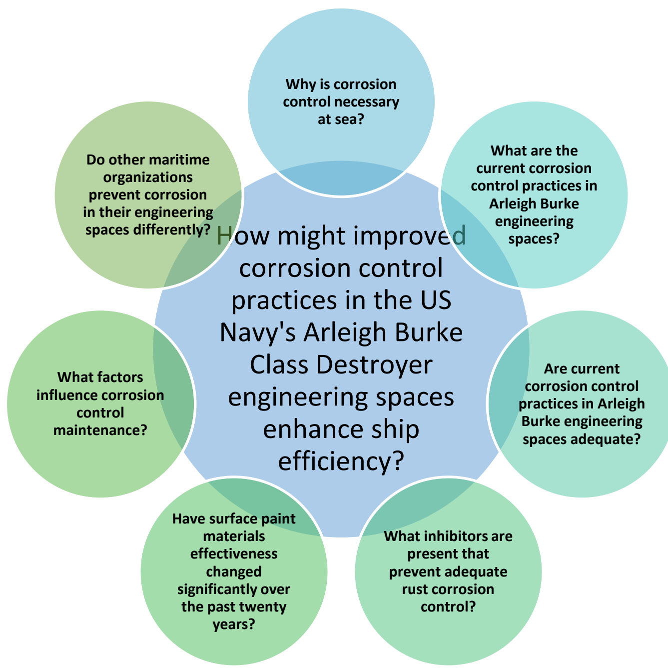

Figure 1. Research Lens

B. META-ANALYSIS AND META-NARRATIVES

Meta-analysis in this research is used as a semi-systematic review of a focused topic in the literature. As Russo (2007) asserts, the meta-analysis provides for a structured and standardized approach for identifying and analyzing specific topics in the literature. The technique is used for examining the existing literature on a specific issue. For example, this thesis attempts to answer the question, "How might improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces enhance ship efficiency while operating?" Seven sub-questionss are used for the express purpose of guiding an exploration through the literature in search of an answer. The sub-questions attempt to find and comprehend different but similar research topics that have the possibility to relate to and explain a specific issue being studied. Similar topics being studied that use different research methodologies, can be explored and examined using meta-narratives. Unique insights into the overall topic being studied can be found when the meta-narratives are used to integrate several parallel findings from different research projects (Wong, 2013). Snyder concurs, "By integrating findings and perspectives from many empirical findings, a literature review can address research questions with a power no single study has. It can also help to provide an overview of areas in which the research is disparate and interdisciplinary" (2019, p. 333).

C. ANALYSIS

Identified meta-narratives are recorded, saved and sorted in this research using a tool developed called a Synthesis Matrix (SM). The SM identifies and codes the initial findings by source, but more importantly also by sub-question. The coordinated analysis provides a means to isolate specific conclusions relating to the topic as well as fill some knowledge gaps that currently exist. Special care is also taken to identify connections and links between the sources, how the information overlaps and how new themes and patterns are starting to become identified (*LibGuides: Conducting a Literature Review: Analyzing the Literature*, n.d.). The findings are analyzed and synthesized by completing a thorough content analysis as a way of identifying themes, patterns and designs. This thematic or content analysis is a technique that is well recognized as a method in qualitative research (Braun & Clarke, 2006). Therefore, a Synthesis Matrix Chart is used to sort and categorize the different findings and arguments presented for this topic and the previously developed sub-questions for this study act as the main reference points of reason for the overall research question (Ingram et al., 2006).

D. SYNTHESIS

The final synthesis of the accumulated mined data attempts to identify and provide understanding for all pertinent research findings that impact the overall research topic. This meta-narrative review has two specific parts. The first part, analysis, identifies and maps out specific ideas and patterns that focus on particular concepts and theories which have results that may agree or disagree with each other. In order to interpret, analyze and report the findings and conclusions identified, a total immersion into the data is necessary (Wong et al., 2013).Chapter IV outlines in detail the second stage of this process. It describes how the analysis progresses from the identification of eleven patterns that coalesce into six concise themes and finally into two identified findings by contrasting and comparing the identified meta-narratives. The final synthesis results reported are more concrete than philosophical and summarize the findings using some numerical aggregation, qualitative aggregation and narrative summary which now allow for recommendations and suggestions for further research (Wong et al., 2013).

E. SUMMARY

Forty-six information resources are included in this thesis. These sources yield 118 specific meta-narratives that are categorized using the SM into eleven emerging patterns. Using a detailed process of consolidation, these eleven patterns are condensed into six (6) major themes. The six themes strongly suggest two identified findings that are titled *corrosion control* and *ship efficiency*. Both findings are synthesized into a conclusion that seems to imply that there is a convincing relationship present between ship efficiency and corrosion control within Arleigh Burke Destroyer engineering spaces.

III. LITERATURE REVIEW

A. INTRODUCTION

This thesis is an attempt to answer the question; How might improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces enhance ship efficiency? A semi-systematic literature review is used as a methodological approach because the answer to this question relies heavily upon identifying different points of view from several disparate, but interdisciplinary sources which all revolve around the central issue of corrosion control (Snyder, 2019). Controlling corrosion, historical and proposed methodologies for dealing with corrosion, inhibitors to best practice models, as well as costs, man power allocations and comparisons to other nations' navies and maritime fleets are reviewed.

The literature review is comprehensive and encompasses many areas dealing with corrosion. The review of this extensive literature base leads to a discovery of themes and patterns related to corrosion control. The application of the knowledge collected within these themes is applied to the special circumstances of the engineering spaces of the U.S. Navy's Arleigh Burke Class Destroyer. Consequently, relevant information discovered within the identified themes and patterns provide a better understanding of this unique area of the ship.

B. BACKGROUND

Corrosion and rust control are both serious problems for the U.S. Navy. It is estimated that the Navy was spending in excess of 4 billion dollars on this problem prior to 2007 and the costs have continued to rise since then (Perez, 2007). Building and replacing ageing DDG-51s with new ships is not a realistic alternative to maintaining the vessels now in service so it makes sense to maintain the current fleet for as long as possible, possibly as long as 40 years for an individual DDG-51 (Marais et. al., 2013). The engineering spaces found within the DDG-51 are of significant importance and concern. "At the most basic level, the DDG 51 engineering plant consists of four GE LM2500 gas turbine main engines, connected two to a shaft, propelling the ship with controllable pitch propellers. Electrical power is provided by three Allison 501-K34 gas turbine generator sets" (Anderson, 2013, p. 18).

This study hypothesizes that improved corrosion control practices within these engineering spaces will ultimately enhance ship efficiency while operating at sea. The main engine rooms of a DDG-51 operate are an enclosed space with multiple machines and electronics running. This generates heat and condensation creating a warm, humid environment that the equipment is always subjected to and must exist with on a daily basis. This is challenging because it is apparent that rust and corrosion are going to form because of excess humidity and areas that are hard to access will prevent strategies to maintain it. Many different studies report similar rust and corrosion problems on commercial ships. "Ballast tanks and void spaces, and cargo holds in commercial ships such as bulk carriers, usually are exposed to quite different corrosion environments and this can influence the rate of corrosion" (Gudze & Melchers, 2008, p. 3296). Corrosion causes may be influenced for many different reasons. "For immersion environments, influences on corrosion include chemical factors such as salinity, oxygen content, pH and presence of pollutants; physical factors such as temperature and pressure; and biological factors such as bacteria and biomass" (Gudze & Melchers, 2008, p. 3296).

C. CORROSION CONTROL AT SEA

Corrosion control is extremely important as it relates to readiness, efficiency, and functionality of the fleet. Without proper maintenance and upkeep, a surface ship and its equipment are destined to wear down and cease operating if not properly maintained. U.S. surface ships operate year-round. They operate in a saltwater ocean which is a proven catalyst that accelerates the corrosion growth process. One of the major tests U.S. surface ships' crews confront is dealing with the challenge of maintaining equipment while making sure required daily tasks are accomplished. U.S. Navy ships are costly systems designed to last a very long time. If these ships do not conduct constant maintenance, then this long living system will deteriorate. Maintenance that is completed properly will ensure that the ships will also function properly reducing the TOC through an extension of the ship's lifetime. Evidence seems to suggest however that policies and procedures for U.S. Navy ships appear to have a problem with this concept. Marias et al. say “many United States Navy fleets are plagued with less than expected availability and shorter than hoped lifetimes, which increase Total Ownership Cost (TOC)” (2013, p. 801).

Times for completing maintenance assessments have been limited due to the current high operational tempo expected on a naval vessel. The restricted amount of time available to perform maintenance eventually fatigues ship personnel. For instance, in 2010 a fleet review panel identified several items that lowered fleet efficiency. These included reduced work assessments, reduced repair timelines, elimination of training and inadequate funding for maintenance (Insinna, 2013).

A major reason corrosion control is a prevalent problem is that without constant attention it grows out of control and ends up having disastrous results. Time and resources provide dual challenges in regard to meeting the maintenance needs on a ship. There is an accepted understanding fleetwide that maintenance training is important, but it is limited due to a scarcity of time and resources. Maintenance training has been placed as a low priority. It was noted that a lack of a fleetwide maintenance training program while aboard ship is due more to bureaucratic inefficiencies than it not being needed (Morris, 1987).

Formation of rust follows a process that exhibits a very low aggressiveness. It presents when there is moisture in the air at as little as 10 percent humidity or more (Bishop, 2019). Since U.S. Navy surface ships operate all over the globe during all seasons, corrosion control differs to match each unique challenge. The geographical sea area where a ship operates, coupled with the time of the year, will determine average temperatures for rust to form (Gudze & Melchers, 2008).

Marine corrosion can take many forms and effect many different areas. Note some examples illustrated in Figure 2.

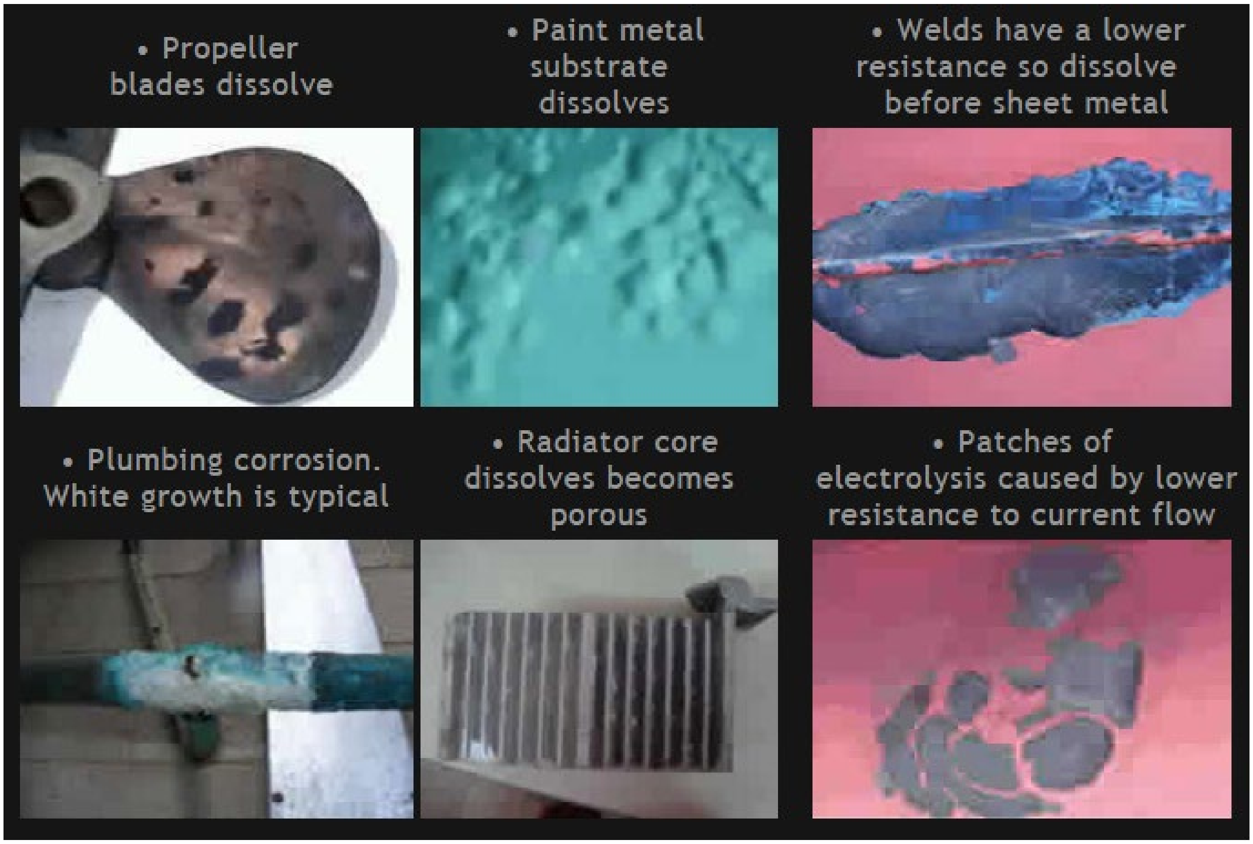

Figure 2. Types of Corrosive Damage Reprinted. How to Stop a Ship's Marine Corrosion in 3 Steps. Source: Bishop (2019).

"The science behind marine corrosion starts with the electrolysis, which continuously dissolves metal, this is generally the cause of marine corrosion. The corrosion occurs between a wet metal or a heating/cooling system and a connection with the earth that is not perfectly dry at least 97 percent of the time" (Bishop, 2019, p. 1). Not only is there constant heating and cooling inside ships, but electrical systems are present as well and cause galvanic reactions. "Galvanic [corrosion] is caused by the natural voltage between two different metals in a conducting medium such as standing water or atmospheric moisture. Electrolysis is generated by all electrics and electronics that have a voltage different from the earth and flows as a current from the installation to the earth, other vessels, or installations" (Bishop, 2019, p.1). Surface ships are constantly being exposed to outside and inside atmospheres and temperatures that effect the growth of corrosion onboard. By recognizing the cause of growth, plans can be developed to focus a maintenance plan on high growth areas. Surface ships are constantly exposed to wetness and salt deposition, it is the ships crews' job to notice and treat it as soon as possible.

Future maintenance needs are planned for at the very beginning of the ship building process. The initial goal is to create a service life for the vessel to be as long as possible. Vessels are usually designed to last a minimum of 25 years. During the design stage, a decisions are usually made whether to invest in more expensive materials and coatings to lower future maintenance costs, or to use cheaper materials initially and defer higher maintenance costs for later (Larsen, 2018). But once the ship is built, it is exposed to the environment and that is where the crew and contractors come into the maintenance picture, when corrosion starts to develop. There are two methods used to moderate corrosion: technical or managerial. Technical methods include using specific coatings or allowing for cathodic protections and/or inhibitors to be used. Managerial methods are not emphasized much, but are taking on new importance. Costs are definitely minimized when corrosion is actively managed through training, design and planning from the beginning to the end of a ship's life (Mathiazhagan, 2011).

The managerial approach appears to be a simple formula to follow, but it is imperative that the problem being considered be analyzed accurately and followed effectively to attain best results. Swanson asserts that there are different managerial maintenance strategies and that these strategies produce different results as it relates to performance. "Proactive and aggressive maintenance strategies are expected to be associated with improved performance. A reactive maintenance strategy is expected to be associated with lower performance" (Swanson, 2001, p. 242).

From the start of a ship's life to the end, it will always go through constant maintenance. The factors that determine how long a ship's life span will be are determined by how well it was maintained. Through the combination of technical and managerial efforts, a ship is able to live out its lifetime and/or longer. The combination of increased operational tempo, followed by lack of resources in material and labor, appear to be a formula for poor results. Surface ships will be doomed to fail if they do not get the proper maintenance that they need. Without proper maintenance, a ship's lifetime will be drastically reduced and the TOC will end up being more then what a government or private owners were expecting to pay.

D. CURRENT CORROSION CONTROL PRACTICES

The current corrosion control practices in Arleigh Burke engineering spaces largely follow the recommendations found within general maritime corrosion control practices. An initial review of the literature indicates that several methods and practices for corrosion control have been extensively identified. Profound evidence exists describing many and various struggles in regard to corrosion control. Not having enough time and resources are repeatedly referenced. However, successful strategies do exist and with the application of standard rules and regulations, effective attention to corrosion control can be performed extremely effectively. For instance, sailors and contractors that handle corrosion maintenance should be adequately trained and supplied in order to perform their job efficiently. But that does not appear to be the case. In 1987 it was proposed the Navy implement a proactive maintenance program called Onboard Maintenance Training (OMT). It was designed to be used by units experiencing problems with specific equipment types when there was an absence of sufficiently trained maintenance personnel help. It was assumed that higher failure rates, would benefit the most from training. However, successful implementation of the training was not realized due to difficulties putting the training into effect (Morris, 1987).

The opposite of proactive maintenance is reactive maintenance. Reactive maintenance allows equipment to run until it fails. It is similar to a firefighting scenario because it is always reacting to a problem or disaster. Proactive maintenance tries to prevent breakdowns by completing minor repairs and predictive maintenance strategies that reduce the probability of breakdowns (Swanson, 2001). This type of maintenance is strived for on the Arleigh Burke Destroyer. There are written rules and procedures on how to deal with corrosion on the ship. The challenge for sailors and officers is to find the time and resources to implement the procedures and eradicate the corrosion when necessary; especially when there are so many causes for rust and corrosion to form. In everyday scenarios though, it appears that corrosion control is not scheduled as preventative maintenance, but as corrective whenever it absolutely needs to be done.

There are many causes for corrosion, and many mitigation strategies to use based upon the type of corrosion exhibited. The design of a ship's structure can result in fatigue and cracking of protective coating barriers due to stress concentrations. Because all metals have very low voltage, the natural voltage combined with moisture can cause galvanic corrosion. When inside the ship, most importantly the engineering spaces, there is ample opportunity for corrosion to form due to the heat, machinery and electronics that are running. The presence of moisture combined with warm air can absorb onto surfaces facilitating a destructive, corrosive reaction. Once the corrosion starts there are other factors that help increase or decrease the rate of corrosion. Research concludes that increasing oxygen concentrations lead to accelerated corrosion rates especially when combined with high rotational velocities. Relative humidity (RH) is important for measuring the estimated atmospheric corrosion loss. The interior ship spaces are highly susceptible and are subjected to RH constantly. The moisture content wets various surfaces then corrosion starts to procced. (Schorr et al., 2016), (Bishop, 2019), (Gardiner & Melcher, 2001), (Hansan & Sadek, 2014), (Gudze & Melchers, 2008). It is imperative to constantly practice corrosion control whenever possible. Once corrosion starts to manifest, there are a number of factors in the environment available to encourage corrosion to grow and become a major threat towards the ship's operational capability.

The U.S. Navy has developed procedures specifically designed to instruct sailors how to perform corrective corrosion control. These procedures attempt to provide as Swanson explains, "A proactive strategy for maintenance [that] utilizes preventive and predictive maintenance activities that prevent equipment failures from occurring" (2001, p. 237). Current practices start by first identifying the affected area then following specific instructions outlined in written naval protocols (Navsea, 2016). This kind of proactive maintenance avoids breakdowns by completing activities that closely monitor equipment and complete minor repairs when needed. Following a path of proactive maintenance is a strategy that aggressively strives to avoid costly equipment breakdowns by undertaking all minor repairs to restore equipment back to acceptable operating levels thus reducing the chance of unexpected equipment failures (Swanson, 2001). There are several steps and specifications that need to be considered to perform basic corrosion control maintenance. Proper knowledge and training will help the sailors perform the maintenance to a higher quality, thus improving the ships life expectancy. The current challenge is finding the time to complete the tasks.

E. CORROSION CONTROL ON AN ARLEIGH BURKE DESTROYER

A current problem with corrosion control in the Arleigh Burke engineering spaces is maintaining a standard of upkeep. Specific maintenance is scheduled to be performed throughout the ship's life cycle but crew and contractors are not always able to perform all the required maintenance in time. Corrective maintenance is a process that repairs something that has already failed and preventative maintenance follows a plan while a system is still operational to prolong and delay any deterioration that may occur. The short-term positive side of deferring maintenance allows for the cost of performing maintenance to be pushed forward to the future. The negative side to the same scenario is that deferred maintenance may result in severe degradation, possibly costing more both in money and lost time due to breakdowns than anything saved earlier (Marais & Saleh, 2009).

A surface warship has multiple systems that work together in symbiotic ways. Kandemir and Celik (2017) explain in their research that there are several physical inhibitors on a ship which are factors that influence corrosion control. They explain that ships are complex structures that are large and difficult to operate. The physical environment includes high heat and humidity, high vibrations due to machinery, and repair processes are time consuming and costly. When the systems are running continuously there seems to be little time and manpower to correct or even notice corrosion growth in the system. Wahid et al. (2018) assert that ships are dynamic open systems; environments that are very hard to manage because naval ships require many areas that all operate simultaneously and are interdependent with each other in series and parallel systems all on a platform that moves and floats. Resolving issues involving complex systems that are found on naval vessels is very difficult and no model has been successfully developed to manage these challenges.

If the practice of deferring maintenance is done regularly through long stretches of time, then it can have disastrous aftereffects. "Without maintenance, long-lived systems will deteriorate due to use or age. Maintenance is especially important for costly systems that are subjected to punishing tasks, such as Navy ships" (Marais et al., 2013 p. 801). Unfortunately, data for deferred maintenance is not available, but corrective maintenance data can be gathered and observed and used as a measurement to deduce how much maintenance was deferred. Deferring maintenance increases the reliance on corrective maintenance. Figure 4 [3] shows how much effort has been expended on corrective maintenance over the program lifetime. In most years, the majority of maintenance man-hours have been corrective. "This high proportion of corrective maintenance is not unusual" (Marias et al., 2013, p. 804).

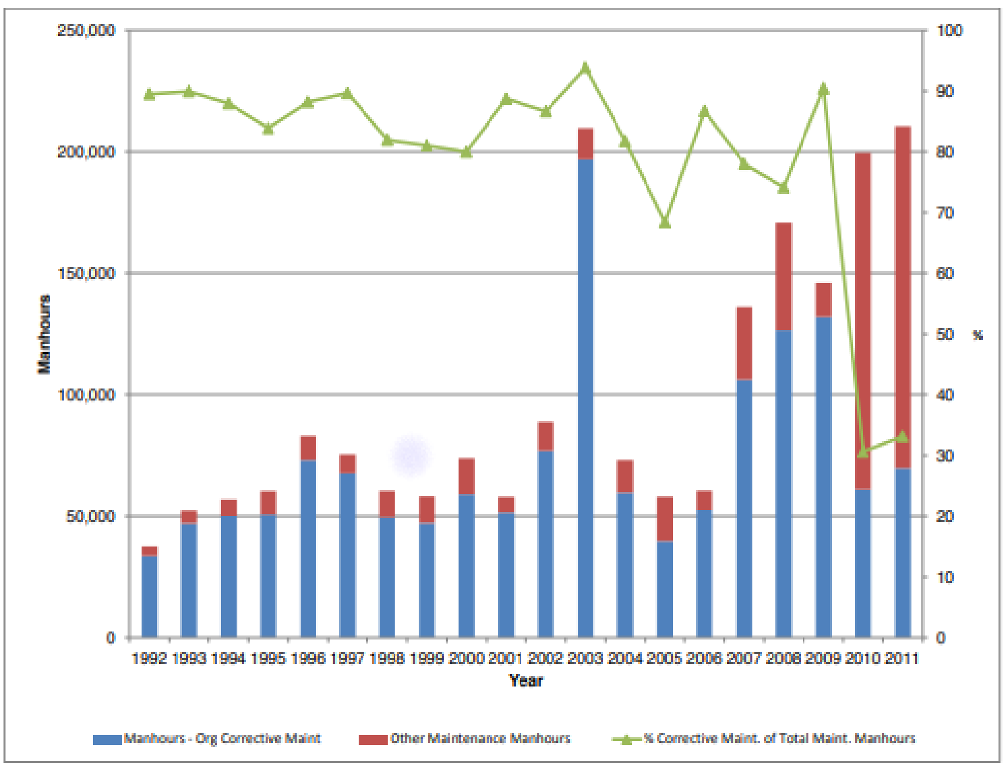

Figure 3. Modeling the impact of maintenance on naval fleet total ownership cost. Source: Marais et al. (2013).

The DDG-51 class is part of an overall pattern of reliance on corrective maintenance. There is a wide variation in the percentage of corrective maintenance, indicating that significant reductions in corrective maintenance are possible within current practices. In addition, there is a wide variation in the percentage of corrective maintenance performed each year, indicating that significant reductions in corrective maintenance are possible within current practices. Over the DDG-51 program lifetime more than 80% of maintenance performed has been corrective. This high reliance on corrective maintenance increases TOC (Marias et al., 2013, p. 804).

The data clearly show that the vast majority of maintenance completed on an Arleigh Burke DDG-51 is corrective or reactive and spontaneous. An assertion may be made that the data indicate crews onboard a DDG-51 spend a majority of their time and energy tracking and addressing equipment breakdowns instead of focusing on preventive maintenance.

Ship engineering spaces have a vast amount of equipment and systems that are interdependent. These systems are meant to be interconnected to work off each other. When one piece of equipment or system is damaged, it often effects other systems onboard. Often, when contractors come on board ships for planned maintenance, they discover enormous amounts of unplanned maintenance due to the symbiotic nature of this design. An anecdote in the literature describes a group of contracted workers that were planning on repairing a diesel engine but also found corrosion in its foundation that needed repair. Before repairing the steel in the foundation, the crew had to remove the fuel to prevent an explosion. The workers then discovered corrosion in the fuel tank (Insinna, 2013). To mitigate such a cause-and-effect scenario, the Navy used to have programs for subject matter experts to come onboard the ship and look around for such discrepancies. For instance, senior enlisted officers used to visit ships to do exams that were associated with various systems. This program was eliminated illustrating that the positive returns in providing training was clearly underestimated (Insinna, 2013, p. 24). Expectations for maintenance on the DDG-51 requires manpower to perform that work. There are many documents, programs and instructions in place to help keep the Arleigh Burk engineering spaces corrosion free. It is a demanding task and the Navy has looked for methods to mitigate the workload. A Navy study that examined reducing numbers of shipboard personnel reviewed three main ideas: moving functions performed by crew to contractors, reducing the numbers of sailors assigned to a ship along with their support services and increasing a reliance on new technology to compliment reduced numbers of personnel assigned (Hinkle & Glover, 2004). The manpower reduction that resulted from the findings added to performing preventative maintenance challenges.

However, one positive example of meeting the reduced manning challenges is described below. “Like all the gas turbine powered predecessors, the Burke destroyers employ an extensively automated remote operating and monitoring capability for the engineering plant, the Machinery Control System, to sustain reduced manning requirements in the engineering spaces” (Bennett & Sloan, 2003, p. 1330). “Thus, the main driver for engineering plant mode selection is to have as few main engines online as is allowed by the tactical environment” (Anderson, 2013, p. 19). With reduced manning, the number of work hours the ship has to correct any issues that may develop is adversely affected. That is why the Navy developed Maintenance Requirement cards (MRC) and Maintenance Index Pages (MIP). This works in part with a program called Planned Maintenance System. Documentation is provided that details when specific maintenance and work tasks are to be completed on ships and boats. The program works to minimize maintenance costs through identification of possible failures and completion of specific maintenance tasks. All work is recorded by the Naval Sea Logistic Center (NSLC) (Team Ships: Surface Ships from Cradle to Grave, Boats and Craft. (n.d.).

The MRCs and MIPs rely upon an extensive data bank maintained by the U.S. Navy. The theory of their use is sound but unfortunately it does not appear to be operating at the potential envisioned. A clear description of the dilemma follows.

> Reports of corrective maintenance are tied to ship configuration files, and orders for replacement parts are tied to the maintenance actions. Configuration Data Managers, located at geographically dispersed locations throughout the United States and usually at Naval or private shipyards, manage the configuration files, which are updated by modernization maintenance action reports. Even though the Maintenance Data Collection System is more sophisticated now than at its inception, there are inherent shortfalls that trace their lineage to the limitations of the mainframes and

> software of the 1960s. As a result of this "dead hand history," the data collected is nearly useless for analysis because of its resistance to data mining. (Bennett, 2003, pp. 1327–1328)

Utilizing approved maintenance procedures is supposed to allow the Navy to be able to follow a standardized way to perform maintenance on their ships. When maintenance is performed correctly it ensures that ships function properly and it also reduces the total ownership costs (TOC) by extending the ship's life. Ship's operating costs are reduced when programmatic decisions guide the maintenance. But this does not seem to be the case as it relates to U.S. Navy statistics. "Many United States Navy fleets are plagued with less than expected availability and shorter than hoped lifetimes, which increase Total Ownership Cost" (Marais & Saleh, 2009, p. 801).

But the Navy is also limited to the amount of maintenance they can perform in accordance to its OPNAVINST 4790.16, Condition Based Maintenance (CBM) Policy. "The CBM strategy is to perform maintenance only when there is objective evidence of need, while ensuring safety, equipment reliability, and reduction of total ownership cost" (Fajardo & Ortiz, 2011, p. 4). It is a constant balance for the sailors to perform the corrective maintenance they need to do in the way they are required to do so.

F. INHIBITORS TO RUST CONTROL

Several examples of inhibitors to corrosion control as it relates to time, resource management and maintenance challenges are described and detailed in previous sections of this thesis. What follows in this section is a more detailed description of the science and chemistry involved with corrosion and methods to control it.

Inhibitors are physical tools to combat corrosion, are quite positive. Impeding and slowing the corrosion process through the use of inhibitor technology is a tool used on all naval vessels. When the start of the corrosion process is examined, it is necessary to focus in at the molecular level. The best way to describe this is that metals and alloys are basically made from their own ores or oxides of the metals made from their ores. Once oxygen is gone, the iron used to form steel goes through many processes before the ship plates used to build the ship are produced. This steel is chemically unstable and it is ready to combine with oxygen to form the stable iron oxide it once was. As the steel moves toward its stable oxide form, it produces red spots or rust which of course uses water to speed up the chemical changes from iron - to iron oxide. But corrosion does not stop there. It is found that when metals possess a different appearance or chemical structure, they also act differently when placed in a solution, which can conduct electricity and possibly work toward reducing corrosion or rust from forming. (*CANADIAN FORCES SPECIFICATIONS*, 2018).

What follows is an illustration of how understanding this chemistry can help develop strategies to inhibit rust and corrosion. There are installed anodes that are the non-organic inhibitors in ships where there is a common exposure to salt water. Those inhibitors are “Metal strips of top-order metals in the reactivity series [which] serve as anodes and are installed for cathode protection. These are called sacrificial anodes” (Wankhede, 2021, para 7). With the correct application, sacrificial anodes help slow down the corrosion process, allowing the ship’s crew ample time to correct any negative issues and sustain the ship’s life. “In general, we can say that the part of the ship to be protected against corrosion is called parent surface or cathode, whereas the more reactive material covering on the ship’s part which acts as an anode is termed as a sacrificial anode” (Wankhede, 2021, para 11).

Figure 4 illustrates this by using two metal strips, one copper, one zinc. By placing them in a solution of zinc sulphate the solution acts as a conductor of electricity by virtue of the fact that the zinc sulphate, when placed in the water, breaks up into charged particles called ions. These ions are current carriers and thus make it possible for current to flow through the solution. This opens up the possibility for zinc to be employed as a sacrificial anode for aluminum as well as iron using the process of electrolysis (Wankhede, 2021)

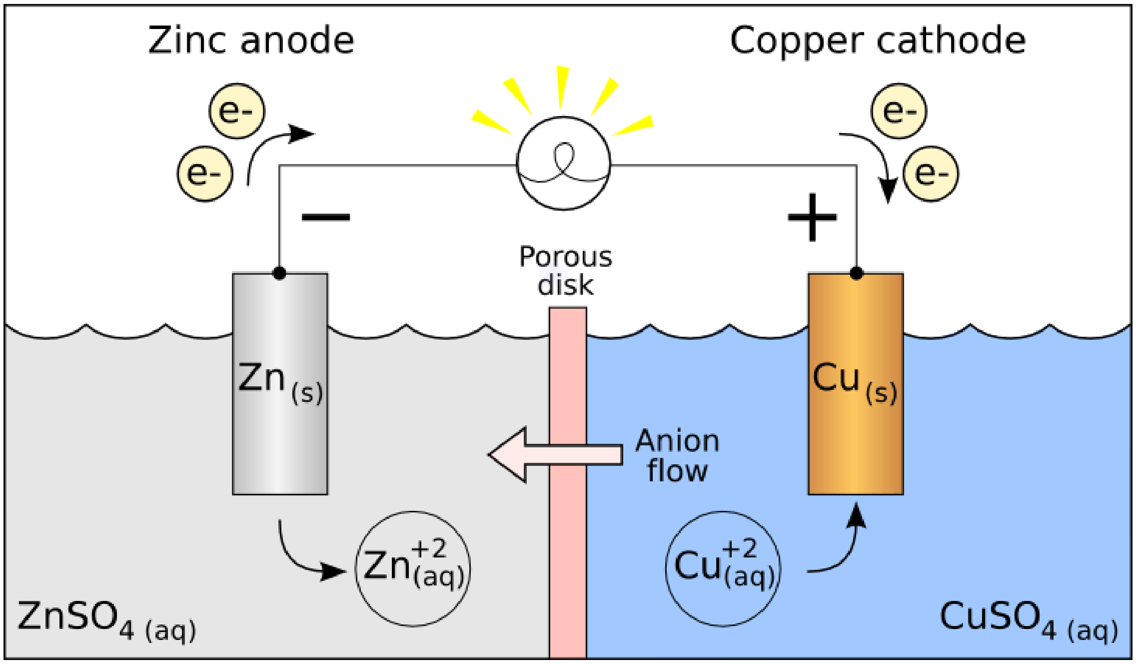

Figure 4. How Sacrificial Anodes Work. Source: Wankhede (2021).

Sacrificial anodes are very important tools that act as inhibitors for the ship to slow down corrosion. To create the electrical connection to the sacrificial anode you need to start with two separate metals. One will serve as an anode when electrolysis is taking place and be called the anode body. The other will be fixed to the parent surface of the ship and be called the anode insert. "Sacrificial anodes work on the principle similar to electrolysis, according to which, if an anode and a metallic strip are dipped in an electrolytic solution, anode electron will dissolve and deposit over the metallic strip and make it a cathode" (Wankhede, 2021, para 22). This process aides greatly with inhibiting rust formation.

A final exciting inhibitor called a Corrosion Prognostic Health Management (CPHM) software system is currently being developed in Australia. The CPHM system is formally called, Environmental Degradation Monitoring and Prognostics (EDMAP) (Knight et al., 2019). This corrosion diagnostics and prognostics software will be explained in detail in an upcoming section dealing with foreign maritime fleets, but it is basically a system that helps predict when corrosion control needs to be initiated.

There are a variety of both positive and negative inhibitors in place for surface ships to consider when dealing with corrosion. The science has been proven to place sacrificial anodes around the ship to absorb more corrosion to keep the ship safe. It is necessary to ensure that the sacrificial anodes be changed on time so the equipment will be useful. Having a system designed to tell you where corrosion is forming will be a game changer to predicting corrosion growth and dealing with it before the corrosion gets out of hand. Sacrificial anodes are a proven system but will only work if crew and contractors make sure that all sacrificial anodes are accounted for and not lost. Naval fleets and maritime ship owners will always need to consider whether extending the service life of a vessel is wiser rather than moving too quickly to new construction especially since the average age of current fleets will inevitably increase as will maintenance, repair, and modernization of equipment costs. Ship owners and governmental entities need to consider all these variables before deciding upon building a new ship or extending the life of an existing one (Koenig et al., 2009).

G. SURFACE PAINTS AND COATINGS

There have been vast improvements to the standard of paint authorized for use in the U.S. Navy. The paint lasts longer and protects more. It is always a struggle to keep up with a seemingly never-ending demand for paint, but through ingenuity and science, longer lasting paint is resulting in more available paint for the fleet. Corrosion prevention and control is routinely addressed by the Office of Naval Research (ONR). ONR encourages and sponsors studies through a multitude of initiatives involving research. All are based upon proven science as it relates to corrosion and developing models to help predict when specific coatings may fail (Perez, 2007).

The paint being used by the navy is providing a significant delay to the corrosion process. Over the years, industry has been working on making resilient, better paint that can cover ship surfaces for longer periods without fresh new coats applied. Other protective coverings are also needed as evidenced by the Navy's installation of nearly 3.7 million square feet of non-skid coatings per year and is reported to cost in excess of $56 million annually (PaintSquare News, 2015).

The Center for Corrosion Science and Engineering (CCSE) is an organization that conducts studies and programs dedicated to reducing the effects on naval systems caused by marine environments. “Within the CCSE, the Marine Coatings Science Section conducts basic and applied research to synthesize and produce advanced, multifunctional marine coatings technology for all naval environments, including immersion, alternate immersion and atmospheric exposures typical of Navy and Marine Corps platforms” (PaintSquare News, 2015).

Ensuring the Navy has the paint supply it needs involves following specific parameters to protect the integrity of the product being purchased. Exacting standards are required. A simple approach that is empirically based should be used in surface coating development that takes the science of corrosion into account. Three simple concepts need to be considered. The first includes a definitive measurement of how long a protective coating lasts prior to the onset of corrosion. The second, the progress of the continued damage should be measured. Finally, the overall process from beginning to end should be measured (Gudze & Melchers, 2008). Vendors that qualify and meet the exacting criteria required must also agree that the Navy still owns the intellectual property rights to the product. Once the approved paint is identified, the Navy still has to purchase and apply the new paint on all of its ships, which is estimated to take about eight years (Insinna, 2013). Overall, it is a three-part challenge. The U.S. Navy develops a paint that will last a long period of time. A vendor qualifies to produce and sell the product. The Navy then purchases the paint and applies it to all of the ships.

There are many types of paint in the world that are specifically made for explicit purposes. The U.S. military actively searches for new and more effective paint to prevent current corrosion issues. One encouraging find is a new paint product developed by ONR. “This new polysiloxane paint — which has a backbone of two silicon atoms bonded to an oxygen atom — is already oxidized before it is used on the ship said Larry Schuette, director of innovation at ONR. This makes it more resistant to corrosion, harsh weather and ultraviolet light” (Insinna, 2013, pp. 24-25). Polysiloxane coating has been mandated to be used for future surface ship maintenance. This new coating is inexpensive but does not require excessive labor to apply. The product costs about 30 percent more per gallon than what is currently being used, but because it only takes two coats instead of three, it actually results in a savings when applied for the long term (Insinna, 2013). The Naval Research Laboratory (NRL)-reports that current nonskid paint coverings have a 1–3-year life and topside paint coverings have about a 2–3-year life. Polysiloxane paint promises twice to three times the lifespans and will be used to significantly reduce the TOC of existing naval ships (PaintSquare News, 2015).

There are other methods of applying different paint coatings besides polysiloxane paint. Spray metal coating is another method that melts certain types of metal to a liquid state so that it can be sprayed onto the surface of a ship. "Coating systems with an aluminum base offer greater corrosion protection and reduce shipboard maintenance. The application of a sealer or topcoat provides the coated surface with long-temi (sic) protection. These coatings also provide electrochemical (cathodic) protection, particularly during exposure to an aggressive marine atmosphere and in proximity to dissimilar metals" (Schorr et al., 2016, p.11). Unfortunately, it is about twice as expensive as conventional paint systems. It is primarily used on equipment located topside, machinery spaces and interior wet spaces. The use of thermal spray aluminum coatings is also a very effective method of corrosion control for marine atmospheric service. However, this method comes with many limitations. Even though there is an advantage of increased cathodic protection compared to epoxy, it cannot be used in several areas of the ship because extreme preparation is required for this type of application (Schorr et al., 2016).

Labor and appropriate manpower are necessary for all paint applications regardless of type. Before any corrosion protection is applied to metal, a very specific surface preparation protocol must be followed. All degraded coatings, dirt, debris, oil, fluids, rust, corrosion and scale must be removed from the metal because proper, performance and protection of the metal depend upon a specific preparation regimen being followed (Navsea, 2016). A short paraphrasing of some of the protocols involved with removal of old coatings and application for new coatings includes the following. First, cleaning is performed using low pressure freshwater to remove any residual soluble salts. Oil and grease are removed by using hand tools, power tools or abrasive blasting using solvent cleaning. Old paint is removed to a standard that ensures no rust or blisters exist underneath. Blast cleaning is recommended for metal surfaces. Once blasting is completed, the entire surface is blown with compressed air and/or vacuumed to remove all traces of blasting dust prior to painting. Finally, bare steel surfaces need to be roughened for the coating system being applied to stick appropriately (Navsea, 2001).

Finally, though not a primary focus of this research, there is also a problem other than corrosion that needs to be controlled on navy ship surfaces. This problem involves marine biofouling. Marine biofouling and corrosion can exist simultaneously requiring surface protection designed to protect against these dual problems. One way to protect and control marine biofouling is by using biocides that are infused into paints and other protective coatings. Saltwater actually stimulates and releases these special biocides which then attack the organisms that cause the fouling (Hellio & Yebra, 2009).

H. INFLUENCING FACTORS REGARDING CORROSION

There are several factors that influence corrosion control maintenance because obstacles on a ship are many and varied and originate in numerous forms. It therefore falls to individuals on board to exercise effective decision making within their managerial roles to identify and find solutions to problems involving corrosion.

One identifiable problem in the fleet is that ships are constantly exposed to the environment. Another problem reported is the lack of manpower to properly control the corrosion growth that comes from this exposure. Rain, sea water, temperatures and humidity are not the only causes of corrosion. Pollution plays a role as well. "Corrosion and pollution are interrelated processes since many pollutants produced by power stations burning fossil fuels, accelerate corrosion and corrosion products such as rust, oxides and salts, pollute water bodies. Both are pernicious processes that impair the quality of the environment and the durability of the marine structures and construction materials" (Raichev et al., 2009, p. 125).Once the effects of pollution begin effecting the metal on a ship, the only way to address the damage is through corrective maintenance. The lack of fleetwide maintenance training programs aboard ship complicates addressing corrosion problems immediately.

We have all experienced the effects of corrosion in the open air such as rust spots on chrome or rust on our cars. The same occurs on untreated steel on a ship. Open air corrosion is a process that when compared with many chemical changes, is a slow process, but when objects are built to last for long periods, corrosion appears to be rapid and severely reduces the effective life of naval vessels (Canadian Forces Specifications*,* 2018). The water that ships sail on change based upon many circumstances. Valdez et al. (2016) explain that corrosive substances affecting fluvial and marine coastal infrastructure are directly caused by the natural environment, industrial effluents and organic matter from agricultural and municipal wastes. Those pollutants have become permanent problems for fluvial and marine environments. The situation is severely aggravated when all manner of pollutants flow into rivers and ports causing extreme damage. The entire sea coast environment is negatively affected (Valdez, 2016). Whenever water pollutants are present, the end result is that human health can be impaired and corrosion problems are exacerbated. Both should be avoided at all costs (Marcos & Botana, 2006).

It is not unreasonable to assert that the same issues that affect marine infrastructure also affect the surface plating of naval vessels. The processes are virtually the same. Corrosion occurs when salts or contaminants deliquesce and absorb water from the atmosphere resulting in wet surfaces. As droplets form micro-corrosion cells containing localized anodes and cathodes they replicate and combine which then results in large scale corrosion. This atmospheric corrosion always occurs when salt combined with surface metal combined with wetness combined with humidity, temperature and sun occur (Knight et al., 2019). There is always a major interest in atmospheric corrosion, but generally speaking, there is greater interest and concern with what is happening on the inside and outside of the underwater hulls of ships. That corrosion is more serious simply because of the nature of the medium in which the ship is placed. Salt water acts as an excellent conductor for the current, which flows during corrosion on immersed surfaces allowing for underwater corrosion which has been found to be electrochemical in nature (*Canadian Forces Specifications*, 2018).

Besides pollution, there are other influencing factors. A study completed prior to 2004 recommended that positive outcomes would result if only minimal maintenance aboard ship was completed. The study determined that performing the majority of maintenance ashore using contractors would dramatically reduce shipboard manning, resulting in a possible reduction of maintenance staff by 60% and culminate in major savings (Hinkle & Glover, 2004). However, in 2010, a navy fleet review panel found that there were consequences to reduced manning that could be attributed to a lack of surface force readiness. It was found that the Navy created shorter time periods to complete repair and maintenance assessments and training times were reduced. Because high operational tempo was stressed, it created pressures that affected and limited time for crew to conduct maintenance assessments who not only did not have time to assess problems, but no time to fix the problem (Insinna, 2013).

A review of what is known about atmospheric rusting includes many factors. The simplest, most important factor is the presence of oxygen and moisture. Oxygen is needed to affect the chemical change and moisture speeds the process. Natural and anthropogenic pollutants also speed up the process of corrosion in steel and a variety of other marine engineering materials. Knowing these materials corrosion characteristics assists with the development of managerial strategies and new technologies to create better materials. Stainless Steel (SS) is an alloy that is broadly used on ships and in other marine environments due to its corrosion resistance (Valdez, 2016).

Manpower is a final influencing factor that inhibits corrosion control. Maintenance is often one of the most significant factors that drives manning requirements on a ship. There are three types of maintenance on a ship. The types include, Preventive Maintenance (PM), Corrective Maintenance (CM) and Facilities Maintenance (FM). PM concerns itself with work accomplished in response to periodically scheduled maintenance normally mandated. The amount of time required for PM is usually prescribed and is different for specific pieces of equipment. CM is unscheduled and occurs when there is a malfunction or failure. Work that is directed toward the material condition of the ship is referred to as FM. Difficulties arise when CM is needed. CM interferes with the process of PM because trying to schedule maintenance around the demands of CM continually puts PM behind schedule. A CM issue may have an extensive time commitment for each occurrence making predicting CM times an inherently difficult task. Too much CM negatively impacts PM and FM (McGovern, 2003).

There are many factors that influence corrosion control maintenance on a ship. But there is a limited number of resources and manpower available to correct all the issues that may occur.

I. OTHER MARITIME ORGANIZATIONS

Other maritime organizations all deal with the same problems caused by corrosion. The literature reveals that other maritime organizations basically follow best practices for corrosion control, but do so more or less aggressively than the U.S. Navy depending upon the circumstances. Each organization reacts differently concerning their motives. Their reactions differ based upon whether or not a new ship is being built, or maintenance initiatives for existing ships in service need adjusting, or decision making in regard to scrapping a ship that no longer can continue need to be made. The realities of the moment influence choices these maritime entities select as they handle similar problems, but for varied reasons. Overall, other governmental navies appear to deal with corrosion the same as the U.S. Navy by trying to look for methods that are both effective and reliable but under all circumstances must keep a maximum number of ships immediately operational. Merchants tend to have much different motives as they look for the most cost effective and efficient methods to increase their profit margin and TOC of their ships.

The longer a ship's life span, the more years companies or navies can use them. This is just a reality. What is important to note though is that long use also must be paired with optimal efficiency and reliability. This requires maintenance of operating systems for the working life of the ship. A major thread that appeared to tie both the merchant navies to navies representing governments as it relates to corrosion control was finance. Budgets are never infinite and both maritime and governmental entities need to consider costs related to personnel, equipment, maintenance, operations and purchasing new ships. A term that was prevalent in all the literature was Total Ownership Costs (TOC). "System Total Ownership Cost seeks to combine aspects related to acquisition costs, operating costs, maintenance costs, and manpower costs (both staffing and training) over the life cycle of the system" (Marais & Saleh, 2009, p. 801).

The best way to approach this concept is to begin with the initial decision to build a new ship. Gratos et al. (2009) report that shipping capacity must ultimately be maintained by building new ships to replace the ones that have been taken out of service. Costs will ultimately be borne by society at large to design, build, man, operate, maintain and repair through natural market mechanisms. The authors suggest that completing an accurate cost/benefit analysis examining how annual costs will progress with corrosion additions at the design stage, will definitely be worth the effort. Merchant mariners strive to design ships that are meant to have a 25-year life cycle with the lowest possible cost in mind. That cost is not the lowest cost to build, but the TOC over the lifetime of the ship. With that in mind, it is beneficial to include certain aspects of the ship that are considered at the very beginning of the design phase. What better way to combat corrosion control than to invest materials and items that will minimize maintenance costs rather than buying cheaper materials that will cost more to maintain and replace over time (Larsen, 2018). Clearly ship design that considers future maintenance costs as well as corrosion control is very important. For some, a major priority is to always plan for corrosion control by building with the proper materials in the first place. The following excerpt provides a specific example of the benefits of correct materials selection to take advantage of the science of anodes and cathodes discussed earlier in this chapter.

> Materials selection is one strategy to address corrosion. Corrosion control can be designed into the ship itself. For example, the deck on a tanker can be fitted with ~3 km (2 mi) of piping. Typically, this piping is constructed of stainless steel (SS); however, SS is cathodic to the carbon steel (CS) used on the supports and structure of the ship, which means the CS acts as an anode for the SS piping, and it will corrode preferentially to protect the SS piping. Ideally, the piping material should be designed so the current density from the cathodes (SS) to the anodes (CS) is reduced, which will then prevent the deck of the ship from corroding. Coatings are very good resistors, and on Stolt Tankers ships, the SS is coated to reduce the current density. The CS supports and structure are also coated to protect them from the corrosive environment. (Larsen, 2018, p. 7)

Merchant fleets report very detailed planning is involved in the beginning of their building process. Maintenance prevention teams are developed with the task of working to enhance future performance by using innovative designs. Maintenance teams interact closely with engineering teams early in the developmental planning stages to ensure future equipment is easy to maintain and operate (Swanson, 2001). The TOC of the ship is a primary focus through initial planning phases resulting in a system to combine acquisition costs, operating costs, maintenance costs, and manpower costs over the life cycle of the system (Marais & Saleh, 2009).

Similar to the U.S. Navy, other maritime organizations are very committed to ship surface preservation. Whereby the U.S. Navy has moved toward using more polysiloxane paint. Other fleets still use reliable high-quality coating systems to control corrosion on the ship as exemplified in the following.

> The main deck is protected with a high-grade, combined composite coating system that starts with a zinc primer, followed by an epoxy coating with aluminum pigment as the second coat, and then a topcoat of polyurethane (PUR) coating. Zinc primer is used for adhesion purposes, enabling the coating system to adhere to the metal surface. The epoxy acts as a barrier to protect the metal surface, and reduces the amount of water, chlorides, and other contaminants that can access the surface and cause corrosion problems. The PUR topcoat acts as a sunscreen and protects the epoxy from ultraviolet light. Otherwise, the epoxy would chalk and deteriorate. The PUR is tinted and provides an aesthetically appealing finish to the deck as well. (Larsen, 2018, p. 8)

Preservation application is still a big part of corrosion control on a ship. No matter what is put on a surface, contaminates will always find a way into the metal. However, both types of fleets share one bit of dissimilarity in their response to this problem. The private merchant fleets tend to rely more on shipboard maintenance and less on off ship repairs while the U.S. Navy tends more toward off ship repair and maintenance and less shipboard work. Morris (1987) explained that shipboard training for crew benefited both the crew and the financial bottom line especially when viewed as a personnel decision. The equipment on board can be repaired considerably cheaper than off ship repair and specialized skill training is much cheaper than off ship costs.

Australia is investing time in studying how to implement and achieve a preventative maintenance protocol in order to mitigate technical risks. The goal is to reach acceptable levels of success while complying with regulations and policy at the lowest ship life cycle cost (Wahid et al., 2018). Consequently, Australia is examining a new software system that is designed to help in the fight for corrosion control. The software is primarily developed for use in aircraft and it purports to be an effective strategy to use to properly preserve equipment by knowing when it is in jeopardy and needs corrective maintenance. The software package loads, filters and displays monitored sensor data for a squadron or fleet of aircraft. Embedded corrosion diagnostics and prognostics are used to determine corrosion severity that is occurring. The system subscribes to Condition Based Maintenance (CBM) philosophy and facilitates maintenance planning. As a user interface for corrosion sensor measurements, it can be processed and easily interpreted by maintainers. The Corrosion Prognostic Health Management (CPHM) software allows for the comparison of corrosion conditions for all the planes. It is capable of creating scheduled inspections and maintenance or defer inspections with a high reliability of confidence. It can generate reports for the entire fleet of aircraft to assist with fleet management activities" (Knight et al., 2019). Even though this technology is only designed for aircraft, it does have potential to move laterally to surface ships and help with the fight for corrosion control.

There are multiple stake holders that deal with the same problem of corrosion control when it comes to surface ships. All organizations are researching answers to the same questions of how to be more effective.

J. SUMMARY

This investigation of the literature is purposely broad and covers many aspects of corrosion and corrosion control. It is very uncommon to find studies that focus on corrosion in any one specific area. No detailed study or past research is reviewed that specifically discusses corrosion control only in a DDG-51 engineering space. But corrosion develops in all areas of a ship regardless of the location. All information concerning corrosion has value and is useful and the literature review focuses on gaining a better understanding of corrosion control. This research uses a variety of documents that relate to the subject of corrosion control allowing for common themes and patterns to emerge relating to the main question posed for this research. Therefore, this broad literature review guided by seven sub-questions compiles a plethora of information. The specific themes and patterns regarding the thesis' overall research question become apparent and lead toward many conclusions and recommendations. The identified themes and patterns are discussed in Chapter IV using this semi-systematic review of the literature as a methodological strategy and a Literature Synthesis Matrix (LSM) as a data mining tool.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. FINDINGS

A. INTRODUCTION

Chapter IV reports the major findings of this research project. The initial findings are presented with extensive descriptors, but minimal discussion, because the substantial relevance of what the data suggest is examined in depth later in the Chapter. In this section, data gathered through the literature review is described, categorized and explained. Patterns and themes are categorized and clarified as they present themselves within the broad-based literature review. Every attempt is made to report the facts using data that were discovered through the use of a data mining tool called a synthesis matrix. Eleven (11) identified patterns lead to six (6) specific themes which are significant to the results of the research because they underscore the components that are mainly involved with corrosion control in engineering spaces. Utilizing the mined data as evidence, graphs and tables are used to present the data simply in order to perceive and understand the findings more easily. Finally, this chapter concludes with a synthesis of the identified themes leading to the conclusions reported in Chapter V.

B. DATA ANALYSIS

The data were initially mined using a synthesis matrix to separate key statements and findings in quadrants within each sub-question. The first attempt provided a very large amount of evidence that was successfully captured within the seven initial sub-questions used for this research. What is especially important with this technique is that samples from the literature representing many various studies from different disciplines produced similar reviews and findings in regard to the overall question asked in this thesis. Table I offers more detail providing the number of instances specific topics were discussed in the literature as they relate to the patterns identified.

Table 1. Synthesis Matrix Initial Emerging Patterns Identification

	EMERGING PATTERNS A-K										
SUB-QUESTIONS	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**TOTAL**
Why is corrosion control necessary at sea?	5	2	0	0	0	0	0	0	4	0	0	11
What are the current corrosion control practices in Arleigh Burke engineering spaces?	5	2	1	1	4	0	0	0	0	0	0	1.3
Are current corrosion control practices in Arleigh Burke engineering spaces adequate?	7	5	1	6	0	0	0	0	1	2	0	22
What inhibitors are present that prevent adequate rust corrosion control?	3	2	5	0	1	1	0	0	5	0	1	18
Have surface paint materials effectiveness changed significantly over the past twenty years?	0	4	0	3	0	0	0	1	0	0	0	8
What factors influence corrosion control maintenance?	4	5	1	2	1	0	4	5	3	5	0	30
Do other maritime organizations prevent corrosion in their engineering spaces differently?	3	5	3	1	1	0	0	0	2	0	1	16
TOTALS	**26**	**24**	**11**	**13**	**9**	**1**	**4**	**6**	**15**	**7**	**2**	**118**

Emerging Patterns Key: A) scheduled maintenance, preventative maintenance, types and cost, B) Total Owner costs (TOC), C) Ship design decisions materials selections, anodes, cathodes, metal types, D) High quality surface coating systems for ships and marine structures, E) Onboard maintenance training, F) Safety and environmental concerns, G) Off-ship maintenance training, H) Marine biofouling and pollution, I) Corrosion science, J) Reduced manning on surface ships, K) Emerging technologies

Eleven (11) patterns present themselves as the data are categorized ranging in value from one through twenty-six representing the number of times the topic is referenced in the literature review. Forty-four sources provide for 118 distinct statements or meta-narratives referencing the topics identified as emerging patterns. Figures 5 and 6 describe the data displayed in the table above with a broader criteria definition used to describe and illustrate the topics.

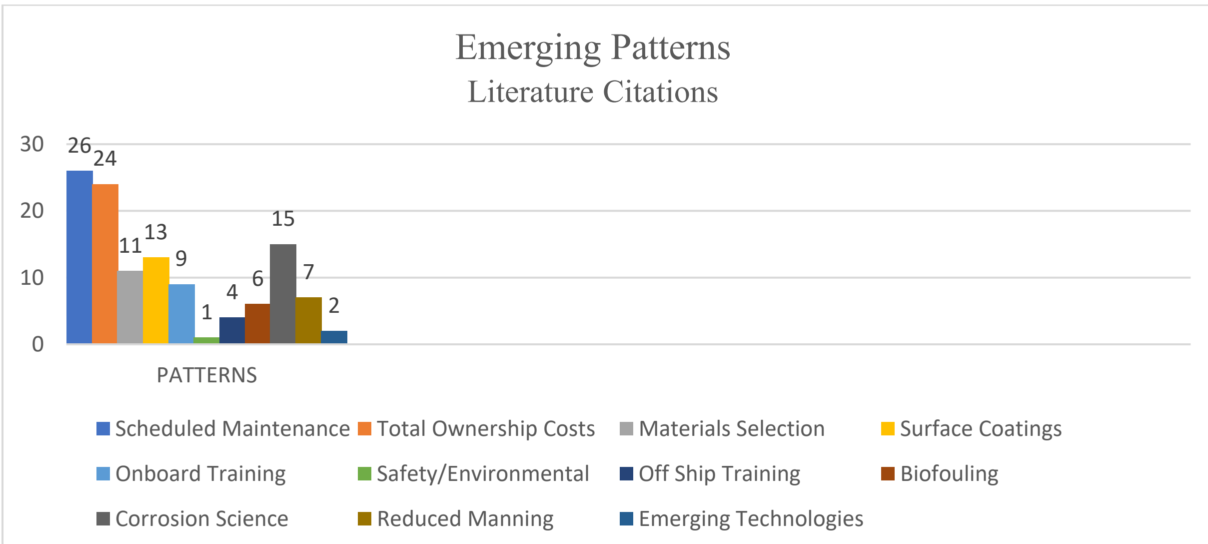

Figure 5. Priority Patterns Identified for Corrosion Control

Figure 5 uses the same values as the table with one-to-one numbering per occurrence of the pattern descriptor statement. Figure 6 attempts to provide the same illustration, but uses percentage values. The results are virtually the same.

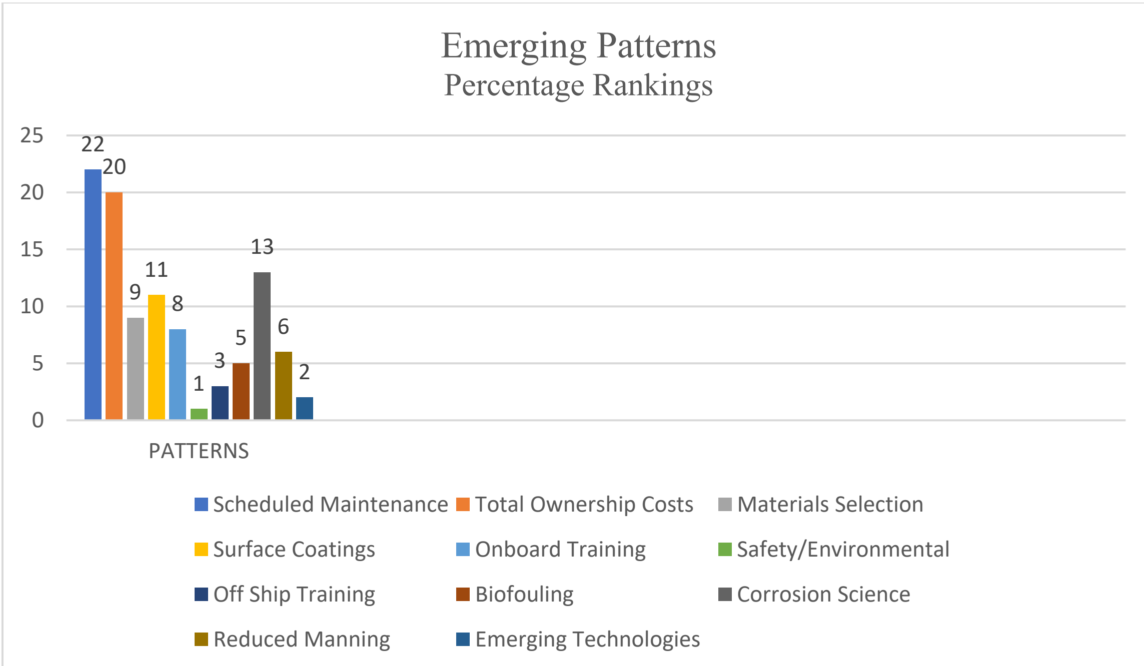

Figure 6. Percentage Reports for Corrosion Control Patterns

The eleven (11) patterns are reduced to six (6) clearer, recognizable themes as the data continue to be delineated and condensed using the same SM. The six final themes are finally identified by collapsing five of the lowest number pattern classes and combining them, which result in themes that reflect similar functions. The final six themes are broadened slightly to accommodate the collapsing pattern groups, but still retain the essential elements of the original patterns. The following combinations are used which come from Table 1.

Scheduled maintenance (A26) is combined with off - board maintenance (G4) and emerging technologies in maintenance (K2) to receive a total of 32 references under the consolidated theme of Maintenance, which includes both preventative and corrective maintenance. Total ownership cost (B24) is combined with reduced manning (J7) to complete the theme of Total Ownership Costs with thirty-one references. Materials selection remained the same including ship design decisions, materials selections, anodes, cathodes, metal types (C11) but is changed to Selecting Materials as a thematic category with the original eleven (11) references. Surface coatings, including high quality surface coating systems for ships and marine structures (D 13) is combined with marine biofouling and pollution (H 6) for a total of nineteen (19) references under the theme Surface Coatings. Corrosion science (I 15) is combined with safety and environmental concerns (F 1) for a total of sixteen (16) references under the theme of Corrosion Science. And finally, off ship training nine (9) changed to an all-inclusive theme of Training with a total of nine (9) references. Table 2 illustrates the consolidation of the data.

Table 2. Thematic Identification and Designation

CONSOLIDATED THEMES	A	B	C	D	E	F	G	H	I	J	K	TOTAL
Maintenance	26	0	0	0	0	0	4	0	0	0	2	32
Total Ownership Costs	0	24	0	0	0	0	0	0	0	7	0	31
Selecting Materials	0	0	11	0	0	0	0	0	0	0	0	11
Surface Coatings	0	0	0	13	0	0	0	6	0	0	0	19
Corrosion Science	0	0	0	0	0	1	0	0	15	0	0	16
Training	0	0	0	0	9	0	0	0	0	0	0	9
TOTALS	**26**	**24**	**11**	**13**	**9**	**1**	**4**	**6**	**15**	**7**	**2**	**118**

Headings Key: A) scheduled maintenance, preventative maintenance, types and cost, B) Total Owner Costs (TOC), C) Ship design decisions materials selections, anodes, cathodes, metal types, D) High quality surface coating systems for ships and marine structures, E) Onboard maintenance training, F) Safety and environmental concerns, G) Off-ship maintenance training, H) Marine biofouling and pollution, I) Corrosion science, J) Reduced manning on surface ships, K) Emerging technologies

The literature now reveals specific data points that help with identifying current information, as well as discovering new information relating to improved corrosion control practices in Arleigh Burke Class Destroyer engineering spaces, a key emphasis for this research, by consolidating the initial generic patterns of information into concise thematic topics. Figure 7 illustrates these assertions.

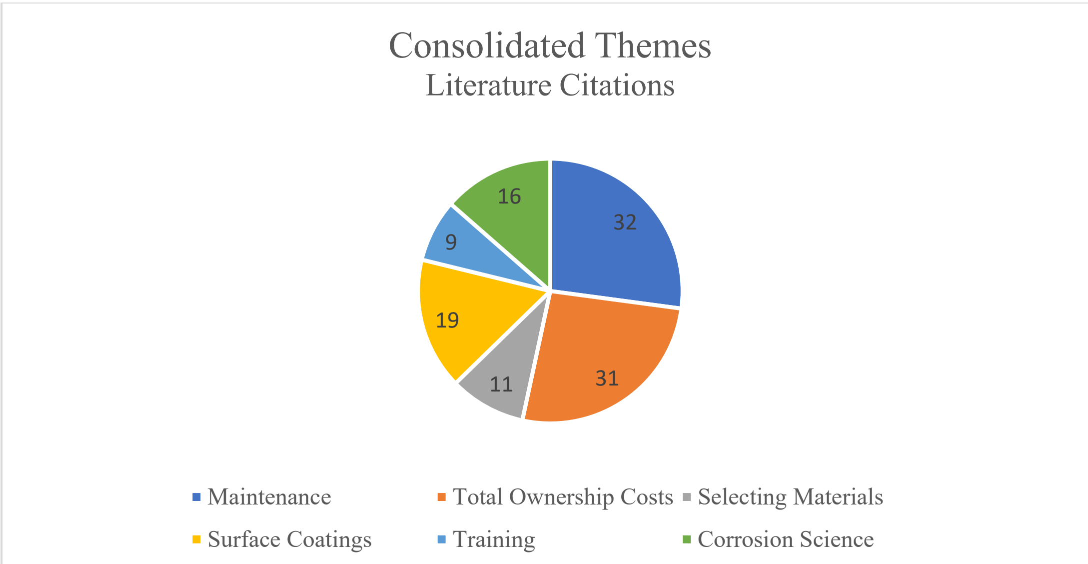

Figure 7. Corrosion Control Thematic Patterns

C. THEMES

Six specific themes emerged from the extensive review of the literature. The themes are extremely significant because they emphasize the components that are mainly involved with corrosion control in engineering spaces and are therefore integral to answering the overall question of this research project, "How might improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces enhance ship efficiency"? The following sub-topics list the major findings identified in each of the themes discovered. Viewed separately, the information reported simply provides explanation for an isolated topic. Put together, or totally assimilated, the information provides data that can be viewed through the lens explained in Figure 1 that the main research question to offer explanations and even recommendations for the future. That will be discussed in the Summary of the Findings section.

1. Maintenance

Maintenance is the main emphasis for discussion in any article dealing with corrosion control on a ship regardless of the discipline or the purpose of the study reviewed. Preventative vs. corrective maintenance is described as a core choice that decision makers must make taking into account many, many factors that affect the ships efficiency. Several specific key points appear to be of major concern. They include the following:

- Surface ships and its equipment will breakdown without proper maintenance and upkeep.
- Maintenance will always be an important factor to measure concerning the deterioration process of a ship because equipment is always being used with no downtime.
- Preventative maintenance is meant to stop corrosion before it even forms and is considered the most affordable and effective of the long term.
- Corrective maintenance is purely reactive and occurs when there is a problem or break down in a piece of equipment, but is considered the most affordable in the short term.
- It is difficult to plan for corrosion and add into the preventative maintenance schedule.
- Current practices appear to suggest that virtually all shipboard maintenance is put off until it is essentially too bad to ignore.
- More corrective maintenance is needed when preventative maintenance is postponed.
- Corrective maintenance results in shut downs and negatively impacts ship efficiency.
- Poor ship efficiency negatively impacts the fleet.

- Reduced manning and fewer billets on the DDG-51 has resulted in more corrective maintenance being completed than preventative maintenance.
- Corrective maintenance impacts other mechanical systems negatively on the ship and appears to require more time over the life of a ship than conducting preventative maintenance to avoid the breakdown.
- New technologies are being developed to help predict corrosive wear for individual ships and fleets as evidenced by successful software being used for aircraft.

2. Total Ownership Costs

A key emphasis discussed was the TOC of every individual ship that has been made when reviewing policies for the U.S. Navy, foreign navies or merchant marine fleets. In theory, the longer a ship is in service, operating efficiently and effectively, then the lower the TOC will be when compared to the total life of the ship. All fleets have one goal in mind and that is to have a well-run fleet that operates efficiently within budget and one that can be maintained and replaced when needed. That is accomplished through an effective fiscal policy. The literature review clearly outlined several key points that were mirrored regardless of fleet type being reviewed. These points included:

- U.S. Navy ships in the fleet are experiencing shorter lifetimes than originally expected.
- Over 95% of maintenance is corrective maintenance on DDG-51 Destroyers; the most expensive maintenance and longest downtime.
- A ship will always go through constant maintenance from the beginning to the end of its life.
- The ship's lifetime will be drastically reduced increasing TOC if a ship does not keep up with required maintenance.

- Overall TOC increases when there is a high reliance on corrective maintenance.
- High quality surface coatings such as paint and newer developed paints lower the cost of TOC by delaying the corrosion process.
- Merchant marine fleets attempt to increase TOC by selecting high quality materials at the design phase of ship building, train their crews for on board maintenance and stress preventative maintenance strategies trying to avoid breakdowns.
- Nothing impacts TOC and efficiency of a ship or the fleet than being taken out of the fleet for an extended amount of time.

3. Selecting Materials

Materials and equipment selection as well as corrosion control products have been hinted at as being very important in the previous two themes. The literature was very clear that decision makers need to clearly make choices as to the types and quality of the supplies and equipment they purchase in order to combat corrosion and properly provide maintenance to essential systems on the ship. The following represent key concepts stressed:

- Materials selection for building new ships or repairing older ships is extremely important as it determines the effectiveness of maintenance completed and TOC.
- Specific materials selections can take advantage of anode and cathode interactions to limit corrosion from natural occurrences and even biofouling or pollution reasons.
- Decisions begin by deciding if it is more important to invest in more expensive materials and most likely have low maintenance upkeep, or invest in inexpensive materials with high maintenance upkeep.

- Engineering spaces have a lot of equipment that relates to each other and are interdependent.
- It is usually discovered that unplanned maintenance is needed due to the cooperative nature of the initial engineering space design when one piece of equipment on a ship has issues.
- Equipment and systems are designed to work in a symbiotic way, when one system is affected by corrosion, then most likely so is a piece that is connected to it.

4. Surface Coatings

Surface coatings are designated as a specific theme primarily because there are several types and they are all designed for different surface types as well as how those surfaces are used. Different coatings require different methods of application as well as different circumstances as to when the work can be completed. The following key points were identified within this theme because of how they can be applied to understanding corrosion control within engineering spaces:

- Surface coatings are one of the main strategies used by ship builders to protect the ship from the environment.
- Maintaining a high-quality surface coating is difficult due to having to constantly assess the conditions and determine if new painting is required.
- Application requirements such as surface preparation and access to space are major decision points as to what product may be the best to use.
- There have been vast improvements in the creation of surface coatings for all areas of the ship.
- A main emphasis is stressed toward development of paint that lasts longer, is easy to apply and requires less applications.

- Other than salt, the environment as a whole causes many problems that accelerate corrosion.
- Pollution and biological life forms in the water have properties that help accelerate the corrosion process.
- Surface coatings have been designed to be completely submersible and not allow marine growth to form.

5. Training

Training is an obvious theme as it is discussed in all areas pertaining to corrosion control throughout the literature review. The studies that were reviewed inferred that there has been a steady emphasis on decreasing maintenance manpower on ships in favor of completing both preventative and corrective maintenance while the ships are in port using contractors. The rationale has been to effect cost savings measures. What has not been determined though is whether or not this affects the TOC over the life of the ship. Some key points have been identified to assist with this determination.

- High operational tempo on ship severely limits time to complete maintenance.
- Lack of time affects shipboard training on how to perform the maintenance.
- The U.S. Navy has instituted shorter periods of time to complete repairs and training that come with maintenance assessments.
- There appears to be a lack of time and resources provided to accomplish maintenance objectives on ship.
- Successful strategies exist within Navy procedures that involve standard applications, rules and regulations with proper attention intended to produce positive results.
- Without proper training, crews tend to have higher failure rates.

- Instructions exist that instruct a sailor how to properly perform corrosion maintenance.
- Training is considered important, but priorities of operational training off the ship tend to dimmish maintenance training that the crews appear to need.
- A major challenge is an ability to complete daily tasks as well as maintenance.

6. Corrosion Science

Much is known about corrosion and how it occurs. The literature was full of information and suggestions to combat the natural reaction of rust. Understanding the science of the problem has helped develop many ways to address the issue. The following are identified points of interest that can be applied toward the engineering spaces on the DDG-51 Destroyer:

- The formation of rust presents with a very low aggressiveness when measured over time.
- Different ships experience different environmental factors that contribute to corrosion growth.
- There are many factors that contribute to corrosion.
- Electrolysis and galvanic corrosion are produced in certain areas of the ship.
- Ships are exposed to the environment inside and outside of the ship.
- It is typical for ships to have special coatings to protect installed cathodic protection in various places onboard.
- It tends to be hot and have a high amount of moisture in the air when inside machinery spaces on ship.

- Relative Humidity (RH) is related to atmospheric corrosion loss and wet surfaces help accelerate the corrosion process.
- Salt greatly alters the rate of atmospheric corrosion.
- After metal is made, the metal tends to be in an unstable form and when combined with oxygen begins to form corrosion.

D. SUMMARY OF THE FINDINGS

Examination of the literature using a synthesis matrix tool identified six specific themes and patterns as they relate to the overall research question guiding this thesis. Special care is taken to identify connections and links between the sources, how the information overlaps and how new themes evolved from the raw patterns initially identified. These overlapping dependencies of the six identified themes are further synthesized below using two key categories; corrosion control and ship efficiency. Synthesizing the remaining themes into two final categories provides the closing evidence supporting an assertion that improving corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces will definitely enhance ship efficiency.

1. The Case for Improved Corrosion Control

The large amount of information gleaned from the literature using meta-analysis and meta-narratives provide a compelling case for improved corrosion control on U.S. Surface Warfare Vessels and there are clearly three main themes that relate specifically to the explanation of the problem of corrosion control and its solutions. The three main themes are maintenance, training and knowledge of corrosion science. What follows is a culmination of the findings illustrating the importance and necessity of improved corrosion control.

Naval crews must be able to keep up with proper maintenance and upkeep on surface ships, including when the equipment breaks down. This is important because a ship's equipment is always being used and it is the crew's duty to make sure that maintenance will always be an important factor to measure and monitor since it concerns the deterioration process of a ship. Understanding that equipment is being used all the time is essential. Therefore, it is imperative that preventative maintenance be performed to stop corrosion before it even forms. The data are clear that that this is considered the most affordable and effective strategy over the long term.

Corrective maintenance is purely reactive and occurs when there is a problem or break down in a piece of equipment. The research indicates that it is difficult to plan for corrosion, thus difficult to include in the preventative maintenance schedule. Also, current practices appear to suggest that virtually all shipboard maintenance is put off until it is essentially too bad to ignore. Unfortunately, when preventative maintenance is postponed, more corrective maintenance is eventually needed. Corrective maintenance results in shutdowns and negatively impacts ship efficiency. Having poor ship efficiency automatically produces a negative impact on the fleet. Selected research indicates that reduced manning and fewer billets on the DDG-51 has resulted in more corrective maintenance being completed than preventative maintenance. Corrective maintenance impacts other mechanical systems negatively on the ship and appears to require more time to complete over the life of a ship than conducting preventative maintenance to avoid the breakdown. There are new technologies being developed to help predict corrosive wear for individual ships and fleets as evidenced by successful software being used for aircraft, but nothing substantive is available today.

Investigations into crew training reveal that there are identifiable obstacles that hinder the process. One is the high operational tempo on a ship that severely limits time to complete maintenance; not to mention the lack of time there is to conduct shipboard training on how to perform the maintenance. Training is considered important, but priorities of operational training off the ship tend to diminish maintenance training that the crew appears to need. Research confirms that without proper training, crews tend to have higher failure rates. A major challenge appears to be the ability to complete daily tasks as well as maintenance. Unfortunately, it is noted that during the dedicated time slots in a ships schedule to perform maintenance training, the U.S. Navy has actually instituted shorter periods of time to complete both repairs and training. There appears to be a lack of time and resources provided to accomplish maintenance objectives on ship; even though successful strategies exist within Navy procedures that involve standard applications, rules and regulations with proper attention intended to produce positive results.

Science demonstrates that the formation of rust on ships has a relatively very low aggressiveness when measured over time. It is hard to judge the exact aggressiveness rate due to different ships experiences and different environmental factors that contribute to corrosion growth. This is due to Navy ships operating all over the world. Essentially, electrolysis and galvanic corrosion are produced in certain areas of the ship. It is not only just outside exposure; ships are exposed to the environment both inside and outside of the ship. In order to prevent some of the exposures, it is typical for ships to use special coatings to protect installed cathodic protection in various places onboard. It tends to be hot and have a high amount of moisture in the air when looking inside a ship, especially the machinery and engineering spaces. The relative Humidity (RH) is related to atmospheric corrosion loss and wet surfaces help accelerate the corrosion process. Salt greatly alters the rate of atmospheric corrosion because after metal is made, the metal tends to be in an unstable form, and when combined with oxygen, begins to form corrosion.

2. The Case for Enhanced Ship Efficiency

Once again, the large amount of information gleaned from the literature using meta-analysis and meta-narratives provide a clear case for another aspect of this research; enhanced ship efficiency on U.S. Surface Warfare Vessels. There are three main themes that clearly relate specifically to the explanation of the problem as well as offering up solutions. The three main themes identified are total ownership costs, selecting materials and surface coatings.

The U.S. Navy is always in the process of trying to obtain a minimal (TOC) for their ships. From the beginning to the end of a ship's life, it will always go through constant maintenance. Merchant marine fleets attempt to increase TOC by selecting high quality materials at the design phase of ship building, train their crews for on board maintenance and stress preventative maintenance strategies trying to avoid breakdowns. High quality surface coatings such as paint and newer developed paints, lower the cost of TOC by delaying the corrosion process, giving the crew time to deal with corrosion as it occurs.

But the U.S. Navy ships in the fleet are experiencing shorter lifetimes than originally expected. If a ship does not keep up with required maintenance, the ship's lifetime will drastically reduce, which increases TOC. Even though the Navy spends a lot of effort to focus on preventative maintenance. Over 95% of maintenance is corrective maintenance on DDG-51 Destroyers; this represents the most expensive maintenance, most downtime and most money spent over the life of the ship. When there is a high reliance on corrective maintenance, overall TOC increases. Nothing impacts TOC and efficiency of a ship or the fleet more than a ship being taken out of the fleet for an extended amount of time.

During the initial design and manufacturing of a ship, the material selection process is a very important decision. Materials selection for building new ships or repairing older ships is extremely important as it determines the effectiveness of maintenance completed and TOC. Decisions begin by deciding whether it is more important to invest in more expensive materials and most likely have low maintenance upkeep, or invest in inexpensive materials with high maintenance upkeep. Engineering spaces have a myriad of equipment that relates to each other and are interdependent. Quite often, when one piece of equipment on a ship has issues, it is usually discovered that more unplanned maintenance is needed due to the cooperative nature of the initial engineering space design. To slow down some of the corrosion build up, certain inhibitors are installed in these spaces. Specific materials selections can take advantage of anode and cathode interactions to limit corrosion from natural occurrences and even biofouling or pollution reasons. Equipment and systems are designed to work in a symbiotic way, when one system is affected by corrosion, then most likely so is a piece that is connected to it. Currently there is no model created that fully resolves all the issues that involve all the complex assets in a navy ship nor recommendations to follow.

The ships Surface Coatings are one of the most influential efforts a ship builder and crew can make because ship builders use it to protect the ship from the environment. There have been vast improvements in the creation of surface coatings for all areas of the ship. A main emphasis is stressed toward development of paint that lasts longer, is easy to apply and requires less applications. Surface coatings have been designed to be completely submersible and not allow marine growth to form. Maintaining a high-quality surface coating is difficult due to having to constantly assess the conditions and determine if new painting is required. Application requirements such as surface preparation and access to space are major decision points as to what product may be the best to use. Other than salt, the environment causes many problems that accelerate corrosion. Mostly because of all the pollution and biological life forms in the water have properties that help accelerate the corrosion process.

E. CONCLUSION

The final synthesis of the findings indicates that a case can be made for pursuing both corrosion control and ship efficiency when considering the engineering spaces of a DDG-51. Several redundant findings repeat themselves in both categories suggesting strong relationships existing between them when specific actions are taken in both areas. No causal relationships can be proved, but they certainly can be suggested especially since so many findings in both categories appear to be interrelated. For example, when decision makers institute proven efficiency models, corrosion control is addressed as a means of reaching an efficiency goal. Conversely, it appears when corrosion control goals are met, efficiency standards increase by maximizing (TOC) through an extension of a ship’s life.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS, ASSUMPTIONS AND RECOMMENDATIONS

A. INTRODUCTION

Chapter V presents a summary of the findings, conclusions and recommendations for future research. This chapter explains how the information gathered and studied appears to imply that there are several common factors that suggest some material inefficiencies in the Arleigh Burke Class Destroyer Main Engineering Spaces that need to be addressed as they relate to corrosion and its control. I set out to answer how improved corrosion control practices in the U.S. Navy's Arleigh Burke Class Destroyer engineering spaces might enhance ship efficiency. Seven sub-questions were used that generated information that allowed for a better understanding of the many factors involved with corrosion and its control. I am now better able to provide specific recommendations and solutions because of mining the available data.

B. DISCUSSION

Chapter IV clearly explains how the literature review provides information that is analyzed, explained and coded. This is accomplished by examining the meta-narratives produced by overlapping the sub-questions with the primary research question to create a research lens (Figure 1) able to find, focus and interpret finite information acquired through a SSRL. The overlapping information mined from the extensive data retrieved from the use of a SM reveals eleven emerging patterns which provide insight toward answering the overall question of this thesis. These emerging patterns are identified and coded as Scheduled Maintenance, Total Ownership Costs, Materials Selection, Surface Coatings, Onboard Training, Safety/Environmental, Off Ship Training, Biofouling, Corrosion Science, Reduced Manning, and Emerging Technologies. After further reflection and consideration, six common themes naturally materialize from the eleven identified emerging patterns. These themes are identified and coded as Maintenance, Total Ownership Costs, Selecting Materials, Surface Coatings, Training and Corrosion Science and are essential to totally understanding and assimilating the wide array of information reviewed. Finally, the themes are separated into two main areas of discussion that are thoroughly discussed in Chapter IV; corrosion control and enhanced ship efficiency. Minor summaries of each are compiled and reviewed below as they serve as the basis for the final conclusions of this research.

Much is known about corrosion and how it occurs. Understanding the science of the problem has helped develop many ways to address the issue and many identified points of interest can be applied directly toward the engineering spaces on the DDG-51 Destroyer. The chemical reaction of corrosion can be slowed down so the U.S. Navy can get the most TOC out of a ship. Simply understanding the causes and being able to predict what areas of the ship corrosion is most likely to occur assists the crew to focus their efforts and have a better chance at combating this problem. Maintenance and training are both highly emphasized when dealing with corrosion control on a ship and fall into two categories; preventative and corrective. Preventative vs. corrective maintenance is a core choice that decision makers must make considering many, many factors that affect the ships efficiency. This leads to competent training. It is an unfortunate reality that time for training is limited at best. What has been determined though is that training, maintenance and an understanding of the science affects the TOC over the life of the ship and increased TOC equals more efficiency.

A key emphasis for discussion is the TOC of every individual ship that has been made. In theory, the longer a ship is in service, operating efficiently and effectively, then the lower the TOC will be when compared to the total life of the ship. All fleets have one goal in mind and that is to have a well-run fleet that operates efficiently within budget and one that can be maintained and replaced when needed. An example using the DDG-51 and data already mined and discussed in Chapter IV illustrates that a high reliance on corrective maintenance increases the overall ship's total ownership costs by experiencing a ship life that is lower than what was previously expected. This efficiency problem is therefore a result of a maintenance decision.

Figure 8 illustrates the balancing act that occurs as efficiency and corrosion control are equally and unequally addressed.

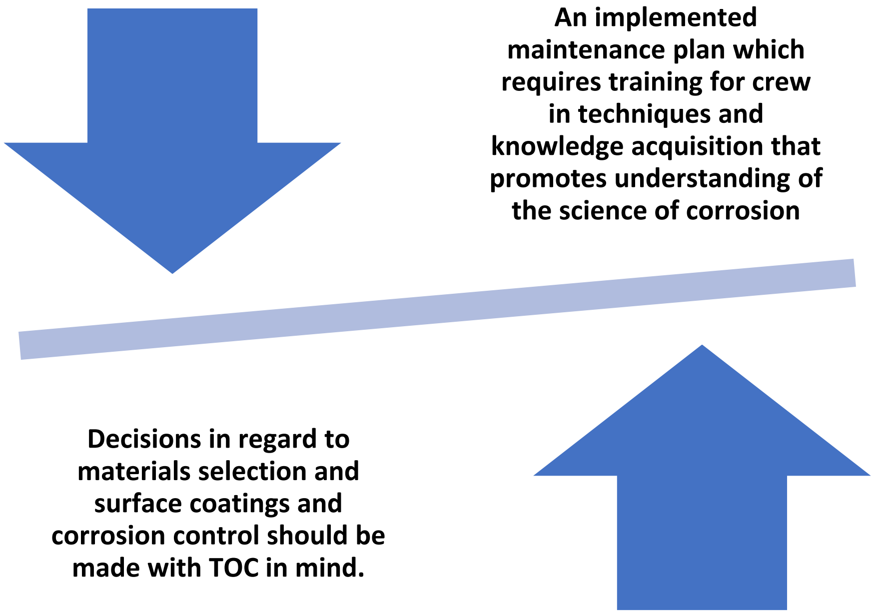

Figure 8. Corrosion Control and Efficiency

Materials and equipment selection as well as corrosion control products have been hinted at as being very important as well. The general balance of material selection can be a dilemma. Should the builder invest in higher cost materials for less maintenance along the ship's life span, or use cheaper materials and pay it back with more need for corrective maintenance? That same issue applies to surface coatings. Surface coatings are designed for different surface types as well as how those surfaces are used. Different coatings require different methods of application as well as different circumstances as to when the work can be completed. Surface coatings have been specifically engineered to protect equipment from many different variations of exposure. The whole point of applying surface coating is to slow down or even prevent corrosion before it ever begins increasing a ship's efficiency. In the long term it is far cheaper to invest in paint then spend the money to replace steel that has been exposed to the environment for too long.

C. CONCLUSION

Corrosion control and ship efficiency appear to be closely interrelated. No causal relationships can be proved, but they certainly can be suggested. Especially since so many findings in the synthesized final two categories found in Chapter IV suggest strong interrelationships existing between them. This is demonstrated in the discussion section of this chapter when described specific actions are taken in one area (corrosion control) and results are seen in the other (ship efficiency). Or, vice versa, when specific actions are taken in (ship efficiency) and results are seen in (corrosion control). Therefore, it can be confidently stated that effective corrosion control in Arleigh Burke Destroyer engineering spaces will clearly enhance efficiency.

Undoubtedly, the findings of this research have demonstrated that in order to control corrosion and enhance ship efficiency, two strategies should be followed. 1) An implemented maintenance plan which requires training for crew in techniques and knowledge acquisition that promotes understanding of the science of corrosion and 2) For a ship to function efficiently it must be operational a majority of its work life, therefore decisions in regard to materials selection and surface coatings and corrosion control should be made with TOC in mind.

An overall problem exists with the lack of corrosion control in DDG-51 engineering spaces. Corrosion, repair work and repair history on DDG-51's appear to reflect many challenges that prevents these ships from keeping up with their repairs. Recognition of this problem is important because corrosion issues tend to cause disruption that will eventually affect a ship's performance and then most notably effect the performance of the fleet. The U.S. Navy fleet is spending a large proportion of its budget for corrosion and corrosion related maintenance and repair. Each year the spending increases to keep the U.S. Navy fleet properly maintained. This thesis is an attempt to assist with this problem. Six clear categories or trends that distinguish the problems and infer clear solutions have been identified and are compiled using multiple resources and references that focus on the dual problems of corrosion control and efficiency. A clear understanding of the common problems that keep accruing with corrosion control and lost efficiency can aid to align a fleet focus to substantially assist the fleet with its objective to combat corrosion. I chose to end this study where it is because I ran out of time and resources for more research. Also, the same trends continue to consistently reappear in various, different sources. When I reached over 40 sources for my literature review, I made the determination that I would continue to see the same trends and decided to stop the research and move forward and codify the results with what I had.

D. RECOMMENDATIONS

I am basing my recommendations using the U.S. Navy Goal for a forty-five (45) year use goal for all DDG-51's. This will be used as a reachable goal as it relates specifically to the engineering spaces. To accomplish this goal, the following are recommended based upon the findings of this study.

1. Increase training for on board maintenance and make it a mandatorily requirement. If training is skipped or not completed rescheduling would be required.
2. Create mandatory inspection of engineering spaces to recommend retro fitting that includes increased anode/cathode technology by a team outside of the ship.
3. Provide inspection teams authority to properly identify problems, acquire replacements and conduct training for the crew.
4. Increase billeting numbers on the ship to ensure that all required maintenance can be completed as well as regular ship board duties.
5. Invest in software solutions to predict maintenance needs.

E. FURTHER RESEARCH

Three ideas surfaced while doing this study and two involve using a case study or case studies or case studies with cross case analysis as methodologies. One includes an experimental design. Attempting a singular case study using data specifically related to the engineering spaces for one DDG-51 over a set period of years that occurred in the recent past would be helpful for making specific recommendations for this class of destroyers.

Data analysis could include heat tables, humidity tables, onboard maintenance, off ship maintenance, scheduled maintenance, preventative maintenance history, constructive maintenance history, historical billet numbers, onboard training, off ship training, surface coatings and materials used especially with anodes and cathodes in mind. One ship or multiple ships could be included with this initial research.

An experimental quantitative three-year study to explore TOC for three specific DDG-51 ships to reach a 45-year use could be tried. Findings could be extrapolated to the fleet. Data gathered would include all of the above mentioned in the proposed case studies, specifically labeled with cost assignments. Four similar ships could be identified. Constructive maintenance could be performed on three ships, but a strict schedule for preventative maintenance would be established for only two ships over a three-year period. Maintenance billeting would be increased, and training increased. The third ship would follow current navy policies for training, billeting and preventative maintenance. The fourth ship would receive no special constructive maintenance in the beginning of the study but follow standard Navy policies acting as a control for the experiment. Results from all four ships could be studied at the end of a three-year period to determine TOC and make recommendations.

Obtain the heat index of multiple DDG-51s that have similar operational schedules in the same area of the world for a long period of time. After they complete a maintenance availability, gather the data and explore comparisons of the maintenance that needed to be done in the main engineering spaces to see if the ships who had extreme heat and humidity in the spaces had less of more maintenance requirements for the availability.

LIST OF REFERENCES

Anderson, T. J. (2013). *Operational profiling and statistical analysis of Arleigh Burke-class destroyers* [Doctoral dissertation, Massachusetts Institute of Technology].

A. (2021, September 23). *Understanding sacrificial anodes on ships*. Marine Insight. https://www.marineinsight.com/tech/understanding-sacrificial-anodes-on-ships/

Bennett, R. D., & Sloan, C. D. (2003, July). 3.8. 1 Repeating Design Errors or "Where's The History?." In *INCOSE international symposium* (Vol. 13, No. 1, pp. 1327–1337).

Bishop, G. B. (2019, October 14). *How to stop a ship's marine corrosion in 3 steps*. *Corrosionpedia*, https://www.corrosionpedia.com/2/5388/corrosion/corrosive-process/how-to-stop-a-ships-marine-corrosion-in-3-steps

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology*, *3*(2), 77–101.

Canadian Forces Specifications. (2018, December 1). *Specification for maintenance painting of HMC ships* (D-23-003-005/SF-002) National Defence. Https://Buyandsell.Gc.Ca/. Retrieved March 20, 2022, from https://buyandsell.gc.ca/cds/public/2019/05/22/ 84a1a4e88ed3e405ffc2344297627f06/d-23-003-005-sf 002_specification_for_maintenance_painting_of_hmc_ships_en_and_fr.pdf

Dunleavy, G. D. (2018). Prioritizing Painting in Ship Maintenance. *Maritime News*, *1*(3), 4–5.

Fajardo, M., & Ortiz, L. V. (2011). *Analysis of the Preventive/Corrective Maintenance ratio for DDG Class Ships* [Doctoral dissertation, Naval Postgraduate School]. NPS Archive: http://hdl.handle.net/10945/5722

Gardiner, C. P., & Melchers, R. E. (2001). Enclosed atmospheric corrosion in ship spaces. *British Corrosion Journal*, *36*(4), 272–276. https://doi.org/10.1179/ 000705901101501730

Gratsos, G. A., Psaraftis, H. N., & Zachariadis, P. (2009, October). Life cycle cost of maintaining the effectiveness of a ship's structure and environmental impact of ship design parameters: an update. In *RINA Conference on the Design and Operation of Bulk Carriers, Athens, Greece*. https://nee.gr/downloads/ 176Life.cycle.cost.pdf

Gudze, M., & Melchers, R. (2008). Operational based corrosion analysis in naval ships. Corrosion science, 50(12), 3296–3307. https://doi.org/10.1016/j.corsci.2008.08.048

Hansan, B. O., & Sadek, S. A. (2014). The effect of temperature and hydrodynamics on carbon steel corrosion and its inhibition in oxygenated acid–salt solution. *Journal of Industrial and Engineering Chemistry*, *20*(1), 297–307. https://doi.org/10.1016/j.jiec.2013.03.034

Hellio, C., & Yebra, D. (2009). Advances in marine antifouling coatings and technologies. Woodhead Publishing Limited.

Hinkle, J. B., & Glover, T. L. (2004). *Reduced manning in DDG 51 Class warships: Challenges, opportunities and the way ahead for reduced manning on all United States Navy ships*. Anteon Corp Arlington VA.

Ingram, L., Hussey, J., Tigani, M., & Hemmelgarn, M. (2006). Writing a literature review and using a synthesis matrix. *NC State University: NC State University Writing and Speaking Tutorial Service*. https://wac.colostate.edu/resources/wac/programs/description-ncstate/

Insinna, V. (2013). Navy surface fleet faces rough waters trying to maintain ships. *National Defense*, *97*(712), 24–25. https://www.nationaldefensemagazine.org/articles/2013/2/28/2013march-navy-surface-fleet-faces-rough-waters-trying-to-maintain-ships.

Kandemir, C., & Celik, M. (2017, September). Identifying training requirements to enhance basic skills for maintenance 4.0 in marine engineering through engine room simulator. In *13th International Conference on Engine Room Simulators* (pp.20-21).

Knight, S., Wade, S., Palanisamy, S., Colwell, J., Du Preez, D., Bottle, S. E., ... & van Duin, S. (2019). Corrosion costs of the Royal Australian Navy Frigate Fleet. *Materials Performance*, *58*(8), 52–57. https://www-s.corrosionanalysisnetwork.org/publications-standards/-/journal_content/56/33542825/37836951

Knight, S. K., Will, G. W., Sudholz, A. S., & Wade, S. W. (2019, November). Observations of mild steel corrosion during anzac class ship trials. *Observations of Mild Steel Corrosion during ANZAC Class Ship Trials*, 1–17

Koch, M. (2014). *Corrosion control in the U.S. Navy: Ships & USMC vehicles* [Presentation]. Naval Air Systems Command Patuxent River MD, United States. https://apps.dtic.mil/sti/pdfs/ADA617077.pdf

Koenig, P., Nalchajian, D., & Hootman, J. (2009). Ship service life and naval force structure. *Naval Engineers Journal*, *121*(1), 69–77. TECHNICAL PAPER.

Larsen, K. L. (2018). Corrosion on the High Seas: How Ship Owners Battle Rust. *Corrosion on the High Seas: How Ship Owners Battle Rust*, *1*(1), 6–9. www.nace.org/resources/newsletters/maritime-news, *published by NACE International*

LibGuides: Conducting a literature review: Analyzing the literature. (n.d.). Washington State University Libraries. Retrieved March 9, 2022, from https://libguides.libraries.wsu.edu/litreview/analysis

Lundh, M., Lützhöft, M., Rydstedt, L., & Dahlman, J. (2011). Working conditions in the engine department–A qualitative study among engine room personnel on board Swedish merchant ships. *Applied ergonomics*, *42*(2), 384–390. https://doi.org/10.1016/j.apergo.2010.08.009

Marais, K. B., & Saleh, J. H. (2009). Beyond its cost, the value of maintenance: an analytical framework for capturing its net present value. *Reliability Engineering & System Safety*, *94*(2), 644–657. https://doi.org/10.1016/j.ress.2008.07.004

Marais, K. B., Rivas, J., Tetzloff, I. J., & Crossley, W. A. (2013, April). Modeling the impact of maintenance on naval fleet total ownership cost. In *2013 IEEE International Systems Conference (SysCon)* (pp. 801–808). IEEE. doi: 10.1109/SysCon.2013.6549975.

Marcos, M., & Botana, J. (2006). Polución y corrosión en ríos contaminados. III Congreso de ingeniería civil, territorio y medio ambiente. Agua, Biodiversidad e Ingeniería. *Zaragoza*, 25–27. https://www.aecarretera.com/congresos/IV-Boletin.pdf

Mathiazhagan. (2011). *Corrosion Management for effective mitigation of corrosion in Ships - Overview*. 2011 3rd international conference on information and financial engineering IPDER VOL. 12 2011, SINGAPORE. http://www.ipedr.com/vol12/1-C001.pdf

McGovern, W. (2003). *Manpower Determination Methodology*. The Process.

Morris, C. A. (1987). *The impact of onboard maintenance training on surface ship readiness*. [Master's thesis, Naval Postgraduate School]. NPS Archive: DTIC Technical Reports. https://apps.dtic.mil/sti/pdfs/ADA192218.pdf

Navsea (2001, Dec) Naval Ships' Technical Manual (NSTM) Chapter 631 Volume 3. Preservation Of Ships In Service-Surface Ships/ Submarine Applications. S9086-VD-STM-030/CH-631V3R2. Department of the Navy.

Navsea (2016). *NAVSEA technical manual for corrosion control assessment and maintenance manual (CCAMM)*. Department of the Navy. https://www.navsea.navy.mil/Portals/103/Documents/SUBMEPP/Volume%20VI.pdf?ver=2019-08-20-101241-017

Navy science team advances coatings :PaintSquare News. (2015, October 1). Paint Square. https://www.paintsquare.com/news/view/?13828

O'Rourke, R. (2020, July). *Navy DDG-51 and DDG-1000 destroyer programs: Background and issues for Congress*. (Report No. RL32109) Library of Congress Washington, DC, Congressional Research Service. https://apps.dtic.mil/sti/pdfs/AD1123214.pdf

Perez, A. (2007, December). Navy Corrosion Prevention and Control Program. In *Proc. Tri-Services Corrosion Conference*. https://nace.confex.com/nace/tri07/techprogram/P1860.HTM

Raichev, R., Veleva, L., & Valdez, B. (2009). Corrosión de metales y degradación de materiales. *Editorial UABC*, 155–170.

Schorr, M., Valdez, B., Salinas, R., Ramos, R., Nedey, N., & Curiel, M. (2016). Corrosion control in military assets. *MRS Online Proceedings Library (OPL)*, *1815*. Imrc2015.7. doi:10.1557/opl.2016.88

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of business research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Swanson, L. (2001). Linking maintenance strategies to performance. *International journal of production economics*, *70*(3), 237–244. https://doi.org/10.1016/S0925-5273(00)00067-0

Team Ships: Surface Ships from Cradle to Grave, Boats and Craft. (n.d.). Https://Www.Navsea.Navy.Mil/. Retrieved February 8, 2022, from https://www.navsea.navy.mil/Home/Team-Ships/PEO-Ships/Support-Ships-Boats-and-Craft/Boats-and-Craft/Planned-Maintenance/

Valdez, B., Ramirez, J., Eliezer, A., Schorr, M., Ramos, R., & Salinas, R. (2016). Corrosion assessment of infrastructure assets in coastal seas. *Journal of Marine Engineering & Technology*, *15*(3), 124–134. https://doi.org/10.1080/20464177.2016.1247635

Vandroff, M. R. (2013). *DDG 51 Arleigh Burke Class Guided Missile Destroyer (DDG 51)*. NAVY PEO (SHIPS) Washington Navy Yard, Washington, DC. https://apps.dtic.mil/sti/pdfs/ADA613364.pdf

Wahid, A. S. B. A., Ahmad, M. Z. B., Ahmad, K. A. B., Taylor, J. P., Abdullah, A. B., Al-Shafiq, A. A. B., ... & Kitagawa, K. (2018). Demystifying ship operational availability–An alternative approach for the maintenance of naval vessels. *Journal of Engineering Science and Technology*, *13*(12), 4326–4346. http://jestec.taylors.edu.my/Vol%2013%20issue%2012%20December%202018/13_12_30.pdf

Wong, G., Greenhalgh, T., Westhorp, G., Buckingham, J., & Pawson, R. (2013). RAMESES publication standards: realist syntheses. *BMC medicine*, *11*(1), 1–14. https://doi.org/10.1186/1741-7015-11-21

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California