NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

THESIS

APPLYING SYSTEMS ENGINEERING TO IMPROVE THE MAIN GAS TURBINE EXHAUST SYSTEM MAINTENANCE STRATEGY FOR THE CG-47 TICONDEROGA CLASS CRUISER

by

Robert D. Sparks

September 2015

Thesis Advisor:	Gary Langford
Second Reader:	Gregory Miller

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2015	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE APPLYING SYSTEMS ENGINEERING TO IMPROVE THE MAIN GAS TURBINE EXHAUST SYSTEM MAINTENANCE STRATEGY FOR THE CG-47 TICONDEROGA CLASS CRUISER	**5. FUNDING NUMBERS**
6. AUTHOR(S) Sparks, Robert D.	
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. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The problem of effectively maintaining surface ships without sacrifice to operational availability and expected service life is receiving considerable attention from Navy leadership. The balance of cost, schedule, and performance parameters associated with ship maintenance is critical to ensure Naval surface force readiness requirements can be achieved within acceptable life-cycle costs. This thesis examines facets of U.S. Navy surface ship maintenance policy including condition-based maintenance and reliability-centered maintenance (RCM). Analysis and recommendations for improvement of the main gas turbine exhaust system maintenance strategy are the focus of this thesis. The analysis recommends a new hybrid approach to RCM. The hybrid RCM concept blends an inspection task with a repair task based on historical failure data analysis. The hybrid preventative maintenance task recognizes and mitigates the interrelated, multidimensional issues associated with ship maintenance. To decompose and cognize the complexities woven into improving a surface ship system maintenance strategy, systems engineering concepts and applications are introduced and demonstrated. The Navy Standard Titanium Centrifugal Pump serves as a reference system to demonstrate the application of functional decomposition, fault tree analysis, and risk assessment. These concepts and applications provide a logical means to identify and manage challenges associated with developing effective system maintenance strategies.

14. SUBJECT TERMS maintenance, modernization, decision-making, surface ship, readiness, maintenance strategy, reliability-centered maintenance, cost, schedule, performance, growth-work, new-work, optimal fleet response plan, time-directed, condition-based maintenance, condition-directed, failure finding, fault tree analysis	**15. NUMBER OF PAGES** 133
	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

APPLYING SYSTEMS ENGINEERING TO IMPROVE THE MAIN GAS TURBINE EXHAUST SYSTEM MAINTENANCE STRATEGY FOR THE CG-47 TICONDEROGA CLASS CRUISER

Robert D. Sparks
Civilian, Department of the Navy
B.S., United States Naval Academy, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2015

Approved by: Gary Langford
Thesis Advisor

Gregory Miller
Second Reader

Ron Giachetti
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The problem of effectively maintaining surface ships without sacrifice to operational availability and expected service life is receiving considerable attention from Navy leadership. The balance of cost, schedule, and performance parameters associated with ship maintenance is critical to ensure Naval surface force readiness requirements can be achieved within acceptable life-cycle costs. This thesis examines facets of U.S. Navy surface ship maintenance policy including condition-based maintenance and reliability-centered maintenance (RCM). Analysis and recommendations for improvement of the main gas turbine exhaust system maintenance strategy are the focus of this thesis. The analysis recommends a new hybrid approach to RCM. The hybrid RCM concept blends an inspection task with a repair task based on historical failure data analysis. The hybrid preventative maintenance task recognizes and mitigates the interrelated, multidimensional issues associated with ship maintenance. To decompose and cognize the complexities woven into improving a surface ship system maintenance strategy, systems engineering concepts and applications are introduced and demonstrated. The Navy Standard Titanium Centrifugal Pump serves as a reference system to demonstrate the application of functional decomposition, fault tree analysis, and risk assessment. These concepts and applications provide a logical means to identify and manage challenges associated with developing effective system maintenance strategies.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AFFF	aqueous film forming foam
AIT	alteration installation team
AOR	area of responsibility
APL	allowance parts list
BSO	Budget Submitting Office
CBM	condition based maintenance
CCDR	Combatant Commander
CD	condition-directed
CFR	condition found report
CG-47	Ticonderoga-Class Guided Missile Cruiser
CM	continuous maintenance
CMAV	continuous maintenance availability
CMP	Class Maintenance Plan
CMWD	countermeasure wash down
CNO	Chief of Naval Operations
CNRMC	Commander, Naval Regional Maintenance Center
CPAF	cost plus award fee
CSG	carrier strike group
CSMP	current ship maintenance plan
CSWT	class standard work template
DOD	Department of Defense
DON	Department of the Navy
DSRA	docking selected restricted availability
EDSRA	extended docking selected restricted availability
EOC	engineered operating cycle
ESL	expected service life
ESRA	extended selected restricted availability
FF	failure-finding
FAR	Federal Acquisition Regulation
FFP	firm fixed price
FMA	Fleet Maintenance Activity
FMECA	failure mode, effects, and criticality analysis
FRP	Fleet Response Plan
FSA	force structure assessment
FTA	fault tree analysis

GGTB	General Gas Turbine Bulletin
GTE	gas turbine engine
GTB	Gas Turbine Bulletin
GTM	gas turbine module
IDIQ	indefinite-delivery-indefinite-quantity
IMA	Intermediate Maintenance Activity
IMS	integrated master schedule
INCOSE	International Council on Systems Engineering
JFMM	Joint Fleet Maintenance Manual
LLTM	long lead time material
LORA	level of repair analysis
LTA	local technical authority
MDT	maintenance downtime
MFOM	maintenance figure of merit
MGTI	marine gas turbine inspector
MIP	maintenance index page
MRC	maintenance requirement card
MSMO	multi-ship multi-option
MSRA	Master Ship Repair Activity
MT	maintenance team
N8	Deputy CNO (Integration of Capabilities and Resources)
NASA	National Aeronautics and Space Administration
NAVLOGTD	Naval Logistics Technical Data
NAVSEA	Naval Sea Systems Command
NAVSUP	Naval Supply Systems Command
NSA	Naval Supervisory Authority
NSS	National Strategic Strategy
NSTCP	navy standard titanium centrifugal pump
NSWC	Naval Surface Warfare Center
NSY	naval shipyards
NUWC	Naval Undersea Warfare Center
O/I	open and inspect
OEM	original equipment manufacturer
OFRP	Optimal Fleet Response Plan
OM&N	Operations and Maintenance, Navy
OPN	Other Procurement, Navy
OPNAV	Office of the Chief of Naval Operations
OPTEMO	operational tempo
OQE	objective quality evidence

PDA	pre-deployment assessments
PESC	Propulsion Executive Steering Committee
PM	preventative maintenance
PMS	planned maintenance system
PPM	propulsion plant manual
PPMMA	pre-planned major maintenance availability
PTD	provisioning technical documentation
RBD	reliability block diagram
RCC	request for contract change
RCM	reliability-centered maintenance
RMC	regional maintenance center
RMP	risk management plan
RO	reverse osmosis
RPN	risk priority number
SA	single award
SBS	shipbuilding specialist
SIB	ship information book
SM&R	source maintenance and recoverability
SRA	selected restricted availability
SSEOC	surface ship engineered operating cycle
ST1	Surface Team One
SWLIN	ship work list item number
SYSCOM	System Command
T&V	tank and void
TD	time-directed
TIR	total indicated run-out
TOC	total ownership cost
TPD	technical provisioning documentation
TSRA	total ship readiness assessment
TYCOM	Type Commander

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The national security and prosperity of the United States is strongly dependent on maintaining dominance over the waterways throughout the world. Attaining such dominance requires a technically advanced Navy with a global presence. Building and operating a formidable naval surface force is an undertaking of enormous proportion. Nevertheless, a supreme naval force will not endure without the necessary maintenance to sustain its force structure. Further, unless the maintenance is effective and efficient, sustaining a sizeable naval force will become cost prohibitive and yield insufficient operational readiness. The United States depends on its in-service surface ships to remain operationally relevant and capable throughout their expected service lives. Seventy-five percent of the Navy's 306-ship goal is already in today's fleet and it is critical that these ships maintain required operational readiness to meet projected missions (Naval Sea Systems Command 2009b). Sustaining today's fleet demands judicious and disciplined management of maintenance and modernization resources.

This thesis examines existing Navy maintenance policies, programs, practices, and processes to identify maintenance strategy and operational requirement misalignments. System maintenance strategies play a direct role in the success or failure of ship maintenance availabilities. An effective surface ship maintenance strategy is an important aspect of maintaining ships, whereby expected service life within acceptable life cycle costs is achievable, without sacrifice to maintenance schedule constraints critical to operational readiness. Balancing cost, schedule, and performance associated maintenance parameters is determined to be a critical focus of the Navy maintenance community. This balance is also found to be of significant importance to future Navy force structure and stability of the private industrial bases. Additionally, the Navy gives carefully consideration to sequestration and execution of the Optimal Fleet Response Plan (OFRP), which is determined to underscore the importance of successful completion of ship maintenance availabilities within budget and schedule.

The consequences of growth and new work are found to be the principal catalysts that drive increased costs and lost operational and training days (Commander, Naval

Surfaces Forces 2014). This thesis emphasizes the importance of controlling growth and new work to reduce the risk of maintenance availability cost and schedule growth. This thesis posits a systems engineering approach to aid the complex decision-making process of ship maintenance. Systems engineering concepts and applications are introduced and provide a logical means to identify and manage challenges associated with the analysis and development of effective surface ship system maintenance strategies. A description of the Navy standard titanium centrifugal pump (NSTCP) serves as a simple reference system to demonstrate the application of various systems engineering tools. The core of this thesis focuses on leveraging systems engineering applications and principles, such as functional decomposition, reliability block diagrams (RBD), fault tree analysis (FTA), context diagrams, and risk assessment to develop a structured systems engineering approach for more effective maintenance decisions.

The principal focus of this thesis is the preventative maintenance (PM) strategy analysis and recommendations for improvement for the CG-47 Class main gas turbine exhaust system. Navy reliability-centered maintenance (RCM), condition-based maintenance (CBM) policies, and historical maintenance inspection data related to the main gas turbine exhaust system is analyzed. This thesis finds a new hybrid approach to RCM that is modifiable and in harmony with existing Navy maintenance policies. The hybrid exhaust system maintenance strategy is the product of careful evaluation of existing maintenance challenges, requirements and stakeholder analysis, and systems thinking. The analysis finds the existing strategy inadequately accounts for maintenance availability schedule constraints critical to future Navy operations. The new recommended hybrid approach mitigates shortfalls with existing condition-directed (CD) and failure-finding (FF) RCM methods that leave exposure to the risks of growth-work associated with availability schedule overruns. A hybrid preventative maintenance approach that combines the necessity of a FF task with the practicality of a TD task creates the sensibility of a blended inspection task with a planned and budgeted repair task. This hybrid approach to RCM for the main gas turbine exhaust system, backed by historical failure data analysis, presents an opportunity to improve maintenance planning and execution effectiveness. The historical failure data analysis provides sufficient evidence to justify a directed repair action. Moreover, accomplishing the FF element of the hybrid preventative maintenance task provides the necessary data for future analysis and amendment. Adjusting the TD task to be made more or less conservative according to historical inspection data analysis is a simple modification. The analysis is shown to be extrapolatable into a comprehensive maintenance strategy for surface ships that delivers "the right maintenance at the right time for the right price" (U.S. Fleet Forces Command 2013, II-II–2-7).

LIST OF REFERENCES

Commander, Naval Surfaces Forces. 2014. *Vision for the 2026 Surface Fleet*. San Diego, CA: Naval Surfaces Forces, U.S. Pacific Fleet, 3.

Naval Sea Systems Command. 2009b. *Strategic Business Plan: 2009–2013*. Washington, DC: Naval Sea Systems Command, 11.

U.S. Fleet Forces Command. 2013. *COMUSFLTFORCOMINST 4790.3: Joint Fleet Maintenance Manual (JFFM)*. Rev C, Change 1. Vol. II. Manual. Washington, DC: U.S. Fleet Forces Command.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to extend my gratitude to those who supported me in completing this thesis and the PD21 program. My completion of this thesis and master's degree could not have been accomplished without the support of my command and supervisor, Kevin Campbell. Thank you for tolerating my time away from work to research, study, and write. I must also give a well-deserved thanks to Dave Bowe, my colleague and fellow classmate, for his motivation and wisdom throughout this journey.

I would like to thank the wonderful Naval Postgraduate School instructors and staff, who carefully and effectively delivered the course material in a relevant and practical fashion. I give special thanks to my thesis advisors, Professors Gary Langford and Gregory Miller, for their helpful feedback and guidance throughout the development of my thesis.

I cannot express enough thanks to my children. To Jackson and Tyler, thank you for allowing me time away from you to complete my studies. You deserve a pool in the backyard! Thanks to my parents, Dan and Cheryl Sparks, as well. The countless times you kept the children during our hectic schedules will not be forgotten.

Finally, to my caring, loving, beautiful, and supportive wife, Amber: my deepest gratitude. Your encouragement during the intense and stressful moments is much appreciated and cherished. It was a great comfort and relief to know that you were willing to provide management of our household activities while I completed my school obligations. Without you, none of this would have been possible. You have my heartfelt thanks.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

An effective surface ship maintenance strategy is an important aspect of maintaining ships, whereby expected service life within acceptable life cycle costs is achievable, without sacrifice to maintenance schedule constraints critical to operational readiness. According to the Office of the Chief of Naval Operations (OPNAV), “Navy ship maintenance policies and actions are designed to ensure crew and ship safety while achieving desired operational readiness levels at the lowest possible total ownership cost, consistent with public law and other directives” (Office of the Chief of Naval Operations 2010a, 2). This thesis examines facets of the Navy’s surface ship maintenance policies and practices related to system maintenance strategy development. Systems engineering concepts and applications are introduced and demonstrated as a logical means to identify and manage strategy challenges. The principal focus of this thesis is the main gas turbine exhaust system maintenance strategy specific to the CG-47 Ticonderoga Class Cruiser. The purpose of this thesis is to emphasize systems thinking and systems engineering applications beneficial to system maintenance strategy development, and recommend an improved main gas turbine exhaust system maintenance strategy.

A. OVERVIEW

The Navy’s surface ship maintenance community has an enduring objective to provide “the right maintenance at the right time for the right price” (U.S. Fleet Forces Command 2013, II-II–2-7). This relatively straightforward objective has proven difficult to achieve and even more difficult to measure. The difficulty in consistently achieving this objective is an outgrowth of a large number of dynamic environmental variables that affect ship maintenance and modernization. These variables range from the size of the national defense budget that directly impacts funding allocation for ship maintenance, to the creation and implementation of a single new maintenance process, which impacts how and what kind of maintenance is executed. Failing to accomplish the effective and efficient maintenance drives inefficiencies in cost, schedule, and performance during ship maintenance availabilities. Growth and new work are the principal catalysts that drive increased costs and lost operational and training days (Commander, Naval Surfaces Forces 2014). It is difficult for maintenance budgets and operational schedules to account for growth and new work accurately. Consequently, to achieve ship readiness in the face of inefficiencies, occasional extraordinary efforts are required. These inefficiencies yield unsustainable material readiness that inevitably negatively correlates with Navy force structure goals. Surface ship maintenance and modernization is a complex undertaking with numerous stakeholders. The Budget Control Act of 2011, most commonly referred to as sequestration, presents a new set of unique challenges to the Navy's ability to deliver ready warships capable of providing sustained combat operations around the world.

This thesis analyzes the existing preventative maintenance (PM) strategy of the CG-47 Class main gas turbine exhaust system in Chapters II and IV. The maintenance strategy analysis emphasizes why systems engineering applications can help improve maintenance planning and execution. Chapter III of this thesis explains the concept of reliability-centered maintenance (RCM) and the Navy's condition-based maintenance (CBM) policy. Chapter IV introduces and demonstrates how the concept of systems thinking and systems engineering applications can help develop improved maintenance strategies in harmony with maintenance and operational community stakeholder requirements. The description of the Navy standard titanium centrifugal pump (NSTCP) serves as a simple reference system to introduce and demonstrate the application of various systems engineering tools. The core of this thesis focuses on leveraging systems engineering applications and principles—such as functional decomposition, reliability block diagrams (RBD), fault tree analyses (FTA), context diagrams, and risk assessments—to develop a structured systems engineering approach for more effective maintenance decisions. Chapter IV also provides a systems engineering analysis of the main gas turbine exhaust system using some of the systems engineering tools introduced earlier in the chapter. Chapter V provides conclusions and recommendations based on the findings of the main gas turbine exhaust system analysis from Chapter IV. This thesis posits a systems engineering approach to aid the complex decision-making process of ship maintenance. The analysis can be extrapolated into a comprehensive maintenance strategy for surface ships that addresses fundamental risks associated with ship maintenance execution, such as growth-work.

B. RESEARCH QUESTIONS

Surface ship maintenance is bound by the Department of the Navy budget. Funding constraints are a natural reality of any budget. To meet defined goals and objectives within a budget requires persistent and disciplined management of finite resources. When Rear Admiral Philip Cullom (2009, 8–9) testified before the Readiness Subcommittee on Armed Services on March 25, 2009, he stated the Navy's 30-year shipbuilding plan and sustainment of a forward-deployed, surge-capable naval force is dependent on each class of surface ships reaching their respective service lives.

For the Navy to maintain combat-ready surface ships fully through their expected service lives, the right maintenance and modernization is vital. Reaching expected service life does not happen by accident; a well-integrated systems engineering approach is critical to the development, planning, and execution of the right maintenance over a ship's lifetime. A technical underpinning to executing the right system maintenance is the maintenance strategy. This thesis investigates methods to select the most effective main gas turbine exhaust system maintenance strategy for the CG-47 Class Cruiser. The following questions are addressed.

- What set of factors influences selecting the most effective main gas turbine exhaust system maintenance strategy?
  - What does effective mean?
  - What are the measures of effectiveness?
- How important are surface ship maintenance and modernization to achieving Navy force structure goals?
  - What are the driving issues?
  - What are the sensitivities?
- What does the current process for developing a surface ship maintenance strategy look like?

- Do any quantitative system models exist today to aid in ship maintenance strategy?
    - How effective are these models?
- What systems engineering applications or principles can be applied to improve the effectiveness of maintenance strategies?
- What is the impact of not selecting the right maintenance or modernization strategy?

C. BACKGROUND

By all measures, dominance over the world's oceans and major waterways is critical to the United States' national security and prosperity (U.S. Navy 2014). In perspective, oceans are the lifeblood of the planet and its entire population. The National Defense Authorization Act (NDAA) for fiscal year 2013 mentions that navigable oceans encompass over 70 percent of the earth's surface. Additionally, in excess of 80 percent of the world's population lives within 100 miles of an ocean and greater than 90 percent of the world's commerce travels via ocean.[1] The same NDAA confirms the national security of the United Sates is closely coupled to its strategic and commercial interests, and both require unfettered global access.

To ensure global access to vital sea lanes, the United States strategically deploys forces from the Navy, the Marine Corps, and the Coast Guard to protect its interests at home and abroad. To defend waterways adequately around the world, the National Defense Authorization Act for fiscal year 2013 states the government must continue to build and deliver new ships, as well as ensure in-service ships achieve their designed service life goals. Between surface ship recapitalization and repair, the latter is of significant importance and the focus of this thesis.

---

[1] Statistics can be found in *National Defense Authorization Act for Fiscal Year 2013: Conference Report (to Accompany H.R. 4310)*. House of Representatives, 112th Cong., 2 (2012), 315.

1. Importance of Ship Maintenance and Modernization to Sustaining Force Structure

The Department of the Navy (DON) report to Congress on the annual long-range plan for construction of naval vessels for fiscal year 2014 (Deputy Chief of Naval Operations (Integration of Capabilities and Resources) [N8] 2013, 3) details the number of ships by platform in accordance with the 2012 Navy force structure assessment (FSA). This determination of ships is based on the Secretary of Defense's 2012 (Panetta 2012) Department of Defense (DOD) Defense Strategic Guidance, *Sustaining U.S. Global Leadership: Priorities for 21st Century Defense.* The shipbuilding plan outlines a long-range projection of new ship acquisition and associated resources required to develop a fleet that meets the FSA's requirements. The Navy's FSA in 2012 determined a force of 306 ships needed to fulfill the National Security Strategy (NSS) requirements. This requirement of 306 ships includes the following.

- 12 fleet ballistic missile submarines
- 11 nuclear-powered aircraft carriers
- 48 nuclear-powered attack submarines
- 0 nuclear-powered cruise missile submarines
- 88 large, multi-mission, surface combatants
- 52 small, multi-role, surface combatants
- 33 amphibious landing ships
- 29 combat logistics force ships
- 33 support vessels (Deputy Chief of Naval Operations (Integration of Capabilities and Resources) [N8] 2013, 12–14).

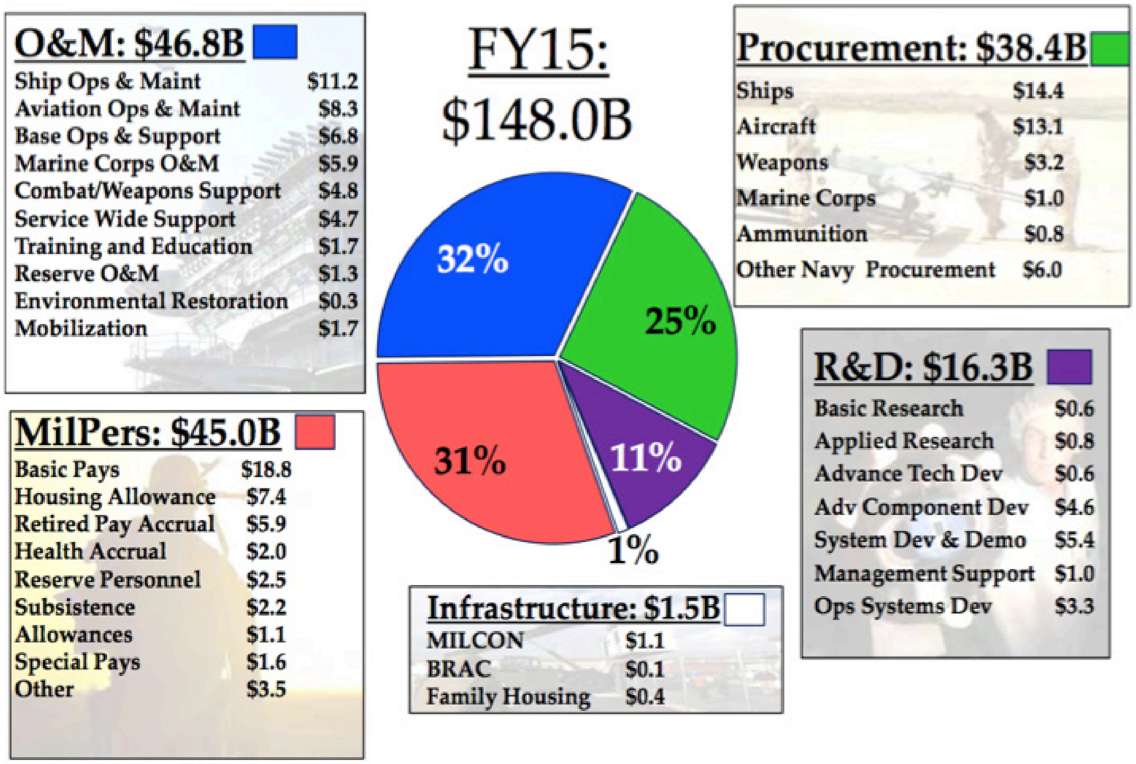
Statistics from the official website of the U.S. Navy indicate today's deployable battle force is 273 warships (United Sates Navy 2015). Sustaining today's fleet is essential to the Navy's ability to achieve the required FSA of 306 ships. Building new ships alone is not an economical or practical option. The Naval Sea Systems Command Strategic Business Plan emphasizes that seventy-five percent of the Navy's 306-ship goal is already in today's fleet and it is critical that these ships maintain required operational readiness to meet projected missions (Naval Sea Systems Command 2009b, 6). Sustaining today's fleet demands judicious and disciplined management of maintenance and modernization resources. Balancing all facets of cost, schedule, and performance for in-service surface ship maintenance necessitates a systems thinking approach. Ignoring one or more of these facets leads to unbalanced requirements and inefficiencies.

2. Surface Ship Maintenance Budget in Perspective

The Navy is a large, global, complex organization. In a speech to the Surface Navy Association in 2013, Secretary of the Navy, Ray Mabus (2013) stated if the DON were a privately held company, it would be the second largest in the world by employees. In the same speech, he mentioned that as a privately held company, the Navy would be the third largest in the world by assets and it would be the fifth largest in the world by budget or revenue authority (1).

Funding resources for the maintenance and modernization of surface ships compete against other Navy budget requirements. To maintain surface ships capable of sustained combat operations, funds are allocated via the DON budget. These funds come from two predominant funding lines, Operations and Maintenance, Navy (O&M,N), and Other Procurement, Navy (OPN). The Under Secretary of Defense's (Comptroller) DOD *Fiscal Year 2015 Budget Request Overview* from March 2014 outlines the President's request to Congress for $495.6 billion in discretionary funding for the base budget of the Department of Defense (Office of the Under Secretary of Defense (Comproller)/Chief Financial Officer 2014, 1). In a presentation on the FY2015 President's Budget, Rear Admiral Lescher (2014, 5) shows the DON's portion of the budget consists of $148 billion of the total DOD budget, or approximately 30 percent. The same presentation shows O&M,N and OPN constitute $46.8 billion and $6 billion of the DON budget, respectively (see Figure 1). Funding for surface ship maintenance and modernization represents only a portion of the overall O&M,N and OPN funds and competes against carrier, submarine, and Navy aircraft readiness requirements. Approximately $2 billion of the $11.2 billion O&M,N funds are dedicated to surface ship maintenance (Commander, Naval Surfaces Forces Pacific 2015; Commander, Naval Surfaces Forces Atlantic 2015).

Figure 1. Summary by Appropriation Group FY 2015 Base Budget



O&M: $46.8B 🟦

Ship Ops & Maint	$11.2
Aviation Ops & Maint	$8.3
Base Ops & Support	$6.8
Marine Corps O&M	$5.9
Combat/Weapons Support	$4.8
Service Wide Support	$4.7
Training and Education	$1.7
Reserve O&M	$1.3
Environmental Restoration	$0.3
Mobilization	$1.7

Procurement: $38.4B 🟩

Ships	$14.4
Aircraft	$13.1
Weapons	$3.2
Marine Corps	$1.0
Ammunition	$0.8
Other Navy Procurement	$6.0

MilPers: $45.0B 🟥

Basic Pays	$18.8
Housing Allowance	$7.4
Retired Pay Accrual	$5.9
Health Accrual	$2.0
Reserve Personnel	$2.5
Subsistence	$2.2
Allowances	$1.1
Special Pays	$1.6
Other	$3.5

R&D: $16.3B 🟪

Basic Research	$0.6
Applied Research	$0.8
Advance Tech Dev	$0.6
Adv Component Dev	$4.6
System Dev & Demo	$5.4
Management Support	$1.0
Ops Systems Dev	$3.3

Infrastructure: $1.5B ⬜

MILCON	$1.1
BRAC	$0.1
Family Housing	$0.4

From Lescher, William, K. 2014. "Department of the Navy FY 2015 President's Budget." Financial Management and Comptroller. 5. http://www.finance.hq.navy.mil/FMB/15pres/DON_PB15_Press_Brief.pdf.

3. Complexity of Ship Maintenance

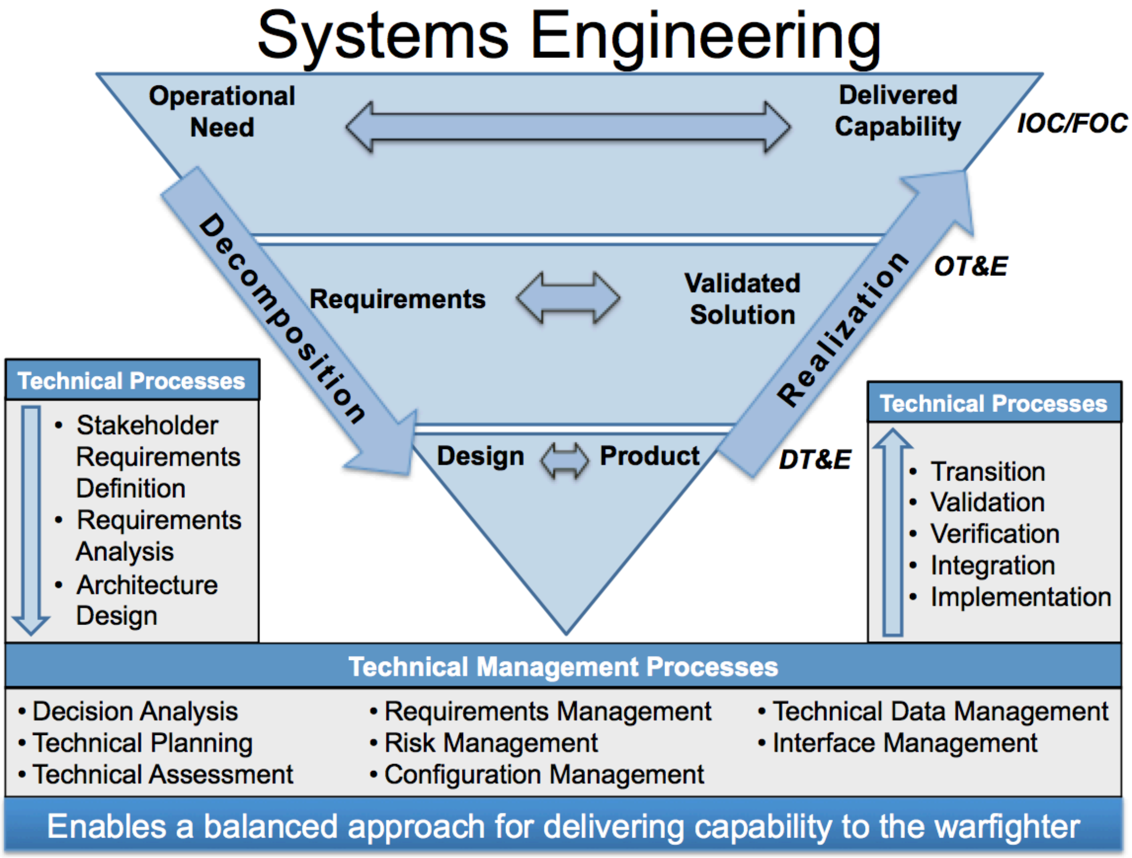
The complexity of surface ship maintenance extends well beyond the intricate design of a ship or individual work specification for repair. As indicated in a Surface Team One (ST1) presentation by Rear Admiral Dave Gale (2011, 2), surface ship maintenance is a multifaceted domain that must account for 12 ship classes, over 160 ships, nine homeports around the world, six multi-ship multi-option (MSMO) prime contract holders, 19 MSMO contracts, frequent military personnel turnover, multiple processes, multiple databases, and many commands with unique organizational processes. A surface ship creates a demanding environment for executing repairs. Careful planning is required to account for work package integration, interference removal, support services, pier laydown, material procurement, and shipyard workload capacities to name a few. Recognizing the complexities of surface ship maintenance gives credence to the necessity of a systems engineering approach to systematically managing the various components of ship repair. A traditional engineering approach lays out a plan that does not recognize fully (or accept as a premise) the interrelated, multidimensional issues of cost, schedule, and performance associated with ship maintenance. System engineering principles, such as requirements analysis focus on the intricacies of balancing cost, schedule, and performance. A systems engineering approach is especially helpful in developing an accurate work specification that defines the right scope of work. The absence of a disciplined tactic to work specification development breeds growth and new work.

4. Systems Engineering Relevance to Maintenance Strategy Development

A precise definition of a system is yet to be universally agreed upon. Langford (2012, 202) defines a system as, "a bounded, stable group of objects exhibiting intrinsic emergent properties that through the interactions of energy, matter, material wealth, and information provide functions different from their archetypes." Objects can include people, services, software, policies, hardware, processes, and documents. The development of a maintenance strategy for a system designed for a surface ship requires the interaction of people (maintenance community), facilities (repair facilities), policies (maintenance, regulatory), processes (budget and schedule), software (databases), and hardware (tools, test equipment). Thus, a maintenance strategy developed via the interaction of objects that delivers the function, performance, and quality needed by the customer that is beyond what the individual objects provide, is a system.

The International Council on Systems Engineering (INCOSE) (2015) defines systems engineering on their official website as "an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle." The Defense Acquisition Guidebook for Systems Engineering says, "systems engineering establishes the technical framework for delivering material capabilities to the warfighter" (Department of Defense 2013, 2). The same source goes on to say, "systems engineering ensures the effective development and delivery of capability (maintenance strategy) through the implementation of a balanced approach with respect to cost, schedule, performance, and risk using integrated, disciplined, and consistent system engineering activities and processes regardless of when a program enters the acquisition life cycle" (Department of Defense 2013, 3). The practice of systems engineering is composed of technical processes and technical management processes, as seen in Figure 2.

Figure 2. Systems Engineering Processes



From Department of Defense. 2013. *Defense Acquisition Guidebook—Systems Engineering*. Washington, DC: Department of Defense, 8.

The Defense Acquisition Guide Book for Systems Engineering claims, "the ultimate purpose of the systems engineering processes is to provide the framework that allows the systems engineering team to efficiently and effectively deliver a capability to satisfy a validated operational need" (Department of Defense 2013, 6). A system maintenance strategy is a valid operational need. This thesis shows how systems engineering principles can guide in the development of system maintenance strategies in Chapter IV. This thesis conceives systems engineering methodology is a logical tactic to aid in the development of system maintenance strategies. The comprehensive and methodical approach characteristic to systems engineering is ideal for breaking down complex issues and aligning maintenance requirements with maintenance business practices, processes, life cycle costs, schedule constraints, and customer and stakeholder needs to create an effective maintenance strategy.

The surface ship maintenance community is not immune to the challenges of balancing cost, schedule, and performance in their mission to support a fluid demand of ready warships by their Combatant Commander (CCDR) customers. Langford (2012, 215–216) explains,

> Systems engineering is challenged to address two seemingly different types of problems—those that are defined in terms of requirements (for customers who have specific needs) and those that are driven by the economics of services (those who want to lower costs and improved schedule). Systems engineering provides the thinking and the approach to establishing performance, cost, and schedule trade-offs that align to requirements. Systems engineers deliver their most beneficial performance on problems whose boundaries (physical, functional, and behavioral) reach well beyond what is often presented in a set of requirements.

The integration of maintenance requirements, stakeholder and customer needs, operational requirements, business practices, and resources is the basis for an effective system maintenance strategy, and the strength of systems engineering is integration.

D. BENEFITS OF STUDY

This study provides for a more predictable and well-rounded maintenance requirement through the application of systems engineering analysis of historical maintenance data and the concept of systems thinking and best value engineering. The resulting maintenance strategy can be adjusted over time to account for data variation. A data-supported directed maintenance requirement allows for more accurate planning, material forecasting, reduced growth and new work, and better supports a firm fixed price contract strategy. A systems engineering analysis of historical maintenance data provides an alternative to condition-based maintenance assessments. A sizeable reduction in time and resources currently expended on condition-based maintenance assessments required to define the scope of repair may be realized. A systems engineered maintenance strategy brings efficiency to ship repair and helps to ensure finite resources are properly applied.

E. SCOPE AND METHODOLOGY

This thesis introduces systems engineering applications beneficial to system maintenance strategy analysis and development. Reference to the NSTCP provides context for the systems engineering tools described in this thesis and a basic illustration of their application relevant to maintenance strategy analysis. This thesis then analyzes the main gas turbine exhaust system using systems engineering applications. The analysis of the main gas turbine exhaust system is limited to the CG-47 Ticonderoga Class Cruiser configuration. The methodology of this thesis focuses on a systematic approach that leverages various reliability analysis applications and processes common to the field of systems engineering. Actual data and metrics are used to the maximum extent possible.

THIS PAGE INTENTIONALLY LEFT BLANK

II. THE RIGHT MAINTENANCE, AT THE RIGHT TIME, FOR THE RIGHT PRICE

A well-engineered system maintenance strategy is an important part of executing disciplined and effective maintenance. The development of such a maintenance strategy necessitates a comprehensive understanding of the system, its functions, boundaries, and interactions. Further, the development or improvement of a system maintenance strategy must be in harmony with other related Navy strategies, such as contracting and logistics. An effective system maintenance strategy must account for established Navy maintenance policies, processes, practices, and programs. System maintenance strategy development requires an analysis of the associated maintenance community stakeholders and elements of each of the aforementioned factors.

A. MAINTENANCE COMMUNITY STAKEHOLDER ANALYSIS

The various stakeholders that comprise the maintenance community influence the scope, periodicity, and price of ship maintenance. It is important to recognize stakeholder's perspectives, needs, motives, interests, requirements, and values when analyzing existing or developing new maintenance requirements. Often times, not all stakeholders are considered or fully evaluated. Failing to recognize stakeholders and fully evaluate their perspectives, needs, motives, interests, requirements, and values may result in insufficient understanding and appreciation of stakeholder's concerns and the development of an inadequate maintenance strategy. According to Langford (2012, 260), "stakeholder analysis is the systematic gathering and analyzing of qualitative information to determine whose interests should be taken into account when developing and/or implementing a policy or program." Reviewing documented group and organization mission descriptions is one means of identifying relevant stakeholders and their interests.

The maintenance community comprises stakeholders from various commands and organizations, each with unique roles and responsibilities. A discussion of key stakeholders within the maintenance community and their applicable roles and responsibilities follows. These stakeholders directly influence all aspects of ship maintenance including policy, process, programs, procedures, budget, and strategy. Many additional stakeholders influence or are influenced by surface ship maintenance not mentioned in this analysis. Additional stakeholders, such as sailor's families, congressional representatives, and the general taxpayer, are not considered directly part of the maintenance community, and therefore, are outside the scope of this analysis.

1. Type Commander

The mission of the Type Commander (TYCOM) is described in their mission, functions, and tasks instruction (Commander, United States Pacific Fleet 2013, 2) as "supporting Combatant Commanders and Navy Component Commanders by providing combat-ready Naval Surface Forces which are forward deployable, fully trained, properly manned, capably equipped, well maintained, and combat-sustainable." The TYCOM has delegated responsibility and authority provided by the respective Fleet Commander for whom they represent. OPNAV states that the TYCOM is responsible to support their respective Fleet Commander with combat-ready forces via administrative management of force-wide plans, concepts, and policies (Office of the Chief of Naval Operations 2010b, 4). As such, the TYCOM has a vested interest in surface ship maintenance and a laser focus on executing all the necessary maintenance on time and on budget. The successful completion of maintenance availabilities on schedule is significantly important to the TYCOM to ensure sufficient time is allowed for the required training cycle prior to a ship's deployment. Curbing maintenance growth and new work is also essential to the TYCOM. Preventing excessive growth and new work is essential to the preservation of limited maintenance funds and associated negative impacts resonating across other budgeted ship maintenance availabilities.

2. Naval Sea Systems Command

The Naval Sea Systems Command (NAVSEA) is the largest of all the system commands (SYSCOMs). The mission of NAVSEA is to "design, build, deliver, and maintain ships and systems on time and on cost for the U.S. Navy" (Naval Sea Systems Command 2009b, 3). The NAVSEA mission is executed across a series of directorates within the overall organization. The NAVSEA directorates are responsible for such areas as developing maintenance and engineering policy, providing independent technical and contractual authority, developing and executing surface ship modernization, and life cycle sustainment. The success of surface ship maintenance and modernization depends on the foundation of processes, policies, programs, and procedures built by NAVSEA.

3. Regional Maintenance Center

The joint fleet maintenance manual (JFFM) defines the regional maintenance center (RMC) as "the command with overall responsibility for efficient planning and execution of all ship maintenance and modernization for assigned ships in its Area of Responsibility (AOR). The RMC is a subordinate command to NAVSEA and has a reporting relationship to the appropriate TYCOM to ensure the TYCOM can effectively carry out their responsibilities relating to material readiness of their ships" (U.S. Fleet Forces Command 2013, II-II–1-1). Additionally, the RMC is generally designated as the Naval Supervisory Authority (NSA) by the TYCOM. The JFFM describes the NSA as "the single Naval activity responsible for the integration, oversight and verification of all work accomplished by all activities (i.e., Naval Shipyards (NSY), Regional Maintenance Centers (RMC), Supervisors of Shipbuilding (SUPSHIP) contractors, Type Commander (TYCOM) sponsored contractors, Intermediate Maintenance Activities (IMA), Alteration Installation Teams (AIT) and Ship's Force) working within the assigned availability, and acts as the single point of contact for this work" (U.S. Fleet Forces Command 2013, II-I–2-2).

4. Commander, Naval Regional Maintenance Center

The official homepage for Commander, Naval Regional Maintenance Center (CNRMC) says its mission is "to deliver quality and affordable material readiness to support U.S. Naval forces worldwide" (Commander, Naval Regional Maintenance Center 2009). CNRMC is an organization under NAVSEA and provides direct oversight and alignment for each of the RMCs.

5. Private Ship Repair Industry

This industry is a collection of qualified Master Ship Repair Agreement (MSRA) eligible contractors. According to the MSRA, these private industrial activities must have the capability to execute the majority of a maintenance work package within their own facility without the support of additional shops or work force. These activities must also be capable of subcontracting for augmented support when internal capability and capacity are exceeded. MSRA contractors are liable for developing and managing a master integrated schedule, cost, and performance of subcontractors (Commander, Naval Sea Systems Command 1996, 9). The private ship repair industry is a vital component of the surface Navy. A symbiotic relationship exists between the surface Navy and private ship repair industry, neither of which could survive without the other. Private industrial activities must competitively compete for ship repair work. For this reason, private shipyards have a keen awareness for executing maintenance within established contractual parameters. Private ship repair activities are for profit organizations and responsible to their shareholders. To achieve company goals and ensure longevity, they must establish strong working relationships with the surface Navy and a record of strong performance.

6. Naval Supply Systems Command

The Naval Supply Systems Command's (NAVSUP) official homepage defines the naval supply system's responsibility "to deliver sustained global logistics and quality-of-life support to the Navy and Joint warfighter" (Naval Supply Systems Command 2015). NAVSUP provides supply support for the weapons systems throughout the Navy. Maintenance strategies that touch the way supply system material is provided for ship maintenance is important to NAVSUP.

7. Fleet Commanders

The missions, functions, and tasks instruction for the Commander of the United States Pacific Fleet says, "the Chief of Naval Operations (CNO) delegates authority to the Fleet Commanders to organize, man, train, equip, and maintain assigned Navy forces and shore activities to generate required levels of current and future fleet readiness" (Office of the Chief of Naval Operations 2010b, 1). According to the same instruction, “the Fleet Commander is the budget submitting office (BSO) with financial management authority and responsibility for their assigned forces, shore activities, military and civilian personnel, infrastructure, and budget” (Office of the Chief of Naval Operations 2010b, 1). The Fleet Commander delegates certain responsibilities and authorities to the applicable surface ship TYCOM. Maintenance strategies that affect how surface ships are manned, trained, equipped, and maintained are of significant interest to the Fleet Commander.

8. Sailors aboard Surface Platforms

The primary mission for sailors aboard surfaces ships is to be capable of performing sustained combat operations and successfully meet all assigned operational requirements. To meet this objective, sailors are dependent in part on effective maintenance strategies to keep their ships materially ready to operate as designed. Moreover, sailors aboard surface ships are responsible for the planning and execution of organizational-level maintenance within their capacity to include planned maintenance and the requisitioning of necessary parts. Sailors are also responsible for preparing systems and equipment for intermediate or depot-level repair via proper system isolation, and tag out and ship compartment availability when required. According to the maintenance policy for U.S. Navy ships, “the Navy ship is a unique entity in that responsibility for both the operation and maintenance of the ship rests with the crew itself. Other Navy organizations exist to support that entity” (Office of the Chief of Naval Operations 2010b, 36).

9. Naval Surface and Undersea Warfare Centers

The official NAVSEA Warfare Center homepage describes the Naval Surface Warfare Center (NSWC) and the Naval Undersea Warfare Center (NUWC) enterprises. The homepage says the warfare centers provide the technical underpinnings needed to support the fleet. The homepage also says, “The Warfare Centers provide depot maintenance and in-service engineering support to ensure the systems fielded today perform consistently and reliably in the future” (Naval Surface Warfare Center 2015).

Warfare center activities must be knowledgeable of Navy system maintenance strategies and are directly involved in maintenance strategy development.

10. Surface Team One

The Surface Team One (ST1) charter signed by Admiral Hunt and Admiral Thomas in 2012 outlines the scope and purpose of the organization as “the unifying mechanism for getting to a coherent, comprehensive, and whole Surface Navy maintenance, modernization, and sustainment program” (Hunt and Thomas 2012, 2). The charter goes on to say, “ST1 provides a structure for the management and long-term systematic improvement of quality, schedule, and cost performance across the Surface Navy end-to-end process while defining, championing, and improving the processes in order to address the challenges of meeting surface ship expected service life as well as current readiness” (2). The charter highlights the importance for maintenance organizations to work seamlessly together across the end-to-end process. ST1 plays a direct role in the development and improvement of system maintenance strategies for Navy ships.

11. Office of the Chief of Naval Operations

U.S. Navy regulations state, “The Chief of Naval Operations (CNO) is the principal naval advisory and naval executive to the Secretary of the Navy on the conduct of the naval activities of the Department of the Navy” (Department of the Navy 1990, 24). The same source explains the CNO is responsible to the Secretary of the Navy for the management of all naval operating forces and assigned shore activities. U.S. Navy regulations also say, “The CNO is responsible to organize, train, equip, prepare and maintain the readiness of Navy forces, including those for assignment to unified or specified commands, for the performance of military missions as directed by the President, the Secretary of Defense or Chairman of the Joint Chiefs of Staff” (Department of the Navy 1990, 24). Surface ship maintenance strategies are one of many factors important to OPNAV.

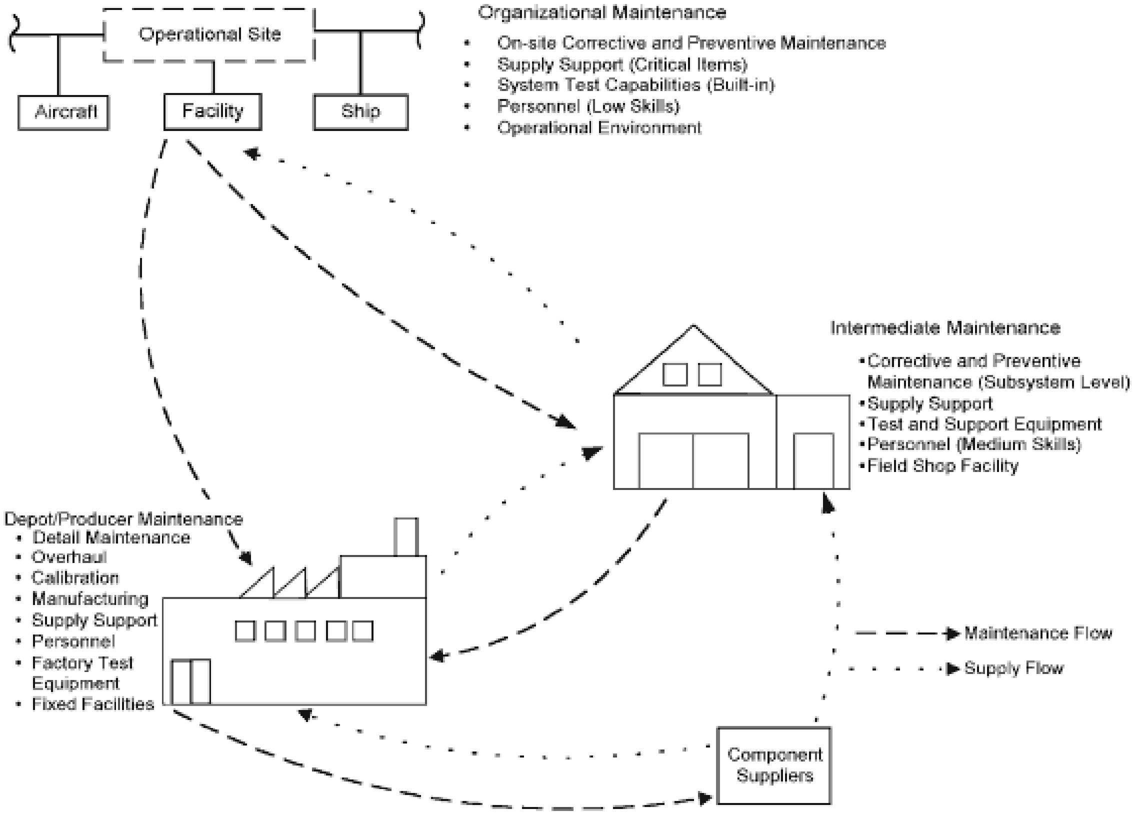
12. System or Equipment Original Equipment Manufacturer

The original equipment manufacturer (OEM) designs, builds, and delivers commercial systems and equipment for installation on Navy surface ship platforms. The OEM develops initial technical provisioning documentation (TPD). TPD includes items, such as maintenance requirements and procedures, technical manuals, system or equipment drawings and schematics, and parts lists. In some cases, maintenance or repair may require special tooling or procedures only the OEM can provide. The OEM also designs and builds necessary upgrades to a system or equipment to improve design, prevent obsolescence, and keep pace with emerging technologies. The OEM is an important stakeholder throughout the life cycle of a system or equipment.

B. THE RIGHT MAINTENANCE

The right maintenance is the accomplishment of the correct maintenance action on the right system, subsystem, component, assembly, or sub assembly with the appropriate material and labor resources. RCM processes provide the technical underpinning for system and equipment maintenance requirements. RCM is an essential part of determining the right maintenance. RCM is discussed in Chapter III of this thesis. Development of a maintenance strategy that safeguards against accomplishing the wrong maintenance must ensure the maintenance is accomplished at the appropriate level. Blanchard and Fabrycky (2011) define maintenance level as a means to describe where maintenance is executed. They also explain that functions performed at different maintenance levels are determined by maintenance frequency and complexity, facility and supply chain requirements, and technician skill set requirements (76). The Navy has three core levels of maintenance: organizational, intermediate, and depot. Figure 3 depicts the basic criteria and differences between the maintenance levels.

Figure 3. System Operational and Maintenance Flow



Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis.* Upper Saddle River, NJ: Prentice Hall.

1. Levels of Maintenance

a. Organizational Maintenance

Organizational-level maintenance is considered ship’s force capable maintenance actions. Organizational-level maintenance accomplished correctly and without deferral prevents the escalation of minor defects from becoming major material problems with operational impacts. The CNO’s maintenance policy for U.S. Navy ships designates organizational-level maintenance actions to include facility maintenance, routine system and component planned maintenance, calibration, lubrication, and corrective maintenance commensurate with ship’s force capability and capacity (Chief of Naval Operations 2010, 22).

b. Intermediate Maintenance

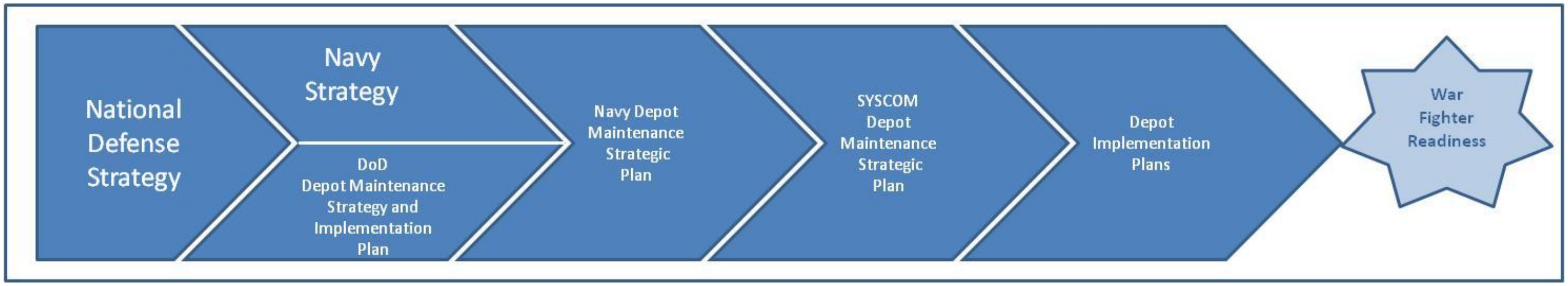
The CNO's maintenance policy for U.S. Navy ships defines intermediate-level maintenance to require technical capabilities, facilities, or capacities that fall between organizational-level and depot-level. Fleet Commanders assign the Fleet Maintenance Activity (FMA) or private shipyards to accomplish intermediate-level maintenance (Chief of Naval Operations 2010, 24). Blanchard and Fabrycky (2011, 78) describe typical intermediate-level maintenance actions to include detailed inspections and system checkout, major servicing, major equipment repair and modifications, complex adjustments, minor calibration, and overload from organizational-level maintenance.

c. Depot-Level Maintenance

Depot-level maintenance is the most complex of all the maintenance levels. Depot-level maintenance requires the technical expertise, larger more capable facilities, and increased capacities that accompany NSYs, private shipyards, OEMs, or NAVSEA designated overhaul points (DOPs) (Chief of Naval Operations 2010, 28). Typical depot-level maintenance actions include complex equipment repairs and modifications, equipment overhaul and rebuild, detailed calibration, and intermediate-level maintenance beyond FMA capacity (Blanchard and Fabrycky 2011, 78). Navy depot-level maintenance comprises a large portion of the critical maintenance and modernization required to sustain the fleet. Additionally, depot maintenance relies heavily on independent non-government entities.

According to Admirals Mathews, Whitney, and Sohl (2013), the Navy's Depot Maintenance Strategic Plan supports the National Defense Strategy, Navy Strategy and the DOD Depot Maintenance Strategy and Implementation Plan. Implementation strategies are developed within the framework and guidelines of the overall Navy Depot Maintenance Strategic Plan (see Figure 4) (7). Each system command incorporates this strategy into its own strategic documents and associated implementation guidance.

Figure 4. Strategic Plan Implementation



From Mathews, Tim, Mark Whitney, and Paul Sohl. 2013. *The United States Navy Depot Maintenance Strategic Plan.* Washington, DC.

2. Current and Future Readiness Balancing Act

In a budget and schedule constrained environment, the surface Navy must contend with striking the correct balance between current and future readiness. To satisfy current readiness expectations, a surface ship must be materially capable of meeting its designed mission requirements when operationally essential. A maintenance strategy with a bias towards a current readiness paradigm will focus on the material availability of critical systems and equipment needed for war fighting. A current readiness paradigm has the tendency to sacrifice the material readiness of slow-to-degrade systems in favor of current mission essential systems when cost and schedule are limited.

In contrast, future readiness centers on maintenance tasks necessary for achieving a ship's expected service live (ESL). The CNO says future readiness tasks aim to reduce out-year maintenance costs, minimize excessive and unplanned maintenance, and influence modernization and new construction budgets to correct maintenance shortfalls (Chief of Naval Operations 2013, 1). Future readiness tasks prevent slow-to-degrade systems such as ship structure from becoming an unmanageable current readiness problem. Neglect of essential future readiness efforts produces a bow wave of maintenance, increasing the total ownership cost (TOC) of a surface ship. Current readiness and future readiness are equally important to sustain a ship's operational capability throughout its ESL. Systems design requirements, redundancy, and degradation characteristics are key elements of determining whether the system aligns with current or future readiness. Corrective maintenance for the repair of a fire pump needed to meet minimum fire protection and dewatering capability is considered a current readiness item. Corrective maintenance for the repair of a minor structural defect in a tank or gas turbine exhaust collector is considered a future readiness item. A maintenance strategy must appropriately account for both current and future readiness aspects.

3. Class Maintenance Plan

The development of a system maintenance strategy must be incorporated into the Class Maintenance Plan (CMP) for the applicable ship class. The CMP identifies all maintenance tasks, with periodicities, for a given class. The JFMM describes the CMP as a database comprising organizational, intermediate and depot-level maintenance tasks. It identifies the specific nature of these tasks such as: "material condition assessment tasks (I-tasks), qualified repair and life renewal tasks (Q-tasks), availability routine tasks (R-tasks), and authorized fleet and program modernization tasks" (U.S. Fleet Forces Command 2013, II-II–1-1). CMP tasks can be scheduled or unscheduled. The JFMM states that scheduled tasks consist of intermediate and depot-level tasks the cognizant technical authority requires to be accomplished on a specific periodicity (U.S. Fleet Forces Command 2013, II-II–1-1). The CMP system automatically sends scheduled tasks to the maintenance team (MT) for action based on accomplishment history and task frequency requirements. A MT has the ability to request a scheduled task to be accomplished before it has been sent to the current ship maintenance plan (CSMP). According to the JFMM, the MT must request unscheduled tasks. The JFMM goes on to list unscheduled tasks to include unscheduled assessment tasks, qualified repair tasks, and modernization items with related support and service tasks (U.S. Fleet Forces Command 2013, II-II–1-1).

4. Surface Ship Engineered Operating Cycle Program

In May 2013, the CNO established the Surface Ship Engineered Operating Cycle (SSEOC) program. This program establishes the framework to identify, document, track, and execute maintenance tasks necessary for a ship to reach ESL (Chief of Naval Operations 2013, 1). SSEOC designated tasks consist of technically validated assessments and repairs considered critical to reducing unexpected corrective maintenance and future maintenance costs (Chief of Naval Operations 2013, 2). The SSEOC program includes the propulsion system under which main gas turbines reside.

5. Maintenance Figure of Merit 2.0

Surface Navy stakeholders committed significant resources to the development of a model capable of supporting a set of software applications called the Maintenance Figure of Merit (MFOM). According to the article, "Fleet-Oriented Maintenance Figure of Merit," authored by several key architects of the model, MFOM was envisioned to be an objective ship material readiness reporting system (Hirschman et al. 2009, 1). In an effort to develop the system, the Navy introduced the ship material condition metric model—Maintenance Figure of Merit (MFOM) 2.0. Schonberg (2013, 31) described MFOM as

> a computer-based tool built on a hierarchical structure that calculated material conditions against operational requirements. It was designed to consistently and objectively calculate a material readiness value for equipment, systems, tasks, and missions for the ship, providing the Navy maintenance community with a single authoritative, centrally managed application that contains the necessary to support readiness and maintenance reporting.

MFOM 2.0 was also going to link cost to the calculated ship's material readiness. Unfortunately, according to Schonberg (2013, 31), the MFOM development effort is reported to have failed due to rising costs, limited scope, disconnected maintenance processes, and data systems. MFOM 2.0 exists today in a limited capacity as "a web-based software tool that operates on unclassified and classified networks both ashore and afloat" (Hirschman et al. 2009, 1). The tool is limited to basic existing maintenance documentation and reporting.

C. MAINTENANCE TIMING AND SCHEDULE

1. Optimal Fleet Response Plan

The high operational tempo (OPTEMO) of Navy surface ships driven by Combatant Commander (CCDR) requests for global presence requires optimal scheduling. To maximize ship deployment and surge capability, the readiness generation process underpinning the fleet response plan (FRP) must be improved. Admirals Gortney and Harris (2014, 40) acknowledge negative trends in maintenance and modernization execution, training, deployment duration, and personnel turnover as unsustainable. The current FRP is characterized as lacking flexibility for changes in maintenance, training, and operational schedules and incapable of maximizing ship operational availability (40). This current FRP leads to the destabilization of maintenance schedules, shipyard loading, training, and Carrier Strike Group (CSG) composition. Furthermore, Admirals Gortney and Harris (2014) explain the lack of operational schedule predictability impacts sailors, their families, and the industrial base. Increased predictability, while enabling critical adaptability for policy makers, is an important aspect of the Optimal Fleet Response Plan (OFRP) (40).

Admiral Bill Gortney (2014, 6) presented the OFRP in January 2014 in which he described a fundamental guiding principle of the OFRP to be the alignment of cruiser and destroyer assignments to the CSGs to create a stable, predictable, and integrated maintenance and modernization schedule that helps both industry partners and sailors. Successful execution of OFRP demands strict adherence to a tightly controlled schedule. Maintenance availabilities forced to be extended due to growth and new work will result in failure of the OFRP model. For this reason, the maintenance community must focus on bringing increased predictability to ship maintenance to deliver the predictability envisioned via OFRP. The shift to OFRP with its success predicated on timely completion of maintenance availabilities raises the importance of schedule to a new level.

2. Types of Maintenance Availabilities

Development of a successful maintenance strategy goes beyond identifying the appropriate level of maintenance. The scope of maintenance coupled to a maintenance strategy requires the appropriate scheduled maintenance availability. The preponderance of surface ship maintenance is executed in scheduled CNO maintenance availabilities and continuous maintenance availabilities (CMAVs).

A variety of CNO availability types exist to accommodate different levels of required maintenance. CNO correspondence on the subject says the CG-47 ship class follows an engineered operating cycle (EOC) (Chief of Naval Operations 2014b, 32–33). The same document describes EOC as a maintenance philosophy designed to sustain or improve ship material readiness and operational availability. This philosophy focuses on minimizing unnecessary time spent in depot-level availabilities and a structured engineered approach to ship maintenance (32–33). The maintenance strategy includes the following elements.

- "Periodic inspection of selected systems and equipment to identify and document necessary repair requirements and material condition trends"
- "Periodic maintenance tasks to be accomplished at specified times during the ship's life cycle"
- "Scheduled intra-cycle depot level intermediate maintenance availabilities, Docking Selected Restricted Availabilities (DSRA), and Selected Restricted Availabilities (SRA) to accomplish the maintenance and modernization required to sustain or improve the material condition of the ships"
- "Extensive modernization to maintain and upgrade the ship class war fighting capability" (32–33)

The description of different Navy maintenance availability types is outlined in the CNO's report, *Representative Intervals, Durations and Repair Mandays for Depot Level Maintenance Availabilities of U.S. Navy Ships*. "Continuous maintenance (CM) includes limited scheduled depot-level maintenance conducted outside of CNO availabilities" (Chief of Naval Operations 2014b, 32). CM is typically scheduled for accomplishment in CMAVs with durations of approximately four weeks. Maintenance and modernization requiring an extensive industrial period are accomplished in SRAs. Extended SRAs (ESRAs) are scheduled to include maintenance and modernization that requires additional funding and schedule duration beyond a SRA. A SRA expanded to include maintenance and modernization that requires dry-docking is called a docking SRA (DSRA). Similar to an ESRA, extended DSRAs (EDSRAs) are scheduled to include maintenance and modernization that requires additional funding and schedule duration beyond a DSRA. Main gas turbine exhaust system repairs are generally scheduled for CNO availabilities unless emergent repairs are required.

3. Matching Scope and Schedule

Successful on-time completion of a maintenance availability schedule is highly dependent on correctly matching the scope of a maintenance package with the availability duration. This effort requires significant planning, attention to detail, and discipline to resist requirements creep. Nonetheless, a maintenance package inclusive of work items that require open and inspect tasks leaves the availability exposed to cost and schedule risk. An integrated master schedule (IMS) with a critical path at risk of being influenced by the results of open and inspect tasks is likely to be an ineffective schedule measure. A proactive schedule risk management plan (RMP) is limited in its ability to mitigate growth and new work for a large magnitude of potential critical path work. Definitive work specification predictability for potential critical path items is the best defense against cost and schedule risk. Consequently, maintenance strategies must be developed with the risk of potential growth and new work in mind.

D. THE RIGHT PRICE

The Navy maintenance community strives to balance cost with schedule and performance properly. Many factors that drive cost, such as competition and timely Congressional budget authorization, are beyond the influence of a system maintenance strategy and outside the scope of this thesis. However, executing maintenance at a fair and reasonable price is critical to ensuring sufficient resources are available to cover all planned and budgeted maintenance requirements. Inefficiently executed maintenance that yields growth and new work, puts maintenance requirements and the budget at risk. The maintenance strategy for a system directly influences the life cycle cost of that system. Furthermore, an engineered maintenance strategy that provides consistent, repeatable, and explicit directive specifications can be budgeted with a high degree of accuracy. A maintenance strategy of this nature can also be effectively planned and integrated, which in turn, drives down cost.

The business and process of ship repair are very complex. The fundamental requirements for ship repair share similarities to shipbuilding. Peters' article (2006, 15) on American shipbuilding states it is possible to extrapolate that successful ship repair is "simply bringing together the following elements in a coherent, planned way: a sound maintenance strategy (the product of engineering effort), necessary materials such as steel, pipe, and pumps (the product of a viable industrial base and second-tier suppliers), and a work force appropriately sized and with the right technical skills." All the elements needed for industry to provide sustained successful ship repair hinge on stability. Peters' (16) article emphasizes the ship repair industry requires workload stability to efficiently hire, train and retain a capable workforce, plan the use of facilities, and keep subcontractor and supplier bases employed.

The surface Navy is heavily dependent on the private industrial base for surface ship maintenance. Performance of the private ship repair industry directly influences the cost of ship maintenance. Positive ship repair industry performance requires effective planning, resource allocation, and project management. Establishing a stable predictable workload in a port improves industry workload forecasting capabilities and resource management. Logically, a system maintenance strategy that produces predictable and reliable maintenance requirements is a key ingredient to enabling the planning of labor, material, and facilities management. The collection of similar system maintenance strategies, planned and executed as a work package in ship maintenance availabilities, is a principal factor to generating industrial base stability and price efficiencies.

THIS PAGE INTENTIONALLY LEFT BLANK

III. RELIABILITY-CENTERED MAINTENANCE

All mechanical systems have components prone to material degradation resulting from wear, corrosion, or fatigue. Material degradation eventually leads to nonconformance from the original design specification. Unless acted upon, a nonconformance will progress until the system, or a related component, fails to meet the designed performance requirements. To disrupt the failure process of a system or part, scheduled maintenance is required. RCM is the technical methodology for the development of scheduled maintenance programs. Nowlan and Heap, considered the founders of the RCM concept, claim maintenance is accomplished based on three general hypotheses:

- Hardware degrades with age
- There is something that can be done to restore or maintain reliability
- Efforts to restore or maintain reliability are cost effective (Commander, Naval Sea Systems Command 2007, 43)

In more precise terms, Blanchard and Fabrycky (2011, 439) define RCM as a "systematic approach to developing a focused, effective, and cost-efficient preventative maintenance program and control plan for a system or product." Blanchard and Fabrycky (439–440) proclaim the RCM technique as beneficial for developing new preventative maintenance programs during initial design and for evaluating existing preventative maintenance programs for improvement. Development of a preventative maintenance process during system design is referred to as the classic RCM process. The evaluation of preventative maintenance programs for existing systems is denoted as the backfit RCM process. The NAVSEA RCM handbook describes the backfit RCM process to include validation of existing maintenance tasks by using operations and maintenance data to correct task intervals and task content where appropriate (Commander, Naval Sea Systems Command 2007, 15). This thesis evaluates aspects of the backfit RCM process to improve the maintenance strategy of the CG-47 class main gas turbine exhaust system.

A. HISTORY OF RELIABILITY-CENTERED MAINTENANCE

RCM has its roots in the airline industry. According to the NAVSEA handbook on RCM, “in 1967, the airline industry’s Maintenance Steering Group (MSG) first applied decision tree logic—a series of questions that lead to a supportable maintenance task decision—to the problem of identifying required preventive maintenance tasks” (Commander, Naval Sea Systems Command 2007, 13). In the early 1970s, the airline industry’s work interested the Office of the Secretary of Defense, the Naval Air Systems Command, the Air Force, and the Army. The RCM handbook claims Naval Air Systems Command as the first organization to apply the airline’s new philosophy. The handbook also attributes the same organization to be the initial architects for an improved methodology called RCM, which they applied to both new design and in-service aircraft (14). In 1978, the RCM methodology was outlined in a book published by United Airlines and sponsored by the Office of Assistant Secretary of Defense (Manpower, Reserve Affairs and Logistics). The application of RCM to ship maintenance is derived from the book, *Reliability-Centered Maintenance* by Stanley Nowlan and Howard Heap (14).

B. FUNDAMENTALS OF MAINTENANCE ENGINEERING AND RELIABILITY-CENTERED MAINTENANCE

NAVSEA defines maintenance as the “set of actions taken to ensure that systems, equipment, and components provide their intended functions when required” (Commander, Naval Sea Systems Command 2007, 33). The NAVSEA handbook states nine core principles of RCM govern the development, implementation, execution, and continuous improvement of ship maintenance programs. These nine basic principles are the following.

- Failures happen
- Failures can have different probabilities of occurrence
- Failures can have different consequences
- Simple components degrade, complex systems fail

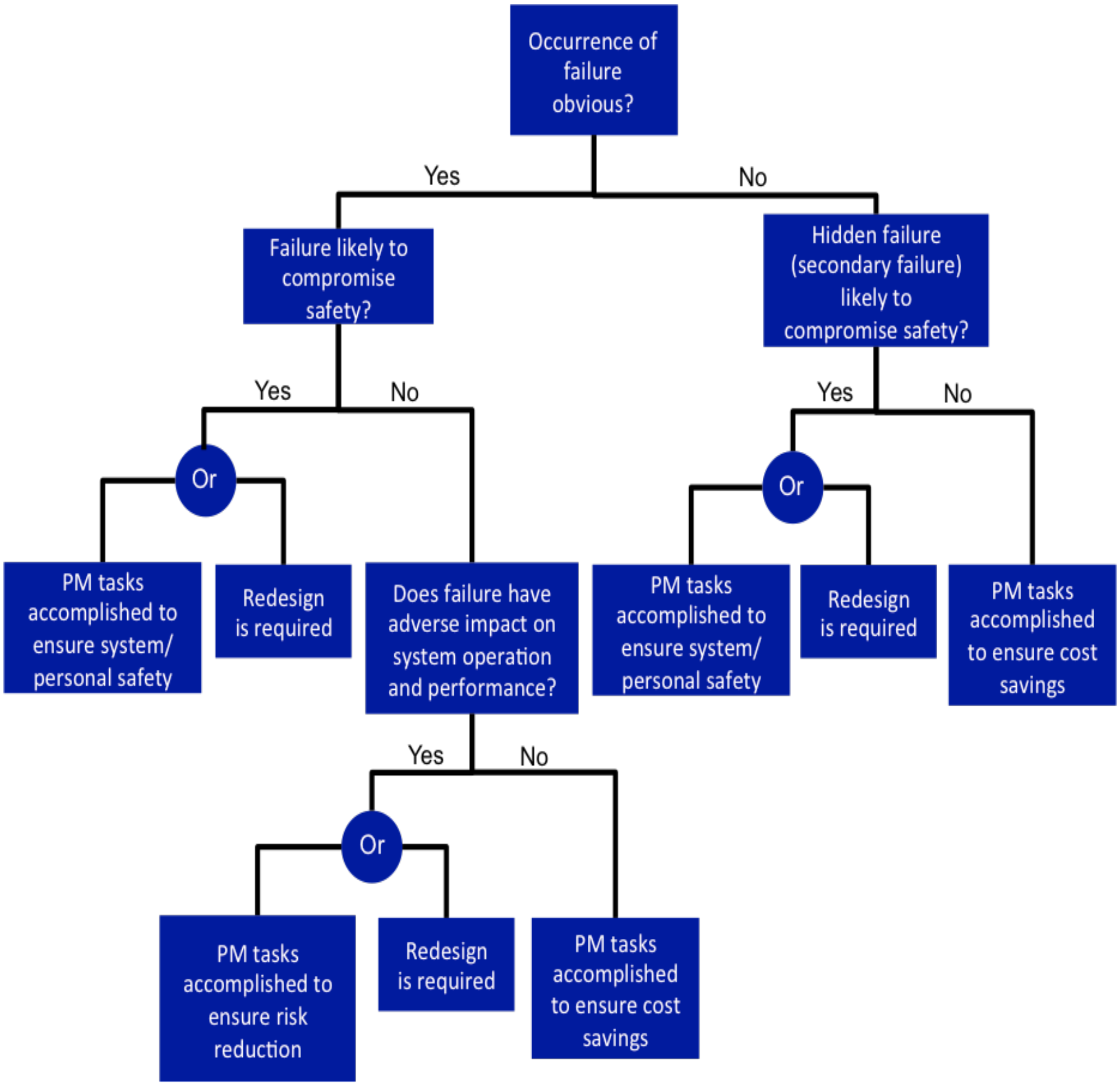
- Required functionality can be achieved at the lowest practical cost with the appropriate maintenance
- Maintenance cannot increase original design reliability
- Hidden functions necessitate special treatment
- Unnecessary maintenance wastes resources
- Continuous improvement is the hallmark of good maintenance programs (Commander, Naval Sea Systems Command 2007, 19).

The fundamental goals of RCM are to develop maintenance tasks that best maintain system functionality at an affordable cost. To accomplish this functionality, the NAVSEA RCM handbook says maintenance requirements should be evaluated via a series of questions, such as the following.

- What functions does the system perform?
- What functional failures might occur?
- Which functional failures are most likely to occur?
- Are the functional failures obvious to the operator?
- Do safety, mission, and cost consequences of failure exist and what are they?
- What is the relative risk of failure?
- Can anything be done to prevent likely failures?
- What is the cost of failure mitigation? (Commander, Naval Sea Systems Command 2007, 15)

Blanchard and Fabrycky (2011, 440) explain RCM results in the most effective preventative maintenance tasks through the use of a “tailored” logic approach and decision tree methodology. Figure 5 depicts a simplified RCM decision logic. The objective of a system maintenance strategy is to align a preventative maintenance program with cost, schedule, performance, contract, logistic, and maintenance policy constraints.

Figure 5. Simplified RCM Decision Logic



After Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. Upper Saddle River, NJ: Prentice Hall.

C. MAINTENANCE POLICY FOR U.S. NAVY SHIPS

Navy ship maintenance policies and actions are steeped in RCM. RCM is at the core of Navy surface ship maintenance and provides the technical and programmatic rigor for selecting the appropriate type of maintenance. In accordance with the RCM handbook, maintenance is comprised of three categories: corrective, preventative, and alterative. Corrective maintenance restores failed functions by accomplishing repair or replacement. Preventative maintenance minimizes the opportunity for functions to fail through the use of tests, inspections, adjustments, replacements, and routine actions, such as lubrication. Alterative maintenance (also known as modernization) eliminates unsatisfactory conditions by removing the cause of failed functions through redesign (Commander, Naval Sea Systems Command 2007, 35). Table 1 summarizes the primary characteristics of these basic categories of maintenance.

Table 1. Three Types of Maintenance

Category	**Corrective**	**Preventive**	**Alterative**
Objective	Correct Unsatisfactory Conditions	Minimize Unsatisfactory Conditions	Eliminate Unsatisfactory Conditions or Allow for Preventive Maintenance
Characteristic Actions	Adjust or Align, Calibrate, Troubleshoot, Replace	Test or Inspect, Restore or Replace or Top Off Consumables, Grease, Lubricate	Modify (Evolutionary Change) or Upgrade (Revolutionary Change)
Scheduling	Planned or Unplanned	Planned (Recurring)	Planned (One Time)
Sample Tasks or Activities	Adjust, Align, Replace Components	Vibration Analysis, IR Imaging, Oil Analysis, etc.	Redesign Components, Equipment or Systems

From Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command.

D. CONDITION-BASED MAINTENANCE

Maintenance and operational readiness are inextricably linked. Likewise, ship maintenance programs strongly influence the total operating cost of a ship. The 2009 NAVSEA instruction on RCM and CBM says "maintenance programs must balance safe material condition, readiness, environmental compliance, and cost throughout the ship's life cycle" (Commander, Naval Sea Systems Command 2009, 2). CBM compliments RCM as the CNO's maintenance plan for ship, aircraft, and infrastructure. The CBM strategy applies throughout a system's life cycle and provides guidance for optimizing maintenance program costs. The NAVSEA RCM and CBM instruction says, "CBM is maintenance performed on objective evidence of need provided by RCM analysis and associated enabling processes and technology" (2–3).

The CNO's CBM policy outlines the use of inspection, embedded sensors, and other equipment monitoring devices to derive objective evidence for maintenance (Chief of Naval Operations 2007, 8).

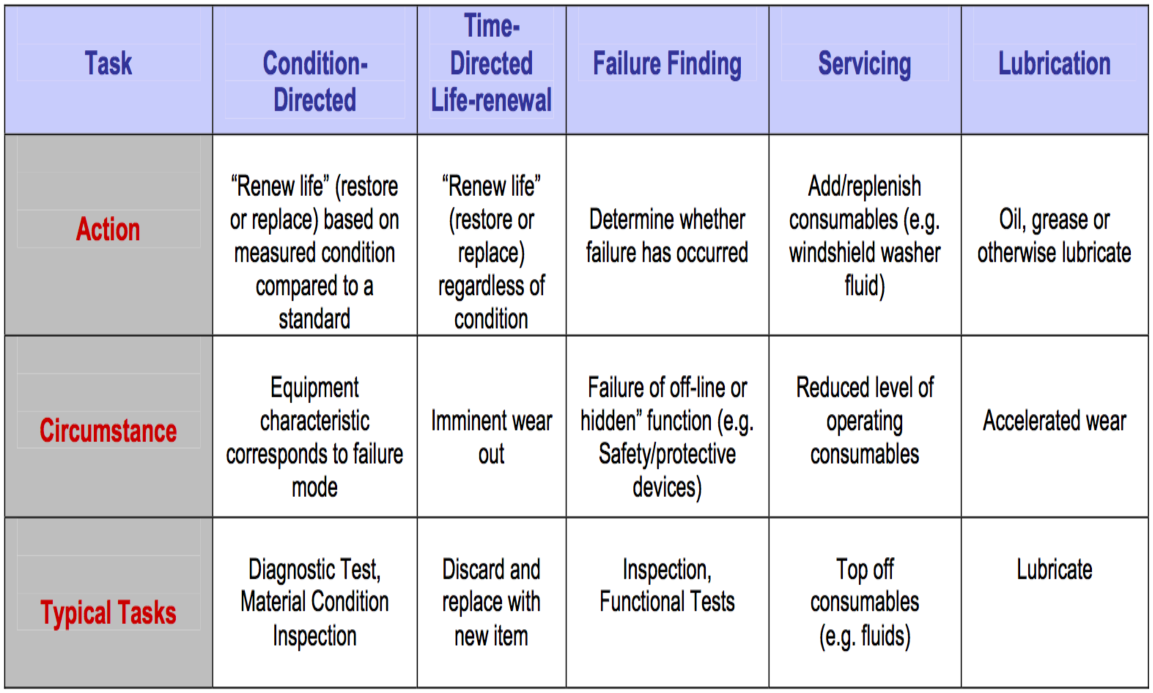
An effective system maintenance strategy must analyze the cost and practicality of method for determining the material condition of a system required for the appropriate selection of CBM. Wiring a system or equipment with sensor capabilities to monitor and forecast material condition may not be cost effective, sufficiently accurate, or comprehensive. Similarly, accomplishment of system inspection comes with its own challenges. A prerequisite for system inspection is the development of inspection procedures and specifications. Inspectors must be trained and qualified. Additionally, inspection may require an operating system to be taken offline and isolated for the safety of the inspector. These are just a sample of considerations for selecting the appropriate CBM approach.

The CBM approach determines whether reactive or proactive maintenance will be performed. Reactive maintenance is performed for items designated fix-when-fail or those items that have unpredictable failure characteristics. The CNO's CBM philosophy says a run-to-failure planned maintenance strategy is effective for items that have little readiness or safety impact (Chief of Naval Operations 2007, 8). The same policy says "proactive maintenance can be considered either preventative or predictive in nature and the maintenance performed can range from an inspection, test, or servicing to an overhaul or complete replacement" (8). Preventative maintenance is also referred to as scheduled maintenance. Scheduled maintenance can be time-based (calendar) or cycle-based (number or equipment starts/stops). In the event of premature failure, an item with an established schedule for planned maintenance can require reactive maintenance to repair. The CBM policy also describes the two subsets of predictive maintenance that fall under proactive maintenance. The two subsets are diagnostic or prognostic. Diagnostic is limited to identifying forthcoming functional failures while prognostics go a step further to enable forecasting of a system or equipment's remaining service life (8–9). Proactive maintenance, and more specifically, preventative maintenance, are most closely related to the focus of this thesis.

E. FIVE TYPES OF PREVENTATIVE MAINTENANCE TASKS

PM tasks are comprised of five different types: condition-directed, time-directed, failure finding, servicing, and lubrication. Table 2 provides a summary of these preventative maintenance tasks.

Table 2. Preventative Maintenance Tasks



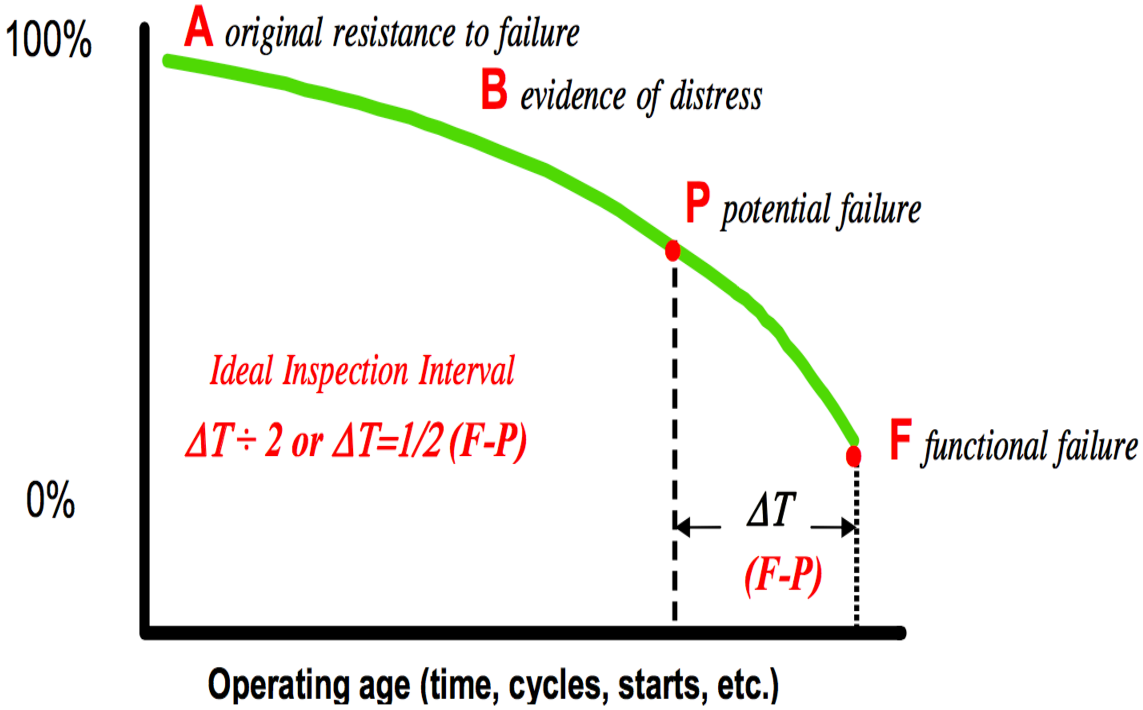
Task	Condition-Directed	Time-Directed Life-renewal	Failure Finding	Servicing	Lubrication
Action	"Renew life" (restore or replace) based on measured condition compared to a standard	"Renew life" (restore or replace) regardless of condition	Determine whether failure has occurred	Add/replenish consumables (e.g. windshield washer fluid)	Oil, grease or otherwise lubricate
Circumstance	Equipment characteristic corresponds to failure mode	Imminent wear out	Failure of off-line or hidden" function (e.g. Safety/protective devices)	Reduced level of operating consumables	Accelerated wear
Typical Tasks	Diagnostic Test, Material Condition Inspection	Discard and replace with new item	Inspection, Functional Tests	Top off consumables (e.g. fluids)	Lubricate

From Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command, 36.

1. Condition-Directed

As defined by the RCM handbook, "a Condition-Directed (CD) task is a periodic diagnostic test or inspection that compares the existing material condition or performance of an item with established standards and directs further action accordingly" (Commander, Naval Sea Systems Command 2007, 37). The purpose of CD tasks is to prevent a functional failure from occurring by means of identifying and mitigating the potential failure. The logic behind this task type is illustrated in the hypothetical P-F (or potential failure—functional failure) curve from the RCM handbook and shown in Figure 6. Figure 6 “depicts the relationship between resistance to failure and operating age for an item. Resistance to failure is measured from the point of initial introduction into service to the point of actual failure” (37). The CD inspection interval (ΔT) is established to provide ample opportunity to detect functional failure before a functional failure can occur.

Figure 6. P-F Curve

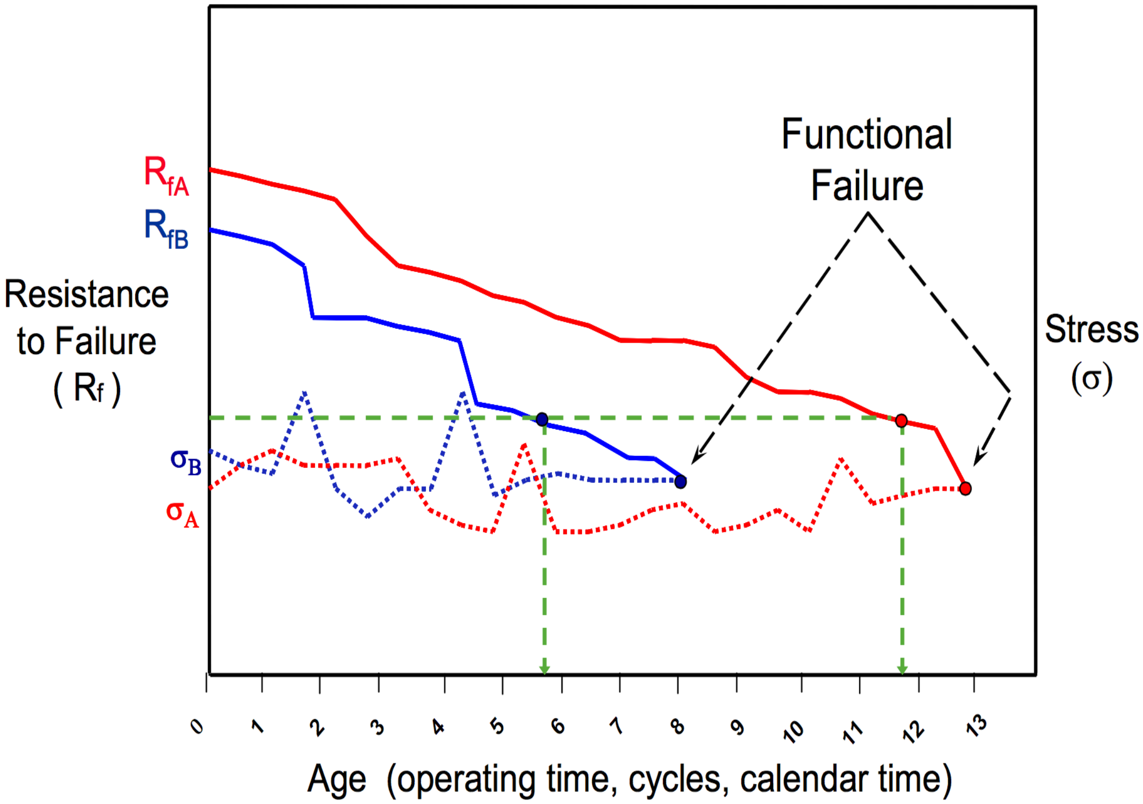


From Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command, 37.

Determining an identifiable physical condition, or potential failure that indicates a functional failure is imminent, can be difficult. CD tasks are not possible without the necessary conditions to provide an alert to failure. Complicating matters further, identical items can fail at different ages in service, as shown by Figure 7. According to the RCM handbook, this variation in failures happens for several reasons, such as the following.

- Manufacturing tolerances
- Different lots or vendors
- Different operating profiles and stresses (Commander, Naval Sea Systems Command 2007, 38).

Figure 7. Like Items Fail at Different Ages



From Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command, 38.

2. Time-Directed Life-Renewal

The RCM handbook explains "time-directed (TD) life-renewal tasks restore or replace an item regardless of its actual material condition before the item reaches an age at which the probability of failure becomes unacceptable" (Commander, Naval Sea Systems Command 2007, 39). The term wear out is used to describe an increase in the probability of failure. The same handbook says Navy maintenance policy deems TD tasks appropriate when evidence is available that most units of the population will end their service life at a specific age and no measureable condition exists to predict failure. An explicit description of what qualifies as evidence of population quantity required to be considered a majority is ambiguous. In any case, the handbook states that when an item reaches this point, two typical actions can be taken to renew useful life of the item.

- Restoration (also known as overhaul or rebuild)
- Replacement (Commander, Naval Sea Systems Command 2007, 39)

Applying a TD task type without sufficient objective evidence of need can lead to excessive maintenance and adversely impact the TOC of the system. This thesis posits a holistic review of a system maintenance strategy that leverages systems engineering methodology, will provide persuasive indications in favor of applying a TD task approach. A maintenance strategy review of this nature goes beyond evidence of population failure data. The need to meet OFRP schedule requirements, avoid long lead time material (LLTM) challenges, decrease maintenance planning and integration risk, and reduce contract change requests are examples of additional items to consider.

3. Failure-Finding

In accordance with the RCM handbook, failure-finding (FF) tasks are an important set of tasks "used to evaluate the condition of off-line or intermittent-use functions whose failures are typically hidden from the operating crew" (Commander, Naval Sea Systems Command 2007, 40). This task type is appropriate when no CD or TD task can be devised to prevent failure. FF tasks discover hidden failures that have already occurred. The handbook recommends periodic inspection for functional failures of both off-line and intermittent-use items to ensure they will operate when needed (40).

4. Servicing

The RCM handbook states servicing (S) tasks replenish operating consumables, such as lubricating oil sumps required for normal operations (Commander, Naval Sea Systems Command 2007, 41). Servicing tasks can be either CD or TD.

5. Lubrication

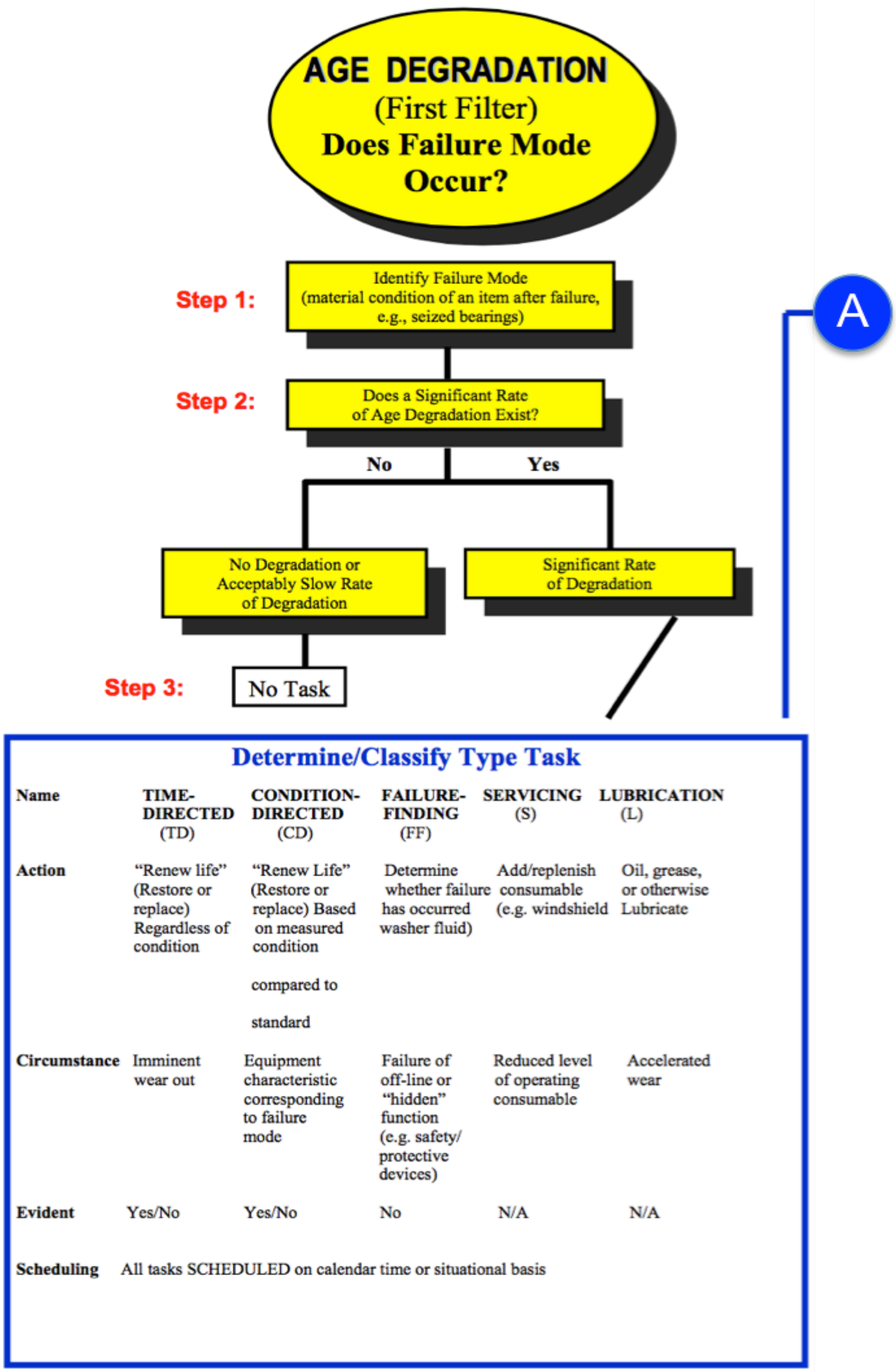
NAVSEA says lubrication (L) tasks direct routine greasing and lubricating of mechanical friction surfaces. This task also includes the application of a grease or lubricant to stationary surfaces to provide protection from the environment (Commander, Naval Sea Systems Command 2007, 41). Lubrication tasks can be either CD or TD.

F. BACKFIT RCM PROCESS

A static maintenance program is not optimal. The classic RCM process is used to develop the right maintenance tasks for new systems, subsystems, and equipment during ship acquisition. This initial task development is based on very limited to no operational data. Consequently, the RCM process should not remain static and necessitates continuous improvement. The backfit RMC process is designed for maintenance program improvement. The RCM handbook explains the process technically reviews the current maintenance tasks for a system using historical operational data (Commander, Naval Sea Systems Command 2007, 74). Information collection is a critical aspect required to support backfit RCM. For this reason, it is imperative that a maintenance program adequately account for all historical maintenance records applicable to a system. The absence of operational maintenance data precludes the necessary objective evidence required to validate technically or improve a maintenance task.

The backfit RCM methodology employs a decision tree with a series of evaluation steps for the topics of reliability degradation, task applicability, task effectiveness, and recommending change. Figures 8 through 10 are a three-part figure that outlines the six steps of the backfit RCM process.

Figure 8. Backfit RCM Roadmap Part A

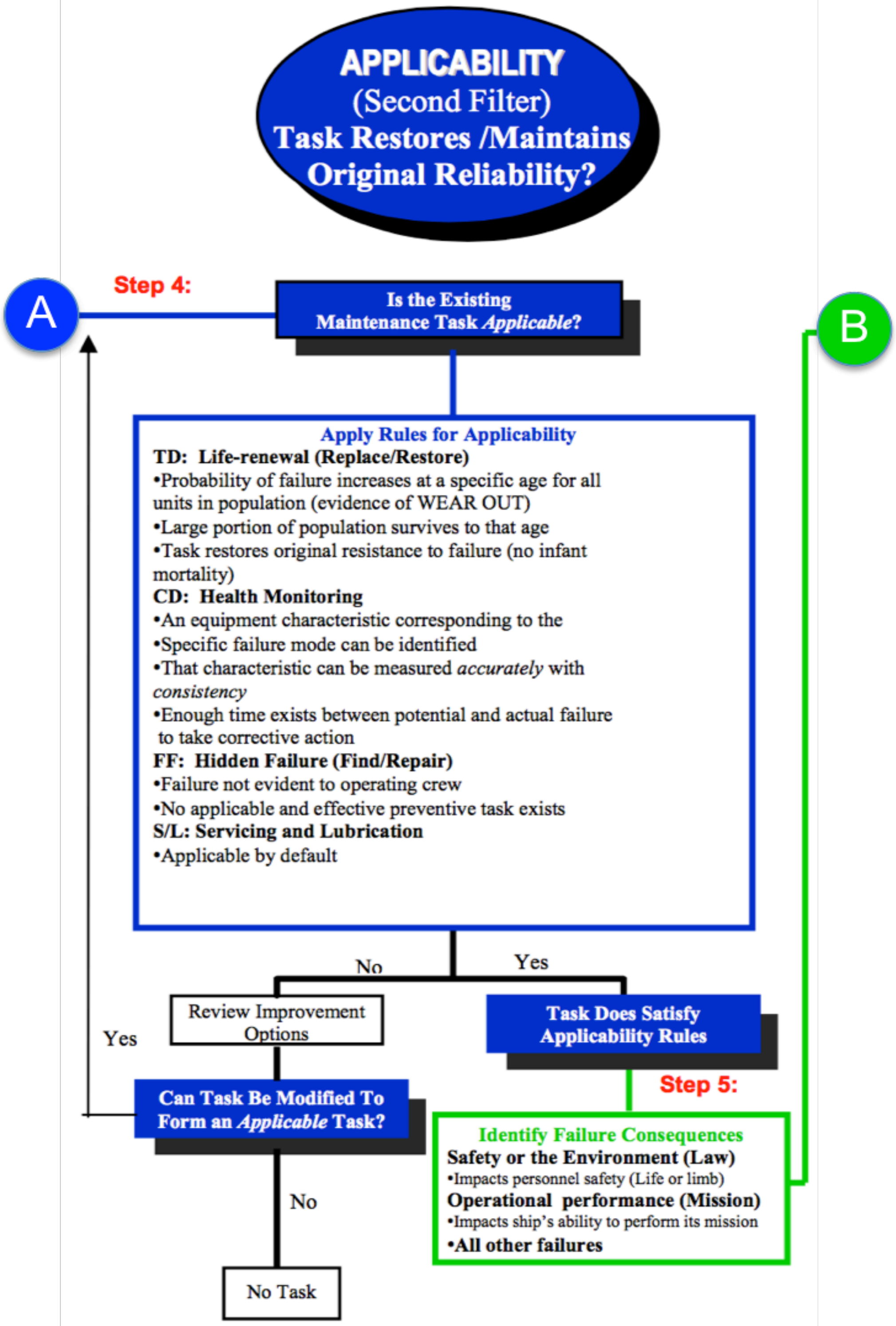


Determine/Classify Type Task

Name	**TIME-DIRECTED** (TD)	**CONDITION-DIRECTED** (CD)	**FAILURE-FINDING** (FF)	**SERVICING** (S)	**LUBRICATION** (L)
Action	"Renew life" (Restore or replace) Regardless of condition	"Renew Life" (Restore or replace) Based on measured condition compared to standard	Determine whether failure has occurred	Add/replenish consumable (e.g. windshield washer fluid)	Oil, grease, or otherwise Lubricate
Circumstance	Imminent wear out	Equipment characteristic corresponding to failure mode	Failure of off-line or "hidden" function (e.g. safety/ protective devices)	Reduced level of operating consumable	Accelerated wear
Evident	Yes/No	Yes/No	No	N/A	N/A
Scheduling	All tasks SCHEDULED on calendar time or situational basis				

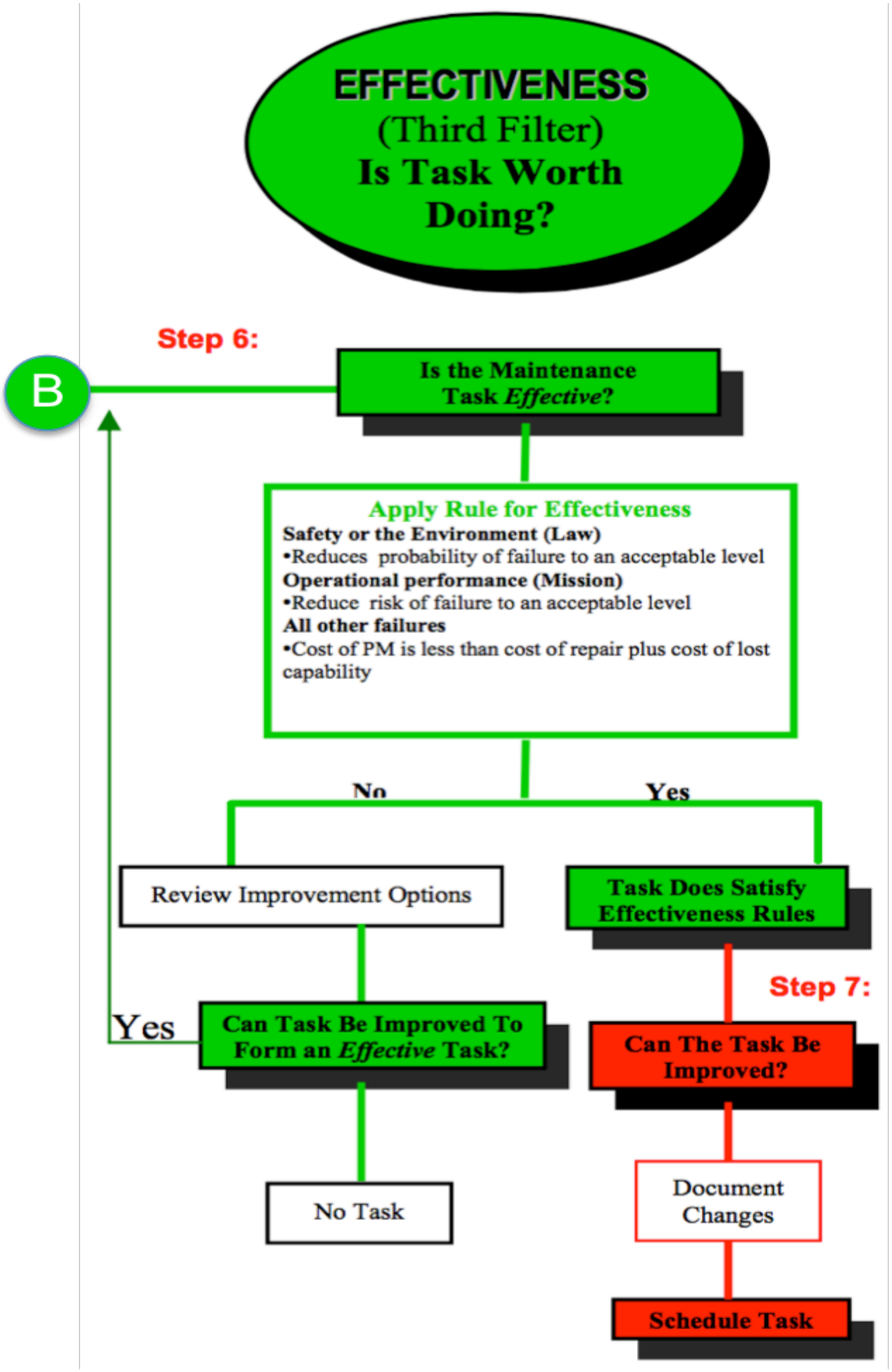
After Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command, 75.

Figure 9. Backfit RCM Roadmap Part B



After Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook*. 1. Washington, DC: Commander, Naval Sea Systems Command, 75.

Figure 10. Backfit RCM Roadmap Part C



After Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command., 75.

IV. CONCEPTS TO IMPROVE SURFACE SHIP MAINTENANCE

A. MANAGING RISK IN A FIRM FIXED PRICE ENVIRONMENT

A concerted effort to cultivate maximum maintenance efficiencies is necessary to achieve ship service life in an increasingly austere funding environment. Maintenance inefficiencies cannot be absorbed or disregarded. To this end, senior surface ship maintenance leaders are aggressively pursuing several maintenance paradigm shifts. An example of one of these paradigm shifts is the surface maintenance community's transference from the MSMO cost-plus-award-fee (CPAF) contracting strategy to a single-award (SA) indefinite-delivery-indefinite-quantity (IDIQ) firm-fixed-price (FFP) environment. According to the Federal Acquisition Regulation (FAR):

> a FFP contract provides for a price that is not subject to any adjustment on the basis of the contractor's cost experience in performing the contract. This contract type places upon the contractor maximum risk and full responsibility for all costs and resulting profit or loss. A fixed price contract strategy provides maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden upon the contracting parties. (General Services Administration, DOD, NASA 2005, 16.2–1)

Simply put, a contractor is paid a fixed price to do a specific job described in the contract. In most cases, a FFP contract strategy is the preferred contract when the work or task is well defined.

The government is subject to cost and schedule overruns in the event work is not well defined, or even worse, required and not defined at all. Poorly defined work specifications have a tendency to yield growth-work. All work after contract definitization is considered new or growth-work in accordance with the Joint Fleet Maintenance Manual (U.S. Fleet Forces Command 2013, II–II–2D–12). A consequence of required growth-work includes contract modifications necessary to re-scope the work package and ensure it properly reflects the maintenance requirement. To minimize schedule impacts of growth-work, the government may have the option to fund additional labor at a premium cost. A benefit of the SA IDIQ FFP contract strategy is the pre-negotiated labor rate for growth-work. Nonetheless, excessive growth-work puts schedule at risk. Eliminating growth-work is the only sure way to avoid the associated uncertainty and risk.

To best mitigate the uncertainty and risk of growth-work and capitalize on the pre-negotiated pricing of work, a directed maintenance strategy should be evaluated. The concern with applying a directed maintenance strategy centers on executing excessive or unnecessary repairs. Conversely, underestimating the scope of work is a concern that ultimately could result in growth-work. However, according to Jonathan Mun (2010, 46) on the subject of modeling risk, risk can be captured quantitatively through step-by-step applications of Monte Carlo simulation. Furthermore, maintenance risk can be quantified and evaluated via equipment RBDs and FTA. RBD and FTA are classic reliability analysis tools that can provide incredible insight into equipment and system risk.

B. PITFALLS OF OPEN AND INSPECT

To minimize growth-work, the scope of work must be accurately defined in the repair work specification. It should also be noted that properly documented references and technically qualified repair procedures are important. Nonetheless, to reduce uncertainty and define a repair requirement in compliance with CBM policy, the typical maintenance strategy calls to open and inspect (O/I) the machinery, which is a PM approach that employs CD tasks type for inspection. The inspection results document the failed component(s) for repair. An open, inspect, and repair approach to ship maintenance raises several concerns. First, labor is the most expensive portion of virtually all ship maintenance. The man-hours spent on inspection do not directly translate to improved readiness. However, with an open and inspect methodology, the inspection man-hours are a necessary step in the repair process. Second, an inspection is highly dependent on the capability and capacity of the inspecting work force. Concerning the former, capability translates to quality of inspection. If an assessor fails to identify the component failure properly or understand the failure mode and mechanism, the repair recommendation will not be accurate. This scenario results in planning for the wrong scope of work and culminates in growth-work. Third, identifying and repairing or replacing the failed component does not mean the material condition or expected service life of the system or equipment has been reset or rebaselined. Rather, depending on the component reliability of the system, the life-limiting component has merely shifted. In other words, the replacement of parts found out of tolerance following an I/O ignores the fact that other components still within tolerance have a finite service life and may now become the life-limiting item. Fourth, an I/O or CD methodology does not allow for sufficient long lead-time repair parts management or parts availability in the event immediate repairs are required. Finally, during availability execution, growth-work as a result of open and inspect requires the contract be modified before the repair can be executed. The combination of long lead-time parts, new schedule integration efforts, and request for contract change (RCC) cycle time can drive noncritical path work onto the critical path. Ultimately, if eliminating growth-work in totality is not possible, understanding the uncertainty and risk of surface ship maintenance is crucial. Traditional RCM analysis does not sufficiently account for all aspects of CD inspection task execution in a maintenance environment governed by specific processes and schedule constraints. Systems engineering applies a more holistic approach to help avoid the pitfalls of open and inspect methods in practice today.

C. APPLYING SYSTEMS ENGINEERING APPLICATIONS TO SYSTEM MAINTENANCE STRATEGY DEVELOPMENT

This thesis introduces and demonstrates the application of systems engineering tools and concepts beneficial to system maintenance strategy development. Reference to the NSTCP is used to aid in familiarizing the reader with the systems engineering applications described in this chapter.

1. Understanding Risk and Uncertainty

Cost, schedule, and performance risks are important concepts to consider when developing a system maintenance strategy. The Risk Management Guide for DOD Acquisition defines risk as a “measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints” (Department of Defense 2006, 1). This guide goes on to list three components of risk.

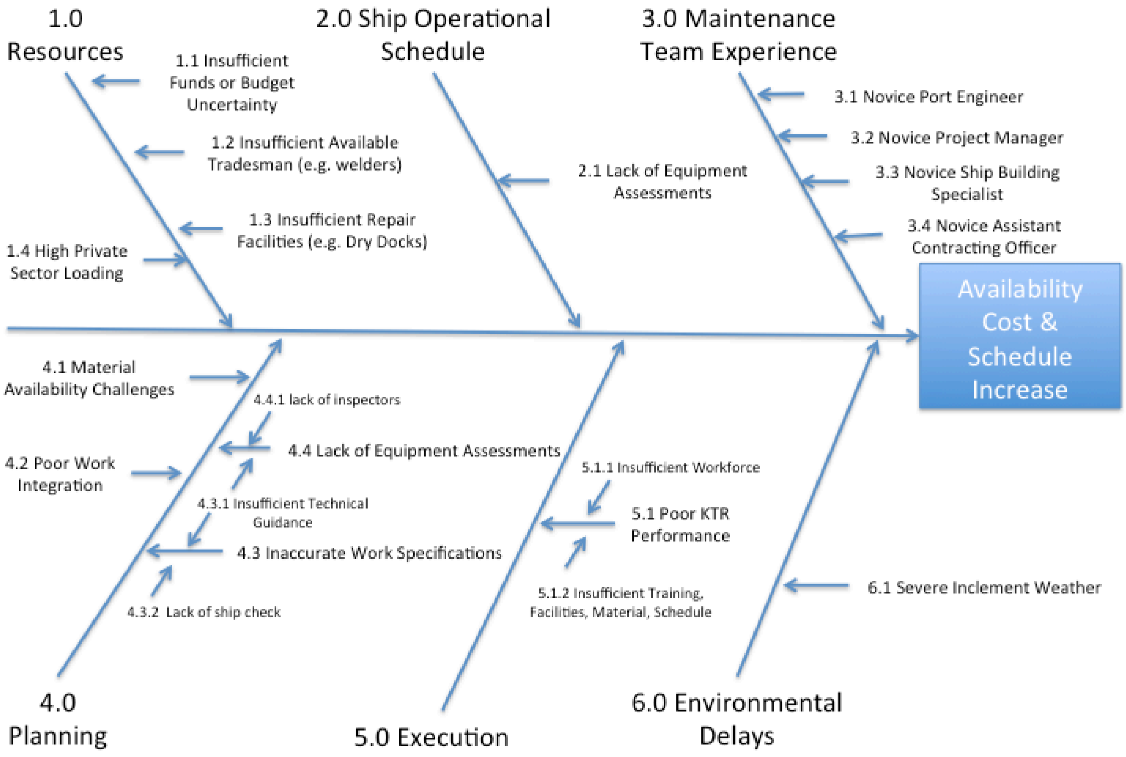
- “A future root cause (yet to happen), which, if eliminated or corrected, would prevent a potential consequence from occurring”
- “A probability (or likelihood) assessed at the present time of that future root cause occurring”
- “The consequence (or effect) of that future occurrence” (1).

To manage, risk five fundamental questions must be understood;

- What can go wrong?
- What is the probability (likelihood) the event will happen?
- What are the consequences?
- What can be done to prevent or mitigate the event within the schedule?
- Can we afford it?

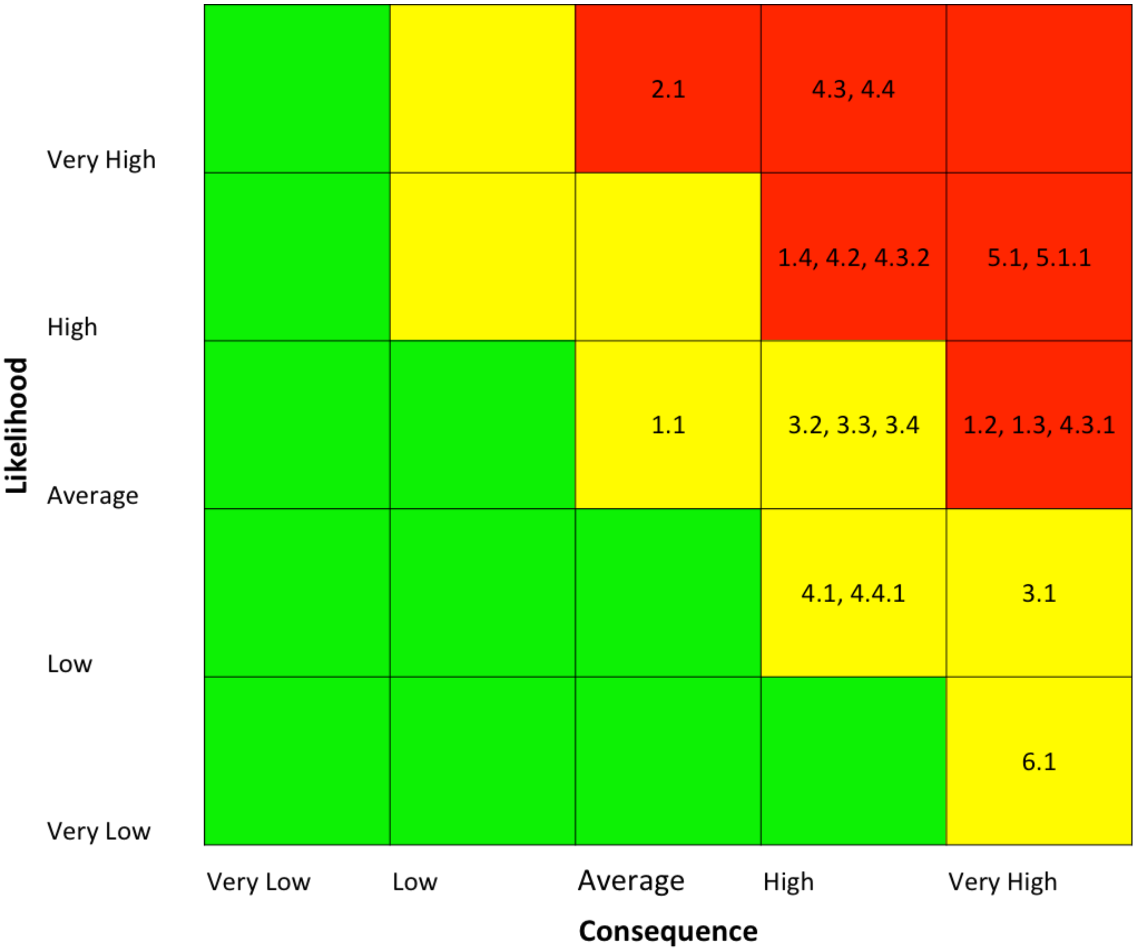
Maintaining warships ready for tasking to support operational schedule requirements depends heavily on ship maintenance availabilities meeting cost, technical, and schedule timeline requisites. Surface ship maintenance is an incredibly complex business. Numerous causes and effects, some of which are interrelated, drive surface ship maintenance availability budget and schedule risk. Brassard and Ritter (1994, 23) describe “a Fishbone diagram is a useful tool to identify, explore, and graphically display, in increasing detail, all of the likely causes related to a problem or condition to discover its root cause(s).” A Fishbone diagram illustrating the causes and effects for surface ship maintenance availabilities not finishing on budget and schedule (see Figure 11) also indicates areas of uncertainty that warrant further evaluation. The fishbone diagram in Figure 11 is a dispersion analysis type. This type of fishbone diagram is constructed by placing individual causes within each “major” cause category to explain the effect in question. Individual causes point to the “major” cause category arrow. For example, a major cause for the effect “availability cost and schedule increase” is “planning,” numerically designated 4.0. “Inaccurate work specifications” numerically designated 4.3 is an individual cause under the major cause category “planning.” Vertical arrows pointing to individual causes are in themselves identified causes for the individual cause. For example, “insufficient workforce” numerically designated 5.1.1 is a cause for “poor contractor performance” labeled 5.1.

Figure 11. Surface Ship Maintenance Availability Fishbone Diagram



Risk for each of the areas identified in the fishbone diagram can be subjectively reported using a risk matrix (see Figure 12). The level of likelihood of each cause is established utilizing specified criteria (see Table 3). “For example, if the cause has an estimated 50 percent probability of occurring, the corresponding likelihood is average” (Department of Defense 2006, 12). For the fishbone diagram in Figure 11, cause 1.1, “insufficient funds and budget uncertainty” is estimated to occur approximately 50 percent of the time. “The level and types of consequences of each risk are established utilizing criteria, such as those described in Table 4” (Department of Defense 2006, 12). A single consequence scale is not appropriate for all programs. For this reason, the user can tailor the levels and types of consequences in Table 4 to suit a specific project or availability. Continuing with the example insufficient funds and budget uncertainty, “this same cause has no impact on performance or cost, but may result in a minor schedule slip that will not impact a key milestone. The corresponding consequence is average for this risk” (Department of Defense 2006, 12). Analyzing risk of an existing maintenance strategy is a necessary first step towards improving the strategy.

Figure 12. Surface Ship Maintenance Availability Risk Matrix



Likelihood \ Consequence	Very Low	Low	Average	High	Very High
Very High	🟩	🟨	🟥 2.1	🟥 4.3, 4.4	🟥
High	🟩	🟨	🟨	🟥 1.4, 4.2, 4.3.2	🟥 5.1, 5.1.1
Average	🟩	🟩	🟨 1.1	🟨 3.2, 3.3, 3.4	🟥 1.2, 1.3, 4.3.1
Low	🟩	🟩	🟩	🟨 4.1, 4.4.1	🟨 3.1
Very Low	🟩	🟩	🟩	🟩	🟨 6.1

Table 3. Levels of Likelihood Criteria

	Level	Likelihood	Probability of Occurrence
Likelihood	Very High	Near Certainty	~90%
	High	Highly Likely	~70%
	Average	Likely	~50%
	Low	Low Likelihood	~30%
	Very Low	Not Likely	~10%

After Department of Defense. 2006. *Risk Management Guide for DoD Acquisition.* Washington, DC: Department of Defense.

Table 4. Levels and Types of Consequences Criteria

Consequence

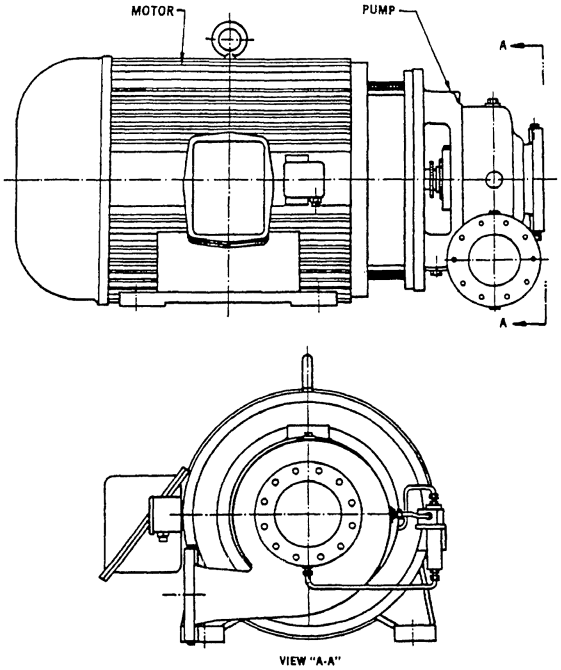
Level	Technical Performance	Schedule	Cost
Very Low	Minimal or no consequence to technical performance	Minimal or no impact	Minimal or no impact
Low	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program	Able to meet key dates. **Slip < _*_ month(s)**	Budget increase or unit production cost increases. **< _**_ (1% of Budget)**
Average	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float. **Slip < _*_ month(s)** **Sub-system slip > _*_ month(s) plus available float.**	Budget increase or unit production cost increase **< _**_ (5% of Budget)**
High	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected. **Slip < _*_ months**	Budget increase or unit production cost increase **< _**_ (10% of Budget)**
Very High	Severe degradation in technical performance; Cannot meet KPP or key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones. **Slip > _*_ months**	Exceeds APB threshold **> _**_ (10% of Budget)**

After Department of Defense. 2006. *Risk Management Guide for DoD Acquisition.* Washington, DC: Department of Defense.

2. Navy Standard Titanium Centrifugal Pump Description

The NSTCP is a critical piece of equipment in the firemain system. The NSTCP is used to develop the required seawater pressure for the ship's firefighting system (see Figures 13 and 14). The website for Navy maritime damage control information sharing states the "shipboard firemain system consists of fire pumps, piping consisting of vertical pump risers, longitudinal service mains, cross-connects, service risers, branch lines, and valves through which seawater is pumped to fire hose stations, aqueous film forming foam (AFFF) stations and sprinkler systems" (Maritime DC & PPE Information Center 2015). This same website explains the NSTCP also "supplies water to flushing, emergency drainage, backup seawater service, machinery and electronic cooling systems. The Countermeasure Wash down System (CMWD), magazine sprinkler, weapons elevators, missile water deluge system, trash burner, flight deck weapons staging area and compartment sprinkling systems are also supplied by the firemain" (Maritime DC & PPE Information Center 2015). The fire pump is a common piece of equipment across all ships classes in the Navy. For this reason, the fire pump is considered an appropriate item to assist with demonstrating various system engineering tools and concepts.

Figure 13. Navy Standard Titanium Centrifugal Pump 1000 GPM



From Naval Sea Systems Command. 2012. *Navy Standard Titanium Centrifugal Pump 1000 GPM.* Technical Manual. Port Hueneme, CA: NAVSURFWARCENDIV NSDSA, 30.

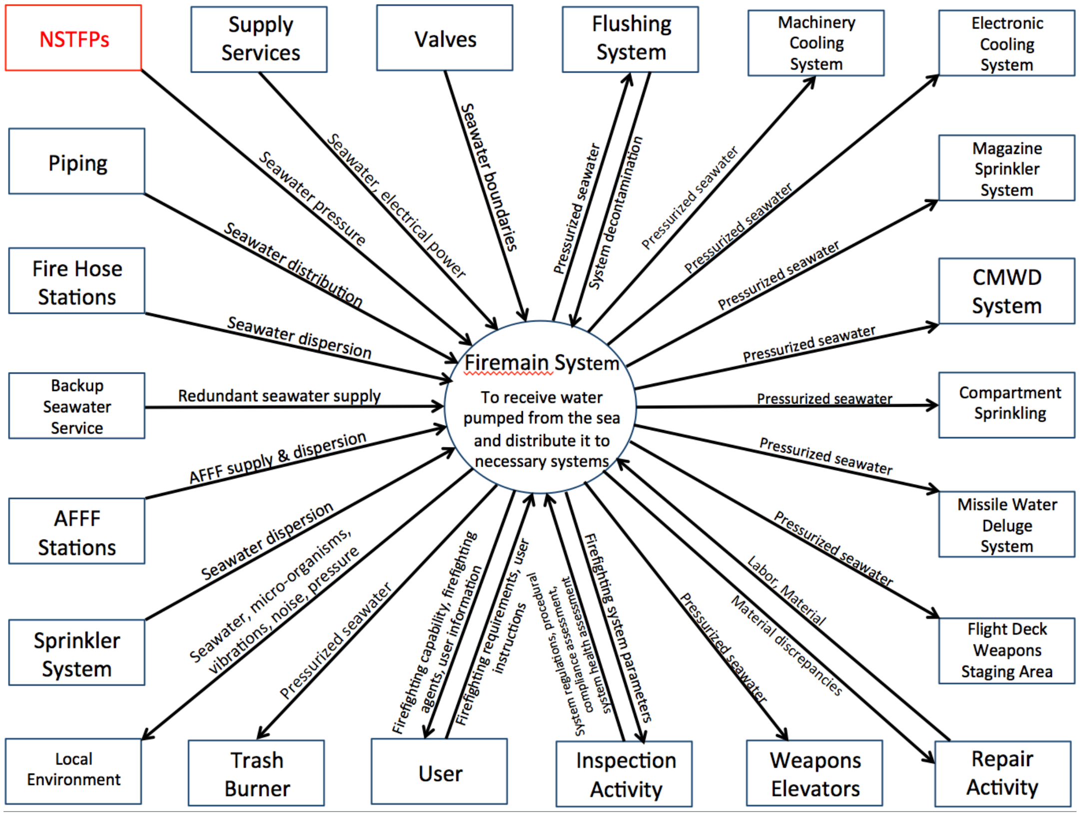
Figure 14. Navy Standard Titanium Fire Pump

From Buffalo Pumps. "Navy/Marine." 2015. http://www.buffalopumps.com/markets-applications/navy-marine/.

3. Context Diagrams

The NSTFP is a system within the firemain system. The firemain system comprises various dispersed, independent systems that interact together to form a complex and integrated aggregate. A context diagram is a useful tool for illustrating system boundaries and is an element of functional modeling. Dr. Stuart Burge (2011, 1) explains that context diagrams provide a basic model depicting system boundaries and its interactions with its environment. He summarizes "a context diagram is a single picture that has the system of interest at the center, with no details of its interior structure or function, surrounded by those elements in its environment with which it interacts" (1). For the purposes of this thesis, a context diagram of the firemain system helps emphasize the system of systems construct and the interactions of the NSTCP within the system (see Figure 15). Understanding system boundaries and its interactions with critical elements in its environment are important to developing the maintenance strategy for a system. Ignoring system boundaries or environmental interactions may result in insufficient or incorrect maintenance and waste resources. Understanding a system's boundaries and interactions is part of recognizing how the system operates.

Figure 15. Firemain System Context Diagram



4. Flow Diagrams and Functional Decomposition

A flow diagram is commonly used to provide a graphical representation that shows the “flow” of data or information exchange through a system. For the purposes of this thesis, a diagrammatic system flow of seawater through the firemain system further illustrates the functions of the NSTCP. The system flow diagram depicts the upstream and downstream interactions with seawater experienced by the various components and systems, including the NSTCP (see Figure 16). To understand objects and their interactions as they relate to integration more deeply, a functional model the NSTCP can be created with the objective of recognizing the natural relations between function and objects. The functional model originates from decomposing the concept of a function from the highest level, for example, to “provide firemain pressure.” The functional decomposition of the NSTCP helps illustrate the basic reasoning for the pump, move seawater (see Figure 17). System flow diagrams and functional decomposition provide important context necessary to understand how a system works. This information is beneficial for maintenance strategy analysis.

Figure 16. Firemain System Flow Diagram

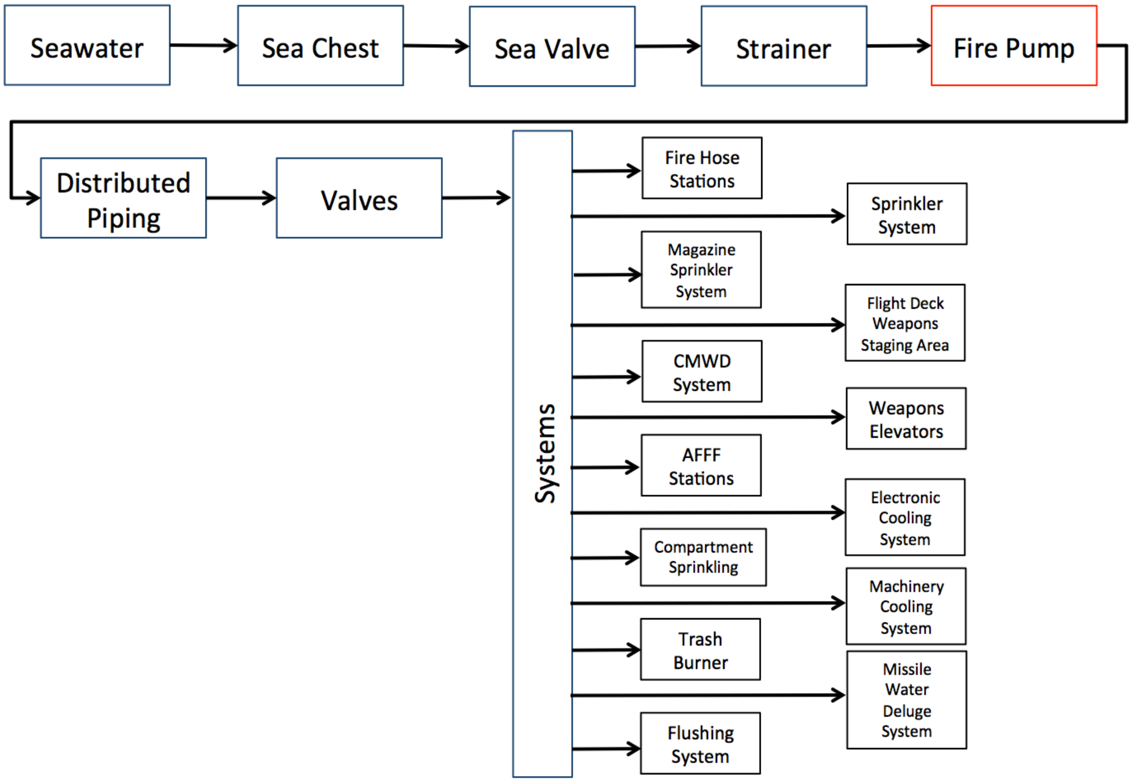
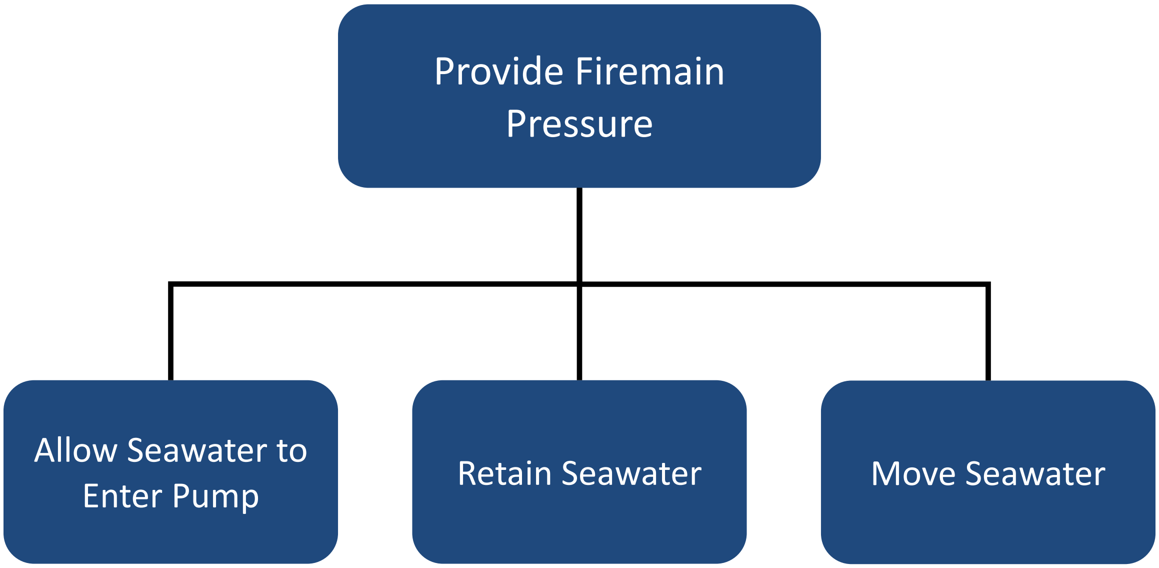


Figure 17. NSTCP Functional Decomposition



5. Reliability Block Diagram

A RBD is a graphical approach for illustrating how component reliability influences the success or failure of a system. Blanchard and Fabrycky (2011, 377) add RBDs to provide a basis of information necessary for the accomplishment of reliability prediction, maintenance, and other reliability analysis tools, such as failure mode effect criticality analysis (FMECA), and FTA. FMECA and FTA are described later in this chapter. RBDs depict system configuration and account for redundancy and single points of failures. RBDs help enable the documentation and analysis of common cause failures indicating vulnerable system components. This information is instrumental in developing a system maintenance strategy or designing improvements to a system.

Redundancy-single point failure relationships are an important aspect of RBDs. Redundancy is diagrammed as components in parallel where all must fail for the system to fail. Reliability of a parallel system is calculated as follows where R is the reliability of a system, i is a component, n is the number of components, and R_i is the reliability of component i:

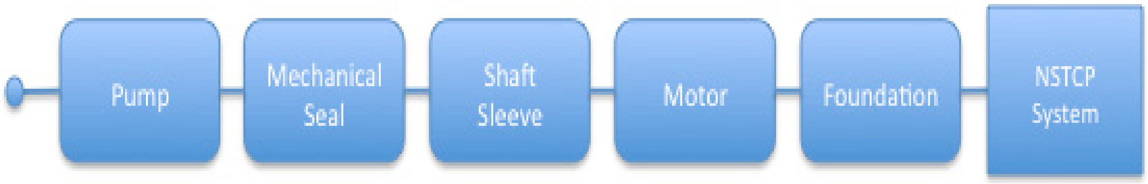
$$R = 1 - \prod_{i=1}^{n} \left(1 - R_i\right).$$

Single point failures are diagrammed as components in series where any failure will cause the system to fail. Reliability of a series system is calculated as follows where R is the reliability of a system, i is a component, n is the number of components, and R_i is the reliability of component i:

$$R = R_1 \dots R_n = \prod_{i=1}^{n} R_i \ .$$

The NSTCP is a system of physical components entirely designed in series (see Figure 18). For this reason, the firemain system is designed with multiple NSTCPs to increase system reliability. In the absence of component reliability data provided with the original equipment provisioning technical documentation (PTD), component failure data analysis over time can be used to calculate component and system reliability. The approach of collecting data over time provides the ability to determine probability of failure occurrence. To help with determining probability of occurrence, simulations can be run. For example, according to Jonathan Mun (2010, 45), Monte Carlo is a simulation that "can be run on a model with multiple interacting input assumptions and the output of interest can be captured as a simulation forecast and the relevant probabilities can be obtained, such as the probability of failure." This type of probability data can be considered the first step in narrowing the repair scope for a piece of equipment. Regarding the NSTCP as an example, if the foundation has a reliability of 0.99 while the mechanical seal has a reliability of 0.80, the logical conclusion is to focus on the mechanical seal. This probability data is also useful in developing standard assessment procedures, as well as possible modernization considerations. The importance of data cannot be overemphasized. Without sufficient data, a determination of proper repair scope via RCM analysis is not possible. A lack of reliability data drives a need for CD inspection tasks to determine repair scope in compliance with Navy CBM policy. Concerning NSTCP, a CD approach of this nature fails to capitalize on years of operational data. The maintenance community must recognize the value of collecting RCM data to analyze actively in support of continuous maintenance strategy improvement.

Figure 18. Navy Standard Titanium Centrifugal Pump (NSTCP) Reliability Block Diagram (RBD)



A reliability block diagram of physical components alone is not sufficient enough data to hedge the risk of growth-work and shift to a directive maintenance strategy. The probability that fixing the most unreliable component of a system each time the system fails does not account for a series of other variables that must be considered. To understand further details of how a system fails, FMECA and system FTA are reviewed.

6. Failure Mode, Effects, and Criticality Analysis

The FMECA is a structured methodology for uncovering and analyzing latent system deficiencies. From Blanchard and Fabrycky (2011, 385), FMECA includes a step-by-step analysis of potential causes for system failure. The analysis focuses on determining the magnitude of a failure on system performance and safety. Blanchard and Fabrycky (2011) go on to explain FMECA is a 12-step process (see Figure 19) that begins with defining system requirements. System requirements are generally known for in-service systems, such as the NSTCP. The second step is to define the system in functional terms. The third step is a top-down breakout of the system-level requirement referred to as requirements allocation. The fourth step is to identify failure modes. A "failure mode" is the way in which a component is prevented from accomplishing its function (Blanchard and Fabrycky 2011, 388). The failure mode is closely related to the failure mechanism. The terminology used to describe a failure mode is important to understanding the failure mechanism. According to Daly (2013, 6), a failure mechanism is the means by which a failure mode develops. Daly (17) summarizes systems with mechanical components, such as the NSTCP, as having four generic categories of failure mechanisms.

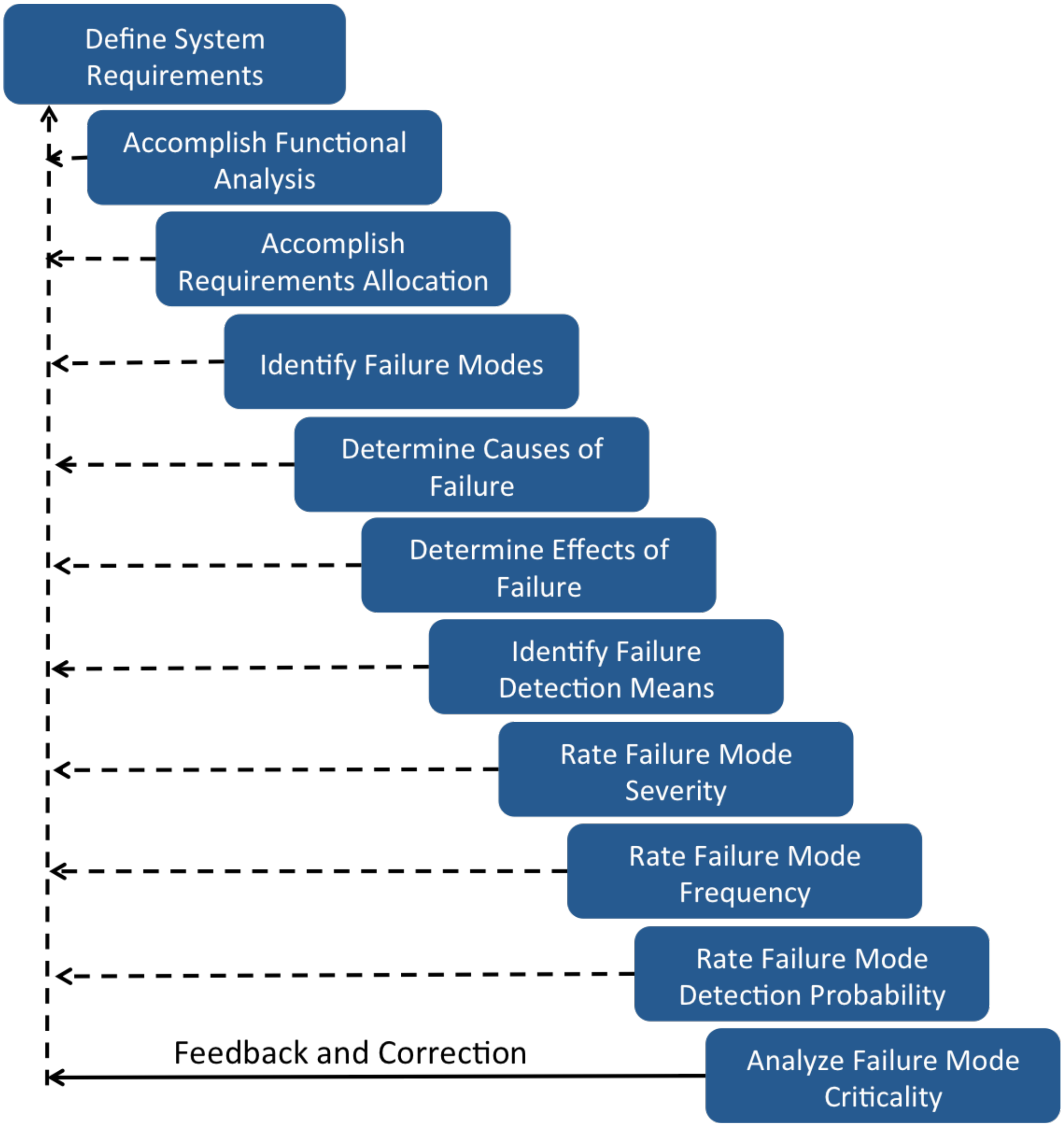
- Corrosion
- Erosion
- Fatigue
- Overload

Recognition of the failure mode and failure mechanism is relevant in the development of a preventative maintenance strategy. A FTA is an effective approach to identify failure modes. The fifth and sixth steps of a FMECA include determining the failure mechanisms or causes of failure and the effects. Step seven is the identification of failure detection means. Step eight is the rating of failure mode severity, which is analogous to levels and types of consequences from Table 4. Similarly, step nine is the rating of failure mode frequency and is similar to the levels of likelihood criteria from Table 3. The tenth step calls to rate the failure mode detection probability identified in step seven. For purposes of quantification, a scale similar to that for steps eight and nine can be used. Step eleven is the analysis of failure mode criticality. According to Blanchard and Fabrycky (2011, 390), generating a risk priority number (RPN) is a valuable way to measure severity, frequency, and probability of detection objectively as a single value. The RPN reflects failure mode criticality and is calculated with the following equation:

RPN = (severity rating) (frequency rating) (probability of detection rating).

Assigning numerical values to severity (consequence), frequency (likelihood), and probability of detection are necessary to calculate a RPN. The probability of detection value is inverse to the actual probability of detection. Specifically, a high probability of detection will have a low numerical value when used to calculate the associated RPN. The final FMECA step is to initiate recommendations for improvement (Blanchard and Fabrycky 2011, 390).

Figure 19. Failure Mode, Effects, and Criticality Analysis (FMECA) Process

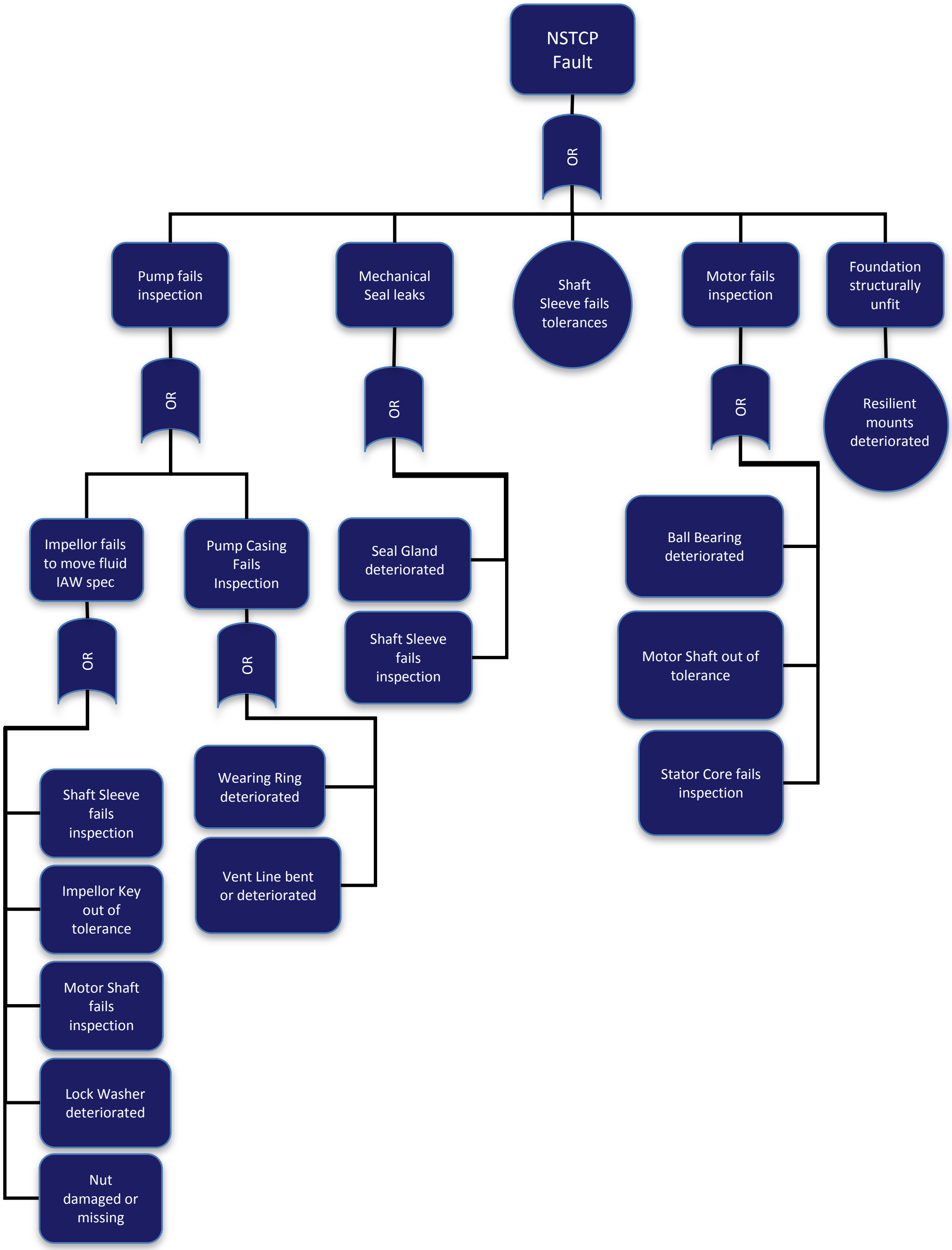


After Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis.* Upper Saddle River, NJ: Prentice Hall, 387.

7. Fault Tree Analysis Benefits to Maintenance Strategy Development

System FTA can positively influence a maintenance strategy. FTA is described as “a systematic, top down, deductive approach involving the graphical enumeration and analysis of different ways in which a particular failure can occur and the probability of its occurrence” (Blanchard and Fabrycky 2011, 390). FTA uses Boolean logic to combine a series of lower-level failure events. The exercise of developing a FTA is an insightful method for recognizing potential failure modes. A FTA enables a technician to understand the interrelationship of components and more accurately plan a repair. A basic example FTA for the NSTCP (see Figure 20) illustrates the underlying failure modes of a mechanical seal. Specifically, after opening and inspecting a failed NSTCP, suppose a technician identifies the mechanical seal as the failed component. The technician will logically repair the mechanical seal accordingly. However, if the mechanical seal failed because of excessive axial movement or imbalance in the total indicated run-out (TIR) of the shaft sleeve, the mechanical seal will repetitively fail prematurely until the root cause is addressed. For this reason, fault trees are an effective tool for recognizing potential underlying failure modes. As a tool to improve the way ship maintenance is planned, in combination with reliability data, a FTA can emphasize where to focus inspection efforts and help avoid overlooking underlying root causes.

Figure 20. Navy Standard Titanium Centrifugal Pump Fault Tree Analysis



8. Level of Repair Analysis Considerations

Level of repair analysis (LORA) is the process of determining whether the components of a system should be designated for replacement or repair. In the case of repair, the process includes determining the appropriate maintenance level. Basten, Schuttne, and Van Der Heijden (2009, 120) state determination to repair a system or subsystem at a specific maintenance level begins with identifying both variable and fixed costs. The article describes variable costs to include labor hours, spare parts usage, and transportation costs. The same article lists fixed costs as costs for warehousing of spare parts and costs for test equipment. It is important to point out that LORA does not consider how long a repair will take and associated impacts on maintenance schedule. Additionally, part criticality is not reflected. According to the Basten, Schutten, and Van Der Heijden article and other works on LORA, "the objective of LORA is to minimize the total (variable and fixed) costs" (121).

LORA for Navy supply parts is documented on the system's allowance parts list (APL) under the source maintenance and recoverability (SM&R) code. An APL is an allowance document produced for installed equipment. More specifically, an APL is a list of all maintenance significant parts, special tools, and consumables necessary to maintain the applicable item in operating condition. The SM&R code reflects the LORA and provides the maintainer guidance as to the appropriate maintenance level (organic, intermediate, supplier/depot) for repair items. The SM&R code for the centrifugal pump indicates it can be removed and replaced by ship's force but must be sent to the depot for complete repair.

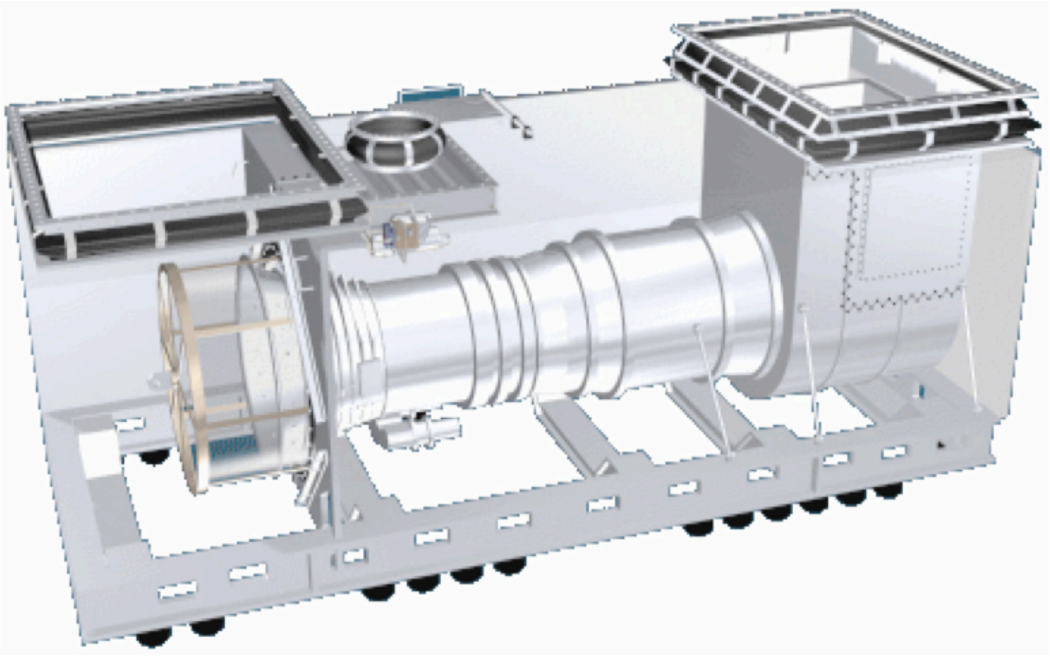
The SM&R code does not take part criticality into account, only cost and quality. Quality is accounted for by way of ensuring the lowest level maintenance organization identified is technically capable of repairing the item. Corrective maintenance cycle time is not a factor of LORA. Consequently, the lack of focus on the schedule parameter of ship maintenance creates risk to the availability and OFRP. Material cannibalization is the fleet's only recourse in the event a spare part needed for repair is not available when required. Material cannibalization carries with it its own risk and can create a ripple effect of material readiness challenges in the fleet if not closely monitored. A system maintenance strategy must account for schedule where reliability analysis techniques and LORA do not. The cost to readiness must be considered when evaluating systems that present schedule risk due to unacceptable maintenance downtime (MDT).

D. MAIN GAS TURBINE EXHAUST SYSTEM DESCRIPTION AND MAINTENANCE STRATEGY

1. Main Gas Turbine Exhaust System Description

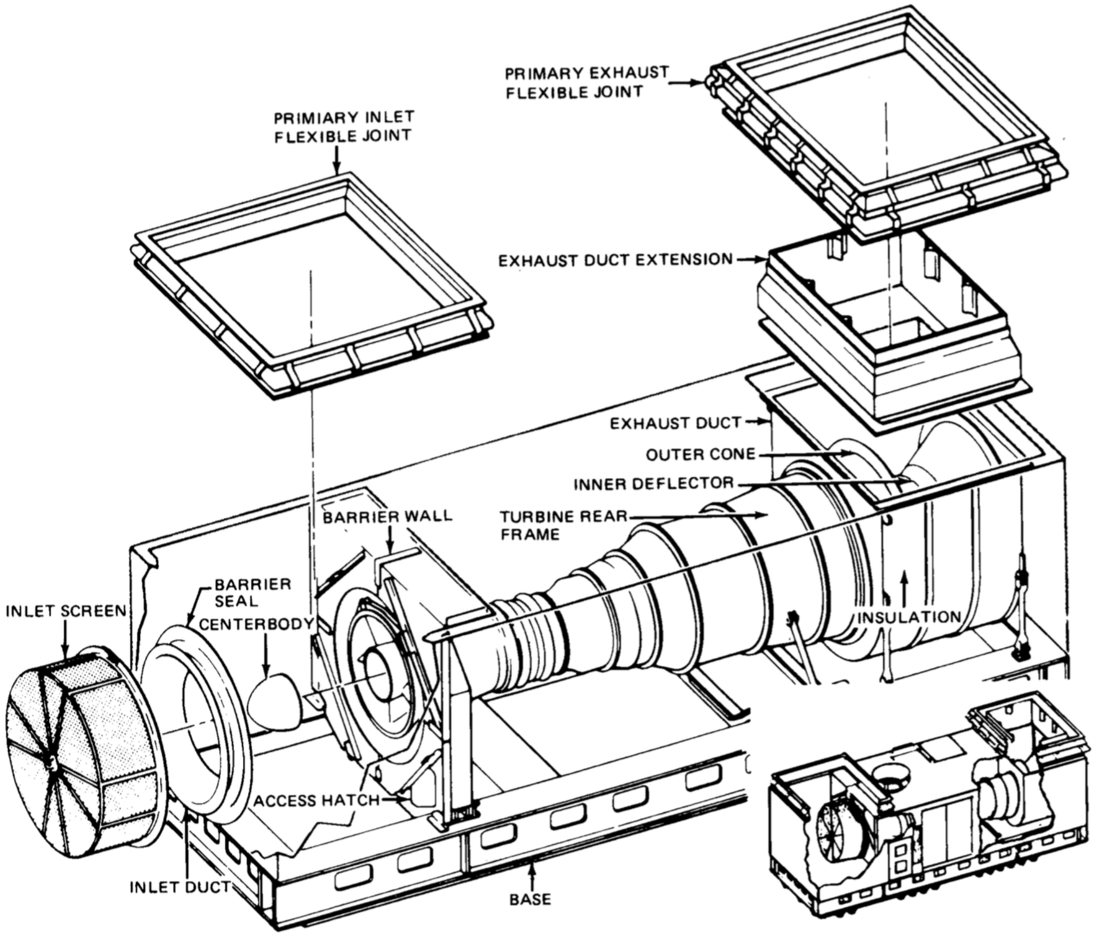
The Navy maintenance community refers to the Ticonderoga Cruiser propulsion system as a complex system of systems designed to provide high performance mobility through the water. While a system of systems is comprised of independent systems that can function completely on their own (U.S. Navy System of Systems Engineering Guide, 2006), this thesis reflects the maintenance community verbiage. The main gas turbine exhaust system is a critical piece of the overall propulsion system. The propulsion system includes four marine type gas turbine engines (GTE) to deliver shaft horsepower to each of the port and starboard shafts. Each gas turbine engine is enclosed inside a gas turbine module (GTM). According to the cruiser propulsion plant manual (PPM), "the module enclosures serve to provide an engine-mounting platform, thermal and acoustical insulation, inlet and exhaust ducting, fire extinguishing capability, and a controlled environment for the gas turbine" (See Figure 21) (Naval Sea Systems Command 2002, 49). The same PPM says an interface is created between the module enclosure and uptake duct provided by the flexible couplings (104). The ship information book (SIB) for CG-52 states, "flexible joints act as airflow path connections between cooling ducts and cooling fans and between the gas turbine exhaust duct anchor supports. In addition, the flexible joints absorb thermal growth (created by operation of the gas turbine engines), shock excursions, pressure forces, and deflection caused by ship motion. Lastly, the flexible joints attenuate transmission of vibration from the GTM enclosure to the ducts and ship" (see Figure 22) (Naval Sea Systems Command 2009, 261). The SIB also outlines "additional major parts of the propulsion and auxiliary systems include the main reduction gears, shafting and bearings, fuel oil service, intake air, lube oil service, reverse osmosis (RO) desalination system, high pressure air, seawater, AEGIS seawater pumps, freshwater, low pressure air, combat dry air, and bleed air" (39).

Figure 21. Marine Gas Turbine Module



From Surface Warfare Officer School. 2000. *LM2500 Material Readiness.* PowerPoint. Newport, RI: Surface Warfare Officer School, 49.

Figure 22. Enclosure Inlet and Exhaust Components



From Surface Warfare Officer School. 2000. *LM2500 Material Readiness.* PowerPoint. Newport, RI: Surface Warfare Officer School, 200.

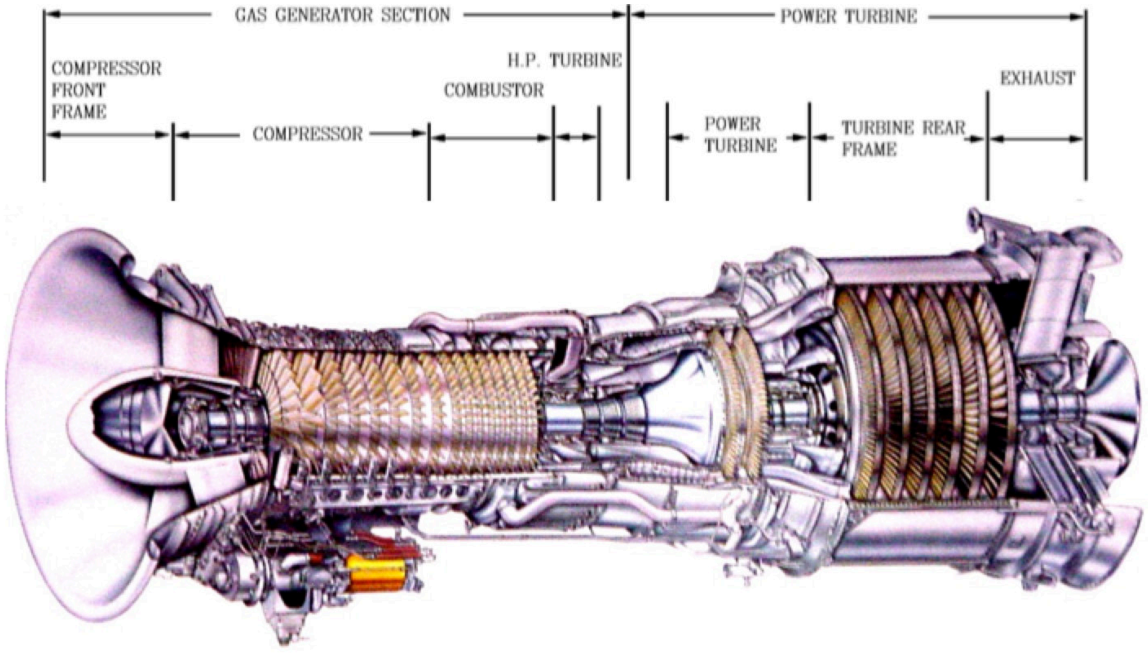
The marine gas turbine comprises the compressor, combustor, and turbine (See Figure 23). The cruiser PPM provides a technical description of the primary airflow across the turbine and says:

> it begins with a draw of air from the intake duct via the gas generator and proceeds through the enclosure inlet, plenum, inlet screen, bellmouth, and front frame. Following compression of the air, it enters the combustion section where some of the air is mixed with fuel, and the mixture is burned. The residual air is used to center the flame in the combustor and for cooling the combustor, the high-pressure turbine rotor and blades, and the first-stage high-pressure turbine nozzle. Hot gas from the combustor passes through the high-pressure turbine where some of the energy is extracted by the high-pressure turbine rotor and used to turn the

> compressor. The hot gas exits the high pressure turbine, passes through the turbine mid frame, and enters the power turbine where the majority of the remaining energy is extracted by the power turbine rotor and drives the high speed flexible coupling shaft. The shaft provides the power to the reduction gear high-speed pinion. Finally, the remaining gas leaves the power turbine, passes through the turbine rear frame into the exhaust duct, and out to the atmosphere via the uptake duct. (Naval Sea Systems Command 2009a, 139)

The exhaust ducts are part of the exhaust system and designed to prevent gas turbine exhaust air from re-entering the ship. The final piece of the main propulsion gas turbine system is the exhaust system.

Figure 23. Main Gas Turbine Engine (LM2500)

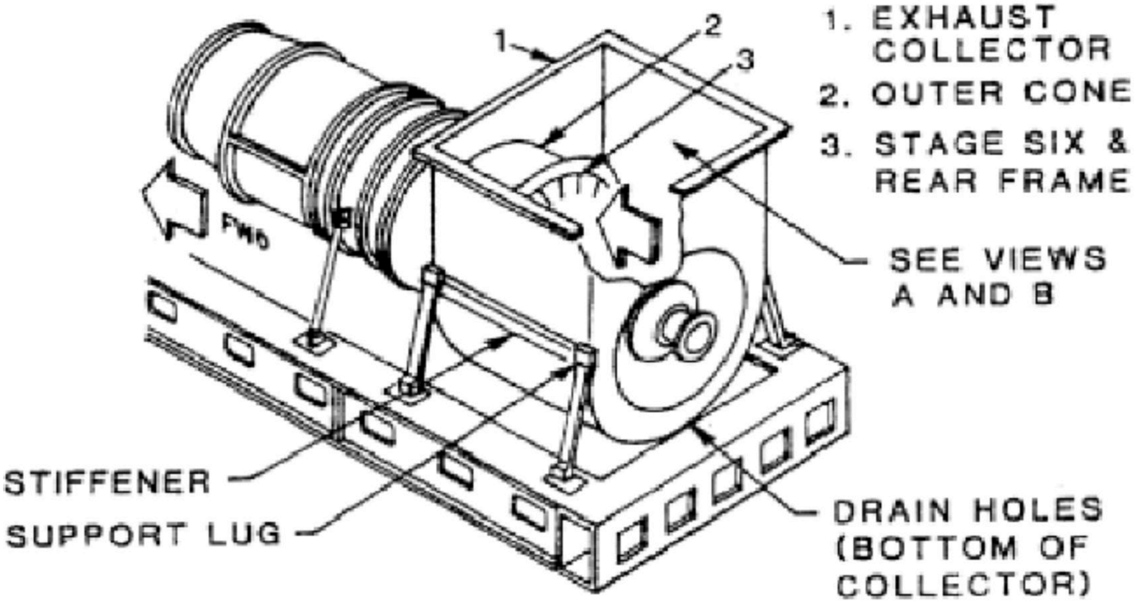


From Surface Warfare Officer School. 2000. *LM2500 Material Readiness.* PowerPoint. Newport, RI: Surface Warfare Officer School, 111.

Analysis and recommendations for improvement of the main gas turbine exhaust system maintenance strategy are the focus of this thesis. Five major parts comprise the exhaust system: the exhaust duct, the inner deflector, the outer cone, the exhaust extension, and the primary outlet flexible joint also known as the exhaust air flexible joint (See Figure 24), according to the cruiser SIB (Naval Sea Systems Command 2009a, 198).

These five parts direct the gas turbine exhaust from the exhaust end of the power turbine to the ship exhaust duct. The inner deflector helps to redirect exhaust air up into the uptake ducting. The outer cone aids in providing protection to the high-speed flexible coupling shaft. Thermal insulation around the exterior of the exhaust duct helps reduces heat transfer to the enclosure (198). The outer cone, inner deflector, and turbine rear frame all reside within the structure of the exhaust duct and form the exhaust duct assembly. The exhaust duct structure is commonly referred to as the exhaust collector (See Figures 24 and 26). The stainless steel structure of the exhaust collector is exposed to extreme cyclic thermal loading. Technical information from the SIB says the exhaust system can withstand a maximum gas flow of 160 lb/sec at 897.5 degrees Fahrenheit exhaust temperature (271). The exhaust collector is held in place within the module enclosure by four support legs attached to support lugs welded to a C-channel stiffener bar running along the left and right side of the exhaust collector. The C-channel stiffener acts as a structural strength member for the exhaust collector. Vent holes located along the interface between the exhaust collector wall and C-channel prevent pockets of hot air from building. Similar drain holes are located at the bottom forward and aft section of the exhaust collector to prevent an explosion from accumulated fuel. The C-channel weld and vent and drain holes are exposed to significant thermal loads and prone to cracking (See Figure 25). Gusset plates are welded at the top of the exhaust collector corners to connect the exhaust collector (See Figures 26 and 27). Gusset plates are also prone to cracking (See Figure 28).

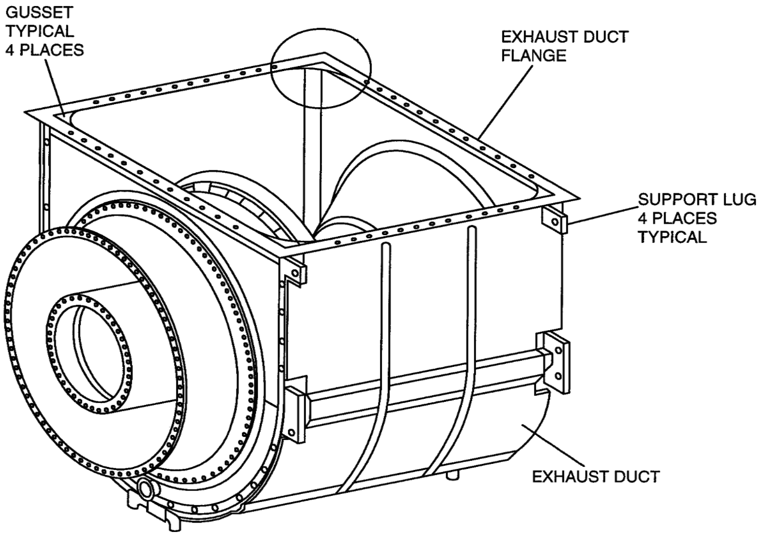
Figure 24. Exhaust Duct Assembly



From Surface Warfare Officer School. 2000. *LM2500 Material Readiness.* PowerPoint. Newport, RI: Surface Warfare Officer School, 7.

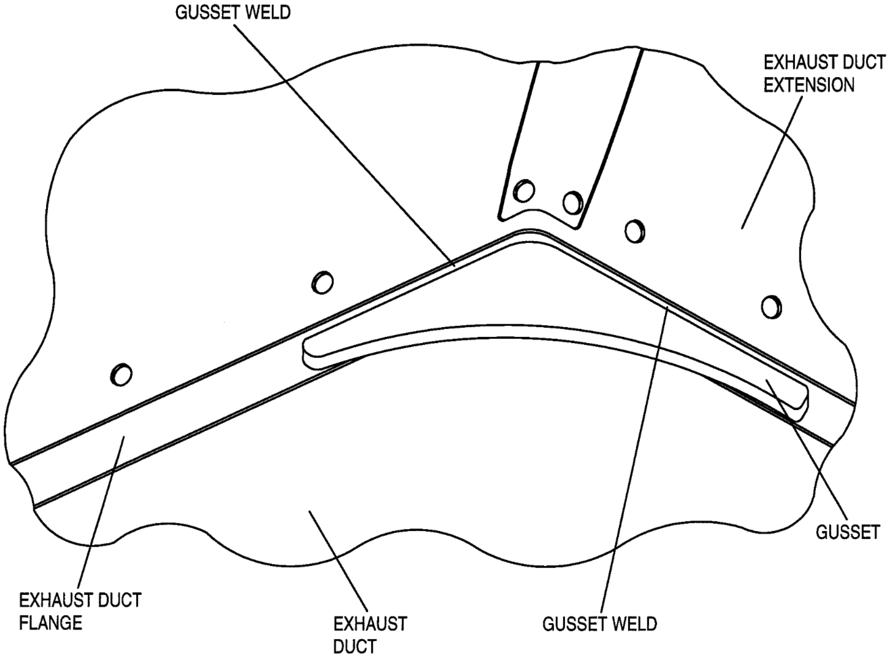
Figure 25. Exhaust Collector Vent Hole Cracks

Figure 26. Exhaust Collector Vent Hole Cracks



After Commander, Naval Sea Systems Command. 2014. *LM2500 Propulsion Gas Turbine Module: Technical Manual, Organizational Level Maintenance.* Vol. 2. Washington, DC: Commander, Naval Sea Systems Command, 1205.

Figure 27. Exhaust Collector Gusset Plate Details



After Commander, Naval Sea Systems Command. 2014. *LM2500 Propulsion Gas Turbine Module: Technical Manual, Organizational Level Maintenance.* Vol. 2. Washington, DC: Commander, Naval Sea Systems Command, 1205.

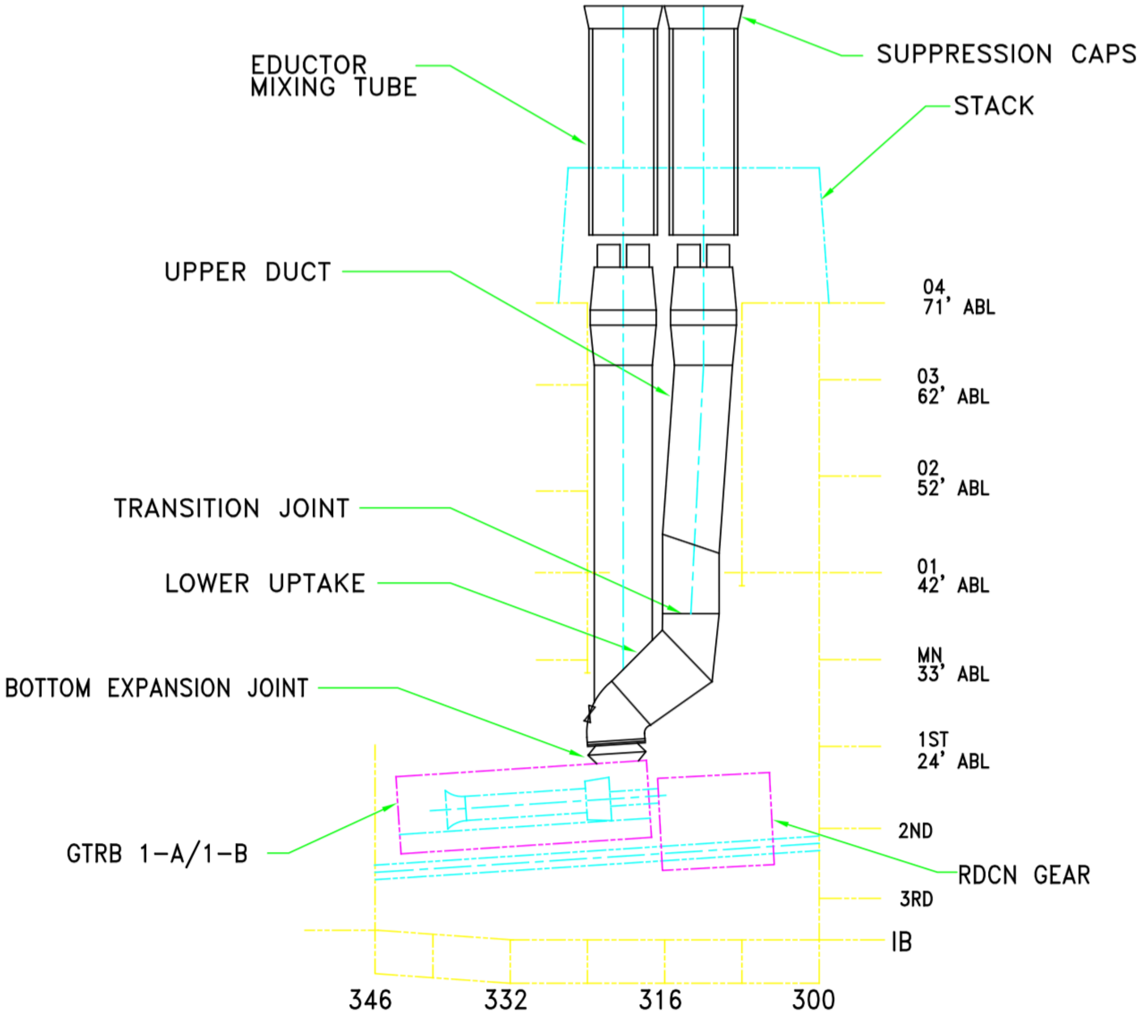
Figure 28. Gusset Cracks

The exhaust air flexible joint connects to the uptake duct. This subtle yet distinct connection has the effect of blurring system boundaries because exhaust air passes seamlessly through the systems and they both serve the same ultimate function, to expel exhaust air. Assessments and repairs of the gas turbine exhaust system and uptake system are often accomplished without bias towards this system boundary. Nonetheless, understanding the system design and boundaries is important to RCM analysis and establishing the correct system maintenance strategy boundaries.

2. Main Gas Turbine Uptake System

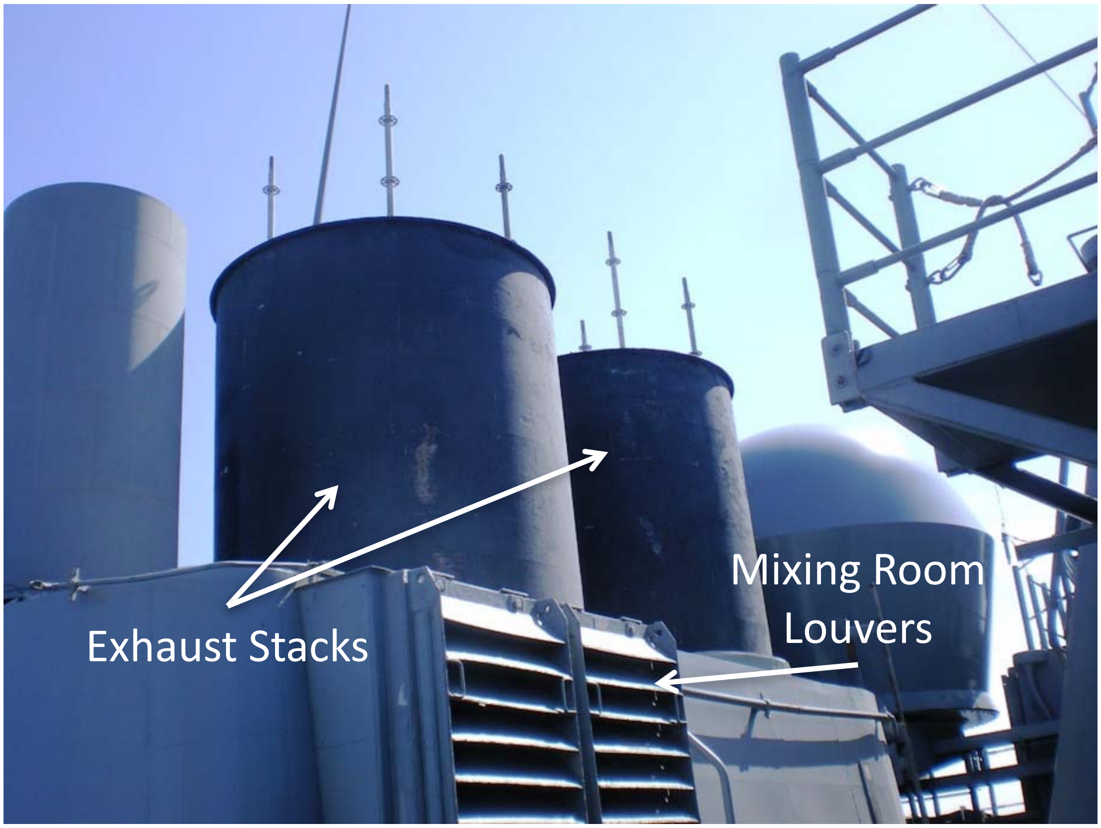
The uptake system of the Ticonderoga Cruiser serves to route the exhaust air safely from the gas turbine exhaust system up through the ship and out to the atmosphere. The uptake system extends from the exhaust duct flexible joint located in the main engine room below the main deck up through the 05 level via the exhaust stacks (See Figure 29). The uptake traverses through the 01, 02, 03, and 04 levels until it reaches the mixing room. The mixing room on the 04-level has louvers on the bulkhead to bring in ambient air to help cool the exhaust air before it leaves the stack (See Figure 30). The coalescing of ambient air with exhaust air is important to reducing the ship's heat signature.

Figure 29. Aft Main Engine (GTM 1A/1B) Uptake Diagram



After Commander, Naval Sea Systems Command. 2013. *MRC: 23 8SWH N, Exhaust Duct 2591*. Washington, DC: Commander, Naval Sea Systems Command.

Figure 30. Exterior Photo of Mixing Room and Louvers



3. Marine Gas Turbine Exhaust System Maintenance

Maintenance associated with the marine gas turbine exhaust system on the CG-47 Class ships is a combination of organizational, intermediate, and depot-level maintenance actions. Routine planned maintenance actions accomplished by the ship's force encompass the majority of the maintenance performed. The planned maintenance for the CG-47 class marine gas turbine exhaust system is documented on maintenance index pages (MIPs) 2340/002 and 2591/002. These MIPs comprise the applicable maintenance requirement cards (MRCs) for the main propulsion gas turbine LM2500 and exhaust. A MRC provides the written maintenance requirement description, safety precautions, procedure for accomplishing the maintenance, and lists of the required instruments, supplies, and test equipment. The scope of these MRCs consists of inspections for cracks, erosion, corrosion, and deterioration requiring maintenance. MIPs and MRCs are accessible online at the Naval Logistics Technical Data (NAVLOGTD) Repository.

Intermediate-level maintenance for the gas turbine exhaust system is accomplished in accordance with the JFMM Volume IV, Chapter 23, and General Gas Turbine Bulletin (GGTB) 11, Marine Gas Turbine Inspectors (MGTIs). MGTIs are trained and certified to perform pre-planned major maintenance availability (PPMMA) inspections, pre-deployment assessments (PDAs), and gas turbine bulletin (GTB) inspections. These inspections provide a comprehensive material review of the entire marine gas turbine system. MGTI facilitated inspections are in accordance with technical guidance derived from technical manuals, planned maintenance system (PMS), and GTBs. MGTI inspection results provide the foundation of gas turbine system repairs for a follow-on maintenance availability to be accomplished by depot-level maintenance activities.

Depot-level maintenance actions associated with the marine gas turbine exhaust system are largely corrective in nature. Repairs are identified and documented as a result of organizational and intermediate-level inspections. Private shipyard activities perform the majority of cruiser exhaust system repairs due to the complexity of structural repair and technical skills required. Repairs range from complete overhaul and restoration of the system to as-built conditions, to less extensive temporary repairs requiring technically authorized deviation from design specifications. Repairs are accomplished in accordance with technical guidance outlined in system technical manuals and GTBs. Local technical authority (LTA) from the RMC, shipbuilding specialists (SBSs) and requisite ship force representatives are involved with ensuring quality assurance and certifying the work is performed correctly.

4. Current Main Gas Turbine Exhaust System Maintenance Strategy

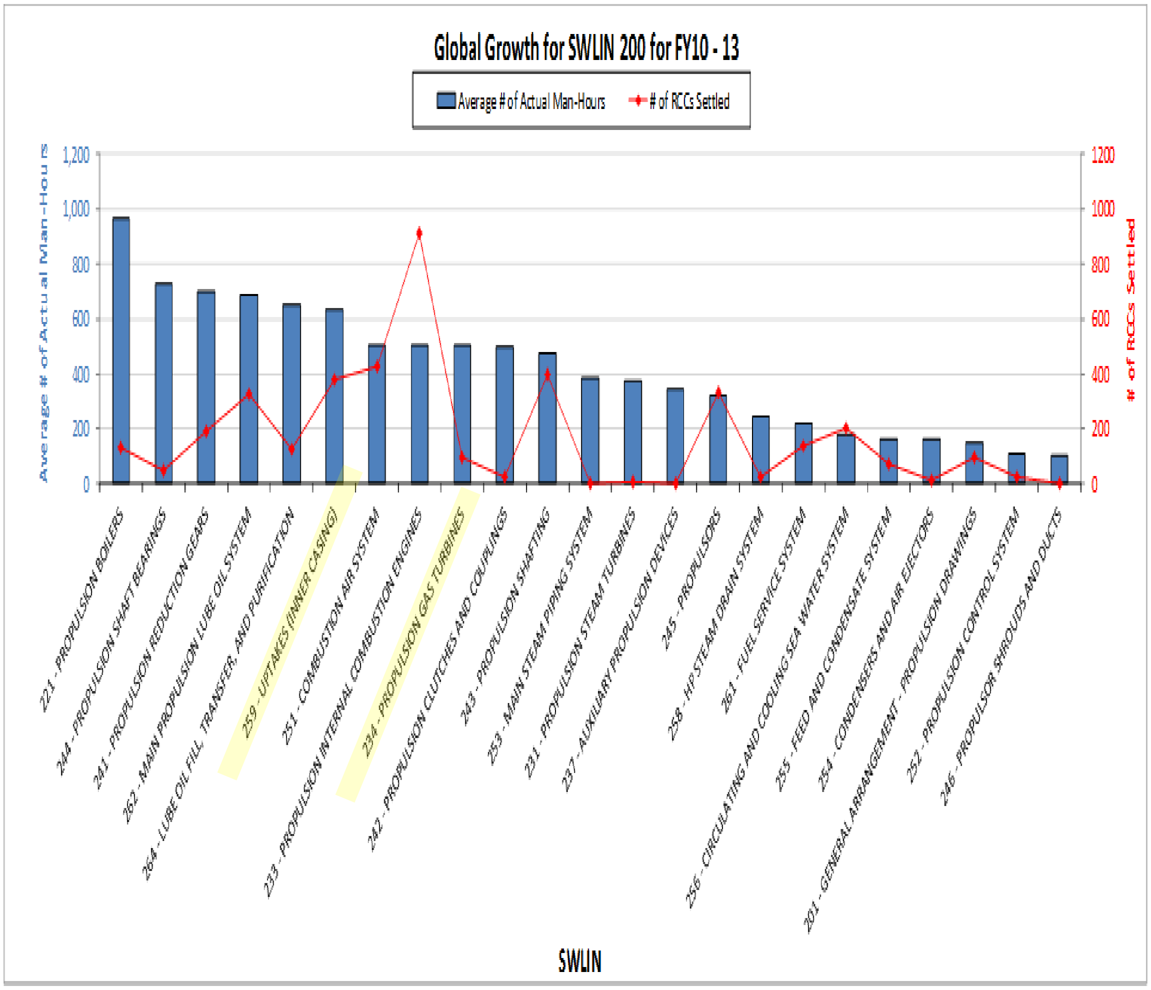
The main gas turbine exhaust system maintenance strategy consists entirely of FF PM tasks. The majority of the FF tasks are listed on the MIPs. The CMP includes one additional FF task by way of a scheduled material condition assessment designated G1E8. All the failure-finding tasks consist of periodic inspection for material discrepancies, such as cracks, corrosion, erosion, plugged drain holes, flammable liquids, and insulation deterioration while the system is off-line. Exhaust system inspections are scheduled to coincide with the total ship readiness assessments (TSRAs) prior to the next scheduled CNO availability in accordance with the joint TYCOM TSRA instruction (Commander, Naval Surfaces Force, U.S. Pacific; Commander, Naval Surface Force, Atlantic; Commander, Naval Regional Maintenance Center 2012, 11). The exhaust system design precludes most functional failures from being observed during system operation. In accordance with the Navy's CBM policy, corrective maintenance actions are planned following a FF inspection.

The severity of material discrepancies found during inspection and ship's operational schedule dictate the urgency of repair. Most repairs are planned for the follow-on CNO availability based on inspection results four to six months prior. Repairs are planned by the MSR under the MSMO CPAF contract. To ensure the necessary repairs are executed during the maintenance availability, the work specification written by the contractor and reviewed by the government begins with an inspection of the system. Following the inspection, a condition found report (CFR) is generated by the contractor and provided to the government maintenance team. The CFR lists all the discrepancies found during the inspection. The SBS verifies the contractor's inspection findings. The maintenance team then generates a RCC to modify the original work item to include the necessary exhaust system repairs. To mitigate potential schedule impacts from growth work of this nature, FF inspections are required to be complete within the first 20 percent of the maintenance availability in accordance with the Joint Fleet Maintenance Manual (JFMM) (U.S. Fleet Forces Command 2013, II-I–3-29). These inspections are rarely all complete within the initial 20 percent of an availability for various reasons including schedule integration challenges, RMC capacity, and poor planning.

5. Main Gas Turbine Exhaust System Growth-Work

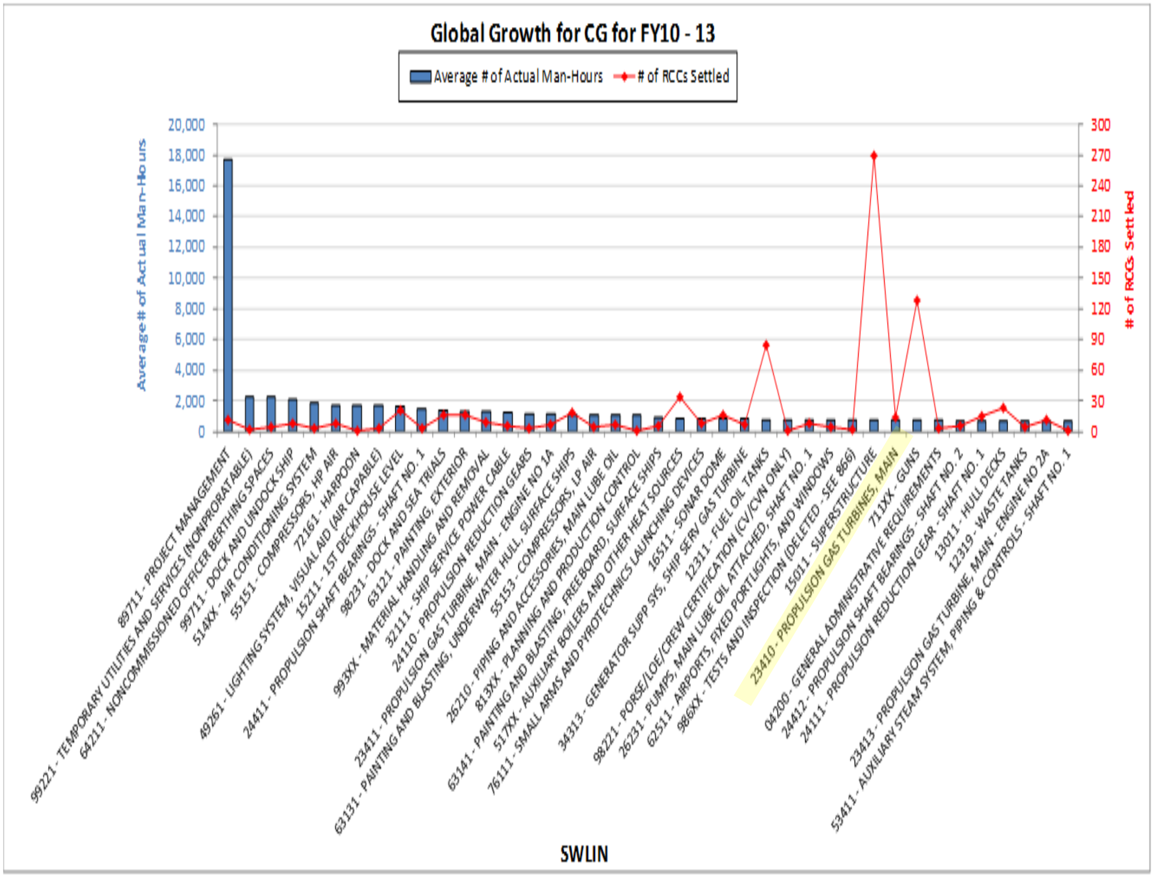
Growth-work associated with the main gas turbine exhaust system is a significant challenge for the maintenance community. The exhaust system is consistently ranked in the top most 40 ship work list item numbers (SWLINs) for growth-work. More than 80 propulsion related SWLINs and an excess of a thousand possible growth-work SWLINs total exist. SWLINs 259 and 234 include main gas turbine exhaust system growth work. CNRMC is the maintenance organization that tracks and develops availability growth-work metrics. Figures 31 through 34 graphically indicate the magnitude of growth-work associated with the exhaust system. Growth-work involving the exhaust system can negatively impact availability schedule and is a risk to OFRP.

Figure 31. Growth-Work for 200 Level SWLINs



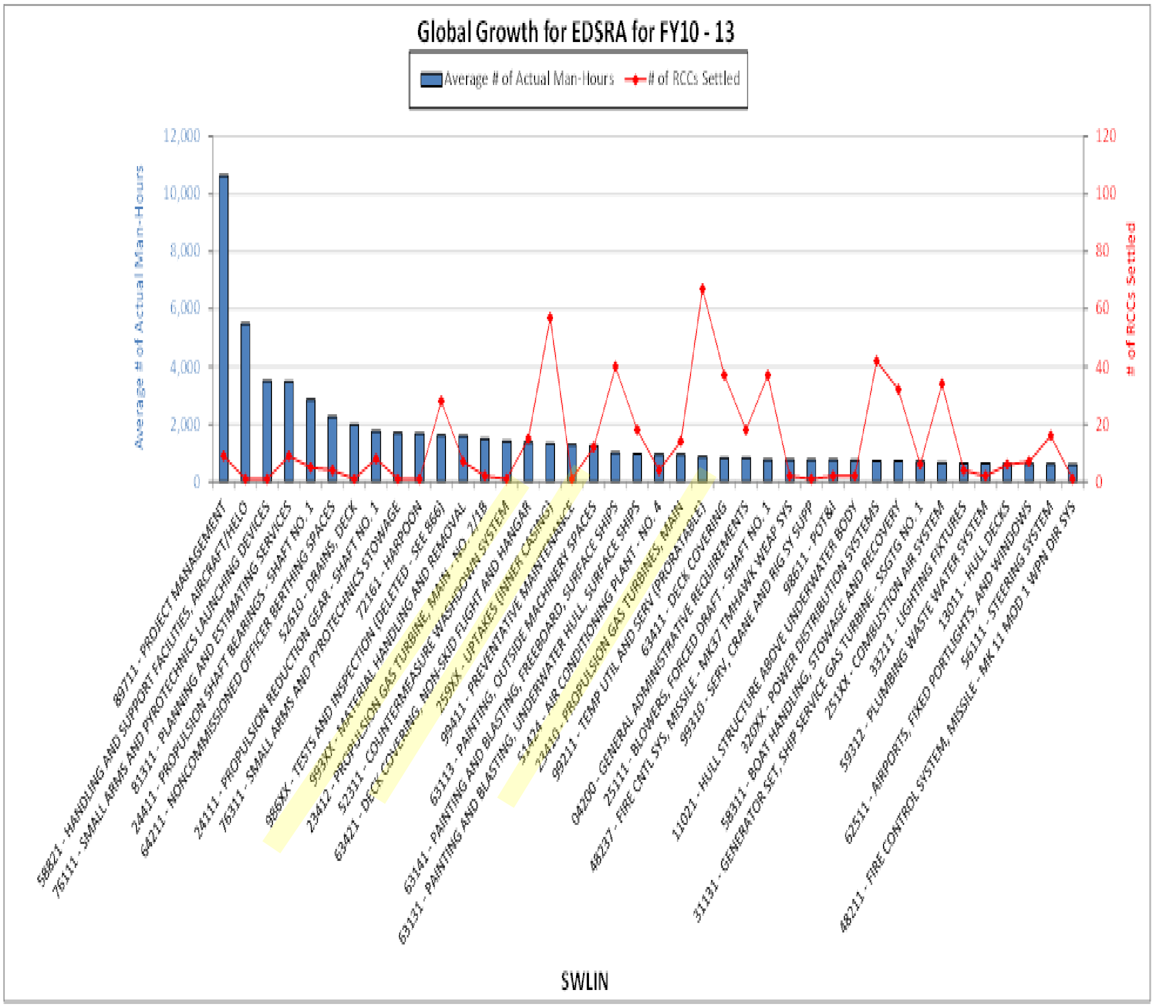
After Commander, Naval Regional Maintenance Center. 2014. *Historical Top Growth by SWILN.* Norfolk, VA: Commander, Naval Regional Maintenance Center, 5.

Figure 32. Top Global Growth for CG Class by SWLIN



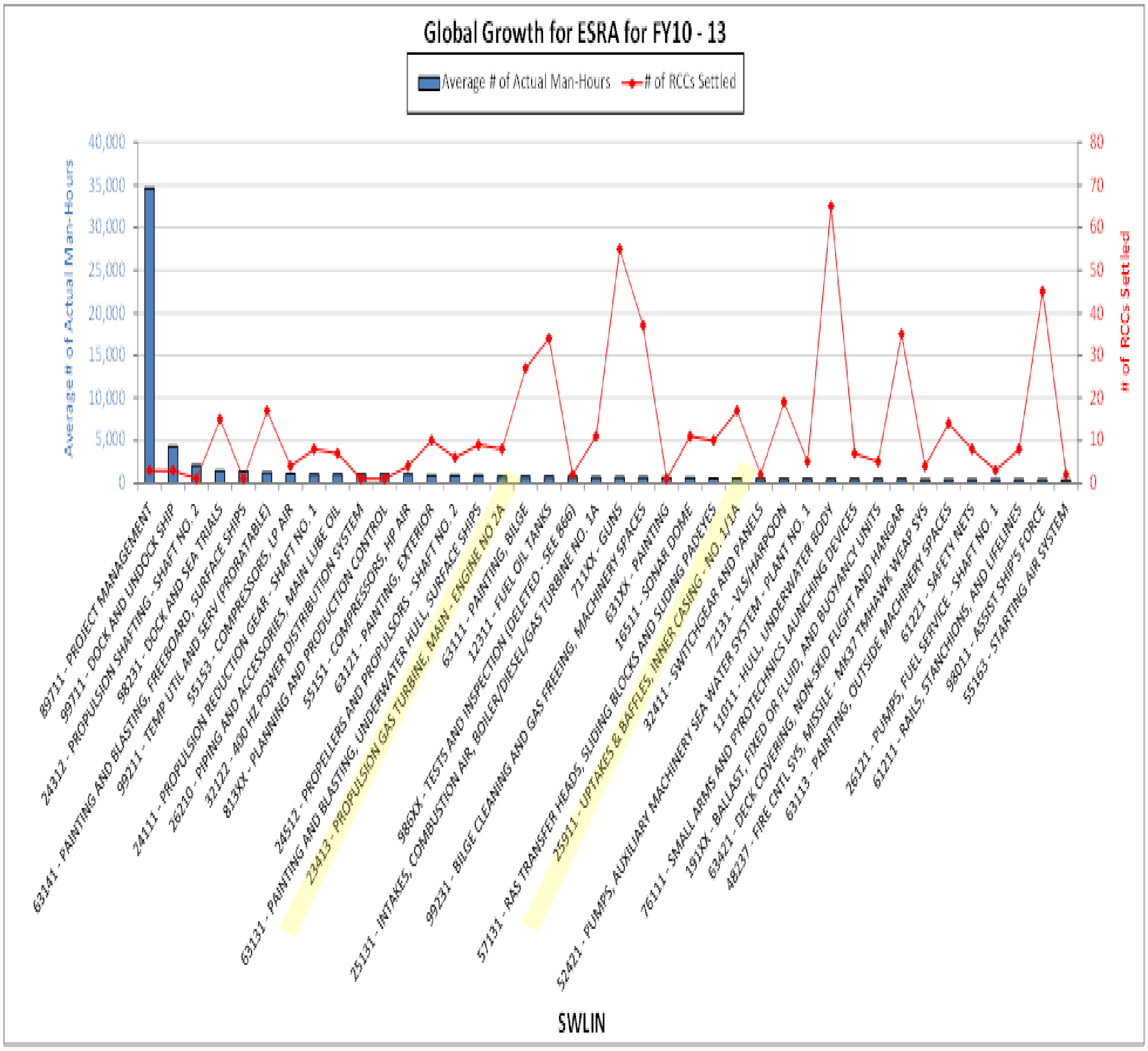
After Commander, Naval Regional Maintenance Center. 2014. *Historical Top Growth by SWILN*. Norfolk, VA: Commander, Naval Regional Maintenance Center, 18.

Figure 33. Global Growth Work by SWLIN for EDSRA Type Availabilities



After Commander, Naval Regional Maintenance Center. 2014. *Historical Top Growth by SWILN.* Commander, Naval Regional Maintenance Center, 24.

Figure 34. Global Growth-Work by SWLIN for ESRA Type Availabilities



After Commander, Naval Regional Maintenance Center. 2014. *Historical Top Growth by SWILN.* Commander, Naval Regional Maintenance Center, 25.

E. RECOMMENDATIONS TO IMPROVE THE MAIN GAS TURBINE EXHAUST SYSTEM MAINTENANCE STRATEGY

Navy leadership has made it clear that ships must complete availabilities on time in support of OFRP. OFRP is an important construct to future naval force employability, sailor quality of life, and the stability of the private ship industrial base. The sanctity of schedule is paramount, and careful management of availability schedule risk is necessary. Efforts to mitigate growth-work due to open and inspect associated failure-finding tasks are a means to mitigate availability schedule risk. Historical maintenance data is the key to provide the objective quality evidence (OQE) needed to technically justify a shift from an entirely FF task approach to a schedule risk accommodating TD PM strategy, in harmony with the Navy's CBM policy.

1. Historical Data and Fault Tree Analysis

Analogous to the NSTCP FTA, a FTA of the main gas turbine exhaust system is beneficial to understanding the potential failure modes of the system. The fault tree also provides a graphical breakdown of the entire exhaust system of systems. A breakdown of the system helps to analyze historical system maintenance data by logically classifying and binning the data by failure mode. Analysis of historical repair data helps determine whether a technically acceptable TD maintenance task can and should be developed. The variance of historical repair data across the class provides indication of risk to over or under executing maintenance. This thesis provides a FTA of the main gas turbine exhaust system and a summary historical data analysis of the gas turbine exhaust components (See Figures 35 through 42). The gas turbine exhaust components include the exhaust collector, exhaust extension, and primary exhaust flexible joint. Unfortunately, only a scant amount of detailed historical failure data on the gas turbine exhaust components is obtainable. A limited random sampling of historical MGTI inspection reports and RCCs form various Cruiser CNO availabilities was analyzed. MGTI inspection reports are maintained online at the Propulsion Executive Steering Committee (PESC) portal. The analysis indicates that an average of 41 linear inches of gas turbine exhaust component crack repairs per engine is required to be accomplished during a CNO availability (See Table 5).

Figure 35. Main Gas Turbine Exhaust System Fault Tree Analysis

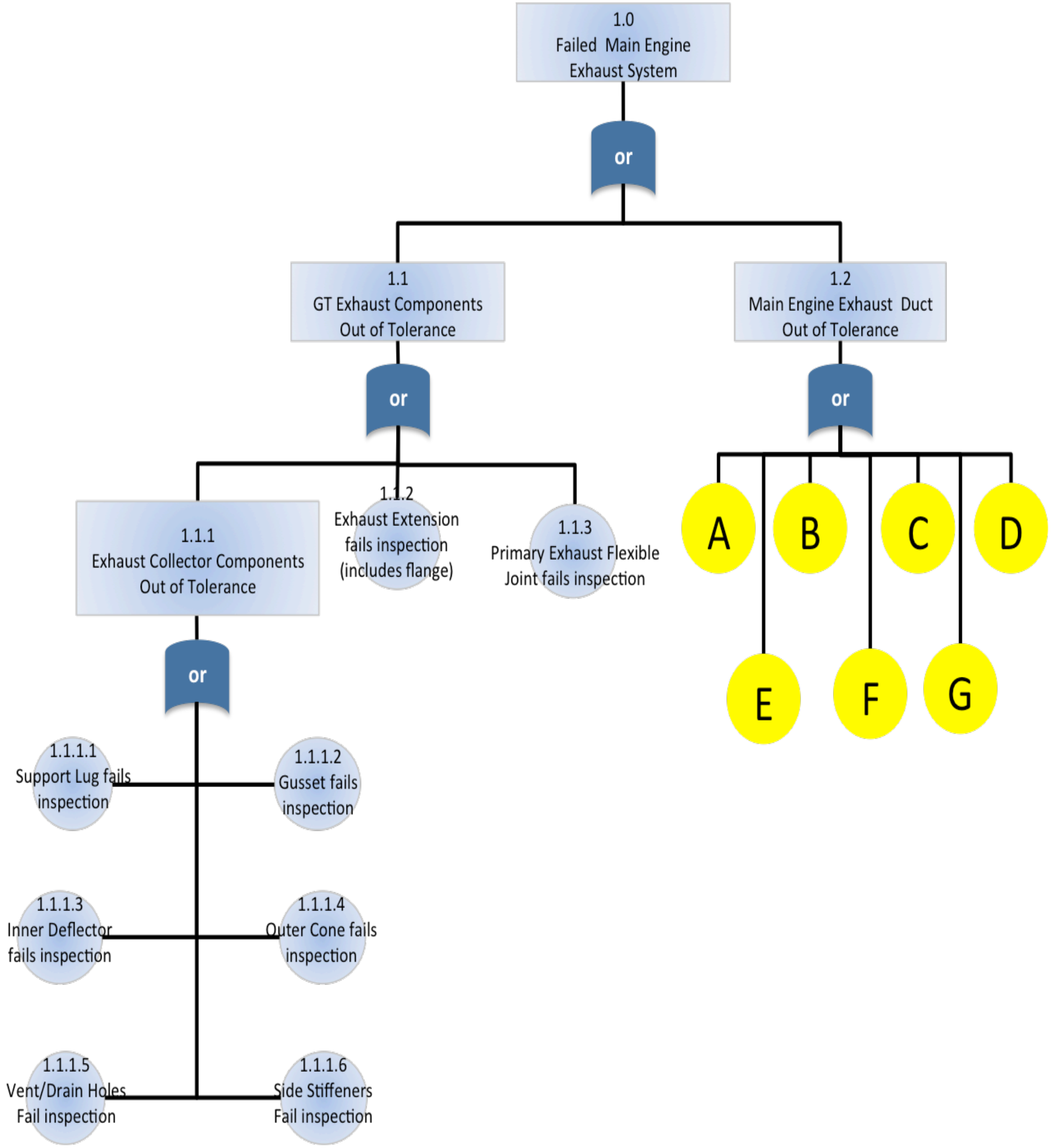


Figure 36. Main Gas Turbine Exhaust System Fault Tree Analysis Part A

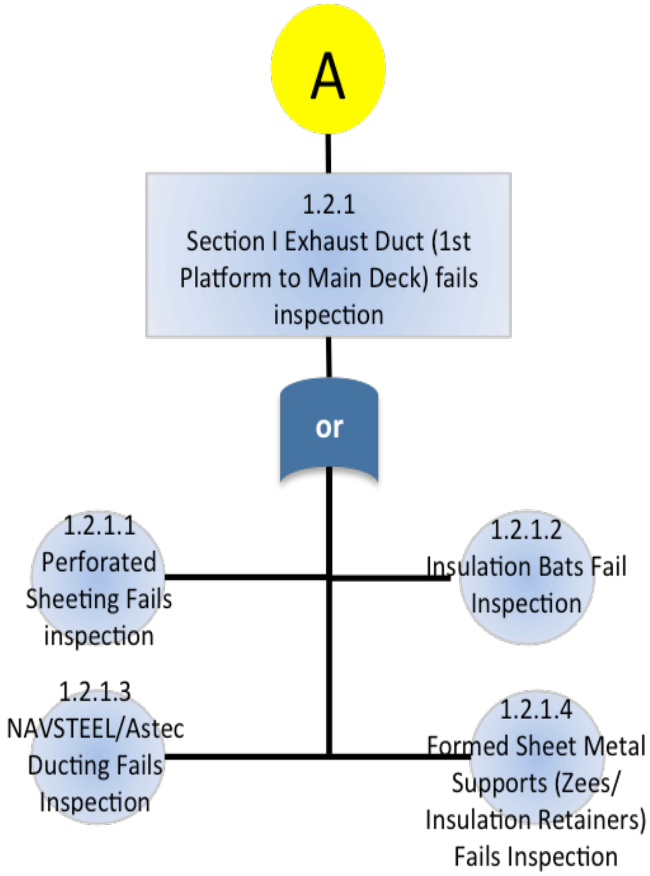


Figure 37. Main Gas Turbine Exhaust System Fault Tree Analysis Part B

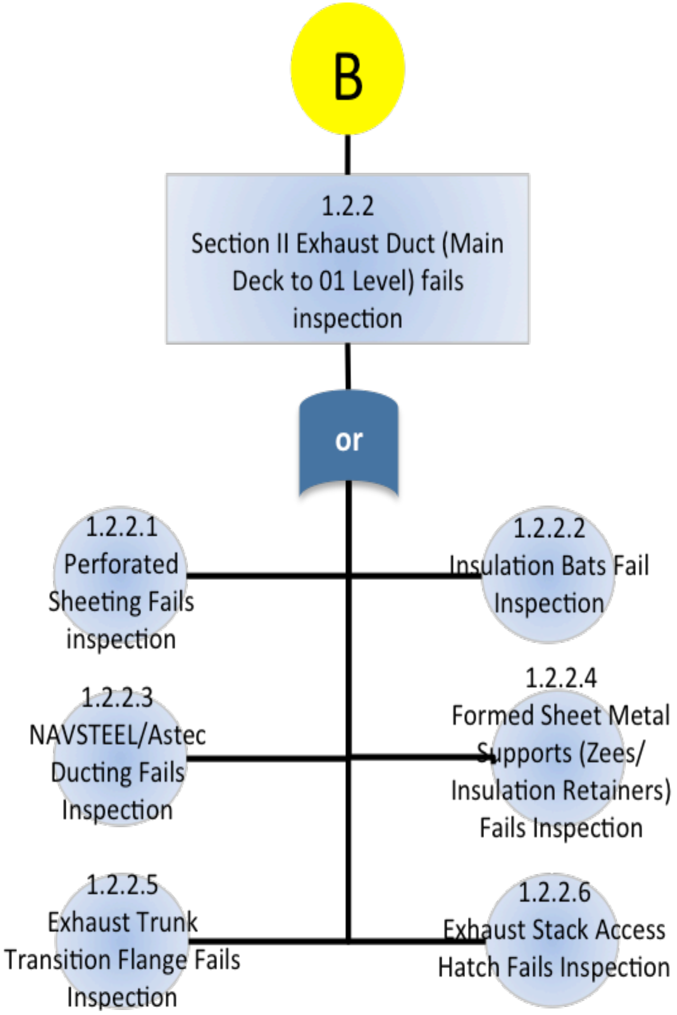


Figure 38. Main Gas Turbine Exhaust System Fault Tree Analysis Part C

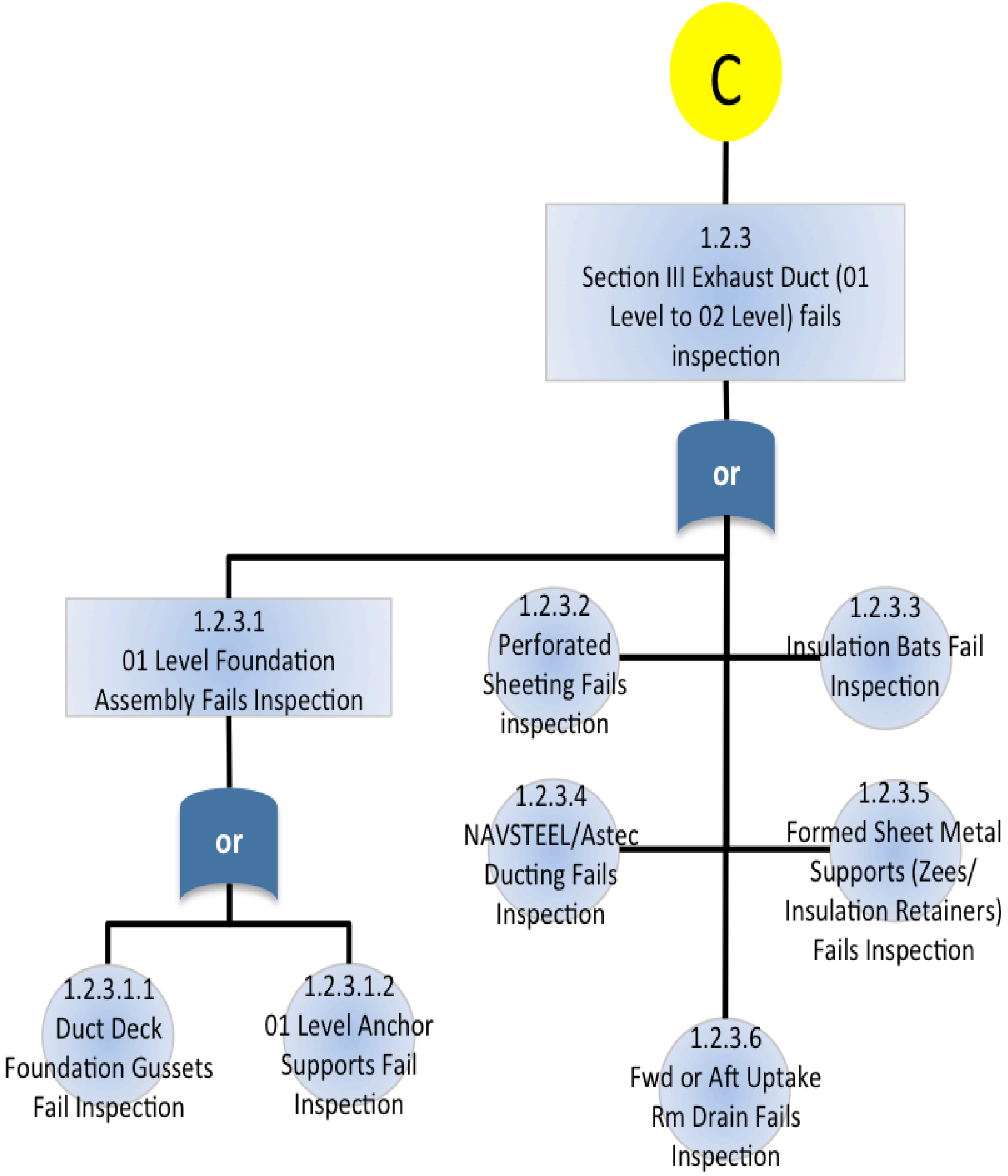


Figure 39. Main Gas Turbine Exhaust System Fault Tree Analysis Part D

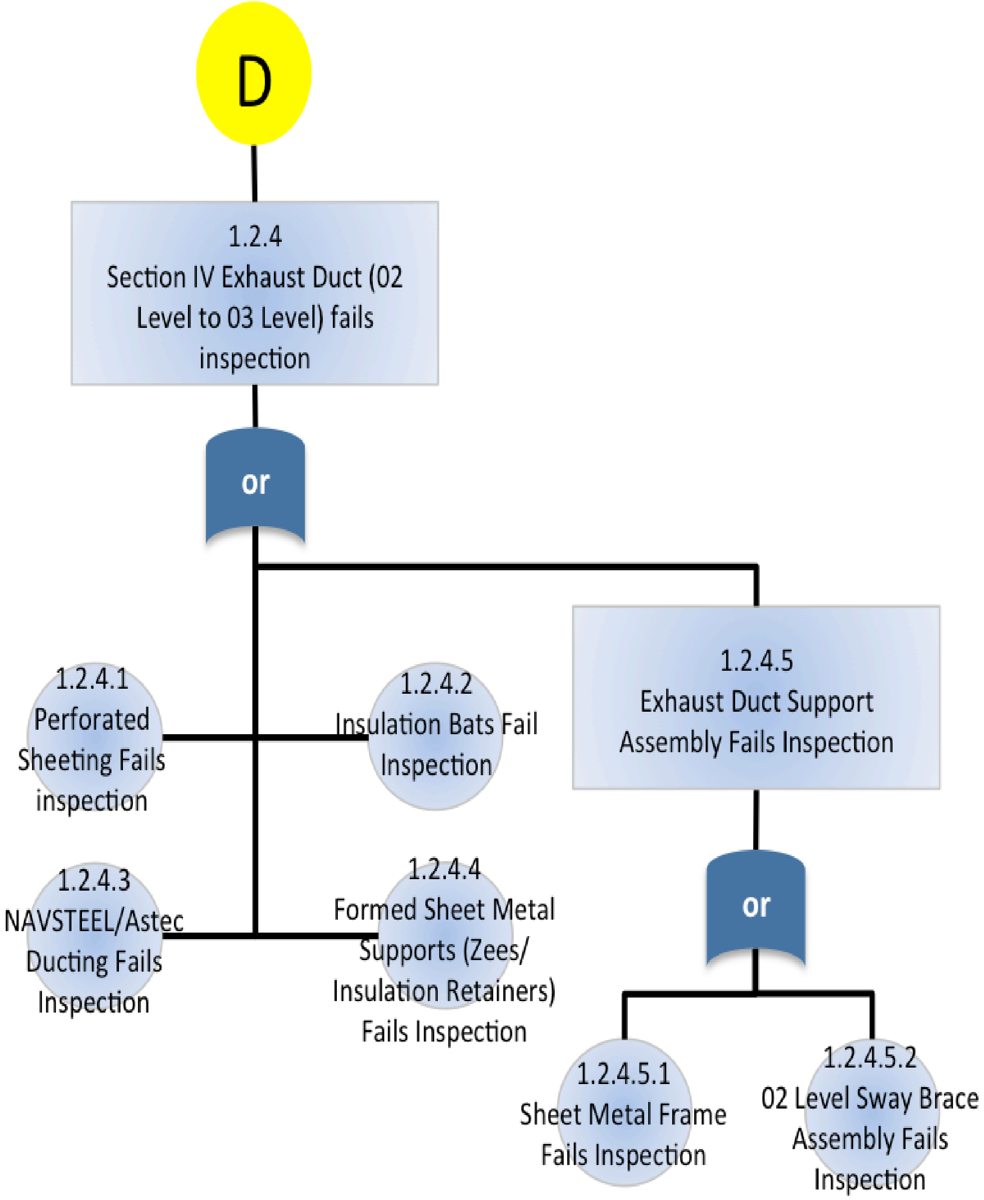


Figure 40. Main Gas Turbine Exhaust System Fault Tree Analysis Part E

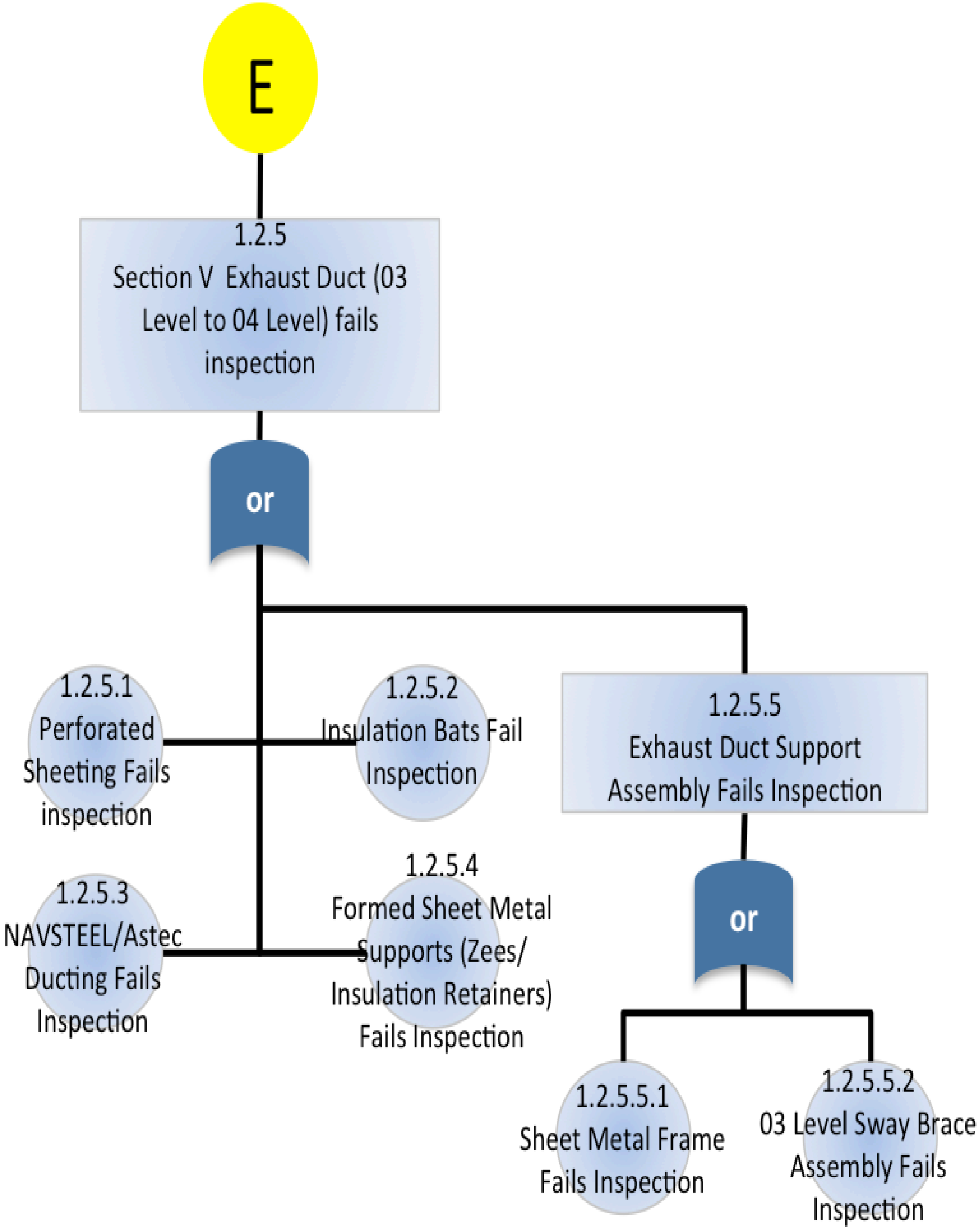


Figure 41. Main Gas Turbine Exhaust System Fault Tree Analysis Part F

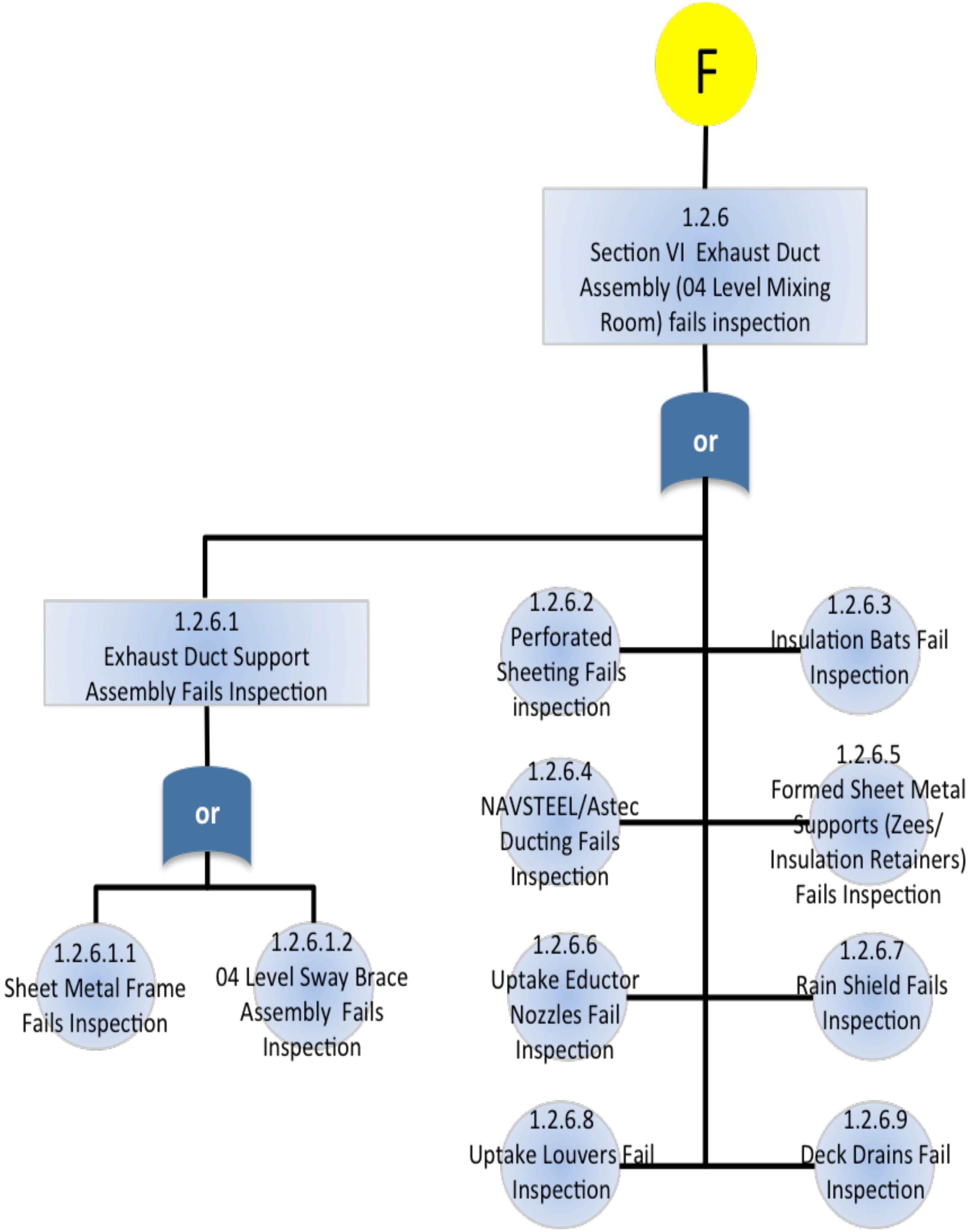


Figure 42. Main Gas Turbine Exhaust System Fault Tree Analysis Part G

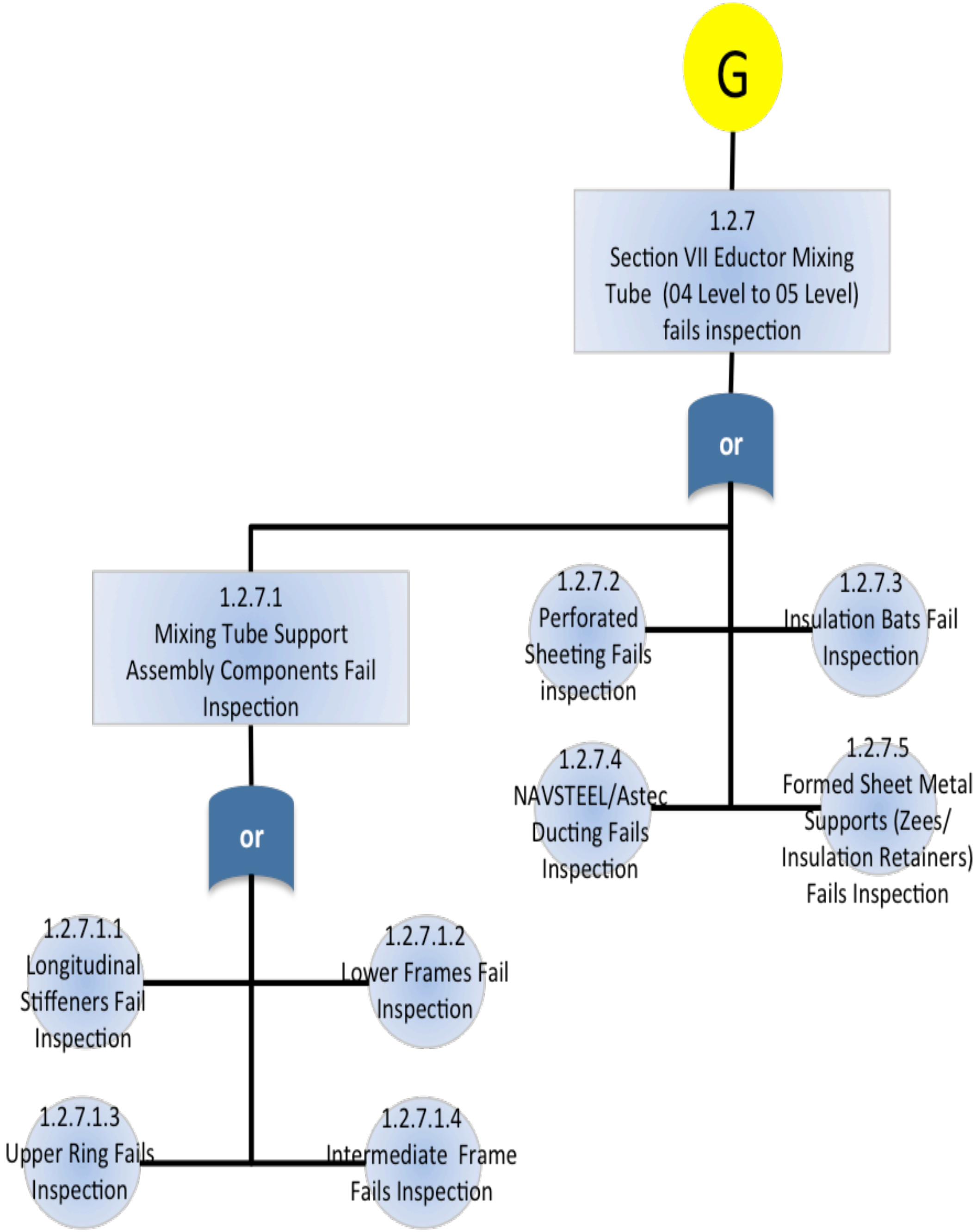
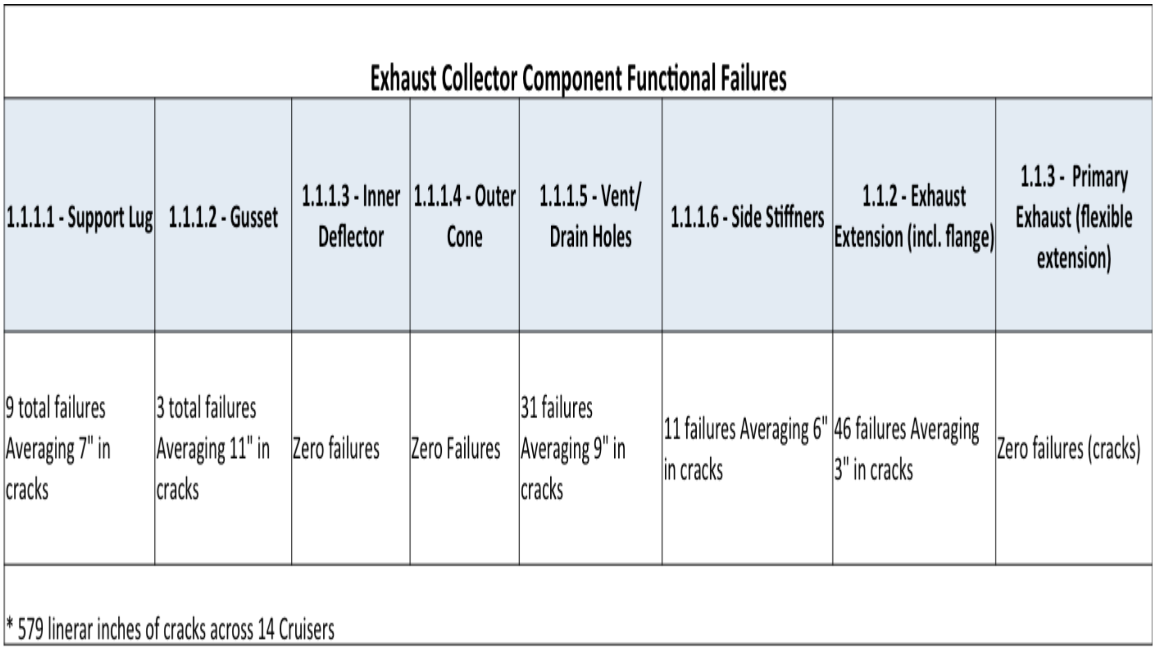


Table 5. Main Gas Turbine Exhaust Collector Failure Data



Exhaust Collector Component Functional Failures							
1.1.1.1 - Support Lug	1.1.1.2 - Gusset	1.1.1.3 - Inner Deflector	1.1.1.4 - Outer Cone	1.1.1.5 - Vent/ Drain Holes	1.1.1.6 - Side Stiffners	1.1.2 - Exhaust Extension (incl. flange)	1.1.3 - Primary Exhaust (flexible extension)
9 total failures Averaging 7" in cracks	3 total failures Averaging 11" in cracks	Zero failures	Zero Failures	31 failures Averaging 9" in cracks	11 failures Averaging 6" in cracks	46 failures Averaging 3" in cracks	Zero failures (cracks)
* 579 linerar inches of cracks across 14 Cruisers							

2. A Hybrid Approach to Preventative Maintenance

Generating a class standard work template (CSWT) that reflects the crack repair requirement in the original description of scope for a work item allows for efficiencies and reduces schedule risk. Acknowledging the crack repair requirement during the planning phase of the availability allows the repair activity to order material in advance, manage workforce requirements, and properly integrate the work into the master schedule. Repairs called out in the original work package are not considered growth-work and do not require a RCC to be accomplished. Conversely, identifying the need for crack repairs during the availability creates growth-work that puts both cost and schedule at risk. Concern of over or under executing maintenance after applying the TD task approach for this system to the entire Cruiser ship class can be easily monitored. A hybrid preventative maintenance approach that combines the necessity of a FF task with the practicality of a TD task creates the sensibility of a blended inspection task with a planned and budgeted repair task. Accomplishing the FF element of the hybrid preventative maintenance task provides the necessary data for future analysis and amendment. Adjusting the TD task to be made more or less conservative according to historical inspection data analysis is a simple modification. Furthermore, the need for initial inspection of systems with inherent hidden failures, such as the exhaust system, is necessary to determine properly precisely where repairs are required. The recommendation for a hybrid preventative maintenance task is the logical improvement for the main gas turbine exhaust system maintenance strategy.

V. CONCLUSION, RECOMMENDATIONS, AND FUTURE EXPLORATIONS

A. MAIN CONCLUSIONS

To achieve Navy surface ship force structure goals, it is imperative that ships in service today are effectively maintained. Sequestration imposes significant budget challenges that require efficiencies to be realized. Further, OFRP presents even greater maintenance availability schedule challenges. Executing "the right maintenance at the right time for the right price" within the schedule limitations is the epitome of efficient and effective ship repair (U.S. Fleet Forces Command 2013, II-II–2-7). Achieving such efficiencies requires a new structured approach to controlling growth-work and its impacts on maintenance availability cost and schedule. Improving something as complex as ship repair must be done one system at a time. A comprehensive analysis that looks across all aspects of ship maintenance is needed to avoid insulated recommendations that fail to account for all factors. Systems engineering makes tools and concepts available to recognize and quantify risk to plan more effectively for ship maintenance. This thesis reviewed programs, processes, policies, and procedures applicable to Navy maintenance strategy development and analysis. This thesis also analyzed the maintenance strategy for the main gas turbine exhaust system and explained a series of system engineering applications. The existing main gas turbine exhaust system maintenance strategy is found to inadequately account for critical schedule factors important to senior Navy leadership. Risk to maintenance availability cost and schedule linked to the preventative maintenance approach in place for the main gas turbine exhaust system was identified. Finally, this thesis identified a hybrid inspection and modifiable repair maintenance strategy with historical data underpinnings. This hybrid approach to the main gas turbine exhaust system maintenance strategy creates an opportunity to mitigate the extensive amount of growth-work currently associated with exhaust system maintenance. The hybrid preventative maintenance task approach to exhaust system maintenance is the product of a systems engineering focused maintenance strategy analysis. The system maintenance strategy analysis through a systems-lens most effectively accounts for cost, schedule, and performance parameters.

B. RECOMMENDATIONS

The Navy should develop and implement a CSWT that reflects the hybrid maintenance strategy recommended by this thesis for the main gas turbine exhaust collector. The system maintenance strategy should be reviewed for effectiveness after one year. The Navy should gather additional failure data to continue developing a hybrid maintenance strategy for the remaining exhaust system. The Navy should also consider efforts to analyze other systems with high historical growth-work. The analysis should target systems and equipment subject to hidden functional failures and currently restricted to FF tasks. Systems subject to FF tasks are most at risk to growth-work during maintenance availabilities. Second, the Navy maintenance community must strictly enforce the collection of maintenance data records for analysis. Historical maintenance data associated with the targeted systems should be analyzed. A shift to a hybrid preventative maintenance strategy composed of inspection and repair should be implemented where data supports. Tanks and voids (T&Vs) are a good candidate for initial analysis.

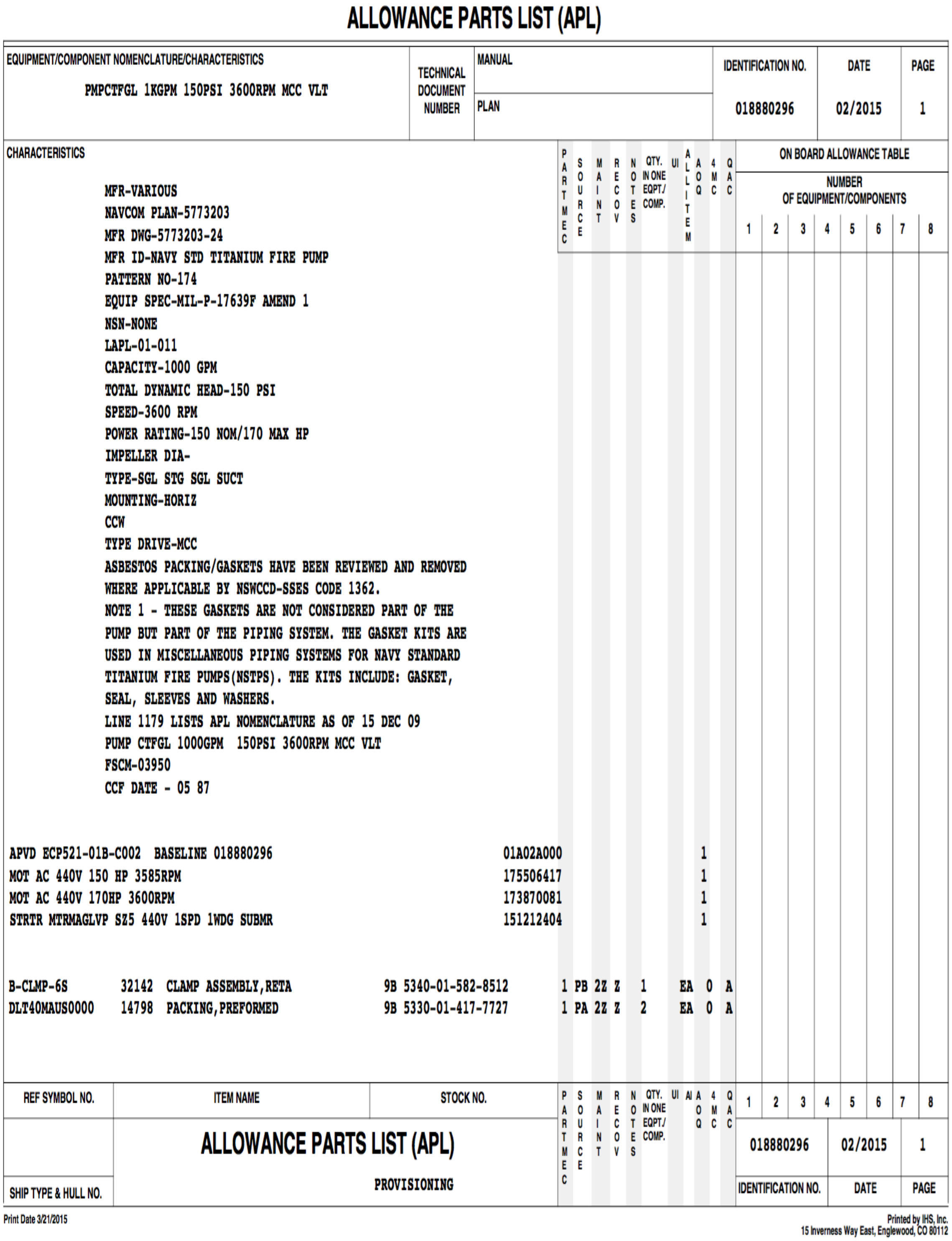
C. FUTURE EXPLORATION

The expanded implementation of sensors and diagnostics should be explored in a continued effort to move to prognosis and equipment failure forecasting. As sensor technology and capability grow, system and equipment material condition analysis becomes more affordable and effective. In parallel, the Navy should carefully analyze FF inspection data for systems similar to the main gas turbine exhaust system for possible design improvements. The frequency of structural cracks may warrant a strengths and materials analysis of the exhaust collector design. It may be determined that a backfit alteration is not cost effective for in-service ships. However, thermal cyclic loading analysis may determine that future ships be built with different material or new thermal venting options to reduce cracking. Finally, NASA probabilistic risk analysis methods should be evaluated to understand equipment and component reliability further where multiple complex scenarios must be analyzed to understand a system fault fully. The correct maintenance recommendation made the first time is essential to avoiding rework. Understanding complex system reliability will aid in the appropriate planning and execution of system repair.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX. PUMP ALLOWANCE PARTS LIST (APL)

Courtesy of Defense Logistics Agency (DLA) Land and Maritime in Columbus, Ohio.



ALLOWANCE PARTS LIST (APL)

EQUIPMENT/COMPONENT NOMENCLATURE/CHARACTERISTICS	TECHNICAL DOCUMENT NUMBER	MANUAL / PLAN	IDENTIFICATION NO.	DATE	PAGE
PMPCTFGL 1KGPM 150PSI 3600RPM MCC VLT			018880296	02/2015	1

CHARACTERISTICS

MFR-VARIOUS
NAVCOM PLAN-5773203
MFR DWG-5773203-24
MFR ID-NAVY STD TITANIUM FIRE PUMP
PATTERN NO-174
EQUIP SPEC-MIL-P-17639F AMEND 1
NSN-NONE
LAPL-01-011
CAPACITY-1000 GPM
TOTAL DYNAMIC HEAD-150 PSI
SPEED-3600 RPM
POWER RATING-150 NOM/170 MAX HP
IMPELLER DIA-
TYPE-SGL STG SGL SUCT
MOUNTING-HORIZ
CCW
TYPE DRIVE-MCC
ASBESTOS PACKING/GASKETS HAVE BEEN REVIEWED AND REMOVED
WHERE APPLICABLE BY NSWCCD-SSES CODE 1362.
NOTE 1 - THESE GASKETS ARE NOT CONSIDERED PART OF THE
PUMP BUT PART OF THE PIPING SYSTEM. THE GASKET KITS ARE
USED IN MISCELLANEOUS PIPING SYSTEMS FOR NAVY STANDARD
TITANIUM FIRE PUMPS(NSTPS). THE KITS INCLUDE: GASKET,
SEAL, SLEEVES AND WASHERS.
LINE 1179 LISTS APL NOMENCLATURE AS OF 15 DEC 09
PUMP CTFGL 1000GPM 150PSI 3600RPM MCC VLT
FSCM-03950
CCF DATE - 05 87

APVD ECP521-01B-C002 BASELINE 018880296	01A02A000	1
MOT AC 440V 150 HP 3585RPM	175506417	1
MOT AC 440V 170HP 3600RPM	173870081	1
STRTR MTRMAGLVP SZ5 440V 1SPD 1WDG SUBMR	151212404	1

REF SYMBOL NO.		ITEM NAME	STOCK NO.	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT./ COMP.	UI	ALLITEM	AOQ	4MC	QAC	1	2	3	4	5	6	7	8
B-CLMP-6S	32142	CLAMP ASSEMBLY,RETA	9B 5340-01-582-8512	1	PB	2Z	Z		1	EA		0		A								
DLT40MAUS0000	14798	PACKING,PREFORMED	9B 5330-01-417-7727	1	PA	2Z	Z		2	EA		0		A								

ON BOARD ALLOWANCE TABLE — NUMBER OF EQUIPMENT/COMPONENTS

REF SYMBOL NO.	ALLOWANCE PARTS LIST (APL)	IDENTIFICATION NO.	DATE	PAGE
SHIP TYPE & HULL NO.	PROVISIONING	018880296	02/2015	1

Print Date 3/21/2015

Printed by IHS, Inc.
15 Inverness Way East, Englewood, CO 80112

ALLOWANCE PARTS LIST (APL)

EQUIPMENT/COMPONENT NOMENCLATURE/CHARACTERISTICS	TECHNICAL DOCUMENT NUMBER	MANUAL / PLAN	IDENTIFICATION NO.	DATE	PAGE
PMPCTFGL 1KGPM 150PSI 3600RPM MCC VLT			018880296	02/2015	2

CHARACTERISTICS

ON BOARD ALLOWANCE TABLE

NUMBER OF EQUIPMENT/COMPONENTS

REF SYMBOL NO.		ITEM NAME	STOCK NO.	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT./COMP.	UI	ALLITEM	AOQ	4MC	QAC	1	2	3	4	5	6	7	8
0.25-250MPGE\E-N/M	0JM95	PARTS KIT,SEAL REPL	9B 5330-01-566-0993	1	PA	2Z	Z		1	EA		0		A								
5-250MPGE\E-N/M	0JM95	PARTS KIT,SEAL REPL	9B 5330-01-566-0987	1	PA	2Z	Z		1	EA		0		A								
5773203-1.2QA	03950	RING,WEARING	9B 4320-01-245-0827	7	PA	2Z	Z		1	EA		0										
5773203-1.3QA	03950	SETSCREW	9B 5305-01-245-0698	3	PA	2Z	Z		4	EA		0										
5773203-1.4QA	03950	STUD,PLAIN	9B 5307-01-245-0779	3	PA	2Z	Z		12	EA		0										
5773203-1.5QA	03950	NUT,PLAIN,HEXAGON	9B 5310-01-245-0722	3	PA	2Z	Z		12	EA		0										
5773203-1.6	53711	O-RING	9B 5331-01-005-0527	7	PA	2Z	Z		1	EA		0										
5773203-1.7.1 AND 12.6.4	53711	O-RING	9B 5331-00-165-1981	7	PA	0Z	Z		9	EA		0										
5773203-1.7QA	03950	PLUG,MACHINE THREAD	9B 5365-01-248-3798	3	PA	2Z	Z		4	EA		0										
5773203-1.8-3.4QA	03950	PACKING,PREFORMED	9B 5330-01-245-0729	7	PA	2Z	Z		2	EA		0										
5773203-1.8.1 AND 3.4.1	53711	O-RING	9B 5331-00-020-0105	7	PA	2Z	Z		2	EA		0										
5773203-1.9.1	53711	O-RING	9B 5331-00-167-5174	7	PA	0Z	Z		2	EA		0										
5773203-1.9QA	03950	PLUG,MACHINE THREAD	9B 5365-01-245-0730	7	PA	2Z	Z		2	EA		0										
5773203-1HQA	03950	HOUSING,LIQUID PUMP	7HH4320-01-245-0963	1	PA	2G	D		1	AY		Z0										
5773203-10.10QA	03950	RETAINER,PACKING	9B 5330-01-245-0740	1	PA	2Z	Z		1	EA		0										
5773203-10.11	53711	O-RING	9B 5331-00-165-1965	7	PA	2Z	Z		1	EA		0										
5773203-10.12QA	03950	RETAINER,PACKING	9B 5330-01-266-6244	3	PA	2Z	Z		1	EA		0										
5773203-10.13QA	03950	SCREW,CAP,SOCKET HE	9B 5305-01-245-0701	3	PA	2Z	Z		2	EA		0										
5773203-10.2	53711	O-RING	9B 5331-00-165-1953	7	PA	2Z	Z		1	EA		0										
5773203-10.4	53711	O-RING	9B 5331-00-165-1948	7	PA	2Z	Z		1	EA		0										
5773203-10A	53711	SEAL ASSEMBLY,SHAFT	9B 4320-01-269-8849	1	PA	2Z	Z		1	AY		0										
5773203-11.4	53711	O-RING	9B 5331-00-166-1020	7	PA	2Z	Z		1	EA		0										
5773203-11QA	03950	SEPARATOR ASSEMBLY	9B 4320-01-245-0860	1	PA	2Z	Z		1	AY		0										
5773203-12.5.1HAQA	03950	TUBE ASSEMBLY,METAL	9B 4710-01-255-2152	1	PA	2Z	Z		1	AY		0										
5773203-12.5.1HBQA	03950	TUBE ASSEMBLY,METAL	9B 4710-01-252-2380	1	PA	2Z	Z		1	AY		0										
5773203-12.5.2HQA	03950	TUBE ASSEMBLY,METAL	9B 4710-01-252-2381	1	PA	2Z	Z		1	AY		0										
5773203-12.5.3HQA	03950	TUBE ASSEMBLY,METAL	9B 4710-01-252-2382	1	PA	2Z	Z		1	AY		0										
5773203-12.6.1QA	03950	REDUCER,TUBE	9B 4730-01-245-0803	1	PA	2Z	Z		6	EA		0										
5773203-12.6.3QA	03950	REDUCER,TUBE	9B 4730-01-245-0804	1	PA	2Z	Z		6	EA		0										
5773203-12.6.5	53711	O-RING	9B 5331-00-166-0988	7	PA	0Z	Z		6	EA		0										
5773203-12.6.6AQA	03950	ADAPTER,STRAIGHT,FL	9B 4730-01-257-2344	1	PA	2Z	Z		1	EA		0										
5773203-12.6.6BQA	03950	ADAPTER,TUBE	9B 4730-01-252-1925	1	PA	2Z	Z		1	EA		0										
5773203-2.1QA	03950	PIN,STRAIGHT,HEADLE	9B 5315-01-245-0853	1	PA	2Z	Z		2	EA		0										

REF SYMBOL NO.	ITEM NAME	STOCK NO.	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT./COMP.	UI	AI	AOQ	4MC	QAC	1	2	3	4	5	6	7	8
	ALLOWANCE PARTS LIST (APL)													018880296			02/2015			2	
SHIP TYPE & HULL NO.	PROVISIONING													IDENTIFICATION NO.			DATE			PAGE	

Print Date 3/21/2015

Printed by IHS, Inc.
15 Inverness Way East, Englewood, CO 80112

ALLOWANCE PARTS LIST (APL)

EQUIPMENT/COMPONENT NOMENCLATURE/CHARACTERISTICS	TECHNICAL DOCUMENT NUMBER	MANUAL	IDENTIFICATION NO.	DATE	PAGE
PMPCTFGL 1KGPM 150PSI 3600RPM MCC VLT		PLAN	018880296	02/2015	3

CHARACTERISTICS

				PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT/COMP.	UI	ALLITEM	AOQ	4MC	QAC	ON BOARD ALLOWANCE TABLE NUMBER OF EQUIPMENT/COMPONENTS 1	2	3	4	5	6	7	8
5773203-2EQA	03950	IMPELLER,PUMP,CENTR	9B 4320-01-245-1159	1	PA	2Z	Z		1	EA		0										
5773203-24QA	03950	PUMP UNIT,CENTRIFUG	7HH4320-01-227-4925	1	PA	GD	D		1	EA		Z0										
5773203-3.2QA	03950	RING,WEARING	9B 4320-01-245-0828	7	PA	2Z	Z		1	EA		0										
5773203-3.3QA	03950	SETSCREW	9B 5305-01-245-0699	3	PA	2Z	Z		4	EA		0										
5773203-3HQA	03950	HEAD,SEAL ASSEMBLY	9B 4320-01-245-0859	7	PA	2Z	Z		1	AY		0										
5773203-4.1	53711	O-RING	9B 5331-00-167-5120	7	PA	0Z	Z		1	EA		0										
5773203-4QA	03950	SLEEVE,SHAFT,PUMP	9B 4320-01-245-0762	1	PA	2Z	Z		1	EA		0										
5773203-5QA	03950	WASHER,LOCK	9B 5310-01-245-0726	1	PA	2Z	Z		1	EA		0										
5773203-6QA	03950	NUT,PLAIN,CAP	9B 5310-01-248-0458	1	PA	2Z	Z		1	EA		0										
5773203-7QA	03950	GASKET	9B 5330-01-305-0241	3	PC	2Z	Z		1	EA		0										
5773203-8QA	03950	KEY,MACHINE	9B 5315-01-265-2170	1	PA	2Z	Z		1	EA		0										
5773203-9QA	03950	SCREW,CAP,SOCKET HE	9B 5305-01-245-0700	3	PA	2Z	Z		4	EA		0										
6-250MPGE\E-N/M	0JM95	GASKET	9B 5330-01-511-4907	1	PA	2Z	Z		1	EA		0		A								

MULTI-REFERENCE NUMBER	FSCM	PRIMARY REFERENCE NUMBER	MULTI-REFERENCE NUMBER	FSCM	PRIMARY REFERENCE NUMBER
-MPGE/E-N/M	0JM95	6-250MPGE\E-N/M	0-936-1955	71724	5773203-10.10QA
03-1.2	53711	5773203-1.2QA	03-1.3	53711	5773203-1.3QA
03-1.4	53711	5773203-1.4QA	03-1.5	53711	5773203-1.5QA
03-1.7	53711	5773203-1.7QA	03-1.8&3.4	53711	5773203-1.8-3.4QA
03-1.9	53711	5773203-1.9QA	03-1H	53711	5773203-1HQA
03-10.10	53711	5773203-10.10QA	03-10.13	53711	5773203-10.13QA
03-11	53711	5773203-11QA	03-12.5.1HA	53711	5773203-12.5.1HAQA
03-12.5.1HB	53711	5773203-12.5.1HBQA	03-12.5.2H	53711	5773203-12.5.2HQA
03-12.5.3H	53711	5773203-12.5.3HQA	03-12.6.1	53711	5773203-12.6.1QA
03-12.6.3	53711	5773203-12.6.3QA	03-12.6.6A	53711	5773203-12.5.2HQA
03-12.6.6A	53711	5773203-12.6.6AQA	03-12.6.6AQA	03950	5773203-12.5.2HQA
03-12.6.6B	53711	5773203-12.6.6BQA	03-2.1	53711	5773203-2.1QA
03-2E	53711	5773203-2EQA	03-24	53711	5773203-24QA
03-3.2	53711	5773203-3.2QA	03-3.3	53711	5773203-3.3QA

REF SYMBOL NO.	ITEM NAME	STOCK NO.	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT/COMP.	UI	AI	AOQ	4MC	QAC	1	2	3	4	5	6	7	8
	ALLOWANCE PARTS LIST (APL) PROVISIONING													018880296			02/2015			3	
SHIP TYPE & HULL NO.														IDENTIFICATION NO.			DATE			PAGE	

Print Date 3/21/2015

Printed by IHS, Inc.
15 Inverness Way East, Englewood, CO 80112

ALLOWANCE PARTS LIST (APL)

EQUIPMENT/COMPONENT NOMENCLATURE/CHARACTERISTICS PMPCTFGL 1KGPM 150PSI 3600RPM MCC VLT	TECHNICAL DOCUMENT NUMBER	MANUAL PLAN	IDENTIFICATION NO. 018880296	DATE 02/2015	PAGE 4

CHARACTERISTICS	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT./ COMP.	UI	ALLITEM	AOQ	4MC	QAC	ON BOARD ALLOWANCE TABLE NUMBER OF EQUIPMENT/COMPONENTS 1	2	3	4	5	6	7	8

MULTI-REFERENCE NUMBER	FSCM PRIMARY REFERENCE NUMBER	MULTI-REFERENCE NUMBER	FSCM PRIMARY REFERENCE NUMBER
03-3H	53711 5773203-3HQA	03-4	53711 5773203-4QA
03-5	57731 5773203-5QA	03-6	53711 5773203-6QA
03-7	53711 5773203-7QA	03-8	53711 5773203-8QA
03-9	53711 5773203-9QA	03 PCS 10A,10.2,10.4	53711 5773203-10A
03 PCS 11.1-11.4	53711 5773203-11QA	69462-1	71724 5773203-10A
8/1-013	53711 5773203-12.6.5	8/1-013	81348 5773203-12.6.5
8/1-024	81349 5773203-11.4	8/1-132	81349 5773203-4.1
8/1-230	81349 5773203-10.4	8/1-235	81349 5773203-10.2
8/1-248	81349 5773203-1.7.1 AND 12.6.4	8/1-248	81349 5773203-10.11
8/1-380	81349 5773203-1.6	8/2-908	81349 5773203-1.8.1 AND 3.4.1
8/2-910	81349 5773203-1.9.1	874	71724 5773203-11QA

THE LSSC OF AA INDICATES THE FOLLOWING:

1ST CHARACTER POSITION- A FULL SUPPORT: PROVIDE EQUIPMENT WILL FULL SUPPLY SYSTEMS SUPPORT FOR INDEFINITE PERIOD OF TIME. ENSURE THIS SUPPORT IS CONSISTENT WITH THE HSC APPROVED PLAN FOR MAINTENANCE, I.E. CORRECTIVE/PLANNED

2ND CHARACTER POSITION- A APL/AEL/SNSL METHOD: AN ALLOWANCE PARTS LIST (APL), PRELIMINARY ALLOWANCE LIST (PAL) OR ALLOWANCE EQUIPAGE LIST (AEL) IS AVAILABLE FOR THIS EQUIPMENT, AND ALLOWED SPARES/REPAIR PARTS ARE INCLUDED IN THE SNSL.

E N D

REF SYMBOL NO.	ITEM NAME	STOCK NO.	PARTMEC	SOURCE	MAINT	RECOV	NOTES	QTY. IN ONE EQPT./ COMP.	UI	AI	AOQ	4MC	QAC	1	2	3	4	5	6	7	8

	ALLOWANCE PARTS LIST (APL)	018880296	02/2015	4
SHIP TYPE & HULL NO.	PROVISIONING	IDENTIFICATION NO.	DATE	PAGE

Print Date 3/21/2015

Printed by IHS, Inc.
15 Inverness Way East, Englewood, CO 80112

LIST OF REFERENCES

Basten, Rob J. I., J. Marco J. Schutten, and Matthieu C. Van Der Heijden. 2009. “An Efficient Model Formulation for Level of Repair Analysis.” *Annals of Operations Research* 172(1): 119–142.

Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis.* Upper Saddle River, NJ: Prentice Hall.

Brassard, Michael, and Diane Ritter. 1994. *The Memory Jogger II.* Methuen, MA: GOAL/QPC.

Buffalo Pumps. 2015. “Navy/Marine.” Accessed July 30. http://www.buffalopumps.com/markets-applications/navy-marine/.

Burge, Stuart. 2011. “The Systems Engineering Tool Box.” *Burge Hughes Walsh Partnership: Trainers and Consultants in Lean, Six Sigma, Leading Change, Systems Engineering, and Systems Thinking.* http://www.burgehugheswalsh.co.uk/uploaded/documents/CD-Tool-Box-V1.0.pdf.

Chief of Naval Operations. 2007. *Condition Baased Maintenance (CBM) Policy: OPNAVINST 4790.16A.* Washington, DC: Chief of Naval Operations.

Chief of Naval Operations. 2010. *OPNAVINST 4700.7L: Maintenance Policy for United States Navy Ships.* Washington, DC: Chief of Naval Operations.

Chief of Naval Operations. 2013. *OPNAVINST 3120.47: Surface Ship Engineering Operational Cycle Program.* Washington, DC: Chief of Naval Operations.

Chief of Naval Operations. 2014a. *Optimized Fleet Response Plan: OPNAV Instruction 3000.15A.* Washington, DC: Chief of Naval Operations.

Chief of Naval Operations. 2014b. *Representative Intervals, Durations, and Repair Mandays for Depot Level Maintenance Availabilities of U.S. Navy Ships.* Washington, DC: Chief of Naval Operations.

Commander, Naval Regional Maintenance Center. 2009. *CNRMC Home.* https://navsea.portal.navy.mil/field/CNRMC/pages/home.aspx.

Commander, Naval Regional Maintenance Center. 2014. *Historical Top Growth by SWILN.* Norfolk, VA: Commander, Naval Regional Maintenance Center.

Commander, Naval Sea Systems Command. 1996. *Master Agreement for Repair and Alteration of Vessels; Master Ship Repair Agreemnt (MSRA) and Agreement for Boat Repair (ABR).* Arlington, VA: Commander, Naval Sea Systems Command.

Commander, Naval Sea Systems Command. 2007. *Reliability-Centered Maintenance (RCM) Handbook.* 1. Washington, DC: Commander, Naval Sea Systems Command.

Commander, Naval Sea Systems Command. 2009. *Reliability-Centered Maintenance (RCM) and Condition-Based Maintenance (CBM) Policy for Ships, Ship Systems, and Equipment: NAVSEAINST 4790.27.* Washington, DC: Commander, Naval Sea Systems Command.

Commander, Naval Sea Systems Command. 2011. *Inspect Exhaust Duct Assembly and Power Turbine Sixth Stage. Maintenance Requirement Card 11 4FHY N.* Washington, DC: Commander, Naval Sea Systems Command.

Commander, Naval Sea Systems Command. 2013. *MRC: 23 8SWH N, Exhaust Duct 2591*. Washington, DC: Commander, Naval Sea Systems Command.

Commander, Naval Sea Systems Command. 2014. *LM2500 Propulsion Gas Turbine Module: Tecnical Manual, Organizational Level Maintenance* . Vol. 2. Washington, DC: Commander, Naval Sea Systems Command.

Commander, Naval Surfaces Force, U.S. Pacific; Commander, Naval Surface Force, Atlantic; Commander, Naval Regional Maintenance Center. 2012. *Total Ships Readiness Assessment (TSRA).* San Diego, CA: Commander, Naval Surfaces Force.

Commander, Naval Surfaces Forces Atlantic. 2015. *1B4B Funding Brief for FY15 FY16 Rev 9.* Norfolk, VA: Commander, Naval Surfaces Forces Atlantic.

Commander, Naval Surfaces Forces Pacific. 2015. *4 AUG 15 N43 CUB Financial 1B4B Input FY15.* San Diego, CA: Commander, Naval Surfaces Forces Atlantic.

Commander, Naval Surfaces Forces. 2014. *Vision For The 2026 Surface Fleet.* San Diego, CA: Naval Surfaces Forces, U.S. Pacific Fleet.

Commander, Naval Surfaces Forces Pacific. 2015. *N43-1B4B (Depot Maint) FY15 Fiscal Execution*. San Diego, CA: Commander, Naval Surfaces Forces Pacific.

Commander, U.S. Fleet Forces Command and Commander, United States Pacific Fleet. 2014. "Optimal Fleet Response Plan—COMUSFLTFORCOM/COMPACFLT INST 3000.15A." Vers. 3000.15A. *Navy Forces Online Portal.* December 8. https://www.COMUSFLTFORCOM.portal.navy.mil/sites/hq.

Commander, United States Pacific Fleet. 2013. *COMPACTFLTINST 5450.124: Missions, Functions and Tasks of Commander, Naval Surfaces Forces , U.S. Pacific Fleet (CNSP) and Commander, U.S. Naval Surface Forces (CNSF).* Pearl Harbor, HI: Commander, United States Pacific Fleet.

Daley, Daniel. 2013. *Failure Modes and Failure Mechanisms.* Stony Point, NY: Continuing Education and Development, Inc.

Department of Defense. 2006. *Risk Management Guide for DoD Acquisition.* Washington, DC: Department of Defense.

Department of Defense. 2013. *Defense Acquisition Guidebook—Systems Engineering.* Washington, DC: Department of Defense.

Department of the Navy. 1990. *United States Navy Regulations 1990.* Washington, DC: Department of the Navy.

Deputy Chief of Naval Operations (Integration of Capabilities and Resources) (N8). 2013. *Report to Congress on the Annual Long Range Plan for Construction of Naval Vessels for FY2014*. Washington, DC: Office of the Chief of Naval Operations.

Gale, Dave. 2011. *Surface Team One, A Powerful Approach to Changing the Culture of the Surface Maintenance Community.* August 31. https://www.navalengineers.org/SiteCollectionDocuments/2011%20Proceedings%20Documents/FMMS2011/Presentations/Gale_Paper.pdf.

General Services Administration, DOD. NASA. 2005. "Subpart 16.2—Fixed-Price Contracts." https://www.acquisition.gov/?q=browse/far/16/2&searchTerms=SUBPART%2016.2%E2%80%94FIXED-PRICE%20CONTRACTS.

Gortney, Bill, and Harry Harris. 2014. "Applied Readiness." *Proceedings Magazine United States Naval Institute* 140(10): 40–45.

Gortney, Bill. 2014. *Optimizing the Fleet Response Plan.* Norfolk, VA: United States Fleet Forces Command.

Hirschman, Dale, C. W. Chesterman, Mathew Lemma, and Kenneth Mobley. 2009. "Fleet-Oriented Maintenance Figure or Merit (MFOM)." *American Society of Naval Engineers.* https://www.navalengineers.org/sitecollectiondocuments/2009%20proceedings%20documents/iss%202009/papers/hirschman_chesterman_leeker_schaum.pdf.

Hunt, Richard W., and David M. Thomas. 2012. "Surface Team One Charter." *USFF Portal.* January. https://usff.portal.navy.mil/sites/surflant/st1/resources/ST1%20charters/st1%20charter.pdf.

International Council on Systems Engineering. 2015. "What Is Systems Engineering." Accessed May 14. https://www.incose.org/AboutSE/WhatIsSE.

Langford, Gary O. 2012. *Engineering Systems Integration: Theory, Metrics, and Methods.* Boca Raton, FL: CRC Press.

Lescher, William, K. 2014. “Department of the Navy FY 2015 President's Budget.” *Financial Management and Comptroller.* http://www.finance.hq.navy.mil/FMB/15pres/DON_PB15_Press_Brief.pdf.

Mabus, Ray. 2013. “Remarks by the Honorable Ray Mabus. Secretary of the Navy. Surface Navy Association. Arlington, VA.” *America's Navy.* January 17. http://www.navy.mil/navydata/people/secnav/Mabus/Speech/surfacenavyassociation17Jan13%20final%20transcript.pdf.

Maritime DC & PPE Information Center. “Firemain System.” 2015. Accessed July 30. http://www.dcfpnavymil.org/Systems/Firemain/fmsys.htm.

Mathews, Tim, Mark Whitney, and Paul Sohl. 2013. *The United States Navy Depot Maintenance Strategic Plan.* Washington, DC: United States Navy.

Mun, Johnathan. 2010. *Modeling Risk + DVD, Applying Monte Carlo Risk Simulation, Strategic Real Options, Stochastic Forecasting, and Porfolio Optimization.* 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc.

Naval Sea Systems Command. 2002. *Propulsion Plant Manual: Propulsion System - Propulsion Plant System for Hulls CG-70 and Subsequent.* Vol. 1. Port Hueneme, CA: Naval Sea Systems Command.

Naval Sea Systems Command. 2009a. *Ship Information Book: CG 52 USS BUNKER HILL Machinery Plant: Propulsion and Auxiliary Support Systems—General Design and Operating Procedures, Part 1.* 1. Vol. 2. Port Hueneme, CA: Naval Sea Systems.

Naval Sea Systems Command. 2009b. *Strategic Business Plan: 2009–2013.* Washington, DC: Naval Sea Systems Command.

Naval Sea Systems Command. 2012. *Navy Standard Titanium Centrifugal Pump 1000 GPM*. Technical Manual. Port Hueneme, CA: NAVSURFWARCENDIV NSDSA.

Naval Supply Systems Command. 2015. “NAVSUP.*”* Accessed April 11. https://www.navsup.navy.mil/navsup.

Naval Surface Warfare Center. 2015. “Home—Naval Surface Warfare Center.” Accessed April 12. http://www.navsea.navy.mil/nswc/default.aspx.

Nowlan, F, Stanley, and Howard, F. Heap. 1978. *Reliability-Centered Maintenance.* Washington, DC: Office of Assistant Secretary of Defense (Manpower, Reserve Affairs and Logistics).

Office of the Chief of Naval Operations. 2010a. "Maintenance Policy for United States Navy Ships: OPNAVINST 4700.7L." Vers. 4700.7L. *Department of the Navy Issuances.* http://doni.daps.dla.mil/.

Office of the Chief of Naval Operations. 2010b. *Missions, Functions, and Tasks of Commander, United States Pacific Fleet.* Washington, DC: Office of the Chief of Naval Operations.

Office of the Under Secretary of Defense (Comproller)/Chief Financial Officer. 2014. *Fiscal Year 2015 Budget Request Overview.* Washington, DC: Department of Defense.

Panetta, Leon E. 2012. *Sustaining U.S. Global Leadership: Priorities for 21st Century Defense.* Washington, DC: Department of Defense.

Peters, Mike. 2006. "American Shipbuilding: An Industry in Crisis." *United States Naval Institute. Proceedings* 123(2): 15–19.

Schonberg, Johannes. 2013. "SEA SWAP REDUX." *United States Naval Institute Proceedings* 139(1): 28–33.

Secretary of the Navy. 2013. "Remarks by the Honorable Ray Mabus. Secretary of the Navy. Surface Navy Association. Arlington, VA." *America's Navy.* January 17. http://www.navy.mil/navydata/people/secnav/Mabus/Speech/surfacenavyassociation17Jan13%20final%20transcript.pdf.

Surface Warfare Officer School. 2000. *LM2500 Material Readiness.* PowerPoint. Newport, RI: Surface Warfare Officer School.

U.S. Fleet Forces Command. 2013. *COMUSFLTFORCOMINST 4790.3: Joint Fleet Maintenance Manual (JFFM).* Rev C, Change 1. Vol. II. Manual. Washington, DC: U.S. Fleet Forces Command.

U.S. Navy. 2006. *System of Systems Engineering Guide: Considerations for Systems Engineering in a System of Systems Environment.*

U.S. Navy. 2014. *About the Navy.* Accessed March 28. http://navy.com/about.html.

U.S. Navy. 2015. *Status of the Navy.* Accessed July 25. http://www.navy.mil/navydata/nav_legacy.asp?id=146.

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