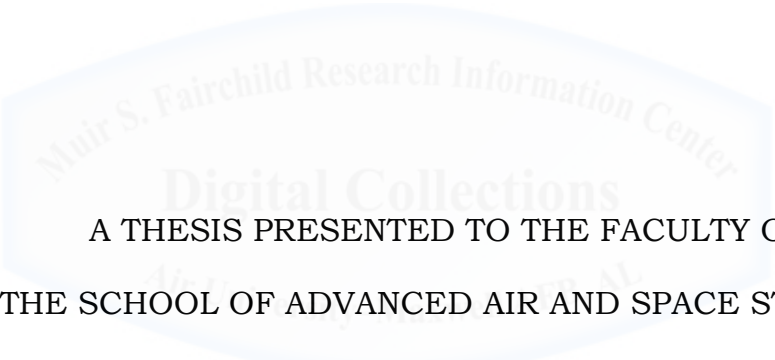


BLUE TO GREEN:
HOW PAST ENERGY TRANSITIONS INFORM THE DEPARTMENT
OF DEFENSE'S ENERGY STRATEGY

BY

CORY A. COOK, MAJ, USAF



A THESIS PRESENTED TO THE FACULTY OF
THE SCHOOL OF ADVANCED AIR AND SPACE STUDIES
FOR COMPLETION OF GRADUATION REQUIREMENTS

SCHOOL OF ADVANCED AIR AND SPACE STUDIES

AIR UNIVERSITY

MAXWELL AIR FORCE BASE, ALABAMA

JUNE 2012

DISCLAIMER

The conclusions and opinions expressed in this document are those of the author. They do not reflect the official position of the United States Government, Department of Defense, the United States Air Force, or Air University. In accordance with Air Force Instruction 51-303, it is not copyrighted, but is the property of the United States Government.



ABOUT THE AUTHOR

Major Cory Cook, a student at the Air Force's School of Advanced Air and Space Studies at Maxwell AFB, Alabama, is a command pilot with more than 3,500 flight hours in the C-9A and the C-17A. Major Cook was born and raised in San Jose, California, and graduated from Norwich University in 1999, earning his commission through the Reserve Officer Training Corps. He is also a graduate of the US Marine Corps Command and Staff College. Major Cook has served in several operational flying assignments throughout his career. In doing so, he has flown MEDEVAC missions throughout the Pacific theater of operations and combat missions in support of both Operation Enduring Freedom and Operation Iraqi Freedom. Major Cook is married to the love of his life, and together he and his wife enjoy spending time on the beach with their three fantastic children.



ACKNOWLEDGMENTS

This paper would not have been written were it not for the love and support of my wife and children. My wife's enduring strength and patience is a testament to what a wonderful woman she truly is. The boundless energy possessed by my kids was a source of inspiration, and their curiosity, vigor, and understanding helped keep me sane over the past year.

I would also like to thank the SAASS faculty for introducing me to a new world of thinking. Dr. Alex Roland's seminars opened my eyes to the impact of technology while Dr. Rich Muller's direction helped lay the foundation that I attempted to build upon in this paper. Without their mentorship and the critical instruction they provided, this paper would have been nothing more than a collection of my musings on the importance of energy. The dedication of the SAASS faculty to their craft and to their students is nothing short of astounding.

Finally, I would like to thank my Advisor, Colonel Schultz, and my Reader, Colonel Buono, whose insightful commentary and steadfast guidance helped me turn a haphazard mix of ideas into coherent thought. This paper is the beneficiary of their combined wisdom and tutelage from the beginning.

ABSTRACT

The Department of Defense (DOD) combines the most powerful collection of armed forces on the planet. To operate this remarkable array of men and machines the DOD depends on the steady supply of a finite resource: oil. To mitigate its singular dependence on oil, the DOD is examining a myriad of alternative energy sources. However, incorporating a new energy source into an existing energy infrastructure is a daunting task that can fundamentally shake an organization to its core. Yet, as the DOD moves forward in assessing new energy technologies it can draw from its rich history of energy transitions and technological evolution to inform its decisions. This study examines three such transformations: the Navy's transition from sail- to steam-powered warships, the replacement of diesel-electric submarines by nuclear-powered submarines, and the DOD's current efforts to incorporate renewable biofuels into its existing oil-based infrastructure. This study evaluates each case study through several different lenses in an effort to distill lessons learned and aid the recognition of recurring themes. In doing so, it builds upon several theories of technological change while also relying on a variety of analytical tools to determine those factors that hindered or aided the military's conversion of a primary energy source. In conclusion, this study recalls and synthesizes the salient points from each example in order to provide a framework for analyzing potential energy transitions of the future.

CONTENTS

Chapter

DISCLAIMER	ii
ABOUT THE AUTHOR	iii
ACKNOWLEDGMENTS.....	iv
ABSTRACT.....	v
Introduction.....	1
1 A Theoretical Framework	8
2 The Navy's Transition from Sail to Steam	19
3 Diesel-Electric to Nuclear-Powered Submarines	45
4 Renewable Biofuel Technology.....	70
5 Conclusion.....	96
Bibliography.....	108

Illustrations

Figure

1 Factors Affecting the Adoption of Steam-Powered Ships	32
2 Spot Price of Oil, 1986-2012.....	74

Introduction – A Context for Analyzing Energy Innovation

Energy is an essential component for virtually all military activities. It serves as the lifeblood of the global economy and is a primary requirement for sustaining America's military superiority. Over the past 70 years, the American military has primarily turned to oil to meet its energy demands. Over time, the Department of Defense's (DOD) thirst for oil has grown into dependence and that dependence now presents a strategic vulnerability for America's armed forces. This predicament is amplified by the growing worldwide demand for oil and political instability in several of the largest oil-producing nations. Therefore, a critical challenge for the foreseeable future is "to manage the consequences of unavoidable dependence on oil and gas...and to begin the transition to an economy that relies less on petroleum."¹

For the DOD, creating an energy system that relies less on petroleum is a monumental task. To prepare the DOD for such a substantial transition, Congress instructed the DOD to develop a new strategy that aims to curb the military's demand for oil. In May 2011, these efforts manifested into the DOD's new strategy for energy, titled *Energy for the Warfighter: Operational Energy Strategy*. Led by the Deputy Secretary of Defense, the strategy's three-part focus sets out to *reduce the demand* for energy in military operations, *expand the supply* of energy available to the military, and *build energy security* into the future force.²

¹ John Deutch and James R. Schlesinger, "National Security Consequences of U.S. Oil Dependency," Council on Foreign Relations Independent Task Force Report No. 58 (New York: Council on Foreign Relations, Inc., 2006), 4.

² US Department of Defense, *Energy for the Warfighter: Operational Energy Strategy* May 2011, http://energy.defense.gov/OES_report_to_congress.pdf (accessed January 15, 2012).

Of the three tenets of the DOD's energy strategy, expanding the sources of supply is arguably the most critical. Given the fact that there is a finite amount of oil on the planet, that demand is steadily increasing, and that the reliability of uninterrupted supply is increasingly questionable, reducing the rate that DOD consumes oil simply delays the inevitable, it does not solve the problem. Likewise, building energy security into the future force assures that the energy resources currently in existence will be made available to the military, but it does not address the fact that eventually the planet's supply of petroleum-based energy will be exhausted. Developing a new energy infrastructure is critical because it is the only component of the DOD's strategy that provides a viable course of action over the long term. To meet the intent of the DOD's Operational Energy Strategy, the services are considering the development and incorporation of a variety of new and renewable energy technologies.³ However, the prospect of developing new energy technologies and making the necessary doctrinal and equipment changes that effectively leverage these technological advances calls for closer inspection. The reason for this added attention is simple, when it comes to innovation and technological change, the military's record of successfully and efficiently achieving technological change is mottled at best.

The reasons for the DOD's struggles with innovation and change are varied, and according to social scientists and military historians they are to be expected. Often, these difficulties are associated with the DOD's organizational structure. Max Weber would suggest that as a large bureaucracy, the DOD tends to emphasize regularity, speed, and

³ The DOD and the Department of Energy are currently analyzing a myriad of new potential energy sources. For more on the Defense Advanced Research Project Agency's (DARPA) renewable energy programs see http://www.darpa.mil/Our_Work/STO/Programs/Biofuels.aspx DARPA. For more on the DOE's experimental projects see the National Energy Technology Laboratory's website at <http://www.netl.doe.gov>.

efficiency; and to achieve these effects, it manages by task division and regulation.⁴ The cumulative effect of this organizational character is a resistance to change. Stephen Rosen points out, “Almost everything we know in theory about large bureaucracies suggests not only are they hard to change, but that they are *designed not to change*”(emphasis in original).⁵ Other reasons why change is difficult include vested interests, cultural inertia, and the financial costs of upgrading or changing physical systems. Illustrating the seemingly timeless difficulties of instilling change, Niccolò Machiavelli wrote, “There is nothing more difficult to carry out, nor more doubtful of success, nor more dangerous to handle, than to initiate a new order of things...the reformer has enemies in all those who profit by the old order, and only lukewarm defenders in those who would profit by the new.”⁶

To overcome some of the difficulties associated with innovation and technological change, DOD leaders charged with effecting the transition to new energy sources would be wise to look at history for successful examples of energy-related military innovation and adoption. Accordingly, the US Navy’s record of energy transformations provides a rich body of experience to inform current and future efforts. The incorporation of two new energy technologies stands out as particularly instructive: the adoption of steam-powered warships during the age of sail, and the Navy’s decision to replace diesel-electric submarines with nuclear-powered submarines.

These examples share several common themes with the situation faced by the DOD today. One obvious thread connecting the current and past case studies is energy. There are countless examples of

⁴ Gareth Morgan, *Images of Organization* (Thousand Oaks, CA: Sage Publications, 2006), 17.

⁵ Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military* (Ithaca, NY: Cornell University Press, 1991), 2.

⁶ Niccolò Machiavelli, *The Prince and The Discourses* (New York: Random House, 1950), 21.

technological innovation available in the annals of military history; however, the naval examples mentioned previously were specifically chosen because they involve the development and incorporation of new energy technologies. A second thread connecting the past and present concerns the existence of the existing energy infrastructure. In this instance, each case study examines a situation where a new energy technology was introduced into an existing energy structure considered adequate by conventional wisdom. For defense officials in each case, the dominant paradigm was largely satisfactory, and there was no acute crisis requiring a major transformation.⁷ While this may seem like a minor point, there is an important difference between innovating by choice and innovating by necessity.⁸ A final thread tying these examples together is the civil-military connection. As we will see, in each case study innovation relied heavily on the cooperative effort between civilian industries and the military.

In addition to the general similarities between case studies, each historical example also offers unique insights that can inform the DOD's current situation while providing a framework for future energy transitions to build upon. For example, the sail-to-steam case study is a classic example of how internal sociocultural factors can affect the incorporation of new energy technologies in the military. This case study also examines why a service might intentionally bypass the newest technological developments and the effects of this decision. In addition to these important points, the sail-to-steam example explores the role of mutually supporting technologies while assessing the symbiotic relationship between a principal technological artifact and those

⁷ For more on paradigms, see Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago, IL: University of Chicago Press, 1996).

⁸ For example, charcoal burning exhausted England's timber supply, providing a powerful incentive for the development of coke smelting and dramatically increasing iron production. See Charles E. Gibson, *The Story of the Ship* (New York: Henry Schuman, 1948), 181.

technological advances that aid in the new technology's advancement and acceptance.

Likewise, the development of nuclear-powered submarines is informative on several levels. Unlike the sail-to-steam example in which the Navy was largely a consumer of the technology available at the time, the diesel-to-nuclear case study reveals the implications of operating on the cutting edge of a new energy technology. Furthermore, where the Navy's transition to a steam-powered fleet took over one hundred years to complete, the Navy's transition to nuclear submarines was decided after only two years. Thus, the Navy's decision to adopt nuclear technology provides an excellent forum for analyzing how a revolutionary technology can facilitate a rapid technological transition. Beyond these salient points, the nuclear case study is an excellent example of how international politics and interservice rivalry can influence military innovation, and how systems builders can exploit their relationships with government officials and commercial industry to overcome the major systemic hurdles that inhibit innovation.

Like the Navy's transition to steam-powered ships and nuclear-powered submarines, the DOD's current efforts to adopt renewable biofuels offer several unique insights that can inform future energy policy. Foremost among these is the challenge of creating energy solutions at the scale required by America's military forces. Whereas the first two case studies are confined to specific weapons systems within the Navy, the final case study examines the challenges of transitioning the entire DOD away from its traditional energy infrastructure. The biofuel case study also addresses the complexity of developing, adopting, and incorporating technological innovations in a wartime environment while assessing the impact of efficiency-based energy solutions on the DOD's ability to transition to new energy sources.

While not all encompassing, after being examined through the theoretical lens of historians and social scientists, these examples should provide an excellent foundation from which to inform the proposed energy transitions of the future. To this end, Chapter 1 establishes the theoretical framework used to examine the historical and current case studies. Chapter 2 explores the evolution of steam technology in the US Navy from marine steam power's origins in 1807 through the end of the nineteenth century. Picking up at the end of World War II, Chapter 3 examines the advent of nuclear-powered submarines. Chapter 4 continues the methodological approach from Chapters 2 and 3, but applies the previously established theoretical framework to the DOD's current engagement with renewable biofuel technology. Chapter 5 provides a synthesis of the lessons learned from the historical case studies, contrasts these lessons against the present day case study, and offers insights relevant to a strategy of energy innovation.

Before beginning, it is important to heed a word of caution.

Writing on the study of history, William H. McNeill observed:

...the lessons of history, though supremely valuable when wisely formulated, become grossly misleading when oversimplifiers try to transfer them mechanically from one age to another, or from one place to another. Anyone who claims to perform such a feat is sadly self-deceived. Practical wisdom requires us instead to expect differences as well as similarities, changes as well as continuities – always and everywhere.⁹

Were it not for McNeill's advice, it would be tempting to take the lessons learned from the current and historical examples and use these lessons to make prescriptive recommendations on how the DOD should usher in a new era of energy technology. That is not the intent of this thesis. Instead, it aims to place the DOD's current energy scenario into its

⁹ William H. McNeill, "Why Study History?" <http://www.historians.org/pubs/archives/whmcneillwhystudyhistory.htm> (accessed December 17, 2011).

proper historical context. By doing so, the aim is to distill the prominent concepts from the aforementioned energy transitions, and use those concepts to help inform, not direct, the DOD-wide energy transformation of tomorrow.



Chapter 1

A Theoretical Framework

To understand the DOD's current energy initiatives and the associated technological change within the services, this thesis builds on theories of technological change and applies the explanatory power of these theories to historical and contemporary case studies. This chapter brings the scholarship of several prominent theorists to light, focusing primarily on the fields of technological change and military innovation. To this end, the theories explored here serve several purposes. First, they define the field of study being examined. By focusing exclusively on technological change and military innovation, they indirectly declare other avenues of approach beyond the scope of this study.¹⁰ Second, they serve as a common foundation from which to assess the different aspects of each case study. Finally, by providing a common starting point, they facilitate useful comparisons between three unique transformations that occurred during three unique eras. In addition to establishing a theoretical foundation for the rest of the thesis, this chapter describes the analytical framework used within each case study. In doing so, it defines how this investigation analyzes the pertinent historical context, quantifies the changes that took place, and assesses the factors that contributed to the eventual outcome.

Case Study Organization

Case studies will be subject to analysis in three main areas. The first section of each case study examines *what* in the existing system changed. In this section the study assesses the context in which change took place. Here, the study looks at physical systems, paradigms, and

¹⁰ In assessing the utility of theory, I have borrowed from Harold Winton's essay, "An Imperfect Jewel." See Harold R. Winton, "An Imperfect Jewel: Military Theory and the Military Profession" in *Journal of Strategic Studies*, Vol. 34, Iss. 6, (2011), 853-877.

culture to determine the degree of penetration the existing technology had achieved, the sources of resistance to change, and the level of inertia overcome by the challenging energy source. The second section of each case study describes *how* the existing system changed. Here the study takes a historical view in order to illustrate how the transition occurred. In addition, the second section of each case study examines the process of adopting a new technology, the advantages and disadvantages of innovation, and the ramifications of transformation on the individual services. Finally, the third section of each case study explores *why* the change happened. Here, using the theories of military innovation and technological change posited by various authors and discussed in this chapter, each case study assesses the internal and external factors that influenced the development, adoption, and incorporation of new energy technology.

The first two case studies respectively examine the Navy's decision to convert its fleet from a sail- to a steam-powered force and the Navy's decision to switch from diesel-powered to nuclear powered submarines. After analyzing the steam and nuclear case studies, the same analytical framework is applied to the DOD's efforts to incorporate renewable biofuel technology into the military's current energy system. Using this theory-based analysis of two historical case studies and one contemporary case study, the conclusion synthesizes the relevant lessons, illustrates the historical hindrances and accelerants of technological change, and makes recommendations for DOD policy-makers charged with effecting energy transformations in the future.

What Changes During Technological Innovation

The first group of theories provides useful tools for answering the question, "What changed?" These theories facilitate a structured approach to quantifying the social and physical context prior to transformation. By focusing on the entities that changed and those that

were affected by the eventual change, these theories help explain how infrastructure, vested interests, bureaucracy, politics, and cultural inertia affect the incorporation of new technologies. One theoretical framework that is particularly helpful in this sense is Edward Constant's discussion of technological paradigms. Borrowing heavily from Thomas Kuhn's work on paradigms within the scientific community, Constant's focus on how technologies evolve and how societies react to innovation is directly applicable to this study.¹¹ For Constant, a technological paradigm consists of a technological artifact sustained by a physical and cultural framework devoted to the use and maintenance of that artifact.¹² An example of a technological artifact is the diesel-electric submarine. For almost 50 years, when it came to powering submarines, the US Navy based its technological paradigm on the diesel-electric motor. Over that span, engineers made improvements to the diesel-electric operating system, gained efficiencies, and improved performance. However, the essence of submersible boat propulsion changed very little until challenged by nuclear technology. As the historical case studies will show, a technological paradigm establishes the bounds for experimentation and development, and in doing so, defines Constant's concept of "normal technology."

Similar to Kuhn's description of normal science, normal technology comprises the actions that improve on the accepted tradition or use of an artifact. When normal technology is occurring, engineers improve on the existing artifact to solve problems that have vexed the community of practitioners.¹³ For example, 16th and 17th century sailors struggled to maneuver large ships in tight spaces under certain wind conditions. To solve this puzzle, sail planners experimented with different sized sails

¹¹ Kuhn, *The Structure of Scientific Revolutions*.

¹² Edward W. Constant, II, *The Origins of the Turbojet Revolution*, (Baltimore, MD: The Johns Hopkins University Press, 1980), 6-32.

¹³ Constant, *The Origins of the Turbojet Revolution*, 10-11.

and new sail configurations until a sufficient balance of fore and aft sails enabled ships to travel forward with a sufficiently reduced tack.¹⁴

Normal technology comprises this development process, expanding the scope and application of the paradigm's central artifact – in this case the sailing ship. By extending the paradigm and making an artifact more useful, normal technology entrenches the paradigm into the existing community of practitioners. As technological paradigms become entrenched, their central artifact can become ubiquitous, making changes more difficult, more expensive, and harder to justify. Put simply, "Few practitioners will abandon a highly successful normal technology in the absence of a convincing alternative."¹⁵

Sub-communities are another useful concept derived from Constant's discussion of technological paradigms. Sub-communities are those groups of actors who have either a direct or an indirect influence on the development of the primary artifact. To illustrate his case, Constant notes that a jet engine manufacturer must work within bounds provided by the airframe community, which in turn must meet the expectations of a customer while conforming to the limits placed by physical structures such as runways and fuel types.¹⁶ These second- and third-order groups are sub-communities, and their role is crucial to the development of new technologies. As the sail-to-steam case study illustrates in Chapter 2, change in one sub-community affects the interests of the other communities, creating a situation in which sub-communities can exercise veto power over significant deviations from standard practice. To mitigate this veto power, instigators of radical change must persuade the other communities that the overall gains to the system are worth the costs to the individuals. This intercourse

¹⁴ Charles E. Gibson, *The Story of the Ship* (New York: Henry Schuman, 1948), 125.

¹⁵ Edward W. Constant II, "A Model for Technological Change Applied to the Turbojet Revolution" in *Technology and Culture*, Vol. 14, No. 4, (October 1973), 553-572.

¹⁶ Constant, *The Origins of the Turbojet Revolution*, 12-14.

between sub-communities is a causal factor in the technological persistence of existing artifacts.¹⁷ The vested interests of any one community can lead to internal resistance to change, while the interaction and consensus building with all other relevant sub-communities can lead to external opposition to change.¹⁸

The concept of technological co-evolution is another helpful tool in Constant's technological paradigm model. Co-evolution refers to the joint evolution of two or more technologies where the development of one technology intimately affects the development of the others.¹⁹ As we will see, technological co-evolution is an especially useful way of accounting for the simultaneous development of mutually supporting technological artifacts such as the steam engine and the screw propeller.

The work of Thomas Hughes forms the second leg of the analytical framework used here to examine the three selected case studies. Thomas Hughes' concepts of technological systems and technological momentum provide a valuable way of analyzing existing systems prior to the introduction of new technology. According to Hughes, a technological system is a conglomeration of socially constructed artifacts and organizations, assembled together to solve problems or fulfill goals.²⁰ Technological systems consist of various physical components and structures, in addition to a network of political, social, and economic

¹⁷ For more on the interaction of technological sub-communities see Constant, *The Origins of the Turbojet Revolution*; and Edward W. Constant II, "Communities and Hierarchies: Structure in the Practice of Science and Technology," in *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant?*, ed. Rachel Laudan, (Hingham, MA: Kluwer Academic Publishers, 1984), 27-46.

¹⁸ Constant, *The Origins of the Turbojet Revolution*, 12.

¹⁹ Constant, *The Origins of the Turbojet Revolution*, 14.

²⁰ Social constructivists argue that the social environment shapes the technical characteristics of the artifact in question. In this view, the social groups that constitute the environment define and solve the problems that arise during development through the process of learning. For more on social construction, see Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," in *The Social Construction of Technological Systems*, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1987), 17-26.

forces that control and shape the technology. Together, the interaction between the physical technology and the societal factors constitutes a “seamless web” that both shapes and is shaped by society.²¹

In response to the rigid theories of technological determinism and social constructivism, Hughes developed the idea of technological momentum.²² Positing that large and mature technological systems tend to shape society rather than be shaped by it, Hughes argues that technological momentum exists somewhere between the two theoretical poles of determinism and constructivism. In this construct, a technological system’s momentum is primarily a function of time and size, and thus is neither predetermined nor fixed in place. Hughes contends that factors such as acquired skill and knowledge, special purpose machines and processes, physical structures, and organizational bureaucracy increase a system’s technological momentum. Furthermore, as the technological system grows older and more mature it gains momentum, making it less susceptible to sociocultural influences, more independent of outside pressure, and thus more deterministic.²³

A final aspect of Thomas Hughes’s work that is relevant to the selected case studies is the reverse salient. Hughes defines reverse salients as those “components in the system that have fallen behind or

²¹ Thomas P. Hughes, “The Evolution of Large Technological Systems,” in *The Social Construction of Technological Systems*, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, MA: The MIT Press, 1987), 51-56.

²² Technological determinists argue that technological artifacts have a sense of causal efficacy, meaning that complex events are the inescapable result of a technological innovation. Technological determinism looks at the effects of the invention, noting how use of the particular artifact determines the course of human events. For more on technological determinism see Merritt Roe Smith, “Technological Determinism in American Culture,” in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds. Merritt Roe Smith and Leo Marx (Cambridge, MA: The MIT Press, 1994), 1-36; and Robert L. Heilbroner, “Technological Determinism Revisited,” in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds. Merritt Roe Smith and Leo Marx (Cambridge, MA: The MIT Press, 1994), 67-78.

²³ Thomas P. Hughes, “Technological Momentum,” in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds. Merritt Roe Smith and Leo Marx (Cambridge, MA: The MIT Press, 1994), 101-112.

are out of phase with the others.”²⁴ The concept of a reverse salient is useful in that it calls attention to those components in expanding systems that hinder the progress of the system at large and are therefore in need of attention. As all three case studies will show, reverse salients are a common feature of expanding technological systems, and failure to resolve them can inhibit a technological system’s ability to evolve, resulting in its subsequent dismissal as a viable alternative.²⁵

Together, the theories of Edward Constant and Thomas Hughes provide insight for understanding the context, social factors, and physical environment that comprised the existing system when new technologies were introduced. When applied to historical case studies of energy transition, these theories help specify what changed, what factors were overcome, and what forces may have been acting to prevent innovation from occurring in the first place.

Why Change Occurs

In the analysis section of each case study, this thesis utilizes varying theoretical explanations to assess why change occurred, why it stagnated, and what factors either catalyzed or attenuated innovation. While drawing on the work of several historians and social scientists, the analytical section of each case study will predominantly feature the theories of Barry Posen and Stephen Peter Rosen.

In his book *The Sources of Military Doctrine*, Posen argues that balance-of-power theory better explains changes in military doctrine than organization theory.²⁶ In crafting his argument for balance of power theory, Posen makes the following hypotheses:

²⁴ Hughes, “The Evolution of Large Technological Systems,” 73.

²⁵ Hughes, “The Evolution of Large Technological Systems,” 73-75.

²⁶ Barry Posen describes organization theory as “a state’s action in international politics as the outcome of pulling and hauling among various self-interested, semiautonomous military and civilian bureaucracies.” See Barry R. Posen, *The Sources of Military Doctrine: France, Germany, and Britain Between the World Wars* (Ithaca, NY: Cornell University Press, 1984), 7.

- Fear for the state's security or survival is a general cause of civilian intervention in military matters
- Fear for the state's security or survival increases the military's receptivity to outside criticism while sharpening the military's self-critical faculties
- The government of a politically isolated state will pay increased attention to the affairs of its military
- Civilian intervention is often a primary driver of innovation in the military²⁷

In addition to concluding that civilian intervention is often required to prompt military innovation, Posen also suggests reasons why the military is resistant to innovation, and conversely, reasons that compel the military to accept innovation. Drawing on organization behavior theory, Posen argues that institutionalization and the inherent uncertainty associated with new technology make autonomous innovation and the acceptance of new technologies a rare occurrence in the military. Posen notes that senior military leaders often achieve their lofty positions by mastering the current doctrine; as such, they are reluctant to engender their own obsolescence by promoting the development of new doctrine.²⁸ Finally, based on the military's need to reduce uncertainty and maintain its control within the civil-military relationship, he suggests three factors will compel the military to accept innovation: failure, pressure from an outside force, and the desire to increase power.²⁹

In contrast to Posen's focus on the external causes of military innovation, in his book *Winning the Next War*, Stephen Rosen attributes innovation to the internal workings of military organizations. Rosen points to a number of examples in which defeat in war was "neither necessary nor sufficient to produce innovation," while at the same time

²⁷ Posen, *The Sources of Military Doctrine*, 74-76.

²⁸ Posen, *The Sources of Military Doctrine*, 54, 224.

²⁹ Posen, *The Sources of Military Doctrine*, 47.

recalling examples of military organizations that innovated without suffering defeat on the battlefield.³⁰ Instead of depending on civilian intervention, Rosen argues that military innovation depends on senior military leaders who can “fight the political battles for the careers of officers involved in the innovation so that the intellectual breakthroughs could be translated into real changes in capabilities.”³¹ Rosen points out that to be effective, senior officers who championed innovation had to first develop their own credibility by establishing a record of excellence in the military’s traditional performance areas. Once accomplished, they had the necessary power, authority, and freedom of movement to create new career paths for the younger officers charged with developing and implementing the new doctrine.³²

Another useful facet of Rosen’s work is his comparison of innovation during peacetime and wartime. Rosen challenges the traditional view that the pressures and incentives of war lead to rapid innovation and technological advancement. Instead, he argues that military innovation conceived in peacetime is more likely to satisfy military requirements and endure. In large part, Rosen attributes the success of peacetime military innovation to the time it takes to work through the innovation process, stating that in wartime, temporal demands restrict the military from conducting a rigorous analysis of strategic demands. Conversely, during peacetime military innovators have the time to develop the supporting analytical infrastructure required to accurately assess the effectiveness of new technological developments.³³

In addition to the theories of Posen and Rosen, Owen Coté and Harvey Sapolsky’s analysis of interservice rivalry’s impact on innovation

³⁰ Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military*, (Ithaca, NY: Cornell University Press, 1991), 9.

³¹ Rosen, *Winning the Next War*, 82.

³² Rosen, *Winning the Next War*, 76-105.

³³ Rosen, *Winning the Next War*, 179-182.

is useful here as well. For instance, while the Navy was working to develop nuclear-powered submarines, Army and Air Force officers were developing atomic programs to help their respective services better compete for a limited budget that was increasingly nuclear focused. Unlike Posen and Rosen, Coté and Sapolsky suggest that civilian and military leaders play an equally important role in military innovation. More importantly, they see interservice rivalry as a positive catalyst of military innovation. According to their rivalry theory, individual organizations competing for influence and a limited defense budget have strong motivation for improvement and creativity. Conversely, collaboration and collusion during times of financial plenty have a deleterious effect on innovation.³⁴ Clarifying this point, Sapolsky astutely noted, "There is no better spur to candor, error correction, and creativity in defense planning than a very tight budget and a few smart rivals competing for budget share."³⁵

Overall, it is important to remember that the incorporation of new energy technologies is a complicated affair that defies prescriptive answers. However, this inherent complexity should not preclude the attempt to decipher those factors that encourage and prevent successful innovation. By closely examining the factors that advance and discourage technological change, the DOD can better prepare the services to incorporate the next generation of energy technology. To this end, the aim of these theories is not to eliminate the problems posed by innovation and technological change. Instead, they are designed to illuminate the relevant aspects of each study. Thus, the theories presented here are valuable for defining, categorizing, and explaining the field of study under investigation. However, they can never fully replicate

³⁴ Owen R. Coté Jr., "The Politics of Innovative Military Doctrine: The U.S. Navy and Fleet Ballistic Missiles," (Ph.D. Dissertation, Massachusetts Institute of Technology, 1996), 88-94.

³⁵ Harvey M. Sapolsky, "The Interservice Competition Solution," in *Breakthroughs*, Vol. 5, No. 1, (Spring 1996), 3.

reality and cannot possibly account for the infinite number of variables in the real world.³⁶



³⁶ Winton, "An Imperfect Jewel," 853-877.

Chapter 2

The Navy's Transition from Sail to Steam

The first energy transition demonstrated by an American military force was the Navy's transformation from sail- to steam-powered warships. Taking place over the course of nearly 100 years, this evolutionary change bore witness to the entire spectrum of social, physical, environmental, and political factors. This timeframe saw periods of unprecedented foresight and vision contrasted against eras of retrenchment, stubbornness, and self-interested political wrangling. The transition occurred during intervals of relative peace, and it unfolded during one of the most savage wars in American history. The transformation pitted outspoken senior leaders from both sides of the argument against each other and threatened to sink the historical legacy of the Navy's line officer corps. Beyond all of this, the sail-to-steam case study demonstrates the profoundly destabilizing effect new technologies can have on the military. Furthermore, this case reinforces the notion that bureaucratic inertia and the military's traditional warrior ethos can act as powerful deterrents against the adoption of new military technologies.

How the Navy managed to overcome such resistance is the central theme of this case study. As such, it illustrates the broad array of factors that inhibited adoption as well as the technological, external, and political factors that prompted the Navy and the nation's civilian leadership to eventually give up the notion of sail-powered warships. This analysis begins by assessing the technological momentum of the Navy's sail-powered fleet, then recounts the Navy's long and painful transition to steam power, and concludes with an assessment of those factors that allowed the Navy to finally overcome the forces aimed at preventing a steam-powered fleet from becoming a reality.

A Legacy of Sail

A critical first step in understanding the Navy's transition from sail to steam is to examine the existing environment at the time of steam's introduction. An effective way to analyze this environment is to focus on the sail and its associated technological paradigm.³⁷ Examining the technological paradigm dedicated to sailing ships provides insight into some of the reasons why steam technology faced the resistance it did. Additionally, Thomas Hughes's notion of technological momentum offers a model for assessing the resistance against steam-powered ships. In accordance with Hughes' definition, sailing ships were artifacts of a mature technological system that possessed strong momentum, making it resistant to change and giving it greater capacity to shape society.³⁸ The sail and its associated cultural and physical factors also fits nicely within Edward Constant's definition of a technological paradigm..³⁹ By examining the sail through these two theoretical lenses, this analysis will help explain how technological momentum made the sailing ship a difficult technological artifact to supplant in the United States Navy.

Prior to the advent of steam-powered ships, every man, woman, and child that colonized North America was affected by the commercialization and economic interdependence made possible by sailing ships.⁴⁰ Ships enabled the intercourse that allowed colonies to prosper and grow while facilitating the communication links that bound the colonies together as a nation. As early as the 1630s, commercial

³⁷ Constant, *The Origins of the Turbojet Revolution*, 6-32.

³⁸ Hughes, "Technological Momentum," 101-108.

³⁹ In *The Origins of the Turbojet Revolution*, Constant describes a technological paradigm as the physical and cultural framework that develops to sustain an exemplary artifact. In comparison to Thomas Kuhn's notion of a scientific paradigm, technological paradigms tend to change faster than their scientific counterparts do. Furthermore, for a technological paradigm to exist, Constant notes that only a small minority of the population must subscribe to that particular technology. See Constant, *The Origins of the Turbojet Revolution*, 12-22.

⁴⁰ Alex Roland, W. Jeffrey Bolster, and Alexander Keyssar, *The Way of the Ship: America's Maritime History Reenvisioned, 1600-2000*, (Hoboken, NJ: John Wiley & Sons, 2008), 13.

shipping and shipbuilding enterprises blossomed in New England where “maritime entrepreneurship held out the promise of profit and capital accumulation.”⁴¹ Soon, individuals and government entities grew dependent on the shipping industry as sub-communities such as importers, exporters, and retailers, began to emerge. Sailing vessels also allowed spinoff industries such as fishing and whaling to take root, providing the additional jobs and revenue streams required for new towns to develop and prosper.⁴² Shipping’s influence was so prevalent on the economic lives of Colonial Americans that, other than agriculture, maritime service was the most common occupation for men in the 18th century.⁴³

During this time, the level of shipping increased and port towns grew in places like New York, Philadelphia, Charleston, and New Orleans. As these cities grew in size and capacity, dependable systemic trade routes expanded commerce between the colonies, allowing economic specialization in fields such as agriculture and manufacturing. A secondary effect of regular shipping was to connect people from different parts of the country by distributing regional newspapers and passing along stories from the disparate colonies. Overall, because sailing ships connected the colonies across social and economic lines their impact on Colonial America was profound. Sailed vessels enabled the economic activity the fledgling colonies depended on, while also giving them common interests and acting as one of the principal means of unifying 13 separate colonies into a nation.⁴⁴

⁴¹ Roland, Bolster, and Keyssar, *The Way of the Ship*, 24.

⁴² For instance, Starbuck demonstrates how fishing and whaling were essential to the early development of cities such as Long Island, Martha’s Vineyard, and Gloucester. Alexander Starbuck, *History of the American Whale Fishery from Its Earliest Inception to the Year 1876*, (Waltham, MA: by the author, 1878), 17-20.

⁴³ Roland, Bolster, and Keyssar, *The Way of the Ship*, 87.

⁴⁴ For a detailed analysis of shipping’s impact on the lives of early American citizens and business owners see Roland, Bolster, and Keyssar, *The Way of the Ship*, 12-24.

Militarily, the sail fostered an American military tradition with a distinctive naval character. Congress passed legislation on October 13, 1775, formally establishing the Continental Navy and providing it with two sailing vessels.⁴⁵ Thrust into immediate action, the Navy served the new nation well, expanding in size and battling Britain's sailing ships in the fight for independence. However, in a move that foreshadowed future events, two years after signing the Treaty of Paris, Congress disbanded the Navy in 1785 and sold the Navy's ships to repay debts accumulated during the years of fighting.⁴⁶ Following the Revolutionary War, America came to rely on revenue-generating enterprises, central to which was the nation's merchant shipping fleet. However, without the protection of the Navy, American ships were subject to pirate attacks and privateering, thus threatening one of the nation's primary revenue streams. In response, Congress passed the Naval Act of 1794, reconstituting the Navy and authorizing the construction of six frigates.⁴⁷ Four years later, diplomatic relations between the United States and France soured and the American Navy engaged the French in a quasi-naval war that concluded with the Convention of 1800. In 1812, when the United States declared war on England, the Navy was largely unprepared to go to war. However, facing a heavy disadvantage in the number of frigates and sloops, the Americans scored several naval victories, taking advantage of England's overstretched forces. These victories boosted the Navy's stature and, after the war's conclusion, resulted in strong public support for a robust navy.⁴⁸

⁴⁵ *Naval Documents of the American Revolution*, Vol. 2, (Washington, D.C.: Government Printing Office, 1966), 442. <http://www.history.navy.mil/faqs/faq59-13.htm> (accessed January 24, 2012).

⁴⁶ Nathan Miller, *The U.S. Navy: A History*, 3rd Ed. (Annapolis, MD: Naval Institute Press, 1997), 33-35.

⁴⁷ Gardner W. Allen, *Our Naval War with France*, (New York: Houghton Mifflin Company, 1909), 42; and Harold D. Langley, *Social Reform in the United States Navy, 1768-1862* (Chicago, IL: University of Illinois Press, 1967), 4.

⁴⁸ Allen, *Our Naval War with France*, 85-86.

For sailors in the early American Navy, the sail was the foundation of a social fabric that exalted line officers as the Navy's aristocracy. Brought up on tales of naval heroism, the legacy of John Paul Jones, and a "Nelsonian" view of naval warfare, sailing ships played an integral role in establishing the Navy's warrior ethos.⁴⁹ From a young age sailors were taught the advantages of achieving the windward position and the perils of being caught leeward. For line officers, command of a sailing ship was a constant attempt to control and take advantage of inherently uncertain elements, and thus formed the locus of the art of naval warfare.⁵⁰ Sailing ships also afforded line officers tremendous independence and freedom. Unlike a steamer, which required a proper repair depot if damaged, the crew's carpenters and sailmakers could usually repair a damaged sailing vessel.⁵¹ This, combined with an abundant and freely available power source, allowed sailing ships to operate thousands of miles away from their home bases. Writing about the difficulty traditional officers had in giving up this freedom, former Bureau of Steam Engineering chief, George Melville noted, "The older officers, who are still the ruling faction and fill the higher positions, find it difficult to adopt enthusiastically a system which is entirely contrary to their training and most cherished traditions."⁵²

⁴⁹ Lord Horatio Nelson of the Royal Navy was an adept naval strategist known for his adroit understanding of politics and military affairs. Widely recognized for his victory at Trafalgar, Nelson advocated for control of the sea through decisive battles and blockade. For more on the early teachings of naval officers and the culture of naval aristocracy, see Peter Karsten, *Naval Aristocracy: The Golden Age of Annapolis and the Emergence of Modern American Navalism* (New York: The Free Press, 1972).

⁵⁰ Bernard Brodie points out that three principles are recognized as inherent to sail warfare: (1) wind always determined the character of the battle, (2) the wind-gage (windward side) almost invariably conferred a great advantage, (3) although this advantage could be gained by superior speed or clever tactics, it was essentially an advantage of accident. Bernard Brodie, *Seapower in the Machine Age* (New York: Greenwood Press, 1969), 79-82.

⁵¹ Gibson, *The Story of the Ship*, 208.

⁵² Melville's Stevens Institute Speech, Papers of George H. Melville, Manuscript Division, Library of Congress, Washington, D.C., Quoted in William McBride, *Technological Change in the United States Navy, 1865-1945*, (Baltimore, MD: The Johns Hopkins University Press, 2000), 33.

In battle, innovative sail designs, such as the jib, the flying jib, and the spanker (gaff mizzen) enabled the development of bigger and more capable ships with larger guns, more ammunition, and greater stores.⁵³ The intricate, highly developed sail patterns on these ships utilized equal numbers of fore and aft sails, allowing them to navigate in virtually any wind condition.⁵⁴ While employing technology that had changed little over 500 years, the sailing ships of the early 19th century were immeasurably more complex and capable than their predecessors. For senior officers in the Navy, “Naval architecture...had reached the final stage of perfection.”⁵⁵

As inventors and engineers began developing steam-powered ships in the early 1800s, they probably did not anticipate their inventions would be suspect to harsh and vigorous criticism. Yet, such criticism is unsurprising given the sail’s importance to both early American society and to the Navy. At the time, sailing ships were not only the symbol of naval mastery, they were also an embedded element in American culture and commerce. Thus, by introducing a technology that disrupted the established paradigm, the pioneers of steam technology threatened the entire cultural and physical system that developed around the sailing ship from the keel up. As one might expect, this disruption rippled throughout society and deeply affected the Navy’s ability to adopt steam-technology.

⁵³ A jib is a triangular sail set out from the foremost mast and connected to the bow or bowsprit of the ship. Similarly, a flying jib was an additional jib sail added forward of the existing (innermost) jib sails. Both of these jib sails provide greater sail area during the ship’s tack. The spanker sail is a gaff-rigged fore and aft sail set out from the aftmost mast used for precision correction and steering. Gibson, *The Story of the Ship*, 124-125.

⁵⁴ Gibson, *The Story of the Ship*, 125.

⁵⁵ Harold and Margaret Sprout, *The Rise of American Naval Power, 1776-1918*, (Annapolis, MD: Naval Institute Press, 1990), 138.

The Advent of Steam Propulsion in the Navy

The Navy's transition to steam-powered ships encompassed the better part of the 19th century. Ignited by the introduction of practical marine steam power in 1807, a host of factors led to a spasmodic transformation. In order to maximize this case study's applicability to the DOD's current energy situation, a review of the relevant history of marine steam technology from 1807-1865 provides the basis for studying the Navy's incorporation of steam-powered ships.

Tracing its origins back to the Continental Navy, the American Navy began as an exclusively wind-powered force until the introduction of steam propulsion in the early 1800s. Since then, the evolution of steam power in the Navy has been a synthesis of civilian innovation, military innovation, domestic influence, and geopolitics. Early American steam development began as a civilian innovation pioneered by inventor Robert Fulton. Fulton sought to improve on the experimental steam propulsion designs he observed in England and France. Building on the work of Edward Symington, in 1807 Fulton built the *Clermont* and successfully tested the steam vessel by plying the Hudson River from New York to Albany at a speed of five knots.⁵⁶ Taking advantage of a financial agreement that gave him exclusive commercial rights to New York's waterways, Fulton and his business partner Robert R. Livingston began the nation's first successful commercial steamer service.⁵⁷

The Navy adopted its first steam-powered vessel in 1814 after Congress agreed to let Fulton design a steam-powered battery to defend New York Harbor from British bombardment.⁵⁸ Designed as a floating battery and fielding 20 guns, *Demologos* was the world's first steam-

⁵⁶ Frank M. Bennett, *The Monitor and the Navy Under Steam* (Boston, MA: The Riverside Press, 1900), 2.

⁵⁷ John Fitch launched the world's first commercial steamboat service on the Delaware River in 1788. However, local prejudice and an oversized engine that allowed little room for cargo resulted in the expedition's failure. For more on the primal stages of steam experimentation see Gibson, *The Story of the Ship*, 146-150.

⁵⁸ Bennett, *The Monitor and the Navy Under Steam*, 14.

powered warship.⁵⁹ However, financial strains imposed by the War of 1812 and the Navy's perception of steam as a "brown-water" defensive technology unable to support the Navy's "blue-water" commerce protection mission resulted in a dismissive attitude by naval leaders.⁶⁰ As a result, the Navy acquired no new steamers until rumors of war with France and the relief of US debt led to the advent of *Fulton II*, the first steamer built by the Navy.⁶¹ Unfortunately, *Fulton II* experienced several design problems that would also plague later generations of steam-powered ships. Three of these problems stand out as particularly noteworthy: first, placing the steam engine and boiler above the waterline made steamers vulnerable to a catastrophic attack; second, inefficient engines meant steamers held little practical advantage over sailing ships when operating over long distances;⁶² finally, side-mounted paddlewheels displaced the ship's broadside guns while creating an inviting target for enemy fire.⁶³

In his book, *Technological Change and the United States Navy*, William McBride noted, "Military hierarchies seek stability, and when a new technology challenges that stability, the reaction can be sharp and hostile."⁶⁴ For the naval bureaucracy, steam technology represented a tremendous challenge to the status quo and consequently met strong negative reactions. Objections to steam-powered ships were rooted in a variety of factors, with most concerns being for either military or social reasons. Military concerns stemmed from the shortcomings of steam when compared to sail. For instance, because of a steam-powered ship's reliance on paddles and boilers, a single shot was more likely to

⁵⁹ Frank M. Bennett, *The Steam Navy of the United States* (Westport, CT: Greenwood Press, 1896), 8-15.

⁶⁰ James C. Bradford, *Captains of the Old Steam Navy, Makers of the American Naval Tradition, 1840-1880* (Annapolis, MD: Naval Institute Press, 1986), 3.

⁶¹ Donald L. Canney, *The Old Steam Navy: The Ironclads, 1842-1885* (Annapolis, MD: Naval Institute Press, 1986), 2-3.

⁶² McBride, *Technological Change and the United States Navy*, 89.

⁶³ Bennett, *The Monitor and the Navy Under Steam*, 24.

⁶⁴ McBride, *Technological Change and the United States Navy*, 4.

incapacitate a steamer in combat than its sailed counterpart. Steamers also required massive amounts of coal, leaving little room for cargo, guns, stores, or ammunition. Furthermore, the need for coal imposed logistical constraints on ships whose previous limits were only the amount of food and water they could carry.⁶⁵ In addition, In combat the black smoke belched by steam engines posed a stark tactical disadvantage for steam captains by making their ships easier to spot and reducing the possibility of surprise.⁶⁶ Finally, steamers had to contend with the prospect of failed engines. While a lack of wind might temporarily render a sailing vessel inert, a destroyed boiler could be disastrous for a steamer and its crew if the ship had no alternative source of motive power.

In addition to creating concerns on tactical and strategic grounds, steam propulsion also conflicted with the Navy's social and professional norms. Writing on the challenges posed by new technologies, Merritt Roe Smith noted, "Change roughs up people by disrupting accustomed ways of doing things...no matter how innocuous new technologies seem to be, they challenge old values."⁶⁷ Such was the case when steam technology began to supplant sail-powered ships. Prior to the advent of steam, line officers commanded, maneuvered, and fought the Navy's ships; their reign was supreme and their decisions absolute. Because fighting in sail vessels was subject to the uncertainties of the wind, line officers viewed the handling of ships under sail as "a difficult and exacting art that could not be improvised."⁶⁸ Yet, as steamers were introduced into the Navy's

⁶⁵ Lance C. Buhl, "The Smooth Water Navy: American Naval Policy and Politics, 1865-1876," Doctoral Dissertation, Harvard University, 1968), 709; also see Brodie, *Seapower in the Machine Age*, 10-11.

⁶⁶ The smoke released by steamers also degraded the ability to read signal hoists making visual communication difficult. See Andrew Lambert, *Battleships in Transition: The Creation of the Steam Battlefleet, 1815-1860* (Annapolis, MD: Naval Institute Press, 1984).

⁶⁷ Merritt Roe Smith, ed., *Military Enterprise and Technological Change: Perspectives on the American Experience* (Cambridge, MA: The MIT Press, 1985), 22-23.

⁶⁸ Brodie, *Seapower in the Machine Age*, 89.

fleet, line officers with little formal training in steam engineering soon realized that steam technology forced them to cede a certain degree of control to engineers who were responsible for the ship's power and control systems. Furthermore, when motive power entered the sailing equation, it threatened to replace the artisanal practice of sail that the Navy's corps of line officers had grown up studying. Thus, for line officers, steam technology represented an innovation that fouled their ships, challenged their authority, and threatened to make them obsolete. The result was a cultural backlash against steam technology and steam engineers that persisted for the duration of the nineteenth century.

Despite these concerns and objections, the Navy began acquiring steam-powered ships in small numbers under the leadership of progressive officers like Matthew Perry, Matthew Maury, and Robert Stockton.⁶⁹ In addition, the prospect of foreign threats convinced Congress to pass the Naval Appropriations Act of 1839, authorizing the construction of three new steam frigates.⁷⁰ While still underpowered and not ideal for open ocean operations, these ships were well suited for use in America's littorals and its expansive network of rivers. Shortly after commissioning this second generation of American steamers, the Navy sent them to fight in the Mexican-American War. Originally deployed to blockade the Mexican coastline, the Navy expanded its mission by sending steamers up Mexican rivers to conduct inland siege operations. Naval officers soon found the steamer's shallow draft and independent power source allowed them to execute river penetrations and assaults against Mexican cities such as Tampico and Tabasco that had previously been deemed unreachable because of light winds and shallow depths.⁷¹

⁶⁹ Perry worked to professionalize the engineering corps by ensuring top pay and benefits for the civilian engineers who joined the Navy. See Bennett, *Steam Navy of the United States*, 22-23.

⁷⁰ Brodie, *Seapower in the Machine Age*, 30.

⁷¹ Jack K. Bauer, *Surfboats and Horse Marines, U.S. Naval Operations in the Mexican War, 1846-1848* (Annapolis, MD: Naval Institute Press, 1969), 114-116.

The lessons learned in Mexico about the benefits of steam technology were not lost on naval officers or American lawmakers. Several officers realized steam power gave the Navy a striking new capability in brown water environments, and lawmakers responded by authorizing the construction of more steam-powered ships. Thus, from 1845 to 1860, the number of sailing warships in the Navy decreased from 59 to 44 while the number of steam warships multiplied from 6 to 38.⁷² This period of acquisition was heavily influenced by the Navy's evolving diplomatic role and the nation's outward focus. As the nation expanded westward and began to look beyond its shores, politicians saw the Navy as a powerful way to "show the flag" while increasing American prestige. Subsequently, the Navy sent steamers abroad to carry out independent diplomatic missions and in support of traditional diplomatic missions.⁷³

While steam technology appeared to prove its worth by successfully operating in the Mexican War and in executing high-profile diplomatic missions, concern remained about the steamer's ability to fight pitched battles on the open ocean. Many Naval officers and their Congressional sympathizers felt steamers were adequate for coastal operations, but that sail was required for operations at sea. Representative of this viewpoint was Naval Committee Chairman Stephen Mallory, who in 1858 tried to steer naval acquisition towards a sail-dominant policy that mirrored American strategy from the War of 1812, in which "frigate was matched against frigate, sloop against sloop, and brig against brig."⁷⁴ The logic of this perspective is difficult to comprehend, given that most major European powers, having witnessed

⁷² Charles Oscar Paullin, *Paullin's History of Naval Administration, 1775-1911* (Annapolis, MD: Naval Institute Press, 1968), 219.

⁷³ Examples of these types of missions abound, with perhaps none so famous as Commodore Perry's famous excursion to Japan, where he initiated negotiations that opened a diplomatic relationship with the Japanese. See Bennett, *The History of Steam*, Chapter IX and Robert W. Love Jr., *History of the U.S. Navy, Volume 1, 1775-1941* (Harrisburg, PA: Stackpole Books, 1992), 217-220.

⁷⁴ Senate Debate, June 7, 1858. Congressional Globe, 35th Congress, 1st Session, 2732. <http://memory.loc.gov/cgi-bin/ampage> (accessed January 22, 2012).

the success of steamers versus sail-powered ships in the Crimean War, concluded the age of sailing warships was over.⁷⁵

Thus, when the Civil War began, steam-powered ships occupied a precarious position within the Navy's fleet. Steam engines powered the monitors, ironclads, and paddle wheels that plied American coastlines and rivers. However, sailing vessels were still responsible for blockading the South under the Navy's primary *guerre de course* mission. As fighting between the Union and Confederacy progressed, the Civil War provided opportunities for rapid proliferation of steam technology. However, this proliferation coincided with only mixed technological advances in the field of steam engineering. Despite the technological achievements represented by ships such as the *Merrimack* and *Monitor*, geographical factors unique to the United States allowed the burgeoning American steam ship industry to languish in a technological stupor while European engineers were incorporating new technological developments into the design of their steamers. For example, from a technological perspective, the steam engines powering the Navy's riverboats were archaic. In Europe, engineers designed economical, fuel-efficient vessels to make commercial steam travel at sea feasible and cost effective. To gain this efficiency, European engineers designed compound engines and cylindrical boilers that allowed steamships to consume up to 50 percent less fuel than the simple steam engines they replaced.⁷⁶ By comparison, American engineers designed steamers to operate primarily in the nation's rivers and estuaries. These vessels had access to ample sources of fuel, thus the driver for fuel economy was minimal, and subsequently American steam engines changed only marginally while the European engines evolved dramatically. This technological stasis is illustrated by

⁷⁵ For example, as of 1857, France only considered steam vessels as ships of war, while England's First Lord of the Admiralty declared that sailing vessels ought to be "left out of consideration." See Brodie, *Seapower in the Machine Age*, 73.

⁷⁶ Richard Woodman, *The History of the Ship* (London: Conway Maritime Press, 1997), 164-166; Gibson, *The Story of the Ship*, 176.

the fact that the basic engine castings for the Navy's marine engines in 1864 were identical to those from the 1830s.⁷⁷

Overall, the Navy's transition from sail to steam lurched to an inauspicious start. In 1814, the Navy named Captain David Porter as commander of the *Demologos*. Captain Porter's first order of business was to outfit his clean new steamer with sails, and he later installed bulwarks to protect the men who would tend the sails.⁷⁸ Fifty years later, steamers still relied on sails to account for the technologically primitive simple-expansion steam engines.⁷⁹ Thus, hampered by a series of social, political, financial, and technological factors, the Navy wrestled with the prospect of transforming the artifact that characterized its existence. These factors were not unique to the Navy, nor were they unique to the period. Many of the issues that hindered the Navy's incorporation of steam technology in the first half of the century would come up again as the Navy sought to define itself in the years following the Civil War. The next section will examine those factors that aided the Navy in eventually overcoming these hindrances.

Why Steam Prevailed

When assessing the factors that enabled a complex technological transformation, it is inaccurate to point to one or two and label them as the key to a successful transition. Such is certainly the case with the Navy's incorporation of steam technology. As shown in Figure 1, it took a variety of technological and social factors to mitigate the disruptions wrought by the introduction of steam. Section 2.2 showed that between 1807 and 1865 there were periods of great technological innovation and forward thinking. Likewise, Section 2.2 illustrated periods of technological stagnation and obstinacy during which the Navy and the country's civilian leadership hindered the development of new

⁷⁷ Canney, *The Old Steam Navy*, 36.

⁷⁸ Bennett, *Steam Navy of the United States*, 11.

⁷⁹ Canney, *The Old Steam Navy*, 9.

technology. To answer the question, “Why was the Navy’s transition to steam-powered ships successful?,” this section will use theories posited by Constant, Hughes, Posen, and Rosen to examine the respective roles technological co-evolution, reverse salients, balance-of-power dynamics, and senior military leaders. In doing so, it will assess the impact each of these factors had in facilitating the Navy’s development of steam-powered ships.

Hindering Factor	Countervailing Factor / Solution
Limited effective range due to the requirement to stay within range of coal stations	Better efficiency
Steamer had large engines/boilers and required massive coal bunkers, limiting the amount of room for stores, ammunition, armament, etc.	Better efficiency
The vulnerability of the ship’s boiler, engine, and paddle wheel meant that steamers were of little practical value in a conventional naval battle	Co-evolution of technology – screws, multi-stage engines, and steel hulls
Smoking ships created tactical disadvantages	The introduction of anthracite coal created less black smoke when burned
Steamers were more expensive than sail-powered vessels	Better efficiency led to increased range. Increased range allowed oceanic travel. Independence of the winds gave ships better speed and made them more predictable. Predictability and better speed led to increased profits
The infrastructure of some waterways required updates and reinforcement to facilitate the use of paddled steamers	The financial benefits of being able to navigate against river currents made the changes to the physical infrastructure worth the cost to the interested sub-communities
There was a social aversion within the Navy to steam technology and engineers	It took an act of Congress (Amalgamation Act of 1899), the work of visionary senior leaders (Perry and Isherwood), and the threat posed by foreign navies to compel the Navy to fully accept steam-powered ships
Steamers were ill suited to meet the needs of the Navy’s <i>guerre de course</i> mission	Better efficiency combined with a new mission increased the applicability of steam to the Navy
Wars were extremely costly, and post-war retrenchment reduced the size and budget of the Navy	The threat posed by the British and the French prompted Congress to authorize the buildup of more technologically advanced ships

Figure 1 – Factors Hindering the Adoption of Steam-Powered Ships

Source: Author’s own Compilation

During the process of technological co-evolution, supporting technologies often develop at the same time. Because the technologies are mutually beneficial, they exert pressure on each other to develop, and thus support the development of the overall system.⁸⁰ In other instances, certain components of the technological system will fail to advance at the same rate as the other components, resulting in a situation that Thomas Hughes refers to as a reverse salient. When a reverse salient is identified, systems builders and engineers will typically devote their attention and energy to addressing the problem causing the reverse salient, thus allowing the technological system to continue progressing.⁸¹ These constructs are especially useful in analyzing the development of the steam-powered ship. As shown in Figure 1, efficiency gains mitigated several of the factors provoking the Navy's resistance to steam. In large part, the development of the steam engine, the screw propeller, and the iron hull facilitated this critical increase in efficiency. To understand how these developments facilitated the incorporation of steam-powered ships in the Navy, each sub-system must be looked at separately.

As an independent technological artifact, the steam engine offered significant advantages to the Navy while also presenting new challenges. Steam engines offered independence from the winds, increased speed, and by virtue of their independence from the winds, a certain degree of predictability. However, for the Navy, the severe penalties imposed by the steam engine overshadowed its advantages. Because of the engine's size and enormous fuel requirements, a ship powered by steam could carry fewer guns, less ammunition, and fewer stores than an equivalent sailing ship. In addition, direct-drive steam engines dictated that engines be placed on the exposed upper deck where they were

⁸⁰ Constant, *The Origins of the Turbojet Revolution*, 12-16.

⁸¹ Hughes, "The Evolution of Large Technological Systems," 73.

susceptible to enemy fire. Finally, marrying the steam engine and the wooden hull created problems for ship designers and steam engineers. Many of these problems stemmed from the structural limits of wooden-hulled ships. For instance, to prevent sagging, wooden ships rarely exceeded 300 feet in length.⁸² A finite amount of space meant ships could carry limited amounts of coal, restricting the effective range of the ship. Due to their flexibility, wooden hulls were also notoriously difficult to mate to a steamer's rigid engine. To prevent engines from damaging their mounts, ship engineers attached them loosely. The resultant loose connection prevented damage to the ship's hull, but meant steam engines were more likely to vibrate beyond limits, causing excessive engine deterioration.⁸³

Like the steam engine, the screw propeller offered both advantages and challenges. First utilized in the 1830s by Swedish inventor John Ericsson, screw propellers offered several improvements over paddle wheels, notably speed and efficiency. An additional benefit of the screw was that it enabled engineers to place the engine and boiler in the hold of the ship.⁸⁴ Lowering these critical components into the ship's hold created two effects. First, it decreased the vulnerability of the engine by placing it below the water line. Second, it solved the problems of top heaviness by redistributing the weight of the engine. Third, it cleared the gun deck from extraneous equipment and personnel, enabling the placement of more guns and making steam-powered warships look and feel more like their sailing predecessors.⁸⁵ Screw propellers also led to new technological challenges. One challenge concerned the ship's hull

⁸² Gibson, *The Story of the Ship*, 121-143.

⁸³ Brodie, *Seapower in the Machine Age*, 154-155.

⁸⁴ James P. Baxter, *The Introduction of the Ironclad Warship* (Cambridge, MA: Harvard University Press, 1933), 11.

⁸⁵ Robert P. Gray, "The Effect of New Technology on the Operational and Strategic Levels of War: The Development of Steam Propulsion in the United States Navy Prior to 1860" (Masters Thesis, US Army Command and General Staff College, 1993), 55, <http://handle.dtic.mil/100.2/ADA273954>.

while the other affected the engine itself. The only way to connect the engine to the propeller was to run a shaft through the hull of the ship. However, putting a hole in the bottom of a ship was counterintuitive to shipbuilders, designers, and even insurers.⁸⁶ Exacerbating this problem was the fact that the transmission shaft put high levels of stress on the ship's hull, loosening bonds, creating leaks, and imposing excessive wear on the ship. The screw propeller also posed a problem for the ship's engine, and thus the engineers. To be efficient, screws turned at higher RPMs than paddle wheels. However, to run a steam engine at high RPMs required higher boiler pressures, which dramatically increased the risk of explosion. Thus, in order for the screw to be effective, engineers had to find a way to increase engine RPMs without sacrificing fuel efficiency – a problem resolved by developing high-pressure boilers and compound steam engines.⁸⁷

As with the advent of the steam engine and the screw propeller, the iron hull presented significant advantages while also creating new challenges. Iron hulls were especially important because their rigid frames helped solve several of the problems that had hindered the steam engine and the screw. However, iron hulls also led to problems with fouling and questions about their ability to withstand enemy fire.⁸⁸ This is an important distinction between the iron hull and the other co-evolutionary technologies. Unlike the screw and the steam engine, co-evolution did little to aid in resolving the problems facing the iron hull. Thus, instead of being co-evolutionary, in this case the iron hull was a solution to the reverse salient caused by advances in screw and the steam engine technology. Consistent with Hughes's assessment of reverse salients, once the underlying condition was resolved, the

⁸⁶ Woodman, *The History of the Ship*, 140-142.

⁸⁷ Gibson, *The Story of the Ship*, 189-192.

⁸⁸ Marine fouling comprises the accumulation of ocean organisms on the underside of a ship. Fouling creates a high coefficient of friction, especially on iron-hulled ships, thus leading to suboptimal sailing performance.

technological development of the steam ship was able to move forward. Unlike the relatively flexible wooden-hulled ships, iron hulls allowed engineers to fix the engine to the ship's frame securely, eliminating a major source of engine deterioration. Iron hulls also enabled designers to build longer ships with larger coalbunkers, thereby increasing the ship's range. Finally, iron hulls helped solve the problem posed by the piercing of a ship's stern with a rotating shaft. In this case, the iron hull's rigidity stopped whips in the transmission shaft and prevented the stern gland from flexing, thereby eliminating the leakage problems experienced by wooden ships.⁸⁹

Examining the advancement of steam propulsion in terms of technological co-evolution and reverse salients reveals how the advancement of three minor artifacts enabled the evolution of a macro technological system based on the steam-powered warship. Thus, the concept of technological co-evolution and reverse salients provides insight into the Navy's transition from sail to steam and informs modern energy-related transitions. However, simply because the technology was available to meet these needs did not mean that its adoption was automatic. As will be shown next, despite these significant improvements to the steam-powered ship, the Navy still resisted including these ships into its fleet.

In his essay, "On Military Change," Harold Winton noted that internal and external factors influence change in the military. Examples of external factors include cultural norms, geography, historical experience, political institutions, and resource availability, while internal factors include service culture, the branches of the service, the process of

⁸⁹ Stern glands, which are nothing more than stuffing boxes or boxes filled with packing material, are designed to keep water from penetrating the boat's hull past the propeller shaft. The increased rigidity of metal-hulled ships prevented distortion of the propeller shaft and the stuffing box, making them less susceptible to leakage. For more, see Brodie, *Seapower in the Machine Age*, 154-155.

doctrinal development, and the actions of key leaders.⁹⁰ As the Civil War ended and steam-powered ships developed to the point that they could meet the Navy's strategic requirements, this confluence of internal and external factors played a large part in influencing the Navy's decision to embrace steam technology. Internally, hide-bound naval officers bent on preserving their aristocratic heritage attacked a nascent engineering corps shielded by a dynamic senior leader. Externally, the Navy juggled massive budget cuts stemming from 5 years of total war with a sudden reinvigoration 15 years later in response to the looming threat posed by foreign navies.

After the Civil War, the Navy went through a massive downsizing period characterized by little to no innovation. Consistent with Barry Posen's interpretation of balance-of-power theory, the United States sought to maintain the status quo and the Navy shifted from its offensive brown-water blockade mission to a defensive blue-water commerce-protection mission.⁹¹ During this period, Congress suspended appropriations for the Navy while reducing the force from 471 ships to 144 ships with only 43 fit for duty.⁹² The result was a period of technological stasis commonly referred to as the American Naval "Dark Ages."⁹³ External factors were not the only aspects obstructing the Navy's incorporation of steam-powered ships into the fleet. During this time of massive reduction and downsizing, line officers strove to institutionalize their superiority over the engineers that had been pivotal in the Navy's Civil War successes. Led by Vice Admiral David Porter, line

⁹⁰ Harold R. Winton, "On Military Change" in *The Challenge of Change: Military Institutions and New Realities, 1918-1941*, eds. Harold R. Winton and David R. Mets (Lincoln, NE: University of Nebraska Press, 2000), xii.

⁹¹ Posen notes that according to balance of power theory, status quo states will generally prefer a defensive doctrine if geography or technology makes such doctrines attractive. See Posen, *The Sources of Military Doctrine*, 79.

⁹² Benjamin Franklin Cooling, *Grey Steel and Blue Water Navy: The Formative Years of America's Military-Industrial Complex, 1991-1917* (Hamden, CT: Archon Books, 1979), 17-18.

⁹³ Canney, *The Old Steam Navy*, 136.

officers supported legislation to submit engineers to the staff officer corps, terminated engineering programs at the Naval Academy, established and funded anti-engineer lobbies in Washington, and purposely reorganized the rank structure to exclude engineers.⁹⁴ The caustic attitude toward engineers was exemplified by Porter, who, after disagreeing with an engineer, threatened “not only to strip him and the engineers of all honors, but to make them the most inferior corps in the Navy.”⁹⁵

Why did line officers so vehemently oppose steam engineers and the ships they powered? As previously mentioned, before the Civil War line officers looked down on steam-powered ships for a number of reasons, namely the shortcomings of the technology and the ideological opposition of officers caught up in the traditional lore of the Navy. While unfortunate, the Navy’s reluctance to support a technology that had little relative advantage over sail and had yet to prove its ability to meet the Navy’s strategic needs is understandable. However, the unwillingness of line officers to accept the new technology even after being proven effective in battle deserves closer scrutiny.

One of the primary internal factors affecting military change that Winton recognized is service culture. Described as a complex aggregate of the service’s attitudes towards its role in war, its promotion system, and its place in society,⁹⁶ the Navy’s culture clearly played an influential role in hindering the adoption of steam-powered ships – both before and after the Civil War. Line officers felt engineers threatened the line officer corps’ place in the Navy and in society, so they carried out a coordinated campaign targeting promotion, education, and retention to suppress the perceived threat. Notably, this threat was real. Generations of naval

⁹⁴ For more on the institutional changes effected by line officers to subjugate the engineering corps, see Bennett, *The Steam Navy of the United States*, Chapter XXXI and XXXIII; and McBride, *Technological Change and the United States Navy*, Chapter 1-3.

⁹⁵ Karsten, *Naval Aristocracy*, 66.

⁹⁶ Winton, “On Military Change,” xiv.

officers began their careers learning how to maneuver and command sailing ships, but they possessed little to no practical experience with steam engines. By comparison, steam engineers often played a vital role in the design and building of the ship, giving engineers the technical expertise needed to manage the ship's systems once the ship was under way. As sail-minded officers assumed the senior ranks within the Navy, it is hard to imagine them advocating for a technology that diminished their perceived superiority. Posen adeptly captured this point, noting, "Military organizations will seldom innovate autonomously...those at the top of the hierarchy, who have achieved their rank and position by mastering the old doctrine, have no interest in encouraging their own obsolescence by bringing in a new doctrine."⁹⁷

After the Civil War, not all of the Navy's officer corps was bent on stymieing the incorporation of steam technology. One of the Navy's main advocates of steam was Benjamin Isherwood. Isherwood entered the Navy in 1844 as an assistant engineer and witnessed the utility of steam in the Mexican-American War. After the war, he experimented with different steam designs aimed at increasing power and efficiency, publishing his results in *Experimental Researches in Steam Engineering*.⁹⁸ Shortly after the Civil War began, President Abraham Lincoln named Isherwood Engineer in Chief of the Navy, putting him in charge of the newly formed Bureau of Steam Engineering. In this role, he fought to overcome the deep-seated bias against steam engineers by creating an engineering curriculum at Annapolis, developing a career track for engineers, and advocating for a modernized naval force equipped with the latest steam-powered technology. However, his efforts were largely ineffective. Isherwood was driven from office in 1869, and

⁹⁷ Posen, *The Sources of Military Doctrine*, 224.

⁹⁸ David A. Mindell, *War, Technology and Experience aboard the USS Monitor* (Baltimore, MD: The Johns Hopkins University Press, 2000), 24-25.

the Navy reversed several of his groundbreaking initiatives as it attempted to withdraw into the familiar world of sail.⁹⁹

Why did Isherwood's efforts fall flat? Rosen suggested that innovation occurs when "respected senior military officers formulate a strategy for innovation, which has both intellectual and organizational components."¹⁰⁰ Isherwood was a senior military officer with a focused strategy for transforming the Navy into a steam-powered force, yet the Navy remained wedded to the sail. The single largest problem Isherwood faced was his occupation as an engineer. Rosen notes that in order to effect doctrinal change, senior officers must have the political power required to manipulate the existing system. A senior officer with brilliant ideas who has rejected the system, or *whom the system has rejected*, is a maverick.¹⁰¹ As an engineer, Isherwood lacked credibility with line officers. Thus, fellow senior Naval officers such as David Porter viewed him as an outsider, damaging his political power and his ability to instill change.¹⁰²

With Isherwood effectively sidelined and his budget eviscerated, the Navy's sail-based technology continued to drift toward obsolescence. As the Navy struggled with the uncertainty of *postbellum* life, it purposely avoided many of the technological leaps taking place around the world and instead opted for a strategy that exemplified Everett Rogers notion of

⁹⁹ To see how the Navy retracted Isherwood's progress, see Bennett, *The Steam Navy of the United States*, Chapter XXXI, which documents how engineers were relieved of duty, reduced in rank, etc. Bennett also shows how the Navy issued new guidance mandating that all ships be rigged with sails in 1869 and then threatened to charge ship captains for the coal they consumed during cruise.

¹⁰⁰ Rosen, *Winning the Next War*, 21.

¹⁰¹ This definition stands in contrast to Posen's depiction of a maverick as a military officer who provides the civilian with the military expertise needed to effect change and acts as a means to steer change from within the organization, see Rosen, *Winning the Next War*, 9-11, 21; and Posen, *The Sources of Military Doctrine*, 174.

¹⁰² As the debate over steam grew more intense, the relationship between line officers and Isherwood grew increasingly adversarial, with Porter's opposition and vilification of Isherwood becoming a full-scale effort that lasted for over two years. See Sloan, Edward, *Benjamin Franklin Isherwood Naval Engineer: The Years as Engineer in Chief, 1861-69* (Annapolis, MD: The United States Naval Institute, 1965), 199-207.

a late majority adopter.¹⁰³ The decision to trail the most progressive seafaring nations put the Navy at a serious disadvantage vis-à-vis its peers, yet it also afforded the Navy an opportunity to bypass several of the incremental technological steps occurring at the time. As one officer noted, “The art of building ships was making such strides that it was out of the question for us with our small appropriations to keep pace with European nations, and we felt that it was just as well to save our money and remain observers...so that when the time came for us to build we might be warned by the mistakes of other nations and profit by their successes.”¹⁰⁴ Unfortunately for the Navy, while its fleet languished and technological stasis set in, a large capability gap started to grow between American naval forces and their European counterparts. As this gap widened, the strategic vulnerability of the United States became increasingly problematic. Here, consistent with Posen’s argument that civilians will interfere in military affairs when they are afraid or threatened, Congress responded.¹⁰⁵

The problem posed by the Navy’s deterioration first came to a head in 1870 when Americans realized they were powerless to confront the Spanish navy’s blockade of Cuba. Three years later, the Spanish captured American gunrunners aboard the *Virginus* and sentenced them to execution by firing squad. In response, the Navy assembled a small squadron off of Key West, but again found itself unable to contest the Spanish fleet. To make matters worse, a short while later the Americans discovered a Spanish ironclad anchored in New York Harbor, only to realize there was nothing they could do about it. Overall, the *Virginus* Affair made it clear to Congress that the Navy was in deplorable shape

¹⁰³ In his book, *Diffusion of Innovation*, Everett Rogers suggests that adopters of new technology can be characterized into one of five categories: innovators, early adopters, early majority, late majority, and laggards. For more on the different categories and the characteristics associated with each adopter category see Everett M. Rogers, *Diffusion of Innovations*, 5th Edition (New York: Free Press, 2003), 273-282.

¹⁰⁴ Cooling, *Grey Steel and Blue Water Navy*, 20-21.

¹⁰⁵ Posen, *The Sources of Military Doctrine*, 47.

and calls to modernize followed shortly thereafter.¹⁰⁶ Unfortunately, these calls did not result in dramatic reform, and the Navy continued its spiral into unprecedented levels of obsolescence.¹⁰⁷ Writing in the late 1800s on the Navy's condition, historian Frank Bennett noted, "By the year 1880, the navy of the United States had fallen to a pitifully new ebb. Its condition ten years before...had been bad enough, but now it had reached the bottom."¹⁰⁸

By this point, the threat posed by foreign navies had reached an unacceptable limit for American lawmakers. Naval battles between Peru and Chile featuring British-built cruisers posed a significant threat to the United States. The modern ships of these South American fleets were more formidable than anything the American Navy could field, raising the question of how the United States could protect its commerce ships, let alone enforce the Monroe Doctrine.¹⁰⁹ Meanwhile, England and France had completely retrofitted its own navies with top-of-the-line steamers featuring iron and steel construction, advanced armor, and powerful new ordnance.¹¹⁰ Americans worried that these technologically superior forces could cut off the vital waterways that led to commercial centers such as New York, Boston, or San Francisco. In response, Navy Secretary William Hunt prepared a statement for Congress outlining the pressing need for new vessels. Congress acted on Secretary Hunt's statement in 1882, authorizing the construction of 68 new ships at the then astonishing cost of \$29,607,000.¹¹¹ This legislation resulted in the construction of the first four ships of the new steel navy, *Atlanta*, *Boston*, *Chicago*, and *Dolphin* – the "ABCD" ships.

¹⁰⁶ Love, *History of the U.S. Navy*, 334-338.

¹⁰⁷ In the immediate aftermath of the *Virginian* Affair, eight new ships were authorized, of which only three were iron hulled. Bennett, *The Steam Navy of the United States*, 643.

¹⁰⁸ Bennett, *The Steam Navy of the United States*, 772.

¹⁰⁹ Love, *History of the U.S. Navy, Volume 1*, 345.

¹¹⁰ Cooling, *Grey Steel and Blue Water Navy*, 19-20; and McBride, *Technological Change and the United States Navy*, 18-19.

¹¹¹ Bennett, *The Steam Navy of the United States*, 773, 781.

It is important to note a critical distinction between the actions that led to the creation of a modern steam-powered navy and Posen's argument that civilians are required in order to effect doctrinal change in the military. For Posen's theory that balance-of-power arrangements impel civilians to lead military innovation to find accurate reflection in this phase of the Navy's transition to steam, the threat presented by England and France would need to have caused American lawmakers to initiate change in the military that it was incapable of making on its own. In reality, the Navy recognized the need to change, and Navy Secretary Hunt initiated the change by pleading with Congress for updated ships. In this particular instance, it is more accurate to note that balance-of-power served two purposes. First, it opened the eyes of senior leaders in the Navy to the fact that resisting steam technology came with the risk of becoming strategically irrelevant. Second, it provided civilians with the motivation to support the Navy's call for a more technologically advanced force.

Overall, one can derive several conclusions from the Navy's transition from sail to steam. The technological co-evolution of the steam engine, the screw propeller, and solving the reverse salient posed by a wooden hull demonstrate the important role complimentary technological artifacts can play in the transformation of a technological paradigm. Examining the effect of the *Virginius* Affair and the impact of technologically superior navies shows how perceived threats can drive states to seek balance by proffering additional attention to their military forces. These examples also show how threats can make traditionally conservative military forces more accepting of doctrinal changes. Benjamin Isherwood's struggle to transform the Navy illustrates the role senior leaders can play in fostering transformation while revealing the challenge a maverick faces when trying to manipulate the social and physical forces that resist change. The final lesson the sail-to-steam

case study teaches concerns the difficulty in changing paradigms. After a clear Congressional mandate ushered in a new era of steam-powered warships, animosity towards engineers, disdain for steamers, and devotion to the sail continued to characterize the line officer corps and in many instances the view of the Navy. Accordingly, the Navy continued to produce hybrid steam-sail warships until 1904.¹¹² This confirmed Max Planck's observation that "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."¹¹³



¹¹² The USS *Intrepid*, a three-masted barque was launched in 1904. See Paolo E. Coletta, *A Survey of U.S. Naval Affairs, 1865-1917* (London: University Press of America, 1987), XX.

¹¹³ Max Planck, *Scientific Autobiography and Other Papers*, trans. F. Gaynor (New York, 1949), 33-34. Quoted in Thomas Kuhn, *The Structure of Scientific Revolutions*, (Chicago, IL: University of Chicago Press, 1996), 151.

Chapter 3

Diesel-Electric to Nuclear-Powered Submarines

Compared to the Navy's long transition from sail to steam-powered warships, its transition from diesel-electric to nuclear-powered submarines was remarkably fast. After putting a nuclear submarine to sea for the first time in January 1955, the Navy had 14 nuclear submarines built, 21 under construction, and 11 more authorized by 1960.¹¹⁴ The transition was so complete and fast that the Navy did not lay a keel for another diesel-electric submarine after June 1957; and within four years, the Navy began systematically replacing its submarine fleet with nuclear-powered vessels.¹¹⁵ How the Navy managed such a rapid transition is especially noteworthy. Equally important are the social, political, and internal factors that prompted the Navy, DOD, and civilian decision makers to develop and adopt a revolutionary new energy technology. To illustrate this point, Chapter 3 begins by assessing the momentum of the Navy's diesel-electric submarine fleet, then analyzes the Navy's journey from diesel to nuclear-powered submarines, and concludes with an assessment of those factors that allowed the Navy to switch its means of propulsion in such a short period of time.

The Diesel-Electric Technological System

One helpful way to assess the Navy's rapid transition is to start by examining the momentum of the submarine force as a technological system. Compared to the sailing ship, which served as a predominant feature of the American Navy since its founding, the gas-electric/diesel-electric submarine was a relative newcomer. In 1888 the Navy sponsored a design competition to assess the current state of submersible

¹¹⁴ Todd Tucker, *Atomic America: How a Deadly Explosion and a Feared Admiral Changed the Course of Nuclear History* (New York: Free Press, 2009), 141.

¹¹⁵ Francis Duncan, *Rickover and the Nuclear Navy: The Discipline of Technology*, (Annapolis, MD: Naval Institute Press, 1990), 50.

technology. The winner of the competition was John P. Holland.¹¹⁶ Holland, a schoolteacher by trade, had several years of submarine design experience, mostly at the behest of Irish revolutionaries living in New York and New Jersey. As the winner of the competition, the Navy awarded Holland a \$150,000 contract to build his design.¹¹⁷ However, before building the new boat, the navy insisted on several modifications and the conglomerate result was a “technical and financial failure” that the Navy never accepted. Undaunted by failure, Holland built a new submarine free of Navy interference and the result was the Navy’s first modern submarine, the *Holland*. Commissioned on October 12, 1900, the *Holland* was a remarkable engineering accomplishment.¹¹⁸ On the surface, she had a cruising range of 1,500 miles; submerged, she could steam for 50 miles.¹¹⁹ However, the truly remarkable achievement was her power plant. The *Holland* featured the first gas-powered internal combustion engine for surface cruising combined with a battery-powered electric motor for subsurface propulsion. This unique propulsion system served as the prototype that submarine designers would emulate for the next fifty years.¹²⁰

After the initial success of the *Holland*, the Navy commissioned the J.P. Holland Torpedo Boat Company to build six additional submarines. Despite the promise of these new weapons, the Navy maintained only a small submarine force in the years leading up to World War I. Germany, on the other hand, saw submarines as a vital new component to a *guerre de course* strategy aimed at stifling Britain’s traditional naval superiority.

¹¹⁶ Robert Barnes, *United States Submarines* (New Haven, CT: H.F. Morse Associates, 1944), 16-17.

¹¹⁷ Barnes, *United States Submarines*, 17.

¹¹⁸ General Dynamics Corporation, *United States Submarine Data* (Groton, CT: The Submarine Library, 1958), 1.

¹¹⁹ Brodie, *Seapower in the Machine Age*, 289.

¹²⁰ Robert F. Burgess, *Ships Beneath the Sea: A History of Subs and Submersibles* (New York, McGraw-Hill, 1975), 103.

The results were devastating. Writing in 1917 about the effect of German submarines, American submarine inventor Simon Lake noted:

As I write, the submarines of Germany are holding the navies of the Allied Powers in check. The British fleet dares not invade German waters or attempt a close blockade of German ports. In spite of the mighty English navy, the German U-boats – the invisible destroyers – are venturing forth daily into the open Atlantic and are raising such havoc with merchant shipping that the world is terrified at the prospect. It is the German U-boat which to-day encourages the Central Powers to battle almost single-handedly against the rest of the world's great nations.¹²¹

Although the German submarine attacks were ultimately defeated, these attacks showed how submarines could achieve strategic results with an amazing economy of effort.¹²² World War II reiterated these lessons. Repeating their early success in World War I, the Germans deployed submarines to threaten the Atlantic sea lanes between the United States and Europe. Similarly, the United States launched submarines in an unrestricted interdiction campaign against Japanese maritime forces. In the end, the lesson was clear. Despite comprising only 2 percent of the naval forces in the Pacific, American submarines sank 30 percent of the Japanese Navy, five million tons of commercial shipping, and destroyed over 60 percent of the Japanese merchant marine.¹²³

The strategic effect of submarines during the First and Second World Wars was staggering. Yet, technologically speaking the submarines used by the American Navy during World War II had evolved very little from the prototype engineered by John Holland in 1900. Both versions relied on internal combustion engines for surface travel, utilized batteries for subsurface travel, and needed to surface for their batteries

¹²¹ Simon Lake, *The Submarine in War and Peace* (Philadelphia, PA: Lippincott, 1918), 3.

¹²² To illustrate this notion, Brodie points out that Britain employed over 2700 ships and aircraft to counter a German submarine fleet consisting of 137 ships. Brodie, *Seapower in the Machine Age*, 324-326.

¹²³ For a synopsis of the Pacific submarine offensive see Robert W. Love Jr., *History of the U.S. Navy, 1942-1991* (Harrisburg, PA: Stackpole Books, 1992), 178-195.

to recharge. Because submarine technology stood relatively still compared to tremendous advancements in the fields of aviation, radar, sonar, and munitions, World War II-era submarines faced a number of challenges unpredicted by Holland. Of particular note were their slow speed, limited endurance, and short range.

World War II-era submarines travelled at approximately 4 to 5 knots submerged. This was problematic because convoys travelled at 7 to 10 knots while independent ships averaged 13 to 15 knots.¹²⁴ Therefore, if a submarine wanted to catch a convoy, it had to travel on the surface where it could make 17 to 20 knots. Aside from the fact that surface travel eliminated the submarine's stealth characteristics, this also made submarines vulnerable to convoy escorts capable of maintaining 25-26 knots.¹²⁵ Most of the submarine's problems with speed were due to its engines. Developing engines that were light enough to operate on a submerged vessel and powerful enough to create high speeds was problematic for submarine designers. As noted by one inventor, "the difficulty is with the engines...the modern submarine builder cannot find an engine of sufficiently light weight to install with safety in a submarine hull which will give all the speed which the government demands that his boat should produce."¹²⁶ The second problem submarines faced involved endurance and range. The largest US submarines in World War II had a range of approximately 12,000-14,000 miles.¹²⁷ For a submarine based in Pearl Harbor and assigned to patrol the waters around Japan, this meant that over half of its fuel would be used just traveling to and from its assigned area of operations. Thus for every 45 days of patrol, the submarine would spend 24 or 25 of

¹²⁴ Robert E. Kuenne, *The Attack Submarine: A Study in Strategy* (New Haven, CT: Yale University Press, 1965), 16-22.

¹²⁵ Kuenne, *The Attack Submarine*, 20.

¹²⁶ Lake, *The Submarine in War and Peace*, 292.

¹²⁷ Theodore Roscoe, *United States Submarine Operations in World War II* (Annapolis, MD: United States Naval Institute, 1949), 13.

those in transit.¹²⁸ To mitigate the submarine's range problems, the Navy sought forward bases and deployed submarine tenders to extend the range of its attack submarines; however, both of these potential solutions came with inherent security risks and were not ideal.

As World War II ended, the Navy was at a crossroads. The submarine campaign against the Japanese was tremendously successful. Yet, it was reasonable to expect that the anti-submarine technological advantages the Americans leveraged against the Germans would proliferate and be used against its own submarine fleet in the near future. Both submarine and anti-submarine forces knew that once a vessel submerged, it could only stay under for a limited time, and when it surfaced, it became conspicuously vulnerable.¹²⁹ Thus, the World War II-era submarine's inability to stay submerged hindered both its offensive and defensive capability. Submerged, submarines were unable to track targets because they were too slow and had a limited battery life. After attacking, they were unable to pursue for fear of exhausting their batteries during the chase and having to surface in close proximity to the enemy.¹³⁰

Overall, diesel-electric submarines were an imperfect jewel.¹³¹ Amazingly capable, they could achieve strategic effects at relatively little cost. However, the nature of their power plants made them vulnerable. As a technological system, the diesel-electric submarine fleet had relatively little momentum. By the time nuclear-powered submarines were introduced in 1955, submarines had only been in the Navy for fifty years and for the majority of that time they were relatively insignificant. It was not until World War II that American submarines demonstrated

¹²⁸ Kuenne, *The Attack Submarine*, 28.

¹²⁹ I.J. Galantin, "The Future of Nuclear Powered Submarines," *United States Naval Institute Proceedings*, 84, No. 6 (1958), 31.

¹³⁰ Kuenne, *The Attack Submarine*, 16.

¹³¹ The term "imperfect jewel" is borrowed from Harold Winton's Essay by the same name; see Winton, "An Imperfect Jewel," 853-877.

their ability to influence a war's outcome. World War II also demonstrated the vulnerability of submarines to rapidly developing technology, and many of their losses were directly attributable to the submarine's propulsion system.¹³²

Thus, one can draw two main conclusions about the Navy's submarine fleet as a system. First, it was relatively young and still developing, making it more open to the sociocultural and geopolitical influences that would shape it in the post-World War II environment. Second, its major limitation was the diesel-electric propulsion system. In other words, as a subsystem of the greater submarine fleet, the diesel-electric propulsion system was a reverse salient – an inefficient component hindering the system's overall development.¹³³ As such, it required further refinement in order to advance the potential of the weapon system as a whole. That refinement would come with the advent of nuclear propulsion.

The Advent of Nuclear Submarines

A fundamental limitation of the modern submarine was the need to carry both fuel and oxygen to operate submerged. This requirement restricted the submarine's range and speed, making submarines vulnerable to aircraft and surface vessels. To solve this problem, scientists and engineers experimented with a variety of technological solutions, including compressed air, carbonic gas engines, fuel cells, a hydrogen peroxide-alcohol steam turbine, closed-cycle diesel engines, and others.¹³⁴ In 1938, scientists Otto Hahn, Lise Meitner, and Fritz Strassmann created a wave of interest in atomic energy after discovering

¹³² Kuenne illustrates how modern anti-submarine warfare (ASW) developments such as submarine tracking aircraft were involved in 43 percent of all U-boat sinkings and 21% of all US submarine sinkings; see Kuenne, *The Attack Submarine*, 54-58.

¹³³ Hughes, "Evolution of Large Systems," 75.

¹³⁴ Kuenne, *The Attack Submarine*, 14; and Joseph-James Ahern, "The United States Navy's Early Atomic Energy Research, 1939–1946," *International Journal of Naval History*, Vol. 1, No. 1 (Spring 2002), http://www.ijnhonline.org/wp-content/uploads/2012/01/pdf_ahern.pdf (accessed February 17, 2012).

nuclear fission.¹³⁵ One organization that took note was the US Naval Research Laboratory (NRL). Under the supervision of Dr. Ross Gunn, the NRL's Mechanics and Electricity Division had been searching for a more effective way to propel submarines and torpedoes; with nuclear fission they thought they may have an answer.

Believing that atomic energy was a possible solution to both the propulsion and oxygen problems vexing submarine designers, in March 1939, Gunn requested \$1,500 from Admiral Harold G. Bowen, director of the Bureau of Engineering, to start uranium research.¹³⁶ After receiving the grant, the NRL began studying uranium enrichment programs that would benefit submarine propulsion, notably liquid thermal diffusion.¹³⁷ Atomic power looked especially promising to researchers in the NRL because unlike traditional combustion engines, an atomic power plant required no oxygen. However, in 1941 President Franklin Roosevelt assigned responsibility for the nation's atomic program to the Army; subsequently the NRL's work on submarine propulsion was deferred to conduct work on isotope separation for the Manhattan Project.¹³⁸ In general, the need for secrecy and interservice rivalry strained the relationship between the NRL and the Manhattan Project managers. Exacerbating this problem were the differing priorities between the two agencies. From the beginning, Gunn's primary goal for the NRL was the development of submarine propulsion, while the Manhattan District's number one priority was developing an atomic weapon before the Germans did.¹³⁹

¹³⁵ Norman Polmar and Thomas B. Allen, *Rickover: Controversy and Genius*, (New York: Simon & Schuster, 1982), 118.

¹³⁶ Polmar and Allen, *Rickover: Controversy and Genius*, 118-119.

¹³⁷ Joseph-James Ahern, "We had the hose turned on us!": Ross Gunn and The Naval Research Laboratory's Early Research into Nuclear Propulsion, 1939 – 1946," *Historical Studies in the Physical and Biological Sciences*, Vol. 33, No. 2, (2003), 217-236, <http://www.jstor.org> (accessed February, 20, 2012).

¹³⁸ Ahern, "We had the hose turned on us!," 218-221.

¹³⁹ Ahern, "We had the hose turned on us!," 229.

With the end of World War II, NRL scientists looked to continue their research on nuclear propulsion for submarines. However, security restrictions placed on the Manhattan Project blocked the NRL from getting access to the information and enriched uranium it needed to conduct a scientific study of nuclear power.¹⁴⁰ In response, Secretary of the Navy James Forrestal wrote to Secretary of War Robert Patterson in 1946 requesting that Navy personnel integrate with the scientific community in an effort to develop atomic power for ship propulsion. Patterson agreed so long as the Navy personnel remained under the umbrella of General Groves' Manhattan District. Thus, by mid-1946, the Navy was putting together an initial cadre of personnel from the Bureau of Ships to go to the atomic energy plant at Oak Ridge, Tennessee to observe the Daniels' Pile project. Their de facto leader was Navy Captain Hyman Rickover.¹⁴¹

While working at Oak Ridge, Dr. Phil Abelson's 1945 report speculating on the potential uses of nuclear reactors as a submarine power source heavily influenced Rickover and the Navy team.¹⁴² Recognizing the potential to create a "true submarine," Abelson's report made suggestions on the power plant, horsepower requirements, coolant types, and other technical details.¹⁴³ The navy team built on Abelson's work and identified several constraints on submarine reactors to which their civilian counterparts were immune. For instance, submarine reactors had to run reliably for sustained periods of time because

¹⁴⁰ James H. Wakelin, Jr., "The Development of Nuclear Propulsion in the Navy," Address by Honorable James H. Wakelin Jr., Assistant Secretary of the Navy for Research and Development before the 22nd Annual Meeting of the American Power Conference in Chicago, Il (March 29, 1960): 4, www.dtic.mil (accessed January 23, 2012).

¹⁴¹ Francis Duncan, *Rickover: The Struggle for Excellence*, (Annapolis, MD: Naval Institute Press, 2001), 95-96.

¹⁴² Phil Abelson was a nuclear physicist from the University of California, Berkeley working in connection with the Manhattan Project; see Clay Blair Jr., *The Atomic Submarine and Admiral Rickover* (New York: Holt and Company, 1954), 24.

¹⁴³ Blair, *The Atomic Submarine and Admiral Rickover*, 24.

engineers could not take them off line for repairs while the submarine was at sea. Furthermore, submarine reactors, their associated turbines, and the necessary shielding had to be small enough to fit within the limited space of a submarine hull and robust enough to withstand the shock and motion of life on a combat ship. Finally, the propulsion system had to be manned by enlisted submariners, not a team of nuclear physicists.¹⁴⁴

On August 1, 1946, President Harry S. Truman signed the Atomic Energy Act into law. The Atomic Energy Act had a three-fold purpose. First, it replaced the military with a civilian institution as the principal arbiter of atomic weapons development and atomic power programs. Second, it established the Atomic Energy Commission (AEC) and assigned it the responsibilities previously held by the military during the Manhattan Project. Third, it prioritized the development of peaceful atomic energy for “improving the public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace.”¹⁴⁵ Once established, one of the programs the AEC was responsible for was marine propulsion. However, with all of its other responsibilities, developing a new method of propelling submarines was not one of the commission’s primary objectives.¹⁴⁶ The Navy’s lack of priority within the AEC led Rickover to note, “It would appear that if we are to have atomic power plants in naval vessels, the inspiration, the program, and the drive must come from the Navy itself.”¹⁴⁷

Although hindered by the lack of support from the AEC, the Navy’s Bureau of Ships began moving forward with initial reactor designs. In June 1947, the Bureau of Ships and General Electric initiated Project

¹⁴⁴ Duncan, *Rickover: The Struggle for Excellence*, 100.

¹⁴⁵ Atomic Energy Act of 1946 (Public Law 585, 79th Congress), <http://www.osti.gov/atomicenergyact.pdf> (accessed March 1, 2012); and Tucker, *Atomic America*, 60;

¹⁴⁶ Duncan, *Rickover and the Nuclear Navy*, 12.

¹⁴⁷ Polmar and Allen, *Rickover: Controversy and Genius*, 131.

Genie to develop a liquid-sodium-based heat transfer system for a submarine-based reactor. One year later, the Bureau of Ships launched Project Wizard with Westinghouse Electric to develop plans for a high-pressure-water-based heat transfer system.¹⁴⁸ By 1949, the Navy and the AEC decided that the pressurized-water design offered the highest probability of success and contracted Westinghouse Electric to develop the Mark I Submarine Thermal Reactor.¹⁴⁹ However, Rickover urged the AEC to develop General Electric's sodium-cooled reactor in parallel to the Westinghouse reactor, thus giving the Navy a credible backup if one or the other reactors failed during test and evaluation.¹⁵⁰

To promote the Navy's desire for atomic propulsion within the AEC, Admiral Earle W. Mills, Chief of the Bureau of Ships, named Rickover as the Bureau of Ships liaison to the AEC. As the Navy's liaison, Rickover was assigned to the Division of Reactor Development. This move effectively "dual-hatted" Rickover and allowed him to manipulate both his naval and civilian counterparts to move his vision for submarine propulsion forward.¹⁵¹ Rickover's work paid off on August 19, 1949 when Chief of Naval Operations Louis E. Denfield announced nuclear propulsion as an official development project, calling for the creation of an atomic-powered submarine by 1955.¹⁵²

With reactor designs moving forward and the nuclear propulsion program officially recognized by the Chief of Naval Operations, Rickover set out to meet the 1955 deadline. To reach this aggressive goal, two major factors were addressed: shipyard selection and congressional approval. Because the Navy was developing both the Westinghouse and the General Electric reactors, the Bureau of Ships decided to build two

¹⁴⁸ Wakelin, "The Development of Nuclear Propulsion in the Navy," 15.

¹⁴⁹ Polmar and Allen, *Rickover: Controversy and Genius*, 143.

¹⁵⁰ Polmar and Allen, *Rickover: Controversy and Genius*, 144-145.

¹⁵¹ Polmar and Allen, *Rickover: Controversy and Genius*, 141-143.

¹⁵² Duncan, *Rickover: The Struggle for Excellence*, 111.

separate submarines.¹⁵³ Due to the size and complexity of the project, Rickover's choice on shipyards was largely restricted to the Electric Boat Company, a private shipbuilder in Connecticut, or the Portsmouth Naval Yard. Recognizing that a civilian shipyard offered more flexibility and a greater degree of control than a government shipyard, Rickover selected Electric Boat to build both submarines.¹⁵⁴ To secure congressional funding for the program, Rickover circumvented traditional naval channels and went directly to Congress, appearing before the Joint Committee on Atomic Energy in February 1950. In his testimony, Rickover conveyed the tremendous advantage nuclear submarines held over their diesel-electric predecessors and related this capability to the threat posed by the Soviet Union. In light of the recent Soviet atomic detonation and escalating tensions on the Korean Peninsula, Congress authorized the 1952 fiscal year shipbuilding program, including plans to build the Navy's first nuclear-powered submarine.¹⁵⁵

Once Congress approved the Navy's shipbuilding plan, Rickover led efforts to build a scaled prototype of the first nuclear submarine at the reactor test facility near Arco, Idaho. Instead of following standard design practice and allowing engineers to spread the reactor and its components out to facilitate access to the myriad components, Rickover demanded that the Mark I reactor be developed within the confines of a mock submarine hull.¹⁵⁶ Doing so allowed Rickover and his team to assess where problems would arise on the actual submarine, and thus enabled them to correct minor design errors before they became major ones. To save time on the project, Rickover authorized the concurrent development of the Mark I while still designing and building the hull of the *Nautilus*. Rickover's gamble paid off, and engineers brought the

¹⁵³ Polmar and Allen, *Rickover: Controversy and Genius*, 146.

¹⁵⁴ Duncan, *Rickover and the Nuclear Navy*, 5; and Polmar and Allen, *Rickover: Controversy and Genius*, 147.

¹⁵⁵ Polmar and Allen, *Rickover: Controversy and Genius*, 147-149.

¹⁵⁶ Polmar and Allen, *Rickover: Controversy and Genius*, 149.

Mark I reactor to criticality in March 1953.¹⁵⁷ Shortly after, shipbuilders at Electric Boat laid the keel for the Navy's second nuclear submarine, *Seawolf*.¹⁵⁸ However, unlike with the *Nautilus*, the atomic reactor powering *Seawolf* used liquid sodium for heat transfer and reactor cooling.¹⁵⁹

With the advent of *Nautilus* and *Seawolf*, a new age of submarine warfare began. Creating a true submarine, one capable of operating completely independent of the surface for extended periods, had been the goal of submarine designers since John P. Holland launched his first submersible in 1878.¹⁶⁰ Nearly eight decades later, engineers were well on their way towards achieving this lofty goal. Nuclear propulsion offered tremendous advantages over diesel-electric powered submarines, and with the advent of ships like *Nautilus* and *Seawolf* the submarine changed from "a slow-moving, limited-endurance, short-legged surface craft with some ability to seek the safety of the waters for short periods, into the largest, longest-winded, widest-ranged unit in the fleet, at home only under the surface."¹⁶¹ Writing on the dramatic impact nuclear propulsion had on antisubmarine warfare (ASW), Owen Coté noted that *Nautilus* "completely undermined all the ASW progress made in the previous ten years."¹⁶²

Along with this tremendous capability came a host of new problems for the Navy to solve. Once put to sea, *Nautilus* ran significantly louder than its diesel-electric contemporaries – a major

¹⁵⁷ Duncan, *Rickover: The Struggle for Excellence*, 128-129.

¹⁵⁸ Duncan, *Rickover and the Nuclear Navy*, 13.

¹⁵⁹ In 1958, the Navy decided that sodium's corrosive effects and high radioactive capacitance posed an unacceptable risk for the *Seawolf* and it was ordered back to Electric Boat where its liquid-sodium reactor was replaced with a pressure-water reactor. See Thomas P. Allen and Norman Polmar, *Rickover: Father of the Nuclear Navy*, (Washington, D.C.: Potomac Books, 2007), 48-49.

¹⁶⁰ Burgess, *Ships Beneath the Sea*, 87; and Owen R. Coté, Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines*, (Newport, RI: Naval War College, 2003), 21.

¹⁶¹ Kuenne, *The Attack Submarine*, 191.

¹⁶² Coté, *The Third Battle*, 21.

problem for an attack submarine. Nuclear submarines were also expensive and difficult to produce en masse. This stood in stark contrast to the Soviet Union's purported production capability of 25 submarines per month.¹⁶³ Furthermore, controlling a fission reaction on a submarine was an extremely complicated procedure made worse by the fact that nuclear reactors and their respective cooling systems were still in their infancy while the Navy was building up its Cold War submarine force. This collection of political, financial, and technological factors all had to be assessed before the Navy could incorporate nuclear technology throughout its submarine fleet. Section III will take a closer look at these factors and determine what dynamics aided the Navy in eventually overcoming them.

Converting to a Nuclear Submarine Fleet

Dr. Philip Abelson was a nuclear expert. As a member of the Manhattan Project working at the Naval Research Lab, Abelson developed a method to create uranium hexafluoride, a critical chemical required to manufacture the uranium isotopes needed for nuclear fission.¹⁶⁴ Thus, when Abelson's 1946 report, "Atomic Energy Submarine" stated, "only about two years would be required to put into operation an atomic-powered submarine capable of operation at 26 knots to 30 knots submerged for many years without surfacing or refueling," the Navy took notice.¹⁶⁵ However, several factors prevented Abelson's assertions from coming to fruition.

First among these was World War II and the priority given to developing an atomic bomb. Because the Manhattan Project was the scientific community's number one priority, work at the NRL was placed under the Manhattan Engineering District (MED) which was given

¹⁶³ Polmar and Allen, *Rickover, Controversy and Genius*, 142.

¹⁶⁴ Ahern, "The United States Navy's Early Atomic Energy Research, 1939-1946."

¹⁶⁵ Allen and Polmar, *Rickover: Father of the Nuclear Navy*, 22.

control of the nation's limited supply of uranium-235.¹⁶⁶ Shortly after V-J Day, the NRL attempted to resuscitate its nuclear propulsion plans in an era characterized by slashed defense budgets, post-World War II drawdown, and nuclear fiefdoms worried about protecting their budgets and missions.¹⁶⁷ Further hindering the development of nuclear submarines was the perceived insignificance of submarines in a future war with the Soviet Union. Although intelligence estimates in 1946 predicted the Soviet Navy was on its way towards building a submarine force exceeding 300 ships, overall the Soviet Union was hardly a maritime heavyweight. By all accounts, the Soviet Union was a continental power whose primary focus was Europe and China, neither of which required a large merchant marine or a large surface navy.¹⁶⁸ Thus, as World War II ended, the Navy's submarine force was without a suitable rival and without a mission necessitating the massive levels of spending required to support nuclear propulsion.

After the Navy commissioned *Nautilus* and *Seawolf* into the fleet, more issues arose that disturbed the progress of this powerful new technology. Some of these issues were so severe that they threatened to derail the progress of the nuclear-powered submarine fleet.. One such reverse salient was noise. Submariners acknowledged that diesel-electric submarines were loud while operating on the surface, but submerged they ran on electric motors making them virtually silent. By comparison, early nuclear submarines were loud all the time. The submarine's reactor required the constant employment of reactor coolant pumps and reduction gears to maintain the reactor and reduce the speed of the turbine shaft.¹⁶⁹ This machinery made the first generation of nuclear submarines particularly loud in the low-frequency part of the sound

¹⁶⁶ Ahern, "The United States Navy's Early Atomic Energy Research, 1939–1946."

¹⁶⁷ Duncan, *Rickover and the Nuclear Navy*, 12.

¹⁶⁸ Jan S. Breemer, "The Submarine Gap: Intelligence Estimates 1945–1955," *Navy International*, February 1986, 100–105; Coté, *The Third Battle*, 18, 26.

¹⁶⁹ Duncan, *Rickover and the Nuclear Navy*, 22.

spectrum, making them easy to track and creating a dangerous liability for the new vessels.¹⁷⁰ Project Nobska, a summer study commissioned by the National Academy of Sciences to examine the threat posed by Soviet submarines noted, “until nuclear plants can be made quiet, they are not necessarily the optimum propulsion system for the true submarine. Any system of reasonable endurance that does not require air and that is really quiet could be a strong competitor.”¹⁷¹

An additional factor hindering the incorporation of nuclear propulsion technology was fear. Nuclear power was completely new when introduced in the 1950s, and the use of atomic weapons in World War II predictably shaped perceptions of the American nuclear enterprise. News articles created a mystique around nuclear power and touted the exploits of the Manhattan Project scientists.¹⁷² The media also captured and spread the image of nuclear power as a universal energy source for the good of humanity.¹⁷³ However, nuclear accidents such as the NRX mishap in Chalk River, Canada, the Windscale Piles fire in England, and the SL-1 reactor accident in the United States propagated fears that scientists did not know enough about nuclear

¹⁷⁰ Owen Coté discusses the susceptibility of early nuclear submarines to ASW practices in great depth. See Coté, *The Third Battle*, 21-24.

¹⁷¹ Committee on Undersea Warfare, National Academy of Sciences, *Project Nobska: The Implications of Advanced Design on Undersea Warfare*, Final Report, Volume 1: Assumptions, Conclusions, and Recommendations, 6, quoted in Coté, *The Third Battle*, 6.

¹⁷² Harry M. Davis, “The Man Who Built the A-Bomb,” *New York Times Magazine*, April 18, 1948, <http://search.proquest.com>; also see David K. Hecht, “The Atomic Hero Robert Oppenheimer and the Making of Scientific Icons in the Early Cold War,” *Technology and Culture*, Vol. 49, No. 4 (October 2008), 943-966, <http://muse.jhu.edu/>

¹⁷³ William Gamson and Andre Modigliani document the impact different forms of media had in shaping public opinion during the Atomic Age in great detail, see William A. Gamson and Andre Modigliani, “Media Discourse and Public Opinion on Nuclear Power: A Constructionist Approach,” *American Journal of Sociology*, Vol. 95, No. 1 (July 1989), 1-15, <http://www.jstor.org>; for specific examples see “Our Free System Will Put the Atom to Work,” *Saturday Evening Post*, August 28, 1954, <http://www.proquest.com>; and Leonard Engel (accessed January 25, 2012), “Forecast of the Age of Atomic Power,” *New York Times*, December 20, 1953, <http://search.proquest.com> (accessed January 25, 2012).

technology for it to be used safely in society.¹⁷⁴ A series of Air Force mishaps involving nuclear weapons further aggravated the public's uncertainty about nuclear technology while damaging the Department of Defense's credibility on nuclear technology issues.¹⁷⁵

A final hindrance or reverse salient in the development of the Navy's nuclear submarine program involved complexity and cost. Nuclear propulsion technology was a revolutionary step towards a new and better submarine. As such, the Navy could not rely on its existing infrastructure to handle the requirements posed by nuclear technology. Instead, the Navy required an entirely new infrastructure capable of building nuclear reactors, maintaining reactors sent to the fleet, decommissioning the reactors, and disposing of the nuclear by-products at the end of the core's usable life.¹⁷⁶ All of these processes equated to higher expenditures, making nuclear vessels cost approximately 50 percent more than their conventional counterparts.¹⁷⁷ Adding to the cost in dollars was the cost in manpower and expertise. Because of the inherent complexity and potential disastrous effects of a mishap, the Navy siphoned off many of its top personnel to operate the nuclear power

¹⁷⁴ The NRX reactor melted down when the emergency cooling rods failed to insert correctly. The Windscale accident, which occurred when the core unit caught fire and released radioactive isotopes into the surrounding community, was one of the worst nuclear accidents in Great Britain's history. The Army's SL-1 reactor exploded when Army technicians were unable to properly insert the control rods, causing the reactor to melt down and killing all three technicians. See William J. Nuttall, *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power* (New York: Taylor & Francis, 2005), 66-69; and Tucker, *Atomic America*, 1-30.

¹⁷⁵ Douglas Keeney documents several of the Air Force's mishaps with nuclear weapons in his book *15 Minutes*; see L. Douglas Keeney, *15 Minutes: General Curtis LeMay and the Countdown to Nuclear Annihilation* (New York: St. Martin's Press, 2011).

¹⁷⁶ Richard G. Hewlett and Francis Duncan, *Nuclear Navy 1946-1962*, (Chicago, IL: University of Chicago Press, 1974), 281-282, 290-295, 366-376.

¹⁷⁷ Duncan, *Rickover: The Struggle for Excellence*, 173. Note, today a Virginia Class nuclear submarine costs approximately \$2 billion while cost estimates for a comparable diesel-electric range from \$500 million to \$1 billion. See Jonah Friedman, "Nuclear vs. Diesel Submarines," The Center for Strategic and International Studies, October 18, 2011, <http://csis.org/blog/nuclear-vs-diesel-submarines> (accessed February 17, 2012).

plants and manage the reactor's associated systems.¹⁷⁸ Together, these factors created a strategic dilemma for the Navy's senior leaders. Given a fixed budget and limited resources, they had to decide between a higher number of less capable submarines, or a lower number of more capable submarines.

A number of internal and external factors influenced these decisions and the eventual incorporation of nuclear technology into the submarine fleet. However, three are of particular importance. One of the first factors that played a role in development and eventual acceptance of the nuclear submarines was interservice rivalry. The second was Hyman Rickover, and the third was the Soviet Union. The confluence of these three dynamics enabled the Navy to either work around or accept many of the problems associated with nuclear technology. Furthermore, it allowed the Navy to do so in a remarkably short amount of time.

In the aftermath of World War II, competition between the Army, Navy, and Air Force had a significant impact on the development of the first nuclear submarine. Having witnessed the awesome power of atomic weapons, the services scrambled to find ways to harness the power of the atom for their own advantage. The Army originally turned to small yield atomic weapons such as atomic cannons and artillery shells. However, by 1952 the Army had also started its own nuclear power program aimed at supplying energy for its remote operating locations.¹⁷⁹ The Army's nuclear program received a considerable boost when President Eisenhower authorized the creation of the Distant Early Warning (DEW) Line. Recognizing that the DEW Line's tremendous energy demands and remote locations made it an excellent candidate for nuclear power, the Army increased its efforts to be the principal energy supplier for this

¹⁷⁸ Herbert J. Gimpel, *The United States Nuclear Navy* (New York: Franklin Watts Inc., 1965), 64.

¹⁷⁹ Tucker, *Atomic America*, 93-95.

massive defense system.¹⁸⁰ Similar to the Army, the Air Force sought to ensure its relevance by focusing on both nuclear weapons and nuclear power. After delivering the two atomic bombs that ended World War II, the Air Force aimed to increase its role within the Department of Defense by developing a large strategic bombing force capable of delivering atomic weapons.¹⁸¹ At the same time, the Air Force was examining the possibility of creating a nuclear-powered supersonic bomber. For airmen, the prospect of nuclear-powered bombers with unlimited range and endurance was captivating. Thus, in 1946 the Air Force contracted with the Fairchild Engine and Airplane Corporation to begin developing a nuclear engine propulsion program for aircraft.¹⁸²

The result of the Army and Air Forces' nuclear programs was a de facto competition between the services. Each service aimed to protect its relevance, and thus its budget by demonstrating how it was uniquely capable of harnessing nuclear energy for the greater benefit of the nation's defense. Writing on the role of interservice conflict in doctrinal innovation, Owen Coté noted that each service aims to protect "its doctrinal vision of itself as an independent, strategically significant actor."¹⁸³ Following World War II, the best way for the services to project an image of themselves as independent strategic actors was via the atom. In the Atomic Age, any service that failed to exploit the power of atomic energy risked obsolescence and a corresponding loss of defense dollars. This created bitter disputes between the services. Coté argues that between 1944 and 1964, these battles over roles, missions, and budgets threatened traditional Navy doctrine and created an impetus for the

¹⁸⁰ The DEW system required 155,000 kilowatts of power, approximately the same as Spokane, Washington; see Tucker, *Atomic America*, 98.

¹⁸¹ For more on the Air Force's prevalent role in the post-World War II era see David Alan Rosenberg, "The Origins of Overkill, Nuclear Weapons and American Strategy, 1945-1960," *International Security*, Vol. 7, No. 4 (Spring 1983), 19-23, <http://www.jstor.org>; and Keeney, *15 Minutes*, 7-104.

¹⁸² Tucker, *Atomic America*, 123-126.

¹⁸³ Coté, "The Politics of Innovative Military Doctrine," 85.

development of new weapons and ideas about warfighting.¹⁸⁴ Thus, the Army and Air Force's nuclear programs put tremendous pressure on the Navy to accelerate its own nuclear program while providing the justification to place its limited resources into developing a yet unproven technology.

A second major factor to consider when examining the incorporation of nuclear propulsion is Hyman Rickover. Rickover's role as the principal architect of the Navy's nuclear program gave him enormous influence on the creation, development, and incorporation of nuclear-powered submarines. Looking back at his role, many authors have classified Rickover as a maverick who flaunted the Navy's rules and regulations to accomplish the task he felt best for the nation.¹⁸⁵ However, as it pertains specifically to the evolution of the nuclear submarines, the notion of Rickover as a maverick is overstated and not entirely accurate. Stephen Rosen notes that the idea of a military maverick is appealing, yet when historical examples of mavericks are examined under scrutiny their role is deemed "less crucial in producing innovations than their public images suggest."¹⁸⁶

A maverick is an independent thinker who refuses to conform to the accepted view on a subject or whose views differ from that of convention. This was clearly not the case with Rickover and the Navy when it came to nuclear submarines. Rickover's views were largely consistent with the Navy, and it was the Navy's support that made Rickover's accomplishments possible.¹⁸⁷ In their biography of Rickover, Thomas Allen and Norman Polmar note, "one can find no opposition to

¹⁸⁴ Coté, "The Politics of Innovative Military Doctrine," 345.

¹⁸⁵ For instance, see Tucker, *Atomic America*, 46 and Edward L. Beach, *Salt and Steel: Reflections of a Submariner* (Annapolis, MD: Naval Institute Press, 1999), 186.

¹⁸⁶ Rosen, *Sources of Military Doctrine*, 11-12.

¹⁸⁷ While Rickover experience more than his fair share of clashes with the Navy's senior leadership, these fights were primarily personality driven and one should take into account that Rickover's views on nuclear-powered submarines were largely congruent with those of the Navy brass.

the development of nuclear-propelled submarines per se in the US Navy...indeed, the US Navy had officially shown interest in nuclear propulsion as early as 1939, and after World War II initiated a nuclear submarine program before Rickover became involved.”¹⁸⁸

A more useful way of examining Rickover’s effect on the nuclear submarine program is by utilizing Thomas Hughes’s construct of a system builder. By Hughes’s definition, a system builder presides over a project from the concept phase, through research and development, and into deployment. System builders are cross-disciplinary, they have an innate ability to focus on the interface between system components, and they typically preside over systems that establish both physical artifacts and organizations.¹⁸⁹ To illustrate his concept of a system builder within the military-industrial construct, Hughes points to General Bernard Schriever, a key figure in the development of the Air Force’s intercontinental ballistic missile (ICBM) program, highlighting his “excellent grounding in science and engineering, intimate knowledge of the workings of the Pentagon and the government as a whole, and an uncanny sense for evaluation of and ‘managing’ people.”¹⁹⁰

A review of Rickover’s interaction with the nuclear submarine program reveals that the system builder model is a much more accurate depiction than that of a maverick. Along the same lines as Schriever, Rickover established technical credibility for himself by studying nuclear energy at the Massachusetts Institute of Technology and by absorbing knowledge from field experts such as Dr. Edward Teller while at Oak Ridge.¹⁹¹ He then used this credibility to circumvent various obstacles that hindered his organization’s progress, creating a system that focused

¹⁸⁸ Allen and Polmar, *Rickover: Father of the Nuclear Navy*, IX.

¹⁸⁹ Thomas P. Hughes, *Rescuing Prometheus* (New York: Vintage Books, 1998), 7.

¹⁹⁰ General Schriever oversaw the development of America’s intercontinental ballistic missile system. Hughes, *Rescuing Prometheus*, 96.

¹⁹¹ Duncan, *Rickover: The Struggle for Excellence*, 94; Polmar and Allen, *Rickover Controversy and Genius*, 127.

as much on safety and technical competence as it did on speed and timeliness. When it came to maneuvering through the bureaucracy of the Pentagon and the government as a whole, Rickover developed an intimate knowledge of politics and the legislative system to garner support for nuclear propulsion. A self-described “creature of Congress,” Rickover used his political clout to bring attention to Navy programs while simultaneously leveraging his position as a key leader of the nation’s civilian nuclear power enterprise to create general support for nuclear technology.¹⁹² As a manager of people, Rickover was notoriously unpleasant and was widely marginalized because of his prickly demeanor. However, he personally selected and interviewed every officer accepted into the Navy’s nuclear submarine program, creating an enduring organizational system with a sterling safety record.¹⁹³

Rickover’s obsession with having the best-trained personnel and an immaculate safety record helped allay the nation’s concerns about the possible catastrophic side effects of nuclear power. He realized that the “whole reactor game hangs on a much more slender thread than people are aware...all we have to do is have one good accident in the United States and it might set the whole game back for a generation.”¹⁹⁴ Safety was important to Rickover for personal reasons as well. As one of the nation’s foremost nuclear experts, Congress and the Navy gave Rickover a great deal of autonomy to run his organization the way he saw fit. This allowed him to take rapid decisive actions without constantly seeking permission from a higher authority. Rickover protected this independence fiercely, leveraging his relationships with Congress to protect nuclear propulsion from the other services, and rewriting his job description as an AEC official to protect Navy programs from the

¹⁹² Polmar and Allen, *Rickover Controversy and Genius*, 208.

¹⁹³ Gimpel, *The United States Nuclear Navy*, 144-145.

¹⁹⁴ Allen and Polmar, *Rickover: Father of the Nuclear Navy*, 59.

bureaucratic grip of the government.¹⁹⁵ However, despite his ability to protect nuclear propulsion from machinations of government and Navy bureaucracy, Rickover recognized that his authority would last only so long as his organization created safe dependable power, and that one slip would spell the end of his nuclear fiefdom.

While Rickover's overall effect on the development and incorporation of nuclear propulsion technology was significant, perhaps the greatest single factor affecting the Navy's adoption of nuclear power was the strategic threat posed by the Soviet Union. Barry Posen argued that the anarchic international system creates external pressures on states and that these external pressures override internal pressures and domestic concerns.¹⁹⁶ Consistent with Posen's thesis, the Soviet Union created enormous external pressures on the United States in the years following World War II. During this period, American intelligence sources believed that the Soviet Union had captured several German Type XXI submarines and their respective engineering diagrams. Further, they believed the Soviets were using these designs to mass-produce a new fleet of submarines capable of cutting off the United States from its Western European allies.¹⁹⁷ This threat was amplified by the Soviet blockades of Berlin, the successful detonation of an atomic weapon in 1949, the rise of communism in Czechoslovakia and China, and the North Korean invasion of South Korea.

Together these factors and the threat of a Soviet invasion of Europe motivated President Truman to build up America's nuclear capability. In 1949, 1950, and 1952 the president authorized substantial increases in nuclear production, establishing the centrality of nuclear weapons in the Department of Defense's strategic posture.¹⁹⁸ The principal benefactor of

¹⁹⁵ Duncan, *Rickover and the Nuclear Navy*, 288-289.

¹⁹⁶ Posen, *The Sources of Military Doctrine*, 79.

¹⁹⁷ Coté, *The Third Battle*, 18.

¹⁹⁸ Rosenberg, "The Origins of Overkill," 21-27.

the nation's nuclear focus was the Air Force's Strategic Air Command (SAC). SAC served as the nation's primary method of delivering nuclear weapons and thus reaped the benefits of enlarged budgets aimed at building up American nuclear capability.¹⁹⁹ The Nation's defense strategy retained its nuclear centrality under President Eisenhower; however, Eisenhower's attempts to curb military expenditures rekindled competition between the services for budget dollars.²⁰⁰ Increased competition prompted the Navy to move forward with the development of the Polaris intermediate range ballistic missile; shortly thereafter, the Navy began promoting Polaris as an alternative to land-based bombers and ICBMs.²⁰¹ The DOD's eventual decision to support the submerged ballistic missile system gave the Navy's submarine force the mission it lacked in the aftermath of World War II. As an additional means of deterring the Soviet Union from attack, the American public viewed nuclear-powered submarines with ballistic missiles as silent sentinels keeping the Soviet aggressors at bay. The Navy took advantage of this newfound attention, rapidly accelerating the entire Polaris program, to include the production of a new generation of nuclear-propelled submarines.²⁰²

Overall, it is possible to take several conclusions away from the Navy's transition from diesel-electric to nuclear-powered submarines. What is particularly important to note is how the confluence of an external threat, interservice conflict, and a dedicated system-builder fostered the rapid acceptance and incorporation of a technological change that was already afoot. The movement to develop a means of air-independent propulsion began in the United States in 1939 but

¹⁹⁹ Rosenberg, "The Origins of Overkill," 19-23; and Keeney, *15 Minutes*.

²⁰⁰ Coté, "The Politics of Innovative Military Doctrine," 354-357

²⁰¹ Coté, "The Politics of Innovative Military Doctrine," 25-27; Rosenberg, "The Origins of Overkill," 51-53; Hewlett and Duncan, *Nuclear Navy 1946-1962*, 307-317.

²⁰² Gimpel, *The United States Nuclear Navy*, 172-181; Duncan, *Rickover: The Struggle for Excellence*, 193.

languished during World War II. After World War II, the Soviet's conventional military strength provided the Navy and Congress with a powerful incentive to revive earlier efforts at developing nuclear propulsion technology. Once begun, interservice rivalry and the actions of Hyman Rickover accelerated the developments that the Soviet Union had helped rekindle. The looming Soviet threat led the United States to adopt a nuclear-centric defense policy that created competition between the services to develop innovative new ways to deliver nuclear weapons. In addition, the Soviet threat helped Hyman Rickover obtain the authority needed to muster America's economic, industrial, and scientific resources together in an effort to develop a nuclear submarine before the Soviets did.²⁰³ These examples are consistent with Owen Coté's argument that interservice conflict can accelerate doctrinal changes begun as a result of other independent actions; and while Thomas Hughes does not make the same argument with respect to system builders, the example of nuclear propulsion demonstrates that such an argument would certainly be valid.²⁰⁴

Several lessons regarding energy transition emanate from the Navy's conversion from sail to steam-powered warships and its transition from diesel-electric to nuclear-powered submarines. One factor not yet addressed is that of scale. When the Navy switched from diesel-electric to nuclear submarines, it was altering only a small percentage of the Navy's overall fleet. Conversely, the transition from sail to steam involved virtually every ship the Navy operated. Hence, the scale was much larger in the case of sail to steam and therefore the degree of transition was markedly more severe. This challenge rises to an entirely

²⁰³ Duncan, *Rickover and the Nuclear Navy*, xi; Duncan, *Rickover: The Struggle for Excellence*, 112. This logic is also consistent with William H. McNeill's argument that the United States began reverting to a command economy in the Cold War in order to counter the threat posed by the Soviet Union. See William H. McNeill, *The Pursuit of Power* (Chicago, IL: University of Chicago Press, 1982), 362-384.

²⁰⁴ Coté, "The Politics of Innovative Military Doctrine," 13.

new level when the transition involves more than just one particular service and instead requires the entire DOD to change. As the next chapter will show, one of its greatest challenges new energy technologies face is overcoming the tyranny of scale.



Chapter 4

Renewable Biofuel Technology

In *The Origins of the Turbojet Revolution*, Edward Constant notes that presumptive anomalies occur “not when the conventional system fails in any absolute or objective sense, but when assumptions derived from science indicate either that under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a much better job.”²⁰⁵ Today, the DOD is struggling to deal with a presumptive anomaly. Scientists have concluded that the Earth’s supply of petroleum is finite, and therefore the existing oil-based system utilized by the DOD is destined to fail under future conditions. To mitigate the problems posed by a future void of petroleum, the DOD is in the early stages of a new energy transition. In some ways the DOD’s current transition mirrors the previously discussed case studies and in other ways is completely unique. Like the Navy’s transition from sail to steam, proponents of new energy technologies such as renewable biofuels face a difficult challenge in overcoming a large and mature technological system. In much the same way nuclear technology forced Navy leaders to make value judgments between quality and quantity, the proposed incorporation of biofuels has forced DOD decision makers to weigh the benefits of domestic fuel production against the high costs currently associated with biofuel technology.

To guide its transition to renewable energy sources, in 2011 the DOD drafted *Energy for the Warfighter: Operational Energy Strategy*. The strategy’s three-part focus targets demand, culture, and supply. On the demand front, the DOD aims to reduce its consumption by developing efficiencies that increase performance, reduce energy expenditures, and

²⁰⁵ Constant, *The Origins of the Turbojet Revolution*, 15.

thereby enhance combat effectiveness.²⁰⁶ With respect to culture, the DOD seeks to alter the processes used for developing military forces in such a way that accounts for energy considerations across the entire range of planning, development, and execution.²⁰⁷ The last focus area of the Department's strategy is supply. The DOD recognizes that depending on petroleum as the single source of energy for the majority of military operations has economic, strategic, and environmental drawbacks. To reduce the risk posed by reliance on a single energy source, the DOD has accelerated efforts to diversify its energy sources with the intent of building a more resilient, reliable, and assured supply of energy in the future.²⁰⁸ One of the most promising ways of diversifying the DOD's energy portfolio is through renewable biofuels. Thus, this final case study examines the incorporation of biofuels into the DOD's predominately oil-based infrastructure.

The American Oil Enterprise

As with the case studies analyzing the adoption of steam and nuclear power, it is important to examine the development of the DOD as an oil-based system in order to understand the context of transitioning to a new energy source. To understand the entrenchment of oil within the military, moreover, it is first necessary to look at the connection between oil and the nation. From its outset, the American association with oil has been characterized by a continuing cycle of booms and busts. First launched in 1859 when Edwin L. Drake drilled a successful oil well near Titusville, Pennsylvania, Americans originally viewed "rock oil" as a means of satisfying the growing demands for lighting and lubricants

²⁰⁶ US Department of Defense, *Energy for the Warfighter: Operational Energy Strategy*, May 2011, http://energy.defense.gov/OES_report_to_congress.pdf (accessed March 20, 2012), 4-5.

²⁰⁷ DOD, *Energy for the Warfighter*, 9-10.

²⁰⁸ DOD, *Energy for the Warfighter*, 7-9.

posed by the industrial revolution.²⁰⁹ Drake's early success in Titusville inspired a new industry of oil explorers and prospectors, causing annual production to jump from 500,000 barrels in 1860 to 20 million barrels by the mid-1870s.²¹⁰ This vigorous industrial exploitation gave the United States an early lead compared to the other oil nations of the era, resulting in the United States producing approximately 70 percent of the world's oil supply.²¹¹ Abundant supply, coupled with the invention of the automobile and the internal combustion engine, led to the rapid creation and boom of an automotive-based culture in the United States.²¹² To meet the energy demands of the nation's growing automobile fleet, over 143,000 gas stations were put in place by 1929, launching the United States' petroleum infrastructure into a new era of expansion.²¹³

Rapid development and consumption led the US Geological Service to speculate that the United States was at the peak of its oil producing days by the mid-1920s. The USGS's warning sparked fears that Americans had depleted their precious oil reserves, which in turn spiked oil prices, and caused the United States to start looking abroad to meet its oil needs.²¹⁴ These fears ended with the discovery of massive new oil fields in the western states of Texas, Oklahoma, and California. Unfortunately for oil men of the day, the new discoveries led to rapid production increases, depressing oil prices to 10 cents a barrel by the 1930s.²¹⁵ During World War II, American support to the Allies quickly

²⁰⁹ Daniel Yergin, *The Prize: The Epic Quest for Oil, Money, and Power* (New York: Free Press, 1991), 25-29.

²¹⁰ The University of Houston, "The Politics of Oil," <http://www.digitalhistory.uh.edu/historyonline/oil.cfm> (accessed March 17, 2012).

²¹¹ The University of Houston, "The Politics of Oil."

²¹² Paul Johnson, *A History of the American People*, (New York: HarperCollins Publishers, 1997), 606-607.

²¹³ For example, in 1916 Americans owned 3.4 million automobiles, yet by 1929, over 23 million vehicles were registered. See Yergin, *The Prize*, 208-209.

²¹⁴ Francisco Parra, *Oil Politics: A Modern History of Petroleum* (New York: I.B. Tauris & Co., 2004) 12-16; and Vaclav Smil, *Energy Myths and Realities: Bringing Science to the Energy Policy Debate* (Washington, D.C.: The American Enterprise Institute, 2010), 62.

²¹⁵ The University of Houston, "The Politics of Oil."

erased the oil surplus as the United States sent a steady stream of oil tankers eastward to maintain the dwindling European stocks of automotive fuel and marine diesel.²¹⁶ Fully aware that the United States was keeping the Allied war effort afloat, Germany began attacking the vulnerable American tankers as they sailed from the Gulf of Mexico and along the East Coast. To help mitigate this threat, the United States built the Big Inch and the Little Big Inch pipelines from Texas and Louisiana to Pennsylvania, New York, and New Jersey. This extraordinary engineering feat reduced the threat posed by submarines, while also demonstrating the value and efficacy of long-range pipelines to the burgeoning American oil industry.²¹⁷

In the years immediately following World War II gas rationing ended, the number of cars increased by 40 percent, oil surpassed coal as America's principle energy source, and an era of consumption swept the nation.²¹⁸ Overall, while comprising only 6 percent of the world's population, the United States consumed 33 percent of the world's oil, making it far and away the world's largest consumer.²¹⁹ At the same time, American policymakers were grappling with the reality that the United States' oil reserves were finite, thus requiring Americans to again look overseas to meet their domestic needs. To satiate this demand, Middle Eastern nations such as Saudi Arabia and Iran dramatically increased production, sinking oil prices further and causing many coal-burning power plants to shift to oil and natural gas. Again, the spike in production dropped oil prices, sending the economies of the world's oil exporters into disarray. In 1960, Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela responded by forming OPEC, a cartel to coordinate and unify their petroleum policies while ensuring the stabilization of prices in the

²¹⁶ Yergin, *The Prize*, 375.

²¹⁷ Yergin, *The Prize*, 375.

²¹⁸ The University of Houston, "The Politics of Oil."

²¹⁹ Parra, *Oil Politics*, 33-42; and The University of Houston, "The Politics of Oil."

international oil market, and thus ensuring the financial interests of member nations.²²⁰

Back in the United States, unchecked consumption and massive industrialization continued throughout the 1960s and into the 1970s, entrenching oil as the lifeblood of the nation's industrial economy and increasing American dependence on foreign oil producers. In 1973, the Organization of Petroleum Exporting Countries (OPEC) demonstrated this dependence by enacting an embargo of all oil exports to nations supporting Israel in the 1973 Arab-Israeli War, quadrupling oil prices and sending shockwaves through the western world.²²¹ As oil historian Daniel Yergin notes, "the shortfall struck at the fundamental beliefs in the endless abundance of resources, convictions so deeply rooted in the American character and experience that a large part of the public did not even know, up until October 1973, that the United States imported any oil at all."²²² Thus, the 1973 embargo opened the eyes of many Americans as to just how reliant the United States had become on foreign oil.

Following the shocks of the 1970s, oil prices returned to their historic prices and remained low throughout the second half of the 1980s and into the 1990s. Like the post-World War II era, rapid industrial growth and high consumption rates characterized this period while the oil industry attempted to keep up with demand by expanding its global infrastructure. In stark contrast to the heady days of the 1990s, the first decade of the twenty-first century saw prices begin to rise rapidly. Largely in response to the September 11, 2001 attacks, the war in Iraq, and instability in the major oil producing regions of the world, oil spiked

²²⁰ Organization of the Petroleum Exporting Countries, "OPEC Statute," 2008. http://www.opec.org/opec_web/static_files_project/media/downloads/publications/OS.pdf (accessed March 17, 2012).

²²¹ Yergin, *The Prize*, 600-612.

²²² Yergin, *The Prize*, 616.

to an all-time high of \$147 per barrel in July 2008 and has remained on an upward trajectory for the last ten years.²²³

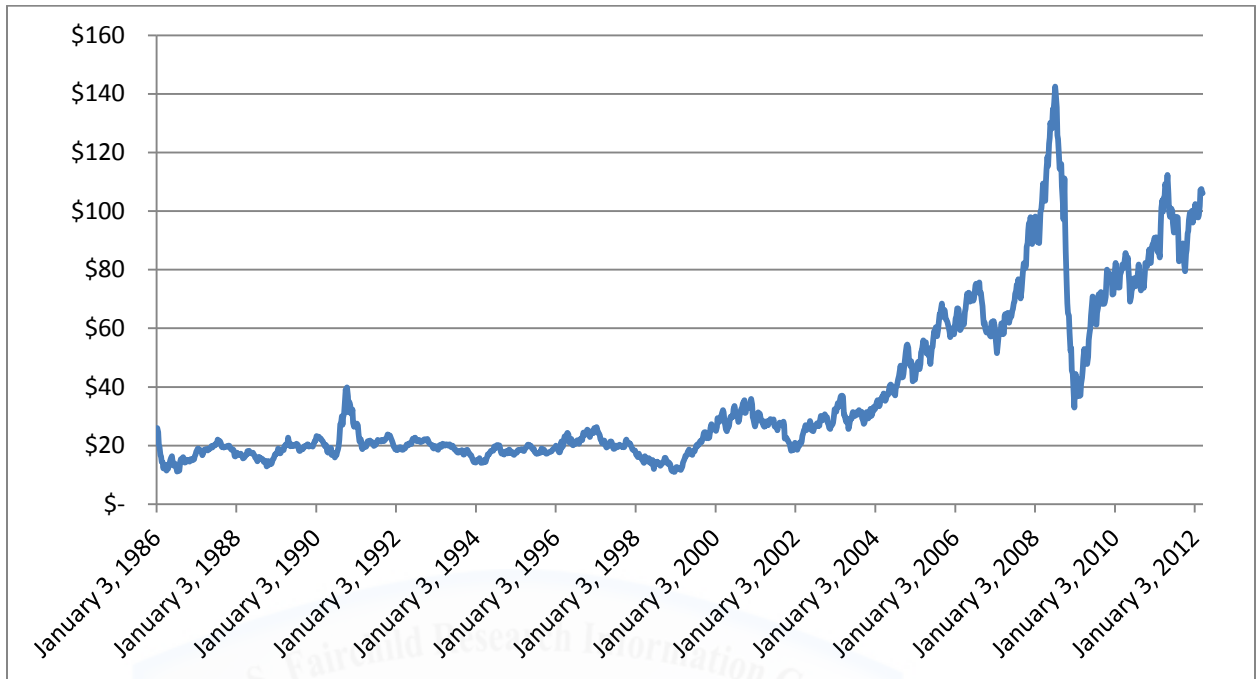


FIGURE 2: SPOT PRICE OF OIL, 1986-2012

Source: Author's Compilation of Data obtained from US Energy Information Agency, "Weekly Cushing, OK WTI Spot Price FOB," <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rwtc&f=w> (accessed March 20, 2012).

The cyclic nature of the American relationship with oil provides several insights into the social factors currently affecting the DOD's transition to renewable fuels. First, the recurring succession of scarcity and abundance discourages innovation. Faced with the prospect of spending more money for more efficient technology or less money for a less efficient product, consumers can point to the historically low price of fuel to justify their decision to forego investing in expensive new technologies. Furthermore, the cyclic nature of oil creates uncertainty in the mind of investors. Developers contemplating the advancement of a

²²³ Leonardo Maugeri, *Beyond the Age of Oil: The Myths, Realities, and Future of Fossil Fuels and Their Alternatives* (Santa Barbara, CA: Praeger, 2008), 10.

new technology are acutely aware that the price of oil has customarily fallen back to its regular low price after periodic spikes. Therefore, given the wide range of oil prices over the past twenty years, new energy sources must be developed with oil's historical low price point in mind, or risk being ignored by the market if the price of oil returns to a more manageable level. The bottom line for commercial developers of new fuels is that oil's price volatility causes uncertainty, and uncertainty breeds caution while inhibiting growth.²²⁴

The second major takeaway revealed by this brief history of American oil consumption concerns mobility. For over one hundred years, oil has fueled American mobility and industry, first fostering the development of the American automotive industry and then facilitating the rise of aviation in the United States. The result is that Americans have grown accustomed to a mobility lifestyle lubricated by oil. As noted by Leonardo Maugeri, author and senior vice-president of one of the world's leading oil and gas companies, "Oil has trivialized the meaning of geographic distance through mass and individual transportation. It has molded our lifestyles and given us many of the comforts and advantages that we take for granted."²²⁵

The third insight worth noting concerns infrastructure and influence. After developing the first oil drills in 1859, Americans began building a massive support infrastructure to facilitate the exploitation of oil resources. The scope of this infrastructure is astounding and includes all of the systems designed to extract oil from the ground, refine the crude into usable products, and then transport both the unrefined and refined oil products around the globe. The result is a deeply rooted system that has taken over one hundred years to build and is currently

²²⁴ Sustainable Aviation Fuels Northwest, "Powering the Next Generation of Flight," May 25, 2011, http://www.safnw.com/wp-content/uploads/2011/06/SAFN_2011Report.pdf (accessed March 18, 2012), 24.

²²⁵ Maugeri, *Beyond the Age of Oil*, 1.

valued at over \$5 trillion.²²⁶ Such infrastructure resides in the congressional districts of American representatives, giving them a strong impetus to either protect or expand oil investment in these areas. This deep attachment also gives the oil industry significant influence on American politics, as witnessed by the fact that oil lobbyists have spent over \$1 billion lobbying American lawmakers since 2001, making them one of the single largest spenders on lobbying in the United States.²²⁷

When looking specifically at the American military, several of the insights gleaned from examining the American public's relation to oil apply to the DOD as well. Like the general public, the American military has co-evolved with the nation's available energy resources. As oil became more widely available in the early 1900s, the military recognized that fuels derived from oil were well suited to meet the propulsion demands of military vehicles and for distribution via the nation's air, road, rail, and sea networks.²²⁸ In World War I, the introduction of revolutionary new weapons such as the tank and airplane went hand-in-hand with the petroleum products needed to keep these technological marvels going. During World War II, the combat forces of nearly all the major combatants included some combination of heavy mechanized ground forces, aircraft, and naval forces. Like their predecessors in World War I, these forces required tremendous supplies of petroleum in order to keep them running and to project them across the large spaces that defined the World War II theaters. Thus, many of the campaigns in

²²⁶ Smil, *Energy Myths and Realities*, 140.

²²⁷ Center for Responsive Politics, "Oil and Gas Industry Profile, 2001-2011," <http://www.opensecrets.org/lobby/background.php?id=E01&year=2001>, (accessed March 22, 2012). See also Dan Briody, *The Haliburton Agenda: The Politics of Oil and Money* (Hoboken, NJ: John Wiley and Sons, 2004) and Kevin Phillips, *American Theocracy: The Peril and Politics of Radical Religion, Oil, and Borrowed Money in the 21st Century* (New York: Viking, 2006).

²²⁸ Scott Thomas and David Kerner, "Defense Energy Resilience: Lessons from Ecology," US Army War College, August 2010, <http://www.strategicstudiesinstitute.army.mil/pdffiles/PUB1011.pdf> (accessed March 17, 2012), 1.

both the Pacific and Europe focused on securing oil reserves, cutting adversaries off from their sources of oil, or destroying the ability of an enemy to refine and distribute the oil they had.²²⁹ Recently, the war in Iraq, the war in Afghanistan, and the logistics disruptions caused by diplomatic disputes with Pakistan demonstrate that the American military depends just as heavily on a robust and secure source of fuel today as it did over sixty years ago.

As the respective services within the DOD have grown, all of them have become more dependent on petroleum-based fuel. In FY2010, the DOD spent \$15.2 billion on energy, of which \$4 billion went towards installation energy requirements while over \$11 billion went towards operational energy requirements. What is especially noteworthy is that of the \$11 billion, 81 percent went towards jet fuel (JP-8 or JP-5) while 12 percent went towards marine diesel fuel (Navy Distillate, NATO F-76), making the Air Force and the Navy the two largest consumers of oil in the DOD.²³⁰ The expenditures on fuel equate to approximately 340,000 barrels of fuel per day, of which 50 percent is procured domestically with the rest obtained abroad.²³¹ To acquire such large amounts of fuel, DLA-Energy purchases fuel on the open market, “relying on competition in the civilian marketplace to drive innovation in fuel production and

²²⁹ Dan Yergin, “Interview with Dan Yergin,” by Scott Tong, *Marketplace*, August 29, 2011, <http://www.marketplace.org/topics/business/news-brief/military-and-oil-historian> (accessed March 22, 2012). For more on strategic attack against enemy petroleum sources see Adam Tooze, *The Wages of Destruction: The Making and Breaking of the Nazi Economy* (New York: Viking, 2007).

²³⁰ The Pew Project on National Security, Energy and Climate, “From Barracks to the Battlefield: Clean Energy Innovation and America’s Armed Forces,” (Washington, D.C.: Pew Charitable Trusts, 2011), 14-15.

²³¹ The middle distillate fuel group includes diesel and jet fuel. Fuels in this group are less volatile and less prone to inadvertent ignition, making them preferable for military applications. Within the distillate group are the three fuels that dominate DOD fuel use: JP-8 and JP-5 (both kerosene based), and naval distillate fuel, F-76, a marine distillate fuel used by all US Navy nonnuclear combatant ship systems. See James T. Bartis and Lawrence Van Bibber, *Alternative Fuels for Military Applications* (Santa Monica, CA: RAND Corporation, 2011), 7-9, 71.

refining.”²³² To distribute this fuel around the globe, DLA and the services depend on a highly optimized infrastructure and logistics network designed to handle the specific fuel types used by the DOD. The DLA’s system, comprised of vehicles, equipment, training, security, and operational plans, is finely tuned to deliver military grade fuels around the world in the most efficient way possible. Yet, this efficiency comes at a price. In the case of the DLA’s logistics network, efforts to optimize distribution mean the DLA’s network is inadequate for delivering a diverse range of energy and power resources.²³³ Thus, much like the American public, the DOD depends heavily on the existing global oil infrastructure while remaining susceptible to international contingencies and political factors that may cause either the supply or the price of oil to fluctuate.

Volatile oil prices do not necessarily affect the military in the same way that they impact the average American citizen. Like the public, the military must operate within generally accepted principles of budgeting and economics. Therefore, a surge in oil prices causes the military to spend more on fuel and forces the services to divert money from their training budgets and procurement programs to cover the unforeseen costs.²³⁴ This exact situation played out recently when the revolution in Libya pushed oil prices up \$30 to \$112 per barrel, causing Navy Secretary Ray Mabus to lament that the spike in price meant the Navy had to scramble to cover an additional \$1 billion in unplanned expenses.²³⁵ However, because the United States Government charges the military with protecting the nation, it is important to keep in mind

²³² Bartis and Bibber, *Alternative Fuels*, 52; and Susan Declercq Brown, “DLA Energy Delivers: Global Storage and Distribution Network Fuels Forces,” *Energy Source*, Nov/Dec 2011, http://www.desc.dla.mil/DCM/Files/ES%20Oct%202011_Ver2.pdf (accessed March 20, 2012), 29-33.

²³³ Thomas and Kerner, “Defense Energy Resilience,” 14.

²³⁴ Mark S. Danigole, “Biofuels: An Alternative to US Air Force Petroleum Fuel Dependency,” Air University Occasional Papers, No. 62, December 2007, vi.

²³⁵ William Matthews, “BioFleet,” *Government Executive*, January 2012, http://digimag.govexec.com/display_article.php?id=927625 (accessed March 22, 2012).

the difficulty lawmakers would have voting to deny the DOD supplemental funding to cover additional fuel expenditures required for national defense. Furthermore, laws such as the Defense Production Act of 1950 (PL 81-774) give energy priority to the DOD should such a situation arise.²³⁶ Over time, the realization that the DOD will not be cut off from its fuel supply has enabled the military to develop an exclusive reliance on oil. Based on the assumption that operational requirements, technological innovation, or new discovery will ensure the continued availability of energy resources, the military has come to expect that whatever quantities of energy are needed will be provided.²³⁷ While the historical record does little to discourage this line of thinking, the dangers of such an approach are obvious. As authors Scott Thomas and David Kerner note, “The assumption of unlimited oil, available whenever and in whatever form it is needed, contributes to an energy myopia that has left DOD systemically calcified and inadequately prepared to employ other energy sources.”²³⁸

In sum, a review of the nation and the military’s history of oil reliance reveals several predicaments for the Department of Defense to address. To begin with, military forces are structured, postured, equipped, and trained in a way that inherently and increasingly depends on large volumes of oil. The military’s dependence on a single energy source creates risk by obligating the nation’s defense to uncertain sources of supply. Furthermore, dependence on oil creates instability for the DOD by subjecting military planners to volatile price changes. Together, these factors make up an untenable strategic vulnerability for the DOD. Section II addresses how the Department is currently seeking to mitigate that vulnerability.

²³⁶ Daniel H. Else, *Defense Production Act: Purpose and Scope*, CRS Report for Congress RS20587 (Washington, D.C.: Congressional Research Service, May 14, 2009, 2-6, <http://www.fas.org/sgp/crs/natsec/RS20587.pdf> (accessed March 25, 2012)).

²³⁷ Thomas and Kerner, “Defense Energy Resilience,” 1-2.

²³⁸ Thomas and Kerner, “Defense Energy Resilience,” 5.

Renewable Biofuel Technology in the DOD

The DOD's energy requirements are enormous. In 2010, the American military was the single largest consumer of energy in the United States Government. In terms of oil, if the DOD was a country, its consumption rate would rank it 35th in the world, between Greece and Kuwait.²³⁹ Of the total energy consumed by the DOD, on average 20-25 percent is used to power facilities and non-tactical vehicles, while the remaining 75-80 percent goes towards operational energy, "the energy required for training, moving, and sustaining military forces and weapons platforms for military operations."²⁴⁰ Analysis of the DOD's operational energy requirements reveals that over 90 percent of the energy used to make the military run goes towards jet fuel and marine diesel. These petroleum-based fuels, also known as middle distillates, are the single largest sources of energy dependence for the DOD and therefore constitute the greatest risk for America's military forces. Thus, Section II examines the DOD's effort to find an alternative to these fuels.

Finding a replacement for oil is not an entirely new endeavor, nor is it exclusive to just the military or civilian sector. After the OPEC oil embargo in 1973 exposed the vulnerability of the United States to large price variations and uncertain avenues of supply, every President from Richard Nixon to Barack Obama has pledged to reduce America's dependence on foreign oil.²⁴¹ One of the principal means of breaking America's insatiable thirst for foreign energy involves new sources of fuel that Americans can produce domestically. While this seems like a relatively straightforward solution, in reality the DOD must take several

²³⁹ CIA World Factbook, "Country Comparison – Oil Consumption," <https://www.cia.gov/library/publications/the-world-factbook/rankorder/2174rank.html?countryName=Argentina&countryCode=ar®ionCode=soa&rank=30#ar> (accessed March 24, 2012).

²⁴⁰ Title 10 US Code § 138C, http://uscode.house.gov/download/pls/Title_10.txt (accessed March 20, 2012).

²⁴¹ Sustainable Aviation Fuels Northwest, "Powering the Next Generation of Flight," 25.

factors into account before deciding to adopt a new source of energy. Those factors are cost, size, compatibility, and the environment.

Cost – in order for an alternative energy source to be considered as a possible replacement for JP-8, JP-5, or F-76, it must be competitive with the market price of these conventional fuels

Size – because the DOD’s energy requirements are so large, developers of a potential replacement fuel must be capable of producing alternative fuels at a scale that satisfies the DOD’s energy needs

Compatibility – due to the DOD’s large and expensive physical infrastructure, alternative fuel candidates must be “drop-in” substitutes for JP-8, JP-5, or F-76. In addition, alternative fuels must have the same or higher energy densities as their petroleum counterparts while matching their lubricity, viscosity, cold-weather performance, and heat absorption capability.²⁴²

Environment – over their lifecycle, alternative energy sources must emit an equal or lesser amount of greenhouse gases than conventional petroleum-based fuels. Furthermore, feedstocks for renewable fuels must take land use transformation, the preservation of foodstuffs, and crop sustainability into account.

To meet these criteria, scientists have developed several different chemical and biochemical methods of producing alternative fuels from renewable fuel sources. The two methods that are currently the furthest developed are *Fischer-Tropsch (FT) synthesis* (biomass to liquid) and hydrotreating renewable oils (hydroprocessed esters and fatty acids – HEFA).²⁴³ First developed in the 1920s, FT synthesis has a proven track record of producing synthetic fuels. During World War II, the Germans used FT synthesis to produce synthetic fuel from coal as its supply of oil

²⁴² Danigole, “Biofuels,” 21-25.

²⁴³ Air Transport Action Group, “Beginner’s Guide to Aviation Biofuels,” http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf (accessed March 18, 2012, 16-18; and Bartis and Bibber, *Alternative Fuels for Military Applications*, 9.

was exhausted. Later, South Africa used FT synthesis to produce fuel during the years of isolation brought on by apartheid.²⁴⁴ In the FT synthesis process proposed by renewable energy developers today, biomass feedstock is heated to an extremely high temperature to break molecular bonds and produce a gaseous mixture.²⁴⁵ After heating, a catalyst is introduced to the gaseous mixture, inciting a chain reaction and converting the gas to liquid hydrocarbons. These liquid hydrocarbons can then be refined into a substitute for middle distillate fuels.²⁴⁶

The second method conventionally recognized as a viable way to derive biofuels is *hydrotreatment*. This process converts the natural oils from renewable sources such as jatropha, camelina, and algae into middle distillate fuels.²⁴⁷ During hydrotreatment, biomass is pressed to extract the natural oils. These oils are then catalytically treated to add hydrogen to the mixture while removing the oxygen, thus yielding a mixture of straight-chain hydrocarbons. The straight-chain hydrocarbon molecules are then isomerized (their internal arrangements are changed) into a liquid mixture of straight- and branched-chain hydrocarbons that is also capable of being distilled into middle distillate fuels.²⁴⁸

²⁴⁴ The National Energy Technology Laboratory, "Gasifipedia: Supporting Technologies," http://www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/5-support/5-11_ftsynthesis.html (accessed March 19, 2012)

²⁴⁵ Biomass feedstock can be any renewable material of biological origin, such as plants, algae, waste, wood chips, etc.

²⁴⁶ The National Energy Technology Laboratory, "Gasifipedia: Supporting Technologies,"

²⁴⁷ The jatropha plant, *jatropha curcas*, yields seeds that when crushed, secrete oil that can serve as the feedstock for a variety of different biofuel blends. See Daemon Fairless, "Biofuel: The Little Shrub that Could – Maybe," *Nature.com*, October 10, 2007, <http://www.nature.com/news/2007/071010/full/449652a.html> (accessed April 13, 2012). Like jatropha, the seeds from the Camelina plant have a high oil content (up to 40%), making it an excellent oilseed crop. Camelina is a short-seasoned, fast-growing crop that is a member of the mustard family. See Sustainable Oils/Camelina at <http://www.susoils.com/camelina/> (accessed March 4, 2012).

²⁴⁸ Gerhard Knothe, "Biodiesel and Renewable diesel: A Comparison," in *Progress in Energy and Combustion Science* Volume 36, (2010), <http://ddr.nal.usda.gov/dspace/bitstream/10113/39385/1/IND44336922.pdf> (accessed March 21, 2012) 364–373; and Bartis and Bibber, *Alternative Fuels for Military Applications*, 13.

Over the past decade, scientists and renewable energy developers have demonstrated that both of these methods are technically capable of producing liquid fuels that are compatible with the DOD's current systems and petroleum-based infrastructure. For the military, domestically produced renewable biofuels present significant benefits. For instance, a robust biofuel industry would weaken OPEC's ability to assert influence on global oil prices, thereby moderating the disruptive price swings that affect military operations.²⁴⁹ Renewable biofuels also reduce the vulnerability of the domestic energy supply chain. Whereas natural disasters such as hurricanes and earthquakes pose a serious threat to domestic oil production in the Gulf of Mexico, biofuels reduce this risk by spreading production across multiple states, multiple crops species, and multiple sources of biomass.²⁵⁰ For the military, a secure domestic supply chain ensures forces will have access to the fuel needed to "get out the door" regardless of the political conditions abroad.

Thus, for the most part, biofuels have met the compatibility criteria established by the DOD. Where biofuels have come up short is a matter of scale. In 2010, the military alone consumed nearly 5 billion gallons of fuel while jet fuel distributors supplied over 20 billion gallons of fuel to the US commercial market.²⁵¹ Thus, one of the major obstacles for renewable energy providers to overcome is developing enough fuel to compete in such a large market. For instance, based on the current level of conversion from camelina plants, one of the most promising feedstocks for hydrotreated oils, it would take approximately 200,000 square kilometers of dedicated land to meet just 10 percent of the United States

²⁴⁹ Pew, "From Barracks to the Battlefield," 4, 18; and Bartis and Bibber, *Alternative Fuels for Military Applications*, xv.

²⁵⁰ Bartis and Bibber, *Alternative Fuels for Military Applications*, xv.

²⁵¹ DOD jet fuel consumption obtained from US DOD, *Energy for the Warfighter*, 4, jet fuel consumption for the United States obtained from http://www.eia.gov/dnav/pet/pet_cons_prim_dcu_nus_a.htm (accessed March 24, 2012).

demand for jet fuel, or an area roughly the size of Nebraska.²⁵² Along the same lines, meeting all of the DOD's fuel demands with a purely camelina-based biofuel would take a dedicated area the size of Spain.

Closely related to the hurdles presented by scale are environmental factors. In many cases, the farmland required to grow the feedstock for biofuels competes directly with foodstuffs. Growing biofuel feedstock in place of food drives up food prices, which the DOD has already identified as an unacceptable side-effect.²⁵³ Alternatively, farmers who choose not to replace food crops with biofuel crops can transform unused or underused land into farmland. However, doing so leads to deleterious effects through soil erosion, deforestation, and increased greenhouse gas levels, virtually eliminating such a method as a possible way of growing feedstock in the United States.²⁵⁴ A final environmental factor that renewable energy developers must account for is greenhouse gas emissions. On the surface, many renewable biofuels appear to emit lower greenhouse gas emission levels than conventional petroleum-derived fuels. Yet, when the greenhouse gases released during land use transformation, planting, harvesting, transportation, production, and distribution are taken into account, fuels derived from some feedstocks prove to be just as harmful to the environment as those derived from oil.²⁵⁵

The final criterion to consider is cost. According to the DOD's Operational Energy Strategy, aside from purchasing small batches for testing and certification, the DOD will only acquire alternative fuels that

²⁵² Air Transport Action Group, "Beginner's Guide to Aviation Biofuels," 18.

²⁵³ DOD, *Energy for the Warfighter*, 8.

²⁵⁴ Smil, *Energy Myths and Realities*, 103-115.

²⁵⁵ Because different feed stocks require different levels of preparation and processing, it is impossible to generalize the greenhouse gas levels of biomass in general. To see a breakdown of the greenhouse gas effects of individual types of biomass; see Ausilio Bauen, et al, "Review of the Potential for Biofuels in Aviation, Final Report," [http://www.thegrounds.nl/roundtable/documents/AT_E4tech%20\(2009\),%20Review%20of%20the%20potential%20for%20biofuels%20in%20aviation.pdf](http://www.thegrounds.nl/roundtable/documents/AT_E4tech%20(2009),%20Review%20of%20the%20potential%20for%20biofuels%20in%20aviation.pdf) (accessed March 19, 2012), 51-62.

are competitively priced with conventional fuels.²⁵⁶ Unfortunately for renewable energy developers, the volatility and uncertainties of commodities such as oil, corn, and wheat makes building a business that can generate a competitively priced product especially challenging. For instance, in order to get a viable renewable energy market off the ground two things are essential: huge capital investments to build the extraction systems, conversion facilities, and refineries, and a large supply of feedstock. The need for a large financial commitment combined with unpredictable oil prices presents a significant planning obstacle. Investors are understandably reluctant to risk their money on a company that is incapable of producing fuel at competitive prices if oil prices drop. Furthermore, they are reluctant to compete in a market where competitors can manipulate the value of the product simply by flooding the market with increased production. Additional risk for investors comes in the form of agricultural commodities and the unpredictable price of foodstuffs such as corn, wheat, and soy are on the rise. When these commodities are selling at a premium, farmers have little incentive to risk planting unproven cash crops such as camelina or jatropha, creating a situation in which producers must pay a premium to acquire the feedstocks necessary for conversion.²⁵⁷

Further complicating the challenge of developing a competitively priced alternative is the size of renewable biofuel operations. Currently, renewable energy projects are predominantly in the pilot or experimental stage, meaning that producers must distribute their infrastructure and development costs over a smaller body of products while their competitors are free to take advantage of economies of scale built over the past hundred years. The disparity in size makes it especially difficult

²⁵⁶ DOD, *Energy for the Warfighter*, 8.

²⁵⁷ Tom Lutey, "Unpopular Crop: Camelina Falling Out of Favor with Montana Farmers," *Billingsgazette.com*, April, 22, 2011, http://billingsgazette.com/news/state-and-regional/montana/article_bcc0ccb7-2aa8-5a5e-bb36-c9dd60995167.html (accessed March 23, 2012).

for small renewable biofuels to prove that they can compete with the larger petroleum-based fuels. For example, under the most favorable circumstances, current estimates for FT synthetic fuel derived from biomass range from \$130 to \$140 per barrel, while synthetic fuel derived from hydrotreated camelina oils were purchased by the DOD in 2010 for \$2,800 per barrel (\$67 per gallon), and from algal oils at \$16,800 per barrel (\$400 per gallon); obviously, all well above the \$84 five-year average for crude (2011 US Dollars).²⁵⁸

Despite the problems posed by environmental concerns, scale, and cost, the DOD has taken a fairly active role in promoting the development of renewable biofuels. In addition it has taken great strides to test and certify renewable fuels as they come available. The Air Force, recognized as the DOD's largest energy consumer, has set a goal of increasing its consumption of alternative energy by 10 percent per year and has stated that it intends to be prepared to use alternative blends of fuel to meet 50 percent of its domestic requirements for aviation fuel by 2016.²⁵⁹ Yet the Air Force's ability to meet this goal relies largely on other government agencies and the commercial market since the Air Force's approach towards renewable fuels does not include paying for research and development. The Air Force's scientific community has clearly stated that it sees little role for the Air Force in the development and production of alternative and biomass fuels, noting, "The Air Force should qualify and certify alternative fuels as they become technically mature; however, it should be a technology watcher related to fuel production

²⁵⁸ The estimated price of FT synthetic fuel was obtained from Bartis and Bibber, *Alternative Fuels for Military Applications*, 23. The purchase prices of oils derived from camelina and algae were obtained from Matthews, "BioFleet." The average price of oil was obtained from The Energy Information Agency, <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RWTC&f=D> (accessed march 20, 2012).

²⁵⁹ United States Air Force, *Air Force Energy Plan*, 2010, <http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf>, 8, (accessed January 14, 2012).

technologies.”²⁶⁰ Thus, the Air Force’s major contribution to the development of renewable energy technology has been largely confined to certifying aircraft to operate on 50-50 blends of synthetic biofuels.²⁶¹

In contrast, the Navy, which is the second largest fuel consumer in the DOD, has been markedly more active in promoting the development of a renewable biofuel industry. In 2009 the Navy set ambitious goals for renewable energy use, calling for half of its total energy consumption to come from alternative sources by 2020.²⁶² In addition, the Navy aims to sail its “Great Green Fleet” in 2016, comprised of ships and aircraft powered exclusively by nuclear energy, hybrid electric power, and renewable biofuels.²⁶³ To generate the biofuels needed for the Great Green Fleet, in 2011 the Navy partnered with the United States Department of Agriculture, the Department of Energy, and private industry in a three-year, \$510 million effort to spur the development of advanced aviation and marine biofuels.²⁶⁴ Under the Defense Production Act of 1950, a law originally passed during the Cold War to provide seed money for developing technologies, the Navy is currently working with these partner government agencies to help build and retrofit the plants and refineries needed to produce renewable biofuels.²⁶⁵

²⁶⁰ The Air Force’s Science and Technology Vision for Energy notes that in the technology watcher role, the Air Force uses and leverages others’ science and technology investments in areas that are not primary or core missions. In the document’s definition, biofuel production is cited as a specific example of an area that is not a primary or core mission of the Air Force. See United States Air Force, *Energy Horizons: United States Air Force S&T Vision, 2011-2026*, January 31, 2012, <http://www.af.mil/shared/media/document/AFD-120209-060.pdf>, 7, 12-13.

²⁶¹ United States Air Force, *Air Force Aviation Operations Energy Plan*, 2010, <http://www.safie.hq.af.mil/shared/media/document/AFD-091208-026.pdf>, 4.

²⁶² Ray Mabus, “Keynote Presentation at the Naval Energy Forum,” October 14, 2009, <http://www.navy.mil/navydata/people/secnav/Mabus/Speech/SECNAV%20Energy%20Forum%2014%20Oct%2009%20Rel1.pdf> (accessed March 20, 2012).

²⁶³ Ray Mabus, “Keynote Presentation at the Naval Energy Forum.”

²⁶⁴ Lisa Daniel, “New Biofuels Market to Reduce Foreign Oil Dependence,” American Forces Press Service, Aug. 16, 2011, <http://www.defense.gov/news/newsarticle.aspx?id=65048> (accessed March 21, 2012).

²⁶⁵ White House Press Release, “President Obama Announces Major Initiative to Spur Biofuels Industry and Enhance America’s Energy Security,” August 16, 2011,

Taken as a whole, all of the defense services have much to gain from a domestically produced source of fuel. Thus, it makes sense that the individual services and the DOD at large are all relatively supportive of renewable energy development programs. Yet looking at the overall level of DOD support for biofuels indicates that they are not a strategic priority for the military. Thus, renewable biofuel technology has not evolved to a degree that allows these fuels to establish a significant presence within the DOD's energy portfolio. This section identified several areas, such as price and scale, where biofuel technology is floundering. Section III will take a closer look at the social, political, and internal factors that may further explain why development of these fuels has languished.

Factors Hindering the Development of Biofuels

The need for energy security and renewable energy was first recognized in 1974 after the OPEC-led oil embargo exposed the fragility of America's energy supply. Given this fact, why do renewable biofuels have only a slightly larger impact today than they did nearly forty years ago? This section takes a step back from the DOD's current efforts to adopt biofuels and identifies three factors that have inhibited the technological evolution of renewable energy within the DOD: the technological momentum of oil, the absence of an existential threat, and the challenge of innovating in a wartime environment.

Section I of this chapter described how over the course of one hundred and fifty years the nation's oil industry, its associated physical infrastructure, and the social connections between the American public and the oil industry developed into a large and mature technological system. When viewed as a system, it is evident that the oil industry possesses a tremendous amount of technological momentum, making it

<http://www.whitehouse.gov/the-press-office/2011/08/16/president-obama-announces-major-initiative-spur-biofuels-industry-and-en> (accessed March 21, 2012).

resistant to change and giving it the ability to shape societal decisions about energy.²⁶⁶ For example, even if scientists developed a revolutionary new energy source today, abandoning the world's oil infrastructure would entail a \$5 trillion write-off by the oil industry.²⁶⁷ The same factors come into play in the Department of Defense. As the owner of an enormous physical infrastructure and a large number of oil-dependent weapon systems, the DOD sensibly attempts to preserve its capital investment by mandating that future renewable energy technologies conform to existing fuel specifications.²⁶⁸

While operating in this fashion makes complete sense on the part of the DOD, defense officials must recognize that doing so also creates a problem for the technological evolution of new energy sources. If the DOD only procures fuels that conform to existing standards, it undermines the commercial incentive to develop new energy technologies. Scientists will be less inclined to explore and develop technologies that do not conform to the DOD's requirements. If scientists are not exploring and developing emerging technologies that focus on new energy sources, then the DOD has little incentive to build or procure systems that can accommodate these new sources, thus creating a self-reinforcing feedback loop that hinders the DOD and the scientific community from moving beyond the existing oil-based paradigm.

Breaking out of such a technological rut is the nexus of the second possible explanation – the lack of an external catalyst. Barry Posen argues that doctrinal changes occur when an external threat to the state causes the state's civilian leadership to instigate change within the military.²⁶⁹ One might argue that the threat of being cut off from its

²⁶⁶ Hughes, "Technological Momentum," 101-108.

²⁶⁷ Smil, *Energy Myths and Realities*, 140.

²⁶⁸ DOD, *Energy for the Warfighter*, 8.

²⁶⁹ Posen, *The Sources of Military Doctrine*, 74-77.

foreign oil supply is all the impetus that America's civilian leaders should need to force the DOD to develop renewable energy, but closer examination reveals little support for this theory. The United States currently meets between 25 percent and 35 percent of its oil consumption through domestic channels while Canada and Mexico represent the two largest sources of foreign oil consumed by Americans. Overall, the United States imports oil from a broad array of nine OPEC and fifty non-OPEC nations, giving the United States a diverse network of crude and refined oil suppliers.²⁷⁰ Thus, a potential non-friendly nation that refuses to sell oil to the United States may have the ability to affect oil prices, but it does not necessarily have the ability to choke oil supply. Expanding on this point, RAND authors James Bartis and Lawrence Van Bibber note, "as long as the military is willing to pay higher prices, it is unlikely to have a problem getting the fuel it requires."²⁷¹

Consistent with Posen's theory, the absence of an existential threat to the United States's energy supply has been complemented by the absence of a political directive to change the way the DOD meets its operational energy needs. Despite the fact that jet fuel and marine diesel make up the largest percentage of the DOD's energy footprint, neither Congress nor the Secretary of Defense has directed the DOD to use renewable biofuels in place of traditional middle distillates.²⁷² Thus, instead of civilians mandating that the military adopt renewable energy, quite the opposite is true. The efforts by the Air Force and Navy mentioned in Section II were the result of self-initiated direction from within the services; in some cases, these actions put the services in conflict with the nation's civilian leaders. For instance, since being

²⁷⁰ US Energy Information Administration, "U.S. Total Crude Oil Imports and Products, U.S. Imports by Country of Origin" http://205.254.135.7/dnav/pet/pet_move_impqus_a2_nus_ep00_im0_mbb1_m.htm (accessed March 20, 2012).

²⁷¹ Bartis and Bibber, *Alternative Fuels for Military Applications*, xv.

²⁷² United States Air Force, *Air Force Aviation Operations Energy Plan*, 2010, 3.

named Secretary of the Navy in June 2009, Ray Mabus has advocated loudly for alternative energy in the Navy. Yet Mabus's aggressive energy agenda and his focus on developing renewable energy sources for the Navy has put him at odds with lawmakers who would rather see the Navy use its budget for ships, planes, and hardware.²⁷³

A final factor to consider when assessing the difficulty biofuels have had over the past decade is the challenge of making changes in a wartime environment. Following the terrorist attacks on September 11, 2001, the United States responded by initiating the "Global War on Terrorism" in Afghanistan and Iraq. These enduring wars have had a significant impact on innovation in the United States military; as such, the DOD's efforts to adopt new energy sources should be examined through this lens as well. Stephen Rosen argues that wartime innovations tend to be limited in their impact due to the difficulties determining strategic levels of effectiveness. Furthermore, Rosen notes that wartime innovation has a propensity to be reactionary and insufficiently thought out because the process of accurately assessing the strategic needs of the military takes a significant investment of time and resources, both of which are in short supply during times of war.²⁷⁴ Instead, the military is inclined to make changes that address short-term needs and utilize the physical systems and processes already in place when the fighting began.²⁷⁵ As the following example illustrates, one of the reasons why the DOD has been slow to support and adopt renewable energy sources such as biofuel was its reactionary response to the energy challenges presented by simultaneous wars in Afghanistan and Iraq.

²⁷³ Austin Right, "Navy Powers Up Campaign for Great Green Fleet," *politico.com*, March 7, 2012, <http://www.politico.com/news/stories/0312/73752.html> (accessed March 23, 2012).

²⁷⁴ Rosen, *Winning the Next War*, 38.

²⁷⁵ Rosen, *Winning the Next War*, 180-182.

Throughout the 1990s, cheap oil meant that calls to modernize the DOD's energy structure were rare.²⁷⁶ Without an impetus to change, the DOD built larger and more powerful weapon systems, increasing the military's overall thirst for fuel.²⁷⁷ After the attacks on September 11, 2001 and the corresponding invasions of Iraq and Afghanistan, two major changes altered the way the DOD viewed oil: the price of oil rose dramatically, and soldiers started dying in convoys as they ferried fuel around the area of operations. Faced with these two dire circumstances, the DOD recognized that it needed to take action.

To solve the problems posed by high fuel rates and the surprisingly effective insurgent attacks on the military's logistical tail, the DOD turned to efficiency. The Department emphasized efficiency across the spectrum of operations, and every service aimed to reduce its fuel demands by eliminating excess equipment, conducting smart operations, and developing new, more efficient technology. For the DOD, the solution to high oil prices and attacks on its fuel supply was to reform the military in a way that made it lighter, leaner, and more efficient. Efficiency was the fundamental tenet of the DOD's energy strategy because it was seen as "the cheapest, fastest, and most effective means of reducing fuel consumption, and addressing risk to soldiers, price volatility, supply security, and mission success."²⁷⁸

While focusing on efficiency should be viewed as a necessary component of the DOD's overall energy strategy, in their paper "Defense Energy Resilience: Lessons from Ecology," Scott Thomas and David Kerner argue that the DOD's exclusive focus on energy efficiency has come at the expense of developing new energy technologies that would

²⁷⁶ From 1990-1999 the price of Oil averaged \$18 per barrel, see US Energy Information Agency, "Weekly Cushing, OK WTI Spot Price FOB," <http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rwtc&f=w> (accessed March 20, 2012).

²⁷⁷ Thomas and Kerner, "Defense Energy Resilience," 1.

²⁷⁸ Pew, "From Barracks to the Battlefield," 5.

increase the DOD's energy resilience. By Thomas and Kerner's logic, "A focus solely on efficiency models is likely to eliminate consideration of redundancies that provide 'response diversity,' the different adaptation strategies or capacities inherent in different solutions to system challenges. Loss of this response diversity reduces resilience in a system."²⁷⁹ In other words, the more the DOD invests in energy efficiency, the more difficult and expensive it becomes to implement long-term technological changes that increase the DOD's energy resiliency. The reasoning behind Thomas and Kerner's argument is easy to follow. If the DOD spends several billion dollars on new high efficiency systems, this action has a twofold effect. First, it prevents those research and development dollars from going to the study of alternative energy sources. Second, by increasing the DOD's investment in mature platforms, those platforms become increasingly entrenched within the services, making their replacement harder to justify.

Thus, it is possible to conclude that over the past decade higher oil prices and increased casualty rates forced the DOD to choose between a strategy that emphasized efficiency and a strategy that pursued resilience. Consistent with Rosen's argument, the military chose to pursue an efficiency-centric strategy that met its short-term goals of reducing fuel expenditures and minimizing casualties. The effect of this decision has been a significant capital investment in new technologies that further entrench petroleum's role as the DOD's principal energy source, leaving renewable energy sources such as biofuels largely underdeveloped.

Overall, this brief study of oil and the struggles biofuel technology has had breaking into and gaining acceptance within the DOD offers several insights that the DOD can apply to future efforts involving energy transformation. Examining the history of oil consumption in the United

²⁷⁹ Thomas and Kerner, "Defense Energy Resilience," 12.

States and specifically within the DOD shows how the ubiquitous, entrenched nature of the petroleum industry and the subsequent dependence on oil that has built up over the past century pose both a risk and an obstacle to changing the oil-based paradigm. Looking closer at the DOD's requirements elucidated the challenge biofuel developers face in creating an energy source that is compatible with the military's current systems yet robust enough to meet its quantitative demands and cheap enough to be a viable alternative. Finally, using the theoretical insights posited by Thomas P. Hughes, Barry Posen, and Stephen Rosen helps explain how the technological momentum of oil, the negligible threat to the American oil supply, and DOD's emphasis on efficiency during the wars in Iraq and Afghanistan have undermined efforts to develop renewable energy technology in the DOD.

Together these factors establish a solid baseline from which to examine the DOD's ability to transition to new energy sources. However, it is important to remember that the military's efforts to develop and adopt biofuels are only a narrow sampling of a rich historical body of energy transitions in the DOD. To fully understand how the military incorporates new energy sources it is critical to contrast the recent efforts to adopt biofuels against the historical precedent established in the first two case studies. Thus, Chapter 5 examines the lessons learned from each case study and synthesizes them into general principles that can inform future energy transitions.

Chapter 5

Conclusion

The linkage between innovation in energy technology and the projection of military power has spanned history. Just as the shift from wind to coal revolutionized naval power in the 19th century, so did the introduction of nuclear-energy – on subs and aircraft carriers – transform the global balance of power in the 20th. Our mastery of energy technology both enabled our nation to emerge as a great power and gave us a strategic edge in the Cold War. Today, staying at the cutting edge of energy technology remains a critical element of our military superiority.

Deputy Secretary of Defense
William Lynn, April 26, 2011

In his influential work, *Analogies at War*, Yuen Foong Khong posits that learning from history occurs when policymakers use the lessons from the past to help them understand the present. A primary tool used in this process is the historical analogy.²⁸⁰ Khong goes on to assert that analogies can be useful when they help define the nature of the situation, assess the stakes of the situation, provide prescriptions, and warn about the pitfalls posed by certain options.²⁸¹ True to Khong's construct, this study aims to inform the DOD's Operational Energy strategy by answering the question, "What insights can be gleaned from historical energy transitions and how might those insights apply to energy transitions in the future?"

Already, the rise of second-generation nuclear propulsion, nano-scale batteries, and algal-based biofuels are forcing defense policymakers to make decisions about whether to adopt and incorporate new energy technologies into the DOD's infrastructure. Furthermore, these new

²⁸⁰ Yuen Foong Khong, *Analogies at War: Korea, Munich, Dien Bien Phu, and the Vietnam Decisions of 1965* (Princeton, NJ: Princeton University Press, 1992), 6.

²⁸¹ Khong, *Analogies at War*, 10.

technological developments are driving decision makers to ask how such a transition might be possible. Thankfully, these decisions do not need to be made in the dark. As Khong argues, historical examples of energy transitions can inform current and future decisions by helping decision makers understand the problem, the context, and the potential risks of the situation. Therefore, as the DOD moves forward with these emerging energy technologies, it would be wise to use the lessons from previous energy transitions to help guide the transitions of the future. To aid in this endeavor, lessons from the Navy's transition from sail to steam-powered ships, its transition from diesel-electric to nuclear-powered submarines, and the still ongoing exploration of renewable biofuels by the DOD can all be applied to the future.

What is important to note is that each of these case studies offers specific lessons that can provide insight into the process of adopting a new energy technology. Taken as a whole they offer general wisdom that can help provide an understanding of complex problems while assisting the DOD in assessing its ability to adopt new energy sources. This final section recounts those lessons that are unique to each particular study as well as those that apply to energy transitions across the board.

Case-Specific Lessons

The Navy's transition from sail-powered ships to steam-powered ships offers several unique insights that can aid decision makers in future DOD energy transitions. Foremost among these lessons is the upsetting effect new energy technologies can have on the social order of an organization. For years before the advent of steam-powered ships, the Navy's aristocracy was comprised solely of line officers who built their reputation by commanding the Navy's fleet of sailing ships. While these officers recognized that steam technology offered significant advantages to the American Navy, they also saw that adopting steam-powered ships into the mainstream involved empowering a young corps of engineers.

Therefore, instead of supporting the technological advancement of steam-powered ships, many line officers took up a campaign aimed at pointing out steam technology's flaws, vulnerabilities, and shortcomings. For these officers, protecting their power, influence, and position in the Navy was more important than any perceived advantages gained by steam propulsion.

One of the key factors in overcoming this internal social resistance was the evolution of steam power into a safer and more efficient technology. Critical to this progression was the technological co-evolution of the steam engine and the screw propeller while overcoming the reverse salient posed by wooden-hulled ships. In this case, advances in steam engine technology and the evolution of the screw propeller exposed the shortcomings of wooden-hulls, creating an impetus for ship designers and engineers to design hulls made out of iron. Thus, by the time metal-hulled ships capable of housing modern steam engines and their screw propulsion systems evolved, even the most reluctant line officers recognized that they were ignoring steam technology at their peril.

The Navy's transition from diesel-electric to nuclear-powered submarines also offers several unique lessons that can inform future energy transitions. First among these lessons is how a revolutionary technology can enable a rapid transition from one energy source to another. Unlike the transition from sail to steam which took place over the course of a century, the Navy's transition from diesel to nuclear submarines occurred just two years after the Navy introduced the *Nautilus*. A key factor in this rapid transition was the fact that nuclear power effectively "completed" the development of the submarine. Since the Navy first incorporated submersibles into the fleet, it recognized the potential of a true submarine and strongly desired to develop a technology that would enable this transition. In this case, the nuclear

reactor was exactly what the Navy was looking for. The advent of nuclear technology and its ability to liberate submersibles from their surface requirements allowed the Navy to abandon diesel technology in favor of a new fleet of nuclear submarines.

Further aiding the Navy's rapid transition was the interservice rivalry that stemmed from the Air Force and Army's emerging nuclear programs. In the years following World War II, shrinking budgets and a nuclear-centric defense posture led each service to develop their own nuclear programs. The services relied on these programs to demonstrate their relevance in the post-World War II era and to help secure each service's share of the budget. The resultant competition between the services provided a large incentive for the Navy to accelerate its own nuclear program while providing the justification to allocate its resources into developing a new and still unproven technology.

A final key component to the Navy's rapid transition from diesel to nuclear submarines was the work of Hyman Rickover. Rickover's role as a systems builder, his ability to navigate through government bureaucracy, and his subject matter expertise helped catapult the Navy to the forefront of the atomic energy field. In addition, these characteristics provided Rickover with the authority needed to run the Navy's nuclear submarine program with a free hand. Due to the massive scale and complexity of any future DOD energy transitions, the role of a systems builder will likely prove essential. Future systems builders must be able to assemble the resources and political support needed to develop new technologies, while also having the vision to manage and exploit the co-evolution of supporting technologies that allow a new technological system to take root. As the RAND corporation's study of alternative energy sources notes, "Alternative fuel production facilities are highly complex and can cost hundreds of millions, or even billions, of dollars. Technical progress often requires simultaneously advancing

performance in multiple subsystems and understanding the intricate interfaces among these systems. A strong and disciplined engineering assessment program is essential.”²⁸²

Like the Navy’s transition from sail to steam-powered warships and from diesel to nuclear-powered submarines, the DOD’s current exploration of renewable biofuels also offers unique insights and lessons that can inform future energy transitions. One such lesson concerns the difficulty of developing an energy source that is both large enough to supply the DOD’s tremendous energy requirements, yet cheap enough to be competitive with the petroleum-based fuels that are currently available. Magnifying this challenge is the added complexity of ensuring that any new energy source is no more detrimental to the environment than traditional petroleum-based fuels. Mitigating these challenges will require a long-term strategic vision that balances the DOD’s need to reduce its demand for energy against its need to develop and incorporate new energy sources that reduce the DOD’s vulnerability to possible disruptions in its energy supply. However, the biofuel case study shows that meeting the efficiency needs posed by the current conflict will often supersede those requirements associated with a long-term plan. John Nagl summed this point up concisely when he noted, “Future conflicts are important, but the present conflicts are critical.”²⁸³

General Lessons

In addition to the case-specific lessons, this collection of studies also reveals several general factors that future decision makers must take into account as they consider the DOD’s ability to incorporate new energy sources into its infrastructure. Arguably, the single most important factor to examine is the technological momentum of the

²⁸² Bartis and Bibber, *Alternative Fuels for Military Applications*, 65.

²⁸³ John A. Nagl, “Let’s Win the Wars We’re In,” *Joint Forces Quarterly* 52 (1st Quarter 2009), 21. <http://www.ndu.edu/press/lib/images/jfq-52/JFQ52.pdf> (accessed April 1, 2012).

existing technological system. The three examples studied in this essay clearly demonstrate that new energy technologies positioned to supplant a robust and mature technological system have a much more difficult task than those that aim to replace a technology with little technological momentum. For instance, the entrenchment of the sail in American society caused significant problems for the Navy as it attempted to adopt steam-powered ships into its fleet. The sail-based technological system was large and mature, with sail-powered ships having undergone countless refinements and evolutions over their long history. The ubiquitous nature of sailing ships led American society to develop deep physical and social connections to the sailing ship, making its replacement costly while greatly upsetting the patterns of thought and practice of a sailing culture.

Similarly, the biofuel case study reveals how the technological momentum of the American oil-based system has created significant challenges for biofuel developers. Of particular note is how to overcome “the tyranny of technological sunk costs” presented by an industry that took over one hundred years to build and is currently valued at over \$5 trillion.²⁸⁴ Like the sail, oil has grown ubiquitous in American society and in the DOD, leaving the military heavily dependent on oil to execute its assigned missions. To achieve the tasks expected of it, the DOD has invested large sums of money developing a physical infrastructure and a fleet of machines that depend on oil to deliver combat power around the globe. Thus, to preserve the DOD’s investment any potential new energy sources must conform to the qualities exhibited by petroleum-based fuels.

On the other hand, the Navy’s transition from diesel-electric to nuclear-powered submarines shows how a system’s lack of technological momentum can facilitate a simpler and swifter transition. Unlike sailing

²⁸⁴ Coté, “The Politics of Innovative Military Doctrine,” 50-51.

ships, which existed for thousands of years before the advent of the steam engine, and oil, which affects the daily life of virtually every person in the United States, the technological system that evolved around the diesel-electric submarine was immature, comparatively small, and did not comprise a large physical infrastructure. These characteristics helped eliminate several key resistance factors that made other energy transitions protracted and difficult.

Another key dynamic to recognize is the effect that the balance of power between states has on the government and DOD's motivation to implement change. In general, each case study supports the argument that periods of technological innovation coincided with the presence of an external threat to the state, while periods of stasis coincided with times where outside forces posed little danger. Because of its long duration, the Navy's transition from sail to steam is especially useful in illustrating this point. Two of the greatest periods of technological innovation concerning marine steam engines were the first and the last twenty years of the nineteenth century. The first twenty years saw the Navy add its first steamers, *Demologos* and *Fulton*, to the fleet, while the last 20 years witnessed the authorization and construction of the highly advanced ABCD ships, ushering the Navy out of the sail age for good. Not coincidentally, during each of these periods the United States was struggling to counteract what it perceived as substantial threats to the nation's well-being. For instance, the United States adopted *Demologos* and *Fulton* to protect America's vital harbors from a British invasion, while Congress authorized the ABCD ships in response to the humiliating *Virginus* Affair and the threat posed by the highly advanced navies sprouting up in Europe and South America.

Balance of power between states and the external threat posed by the Soviet Union played a critical role in the development of the nuclear-powered submarine as well. Following World War II, the Soviet Union's

decision to start mass-producing German Type-XXI submarines, combined with successful nuclear test shots, and the rise of communism in Europe and Asia caused American lawmakers to see the Soviet Union as an existential threat to the United States. In response, the United States created a nuclear-centric defense posture that in turn prompted the military to develop innovative ways of preventing the Soviet Union from destroying America's deterrent threat with a first strike. The Navy took advantage of this situation by demonstrating the resilience of nuclear-powered submarines to a nuclear strike, thus satisfying America's perceived need to ensure a credible second-strike capability.

The DOD's current examination of biofuels also informs the issue of balance of power and external threats. Unlike the sail-to-steam and the diesel-to-nuclear examples, it demonstrates how the lack of an external threat can hinder the development of a new energy source. The biofuel case study showed that while unfriendly states may have the ability to manipulate the price of oil, they do not necessarily have the capacity to cut the United States off from its supply of oil. This is especially true for the DOD which in the event of a national emergency would receive priority on fuel regardless of the source. Therefore, one can surmise that so long as the DOD is willing to absorb higher fuel costs it has no reason to worry about its supply of energy. This lack of an external threat to the military's energy supply removes the impetus to develop new energy sources, while giving defense officials the option of letting the civilian market bear the cost of developing new fuels and then acting as a fast follower when promising energy technologies arise.²⁸⁵

As the military develops future energy policies, historical evidence suggests that overarching strategic issues will play a dominant role in

²⁸⁵ In the fast follower role, the DOD can rapidly adopt and/or, as needed, adapt or accelerate technologies originating from external organizations that are leaders and primary investors in focused science and technology areas as part of their core mission. See United States Air Force, *Energy Horizons*, 6.

the development of this policy. Therefore, defense officials must take these macro-strategic factors into account when assessing the military's ability to adopt a new energy source. For instance, an adversarial contest for resources with a peer or near-peer competitor, a disruption of the nation's domestic petroleum production, or the massive influx of a cheap and readily available new fuel source would all have a dramatic effect on the DOD's decision to adopt, forestall, or gradually incorporate any new energy technologies.

An additional lesson made evident by the three case studies is that technological transformations produce new vulnerabilities and unintended consequences, both real and perceived. For instance, a significant hindrance to the Navy's transition to steam was the increased vulnerability posed by a steam-powered ship's exposed engine, boiler, and paddlewheel. Unlike the durable sailing vessels of the day, a single shot to any of these systems threatened to disable a steamer, leaving the damaged vessel at the mercy of its opponent. In light of this fact, sailors had good reason to be reluctant about adopting first generation steam-powered ships.

Similarly, the first generation of nuclear-powered submarines relied on constant-drive transmissions that vibrated continuously. The vibration and noise from the spinning machinery made nuclear submarines particularly easy to detect compared to their diesel-electric predecessors; this posed a nontrivial problem for submariners who depended on stealth to survive. Thus, it was not until the Navy adopted rafting, the placement of the submarine's power plant on a flexible mount or raft within the submarine, that the Navy was able to use nuclear-powered submarines to execute its anti-submarine warfare mission.²⁸⁶ In addition to the risk posed by excessive vibration and

²⁸⁶ GlobalSecurity.org, "SSN-594 Permit Class," <http://www.globalsecurity.org/military/systems/ship/ssn-594.htm> (accessed December 14, 2011).

noise, nuclear submarines also stoked public fears about nuclear accidents and radioactive waste. While largely stemming from a series of civil accidents involving nuclear reactors, these fears proved to be a major planning consideration for the Navy and especially for Hyman Rickover, who recognized that a single nuclear incident or accident could prove fatal for the Navy's entire nuclear propulsion program.

The DOD's examination of biofuels demonstrates that even an innocuous energy source such as biomass can lead to perceived vulnerabilities and risks. The risks associated with biofuels relate to the process of cultivating the biological material needed for energy conversion. Growing feedstock at the scale necessary to meet the DOD's energy requirements threatens to put upward pressure on food prices, intensify competition for land and water, and has been linked to irreparable environmental damage in the form of land-use transformation and deforestation.²⁸⁷ Such feedstock, moreover, may be vulnerable to natural or bio-engineered pathogens. Furthermore, introducing new, non-native plant species across the United States poses serious ecological risks. These risks stem from the possibility of feedstock crops spreading beyond farmers' control and becoming ineradicable. This risk is exacerbated by the nature of biofuel feedstocks, which tend to have fast growth rates and low resource requirements while being durable and resistant. Thus, the very characteristics that make a biofuel feedstock a worthy candidate for fuel conversion are the same characteristics that make an invasive species difficult to eliminate once introduced in a new environment.²⁸⁸

²⁸⁷ The World Bank, "World Development Report, 2008: Agriculture for Development," http://siteresources.worldbank.org/INTWDR2008/Resources/WDR_00_book.pdf (accessed March 26, 2012), 70-71.

²⁸⁸ Elisabeth Rosenthal, "New Trend in Biofuels Has New Risks," *New York Times*, May 21, 2008, <http://www.nytimes.com/2008/05/21/science/earth/21biofuels.html> (accessed March 26, 2012). For more on the risks posed by biofuel feedstocks, see Adam S. Davis et al., "Screening Bioenergy Feedstock Crops to Mitigate Invasion Risk," *Frontiers in Ecology and the Environment*, Vol. 8, (2010), 533-539.

The final factor policymakers should consider when examining the possibility of developing and incorporating a new energy source is cost. In each of these case studies, the DOD intended to address a perceived deficiency by introducing a new energy technology. The Navy introduced steam propulsion to liberate ships from the prevailing winds; it introduced nuclear propulsion to eliminate the submarine fleet's tether to the surface; and the DOD is currently exploring biofuels to reduce its vulnerability to disruptions in the nation's oil supply. In varying degrees, each of these technological advances has been successful in meeting its desired objective – ships no longer depend on the wind, submarines are free to roam the ocean depths for months on end, and the DOD has certified biofuels for use in a variety of different weapons systems. However, in each case study the new technological solution cost significantly more than the existing technology.

Steam-powered ships were far more expensive than their sailed counterparts, nuclear submarines cost one and a half times more than their diesel-electric predecessors, and biofuels have thus far proven to be exorbitantly expensive compared to their petroleum-based alternative. In a world of fixed defense budgets, higher costs associated with technological solutions force defense officials to make a quantity-versus-quality value judgment. Therefore, before launching headlong into a new energy campaign, defense officials must determine what the new technology is worth to the DOD. In some cases, such as with nuclear submarines, the Navy was content to give up quantity for quality because the final product was so far superior to the prevailing technology. In other cases, such as with the transition to steam power, the Navy was reluctant to convert because, in the view of line officers, the perceived advantages of steamers were not worth the increased cost. This changed, however, when the strategic environment made it clear that maintaining the status quo invited enormous disadvantage. Thus, as the

DOD considers adopting algal-based biofuels, second-generation nuclear reactors, or other significant technological transformations such as robotics or nano technology, it should do so with an idea in mind of what it hopes to achieve, what it is willing to give up in exchange, and how these new energy sources will prepare the military to meet the unfolding strategic concerns of the future.

A Way Forward

Looking broadly across the spectrum of energy transitions provides insight into how the DOD may choose to advance new energy technologies in the future. For instance, one of the most formidable challenges revealed by this study is that of scale. The relatively small scale of the Navy's conversion from diesel-electric to nuclear-powered submarines facilitated a rapid transition compared to its efforts at converting a much larger fleet of ships from sail to steam. Likewise, a principal reason the DOD has struggled to move beyond oil is the tremendous scale of the military enterprise that is currently oil-dependent.

One way of mitigating the problems posed by scale is to adopt a piecemeal approach that confines energy transitions to specific weapon systems or to specific types of weapon systems. Again, the Navy provides an excellent case for analysis should the DOD adopt this methodology. Instead of attempting to convert its entire fleet to nuclear power from the onset, it chose to confine nuclear power first to submarines and then to aircraft carriers. This approach allowed for an easing out of the oil-based paradigm instead of an abrupt shock to the Navy's traditional order while also allowing the Navy to take advantage of advances in the rapidly unfolding field of nuclear propulsion. On the other hand, the DOD must remain cognizant of issues such as potential cost increases and obsolescence while acknowledging that such an approach and the smaller initial investment may preclude a new technology from taking

hold. Therefore, this study recommends the DOD assess the feasibility of a piecemeal approach to energy technology transitions. Moreover, the DOD should examine this approach within the historical context of examples such as the nuclear-powered submarine and the nuclear-powered aircraft carrier. As this thesis demonstrates, analyzing past examples provides critical insight into the advantages and disadvantages of adopting new energy technologies on a smaller scale.

While looking at new ways of overcoming the challenges posed by scale, the DOD should also work to develop a more strategic perspective when it comes to energy technology. This study shows that steam and nuclear technology shattered the existing energy paradigms and created important strategic advantages for those who could harness their effects and use them in creative new ways. To prepare for the next technological breakthrough in the field of energy, the DOD must foster an institutional environment that permits and encourages innovation. Key to the creation of such an environment are leaders who recognize that energy is more than just a logistics problem. To capture the strategic benefits of the nation's science and technology community, the DOD must cultivate leaders dissatisfied by the status quo and who recognize that new energy technologies offer game-changing possibilities. Similarly, the DOD should empower systems builders who can bring new technologies to fruition. By fostering this willingness and ability to transform, the American military will find itself well suited to meet the challenges of an uncertain energy future.

Bibliography

- Ahern, Joseph-James. "The United States Navy's Early Atomic Energy Research, 1939–1946." *International Journal of Naval History* Vol. 1, no. 1, (Spring, 2002).
- Ahern, Joseph-James. "‘We had the hose turned on us!’: Ross Gunn and The Naval Research Laboratory's Early Research into Nuclear Propulsion, 1939 – 1946." *Historical Studies in the Physical and Biological Sciences* Vol. 33, No. 2, (2003): 217-236.
- Air Transport Action Group. "Beginner's Guide to Aviation Biofuels." http://www.enviro.aero/Content/Upload/File/BeginnersGuide_Biofuels_WebRes.pdf (accessed March 18, 2012).
- Allen, Gardner W. *Our Naval War with France*. New York: Houghton Mifflin Company, 1909.
- Allen, Thomas P. and Polmar, Norman. *Rickover: Father of the Nuclear Navy*. Washington, D.C.: Potomac Books, 2007.
- Atomic Energy Act of 1946*. Public Law 585, 79th Cong., 2d sess., 1 August 1946.
- Barnes, Robert. *United States Submarines*. New Haven, CT: H.F. Morse Associates, 1944.
- Bartis, James T., and Van Bibber, Lawrence. *Alternative Fuels for Military Applications*. Santa Monica, CA: RAND Corporation, 2011.
- Baxter, James P. *The Introduction of the Ironclad Warship*. Cambridge, MA: Harvard University Press, 1933.
- Bauen, Ausilio, et al. "Review of the Potential for Biofuels in Aviation, Final Report." [http://www.thegrounds.nl/roundtable/documents/AT_E4tech%20\(2009\),%20Review%20of%20the%20potential%20for%20biofuels%20in%20aviation.pdf](http://www.thegrounds.nl/roundtable/documents/AT_E4tech%20(2009),%20Review%20of%20the%20potential%20for%20biofuels%20in%20aviation.pdf) (accessed March 19, 2012).
- Bauer, Jack K. *Surfboats and Horse Marines, U.S. Naval Operations in the Mexican War, 1846-1848*. Annapolis, MD: Naval Institute Press, 1969.
- Beach, Edward L. *Salt and Steel: Reflections of a Submariner*. Annapolis, MD: Naval Institute Press, 1999.
- Bennett, Frank M. *The Monitor and the Navy Under Steam*. Boston, MA: The Riverside Press, 1900.
- Bennett, Frank M. *The Steam Navy of the United States*. Westport, CT: Greenwood Press, 1896.

- Blair, Clay Jr. *The Atomic Submarine and Admiral Rickover*. New York: Holt and Company, 1954.
- Bradford, James C. *Captains of the Old Steam Navy, Makers of the American Naval Tradition, 1840-1880*. Annapolis, MD: Naval Institute Press, 1986.
- Breemer, Jan S. "The Submarine Gap: Intelligence Estimates 1945-1955," *Navy International*, February 1986.
- Briody, Dan. *The Haliburton Agenda: The Politics of Oil and Money*. Hoboken, NJ: John Wiley and Sons, 2004.
- Brodie, Bernard. *Seapower in the Machine Age*. New York: Greenwood Press, 1969.
- Buhl, Lance C. "The Smooth Water Navy: American Naval Policy and Politics, 1865-1876." Doctoral Dissertation, Harvard University, 1968.
- Burgess, Robert F. *Ships Beneath the Sea: A History of Subs and Submersibles*. New York: McGraw-Hill, 1975.
- Canney, Donald L. *The Old Steam Navy: The Ironclads, 1842-1885*. Annapolis, MD: Naval Institute Press, 1986.
- Center for Responsive Politics. "Oil and Gas Industry Profile, 2001-2011."
<http://www.opensecrets.org/lobby/background.php?id=E01&year=2001> (accessed March 22, 2012).
- CIA World Factbook. "Country Comparison - Oil Consumption."
<https://www.cia.gov/library/publications/the-world-factbook/rankorder/2174rank.html?countryName=Argentina&countryCode=ar®ionCode=soa&rank=30#ar> (accessed March 24, 2012).
- Coletta, Paolo E. *A Survey of U.S. Naval Affairs, 1865-1917*. London: University Press of America, 1987.
- Constant, Edward W., II. *The Origins of the Turbojet Revolution*. Baltimore, MD: The Johns Hopkins University Press, 1980.
- Constant, Edward W., II. "A Model for Technological Change Applied to the Turbojet Revolution." *Technology and Culture*, Vol. 14, No. 4, (Oct 1973): 553-572.
- Constant, Edward W., II. "Communities and Hierarchies: Structure in the Practice of Science and Technology." *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant?* ed. Rachel Laudan. Hingham, MA: Kluwer Academic Publishers, 1984.

- Cooling, Benjamin Franklin. *Grey Steel and Blue Water Navy: The Formative Years of America's Military-Industrial Complex, 1991-1917*. Hamden, CT: Archon Books, 1979.
- Coté, Owen R. Jr. "The Politics of Innovative Military Doctrine: The U.S. Navy and Fleet Ballistic Missiles." Ph.D. Dissertation, Massachusetts Institute of Technology, 1996.
- Coté, Owen R. Jr. *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines*. Newport, RI: Naval War College, 2003.
- Daniel, Lisa. "New Biofuels Market to Reduce Foreign Oil Dependence." American Forces Press Service, August 16, 2011.
<http://www.defense.gov/news/newsarticle.aspx?id=65048>
(accessed March 21, 2012).
- Danigole, Mark S. "Biofuels: An Alternative to US Air Force Petroleum Fuel Dependency." Air University Occasional Papers, No. 62, December 2007.
- Davis, Adam S., et al. "Screening Bioenergy Feedstock Crops to Mitigate Invasion Risk," *Frontiers in Ecology and the Environment*, Vol 8, (2010).
- Davis, Harry M. "The Man Who Built the A-Bomb." *New York Times Magazine*, April 18, 1948.
- Declercq Brown, Susan. "DLA Energy Delivers: Global Storage and Distribution Network Fuels Forces." *Energy Source*, Nov/Dec 2011, http://www.desc.dla.mil/DCM/Files/ES%20Oct%202011_Ver2.pdf (accessed March 20, 2012).
- Deutch, John, and Schlesinger, James R. "National Security Consequences of U.S. Oil Dependency," Council on Foreign Relations Independent Task Force Report No. 58. New York: Council on Foreign Relations, Inc., 2006.
- Duncan, Francis. *Rickover and the Nuclear Navy: The Discipline of Technology*. Annapolis, MD: Naval Institute Press, 1990.
- Duncan, Francis. *Rickover: The Struggle for Excellence*. Annapolis, MD: Naval Institute Press, 2001.
- Else, Daniel H. *Defense Production Act: Purpose and Scope*. CRS Report for Congress RS20587 (Washington, D.C.: Congressional Research Service, May 14, 2009, <http://www.fas.org/sgp/crs/natsec/RS20587.pdf> (accessed March 25, 2012).
- Engel, Leonard. "Forecast of the Age of Atomic Power." *New York Times*, December 20, 1953.

- Fairless, Daemon. "Biofuel: The Little Shrub that Could – Maybe." *Nature.com*, October 10, 2007.
<http://www.nature.com/news/2007/071010/full/449652a.html>
(accessed April 13, 2012).
- Friedman, Jonah. "Nuclear vs. Diesel Submarines." The Center for Strategic and International Studies, October 18, 2011,
<http://csis.org/blog/nuclear-vs-diesel-submarines> (accessed February 17, 2012).
- Galantin, I.J. "The Future of Nuclear Powered Submarines," *United States Naval Institute Proceedings*, 84, No. 6 (1958).
- Gamson, William A. and Modigliani, Andre. "Media Discourse and Public Opinion on Nuclear Power: A Constructionist Approach." *American Journal of Sociology*, Vol. 95, No. 1 (July 1989): 1-15.
- General Dynamics Corporation. *United States Submarine Data*, 3rd Edition. Groton, CT: The Submarine Library, 1958.
- Gibson, Charles E. *The Story of the Ship*. New York: Henry Schuman, 1948.
- Gimpel, Herbert J. *The United States Nuclear Navy*. New York: Franklin Watts Inc., 1965.
- GlobalSecurity.org. "SSN-594 Permit Class."
<http://www.globalsecurity.org/military/systems/ship/ssn-594.htm> (accessed April 1, 2012).
- Gray, Robert P. "The Effect of New Technology on the Operational and Strategic Levels of War: The Development of Steam Propulsion in the United States Navy Prior to 1860." Masters Thesis, U.S. Army Command and General Staff College, 1993.
- Hecht, David K. "The Atomic Hero: Robert Oppenheimer and the Making of Scientific Icons in the Early Cold War." *Technology and Culture*, Vol. 49, No. 4, (October 2008): 943-966.
- Heilbroner, Robert L. "Technological Determinism Revisited," in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds. Merritt Roe Smith and Leo Marx. Cambridge, MA: The MIT Press, 1994.
- Hewlett, Richard G., and Duncan, Francis. *Nuclear Navy 1946-1962*. Chicago, IL: University of Chicago Press, 1974.
- Hughes, Thomas P. *Rescuing Prometheus*. New York: Vintage Books, 1998.
- Hughes, Thomas P. "Technological Momentum," in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds.

- Merritt Roe Smith and Leo Marx. Cambridge, MA: The MIT Press, 1994.
- Hughes, Thomas P. "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems*, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch. Cambridge, MA: The MIT Press, 1987.
- Johnson, Paul. *A History of the American People*. New York: HarperCollins Publishers, 1997.
- Karsten, Peter. *Naval Aristocracy: The Golden Age of Annapolis and the Emergence of Modern American Navalism*. New York: The Free Press, 1972.
- Keeney, L. Douglas. *15 Minutes: General Curtis LeMay and the Countdown to Nuclear Annihilation*. New York: St. Martin's Press.
- Khong, Yuen Foong. *Analogies at War: Korea, Munich, Dien Bien Phu, and the Vietnam Decisions of 1965*. Princeton, NJ: Princeton University Press, 1992.
- Knothe, Gerhard. "Biodiesel and Renewable Diesel: A Comparison." *Progress in Energy and Combustion Science*, Vol. 36, (2010). <http://ddr.nal.usda.gov/dspace/bitstream/10113/39385/1/IND44336922.pdf> (accessed March 21, 2012).
- Kuenne, Robert E. *The Attack Submarine: A Study in Strategy*. New Haven, CT: Yale University Press, 1965.
- Kuhn, Thomas. *The Structure of Scientific Revolutions*. Chicago, IL: University of Chicago Press, 1996.
- Lake, Simon. *The Submarine in War and Peace*. Philadelphia, PA: Lippincott, 1918.
- Lambert, Andrew. *Battleships in Transition: The Creation of the Steam Battlefleet, 1815-1860*. Annapolis, MD: Naval Institute Press, 1984.
- Langley, Harold D. *Social Reform in the United States Navy, 1768-1862*. Chicago, IL: University of Illinois Press, 1967.
- Love, Robert W., Jr. *History of the U.S. Navy, Volume 1, 1775-1941*. Harrisburg, PA: Stackpole Books, 1992.
- Love, Robert W., Jr. *History of the U.S. Navy, Volume 2, 1942-1991*. Harrisburg, PA: Stackpole Books, 1992.
- Lutey, Tom. "Unpopular Crop: Camelina Falling Out of Favor with Montana Farmers." *Billingsgazette.com*, April, 22, 2011. <http://billingsgazette.com/news/state-and->

- regional/montana/article_bcc0ccb7-2aa8-5a5e-bb36-c9dd60995167.html (accessed March 23, 2012).
- Mabus, Ray. "Keynote Presentation at the Naval Energy Forum," October 14, 2009.
<http://www.navy.mil/navydata/people/secnav/Mabus/Speech/SECNAV%20Energy%20Forum%2014%20Oct%2009%20Rel1.pdf>
(accessed March 20, 2012).
- Machiavelli, Niccolò. *The Prince and The Discourses*. New York: Random House, 1950.
- Matthews, William. "BioFleet." *Government Executive*, January 2012,
http://digimag.govexec.com/display_article.php?id=927625
(accessed March 22, 2012).
- Maugeri, Leonardo. *Beyond the Age of Oil: The Myths, Realities, and Future of Fossil Fuels and Their Alternatives*. Santa Barbara, CA: Praeger, 2008.
- McBride, William. *Technological Change in the United States Navy, 1865-1945*. Baltimore, MD: The Johns Hopkins University Press, 2000.
- McNeill, William H. *The Pursuit of Power*. Chicago, IL: University of Chicago Press, 1982.
- McNeill, William H. "Why Study History?"
<http://www.historians.org/pubs/archives/whmcneillwhystudyhistory.htm> (accessed December 17, 2011).
- Melville, George H. "Melville's Stevens Institute Speech," Papers of George H. Melville. Manuscript Division, Library of Congress, Washington, D.C.
- Miller, Nathan. *The U.S. Navy: A History, 3rd Ed.* Annapolis, MD: Naval Institute Press, 1997.
- Mindell, David A. *War, Technology and Experience aboard the USS Monitor*. Baltimore, MD: The Johns Hopkins University Press, 2000.
- Morgan, Gareth. *Images of Organization*. Thousand Oaks, CA: Sage Publications, 2006.
- Nagl, John A. "Let's Win the Wars We're In." *Joint Forces Quarterly* 52, (1st Quarter, 2009). <http://www.ndu.edu/press/lib/images/jfq-52/JFQ52.pdf> (accessed April 1, 2012).
- National Energy Technology Laboratory. "Gasifipedia: Supporting Technologies."
http://www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/5-support/5-11_ftsynthesis.html (accessed March 19, 2012).

- Naval Documents of the American Revolution*, Vol. 2. Washington, D.C.: Government Printing Office, 1966).
<http://www.history.navy.mil/faqs/faq59-13.htm> (accessed January 24, 2012).
- Nuttall, William J. *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power*. New York: Taylor & Francis, 2005.
- Organization of the Petroleum Exporting Countries. "OPEC Statute."
http://www.opec.org/opec_web/static_files_project/media/downloads/publications/OS.pdf (accessed March 17, 2012).
- Parra, Francisco. *Oil Politics: A Modern History of Petroleum*. New York: I.B. Tauris & Co., 2004.
- Paullin, Charles Oscar. *Paullin's History of Naval Administration, 1775-1911*. Annapolis, MD: Naval Institute Press, 1968.
- Pew Project on National Security, Energy and Climate. "From Barracks to the Battlefield: Clean Energy Innovation and America's Armed Forces." Washington, D.C.: Pew Charitable Trusts, 2011.
- Phillips, Kevin. *American Theocracy: The Peril and Politics of Radical Religion, Oil, and Borrowed Money in the 21st Century*. New York: Viking, 2006.
- Pinch, Trevor J., and Bijker, Wiebe E. "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," in *The Social Construction of Technological Systems*, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch. Cambridge, MA: The MIT Press, 1987.
- Planck, Max. *Scientific Autobiography and Other Papers*, trans. F. Gaynor. New York, 1949.
- Polmar, Norman, and Allen, Thomas B. *Rickover: Controversy and Genius*. New York: Simon & Schuster, 1982.
- Posen, Barry R. *The Sources of Military Doctrine: France, Germany, and Britain Between the World Wars*. Ithaca, NY: Cornell University Press, 1984.
- Right, Austin. "Navy Powers Up Campaign for Great Green Fleet."
politico.com, March 7, 2012.
<http://www.politico.com/news/stories/0312/73752.html>
(accessed March 23, 2012).
- Rogers, Everett M. *Diffusion of Innovations*, 5th Edition. New York: Free Press, 2003.
- Roland, Alex, Bolster, W. Jeffrey, and Keyssar, Alexander. *The Way of the Ship: America's Maritime History Reenvisioned, 1600-2000*. Hoboken, NJ: John Wiley & Sons, 2008.

- Roscoe, Theodore. *United States Submarine Operations in World War II*. Annapolis, MD: United States Naval Institute, 1949.
- Rosen, Stephen Peter. *Winning the Next War: Innovation and the Modern Military*. Ithaca, NY: Cornell University Press, 1991.
- Rosenberg, David Alan. "The Origins of Overkill, Nuclear Weapons and American Strategy, 1945-1960." *International Security*, Vol. 7, No. 4 (Spring, 1983).
- Rosenthal, Elisabeth. "New Trend in Biofuels Has New Risks." *New York Times*, May 21, 2008.
<http://www.nytimes.com/2008/05/21/science/earth/21biofuels.html> (accessed March 26, 2012).
- Sapolsky, Harvey M. "The Interservice Competition Solution." *Breakthroughs*, Vol. 5, No. 1, (Spring 1996).
- Sloan, Edward. *Benjamin Franklin Isherwood Naval Engineer: The Years as Engineer in Chief, 1861-69*. Annapolis, MD: The United States Naval Institute, 1965.
- Smil, Vaclav. *Energy Myths and Realities: Bringing Science to the Energy Policy Debate*. Washington, D.C.: The American Enterprise Institute, 2010.
- Smith, Merritt Roe. "Technological Determinism in American Culture," in *Does Technology Drive History: The Dilemma of Technological Determinism*, eds. Merritt Roe Smith and Leo Marx. Cambridge, MA: The MIT Press, 1994.
- Smith, Merritt Roe, ed. *Military Enterprise and Technological Change: Perspectives on the American Experience*. Cambridge, MA: The MIT Press, 1985.
- Sprout, Harold and Margaret. *The Rise of American Naval Power, 1776-1918*. Annapolis, MD: Naval Institute Press, 1990.
- Starbuck, Alexander. *History of the American Whale Fishery from Its Earliest Inception to the Year 1876*. Waltham, MA: by the author, 1878.
- Sustainable Aviation Fuels Northwest. "Powering the Next Generation of Flight." http://www.safnw.com/wp-content/uploads/2011/06/SAFN_2011Report.pdf (accessed March 18, 2012).
- Targeted Growth, Inc. and Green Earth Fuels, LLC. "Sustainable Oils/Camelina." <http://www.susoils.com/camelina/> (accessed March 4, 2012).
- Thomas, Scott, and Kerner, David. "Defense Energy Resilience: Lessons from Ecology." US Army War College, August 2010,

- <http://www.strategicstudiesinstitute.army.mil/pdffiles/PUB1011.pdf> (accessed March 17, 2012).
- Tooze, Adam. *The Wages of Destruction: The Making and Breaking of the Nazi Economy*. New York: Viking, 2007.
- Tucker, Todd. *Atomic America: How a Deadly Explosion and a Feared Admiral Changed the Course of Nuclear History*. New York: Free Press, 2009.
- US Air Force. *Air Force Aviation Operations Energy Plan*, 2010.
<http://www.safie.hq.af.mil/shared/media/document/AFD-091208-026.pdf>.
- US Air Force. *Air Force Energy Plan*, 2010,
<http://www.safie.hq.af.mil/shared/media/document/AFD-091208-027.pdf>.
- US Air Force. *Energy Horizons: United States Air Force S&T Vision, 2011-2026*, January 31, 2012.
<http://www.af.mil/shared/media/document/AFD-120209-060.pdf>.
- US Code. Title 10 § 138C,
http://uscode.house.gov/download/pls/Title_10.txt (accessed March 20, 2012).
- US Department of Defense. *Energy for the Warfighter: Operational Energy Strategy*, May 2011.
http://energy.defense.gov/OES_report_to_congress.pdf (accessed March 20, 2012).
- US Energy Information Administration. "U.S. Total Crude Oil Imports and Products, U.S. Imports by Country of Origin."
http://205.254.135.7/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbb1_m.htm (accessed March 20, 2012).
- US Energy Information Agency. "Weekly Cushing, OK WTI Spot Price FOB."
<http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=rwtc&f=w> (accessed March 20, 2012).
- US Senate. Senate Debate, June 7, 1858. Congressional Globe, 35th Congress, 1st Session, p 2732. <http://memory.loc.gov/cgi-bin/ampage> (accessed January 22, 2012).
- University of Houston. "The Politics of Oil,"
<http://www.digitalhistory.uh.edu/historyonline/oil.cfm> (accessed March 17, 2012).
- Wakelin, James H., Jr. "The Development of Nuclear Propulsion in the Navy" Address by Honorable James H. Wakelin Jr., Assistant

Secretary of the Navy for Research and Development before the 22nd Annual Meeting of the American Power Conference in Chicago, Il, (March 29, 1960).

White House Press Release. "President Obama Announces Major Initiative to Spur Biofuels Industry and Enhance America's Energy Security," August 16, 2011. <http://www.whitehouse.gov/the-press-office/2011/08/16/president-obama-announces-major-initiative-spur-biofuels-industry-and-en> (accessed March 21, 2012).

Winton, Harold R. "An Imperfect Jewel: Military Theory and the Military Profession." *Journal of Strategic Studies*, Vol. 34, Iss. 6, (2011): 853-877.

Winton, Harold R. "On Military Change" in *The Challenge of Change: Military Institutions and New Realities, 1918-1941*, eds. Harold R. Winton and David R. Mets. Lincoln, NE: University of Nebraska Press, 2000.

Woodman, Richard. *The History of the Ship*. London: Conway Maritime Press, 1997.

World Bank. "World Development Report, 2008: Agriculture for Development." http://siteresources.worldbank.org/INTWDR2008/Resources/WD_R_00_book.pdf (accessed March 26, 2012).

Yergin, Daniel. *The Prize: The Epic Quest for Oil, Money, and Power*. New York: Free Press, 1991.

Yergin, Dan. "Interview with Dan Yergin," by Scott Tong. *Marketplace*, August 29, 2011, <http://www.marketplace.org/topics/business/news-brief/military-and-oil-historian> (accessed March 22, 2012).