An Early Conceptual Design and Feasibility Analysis of a Nuclear-Powered Cargo Vessel

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ABSTRACT

Economic globalization has resulted in the tremendous growth of worldwide trade. Much of this trade is carried out via the various waterways of the world. The bulk of these trade goods are transported by merchant ships that burn diesel fuel to propel them through the water. With the cost of crude oil rising to record highs, the cost of operating these ships has been skyrocketing as well, indicating the need for the development of alternative sources of propulsion power.

This thesis focuses on the development of an early stage conceptual design for a nuclear-powered commercial cargo ship and the subsequent economic analysis of that ship in comparison with its conventionally-powered predecessor ship. In addition, this thesis will also analyze and propose solutions to the various non-technical issues that currently stand in the way of building and operating a nuclear-powered cargo vessel. The end result of this research shows that a nuclear-powered commercial cargo ship, while being technically feasible, is still economically inferior to a conventionally-powered cargo ship.

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Table of Contents

1. INTRODUCTION 7

1.1 MOTIVATION FOR RESEARCH 7
1.2 PREVIOUS APPLICATIONS OF NUCLEAR POWER FOR SHIP PROPULSION 10
1.2.1 Military Applications 10
1.2.2 Merchant Cargo Ships 12
1.2.3 Russian Nuclear-Powered Ice Breakers 15
1.3 THESIS OUTLINE 16

2. PRELIMINARY DESIGN CONSIDERATIONS AND ASSUMPTIONS 17

2.1 OVERALL DESIGN PHILOSOPHY 17
2.2 THE PROPOSED SHIP 18
2.3 OTHER ASSUMPTIONS 21

3. DETAILED ANALYSIS 22

3.1 DETERMINATION OF BASIC REQUIREMENTS 22
3.2 REACTOR DESIGN 27
3.2.1 Choosing the Type of Reactor 27
3.2.2 Core Design 36
3.2.3 Basic Concept of Reactor Operations 42
3.2.4 Refueling 42
3.3 PROPULSION PLANT SELECTION 44
3.4 REACTOR AND ENGINEROOM LOCATION 50
3.5 LICENSING 54
3.5.1 Licensing via the NRC 55
3.5.2 Ship Classification via the ABS 62

4. ECONOMICS AND LOGISTICS 65

4.1 GENERAL DISCUSSION 65
4.2 LOGISTICAL ASSUMPTIONS 66
4.3 ECONOMIC ANALYSIS 67
4.3.1 Acquisition Costs 70
4.3.2 Marine Insurance 72
4.3.3 Manning 73
4.3.4 Other Lifecycle Costs 74
4.3.5 Operational Costs 74
4.4 FINAL COST ANALYSIS 74
4.4.1 Base-case Analysis 74
4.5.2 Sensitivity Analysis 76

5. CONCLUSION AND RECOMMENDATIONS 80

5.1 CONCLUSION 80
5.2 RECOMMENDATIONS FOR FUTURE RESEARCH 82

6. REFERENCES 85

APPENDIX A: CASMO-4 ROUTINE 87
APPENDIX B: CASMO-4 END OF CORE LIFE OUTPUT (10% ENRICHMENT) 88
APPENDIX C: NUCLEAR SHIP PV ANALYSIS→BASE-CASE 93
APPENDIX D: CONVENTIONAL SHIP PV ANALYSIS→BASE-CASE 95
APPENDIX E: NUCLEAR SHIP PV DATA FOR INCREASING FUEL COSTS 97
APPENDIX F: CONVENTIONAL SHIP PV DATA FOR INCREASING FUEL COSTS 98
APPENDIX G: NUCLEAR SHIP PV ACQUISITION DATA FOR VARIOUS SUBSIDIES 99

List of Figures

FIGURE 1: TOTAL U.S. CONTAINER TRAFFIC 7
FIGURE 2: AVERAGE COST OF A BARREL OF CRUDE OIL FROM 1988 TO PRESENT 8
FIGURE 3: SIMPLIFIED SUBMARINE REACTOR PLANT 11
FIGURE 4: NS SAVANNAH 12
FIGURE 5: NS OTTO HAHN 13
FIGURE 6: NS MUTSU 14
FIGURE 7: RUSSIAN NUCLEAR-POWERED ICE BREAKER 16
FIGURE 8: THE EMMA MAERSK 19
FIGURE 9: EMMA MAERSK'S PROPULSION DIESEL ENGINE 20
FIGURE 10: ESTIMATED CARGO CAPACITY OF THE EMMA MAERSK 21
FIGURE 11: SPEED VS. POWER CURVE FOR THE EMMA MAERSK 23
FIGURE 12: DAILY FUEL CONSUMPTION OF VARIOUS CONTAINER SHIPS AT VARIOUS SERVICE SPEEDS 24
FIGURE 13: MOTIONS OF A SHIP 28
FIGURE 14: TYPICAL BOILING WATER REACTOR PLANT 29
FIGURE 15: SODIUM-COOLED REACTOR ARRANGEMENT 30
FIGURE 16: MGCR CONCEPT CYCLE DIAGRAM 32
FIGURE 17: CROSS-SECTION OF A STANDARD 17X17 FUEL ASSEMBLY 37
FIGURE 18: STANDARD 17X17 FUEL ASSEMBLY 38
FIGURE 19: PROPOSED CONCEPT OF CORE DESIGN 39
FIGURE 20: GRAPH OF THE INFINITE MULTIPLICATION FACTOR VS. U-235 PERCENT ENRICHMENT 42
FIGURE 21: STANDARD PROPULSION TRAIN 45
FIGURE 22: SIMPLIFIED ELECTRIC PROPULSION SYSTEM 46
FIGURE 23: AMERICAN SUPERCONDUCTOR'S HTS PROPULSION MOTOR 48
FIGURE 24: PROPOSED ELECTRICAL DISTRIBUTION SYSTEM 49
FIGURE 25: OVERHEAD VIEW OF THE REACTOR COMPARTMENT 50
FIGURE 26: TYPICAL CONTAINMENT VESSEL OF A LAND-BASED REACTOR AND SHIP-BASED REACTOR 51
FIGURE 27: ESTIMATED ENGINEROOM VOLUME 52
FIGURE 28: LOCATION OF CONTAINMENT AND MACHINERY SPACE ON THE NS SAVANNAH 54
FIGURE 29: TYPICAL NRC APPROVAL STEPS AND TIMELINE 56
FIGURE 30: EXAMPLE OF A LEARNING CURVE 71
FIGURE 31: NET PRESENT VALUE LIFECYCLE COST COMPARISON 75
FIGURE 32: PV LIFECYCLE COST COMPARISON ASSUMING A 5% INCREASE IN FUEL COSTS 77
FIGURE 33: PV OF LIFECYCLE COSTS ASSUMING A GOVERNMENT SUBSIDY 78
FIGURE 34: PV OF LIFECYCLE COSTS ASSUMING A GOVERNMENT LOAN SUBSIDY 79
FIGURE 35: PV OF LIFECYCLE COSTS ASSUMING A SUBSIDY AND INCREASING FUEL COSTS 80
FIGURE 36: COST OF FUEL WITH A LOW SULFUR CONTENT AT THE PORT OF LOS ANGELES 81

List of Tables

TABLE 1: PERTINENT NAVAL ARCHITECTURAL DATA FOR NS SAVANNAH 13
TABLE 2: PERTINENT NAVAL ARCHITECTURAL DATA FOR NS OTTO HAHN 14
TABLE 3: PERTINENT NAVAL ARCHITECTURAL DATA FOR NS MUTSU 15
TABLE 4: PERTINENT NAVAL ARCHITECTURAL DATA DATA FOR NS SEVMORPUT 15
TABLE 5: PERTINENT NAVAL ARCHITECTURAL DATA FOR RUSSIAN ICE BREAKERS 16
TABLE 6: PERTINENT NAVAL ARCHITECTURAL DATA FOR EMMA MAERSK 19
TABLE 7: REACTOR POWER BASIS BREAKDOWN 25
TABLE 8: EXAMPLE PUGH METHOD MATRIX 34
TABLE 9: REACTOR SELECTION MATRIX 35
TABLE 10: ELECTRICAL DISTRIBUTION SYSTEM SPECIFICS 49
TABLE 11: COSTING DATA 70
TABLE 12: SUMMARY OF THE NPV OF SHIP LIFECYCLE COSTS 75

1. INTRODUCTION

1.1 Motivation for Research

Economic globalization has resulted in the tremendous growth of worldwide trade. It is estimated that almost 90% of the goods that are produced in the world reach their destination via the waterways of the world (1). The United States is a major importer and exporter of the aforementioned goods. The total container traffic within the United States for the six year period from 2000 to 2005 can be seen below in Figure One(1). One can see that the trans-oceanic container traffic increased by approximately 50% during this time frame, growing from about 28.5 million Twenty-foot Equivalent Units (TEU) to 40 million TEU. Worldwide container shipping is also growing at the same rate. Total movements are also expected to more than double in the next ten years.

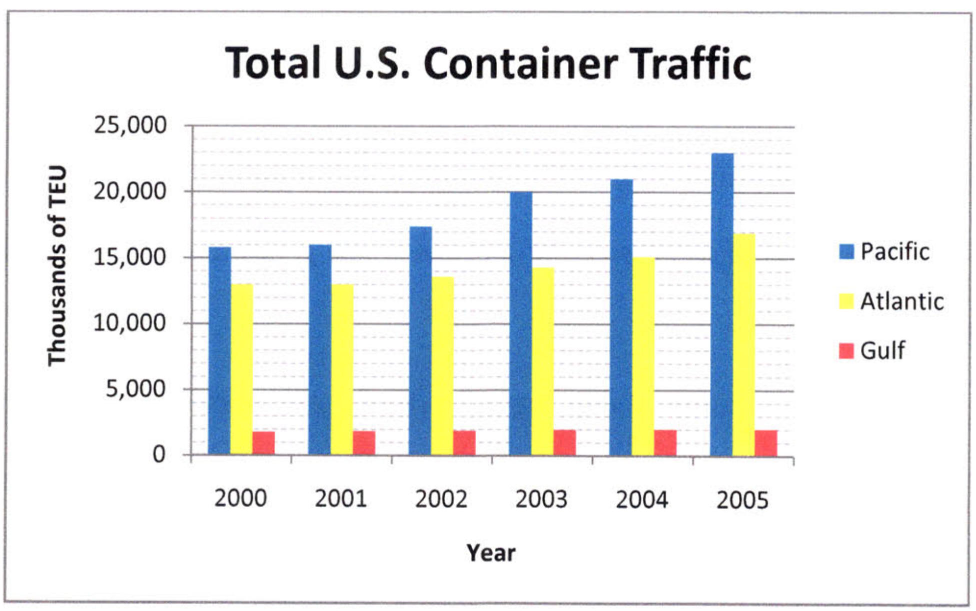

Figure 1: Total U.S. Container Traffic

The bulk of these goods are transported by merchant ships that burn diesel fuel to propel them through the water. With the cost of crude oil rising to record highs, the costs associated with operating these ships has been skyrocketing as well. A plot of the cost of a barrel of gasoline from 1988 up to the present is shown below in Figure 2(2).

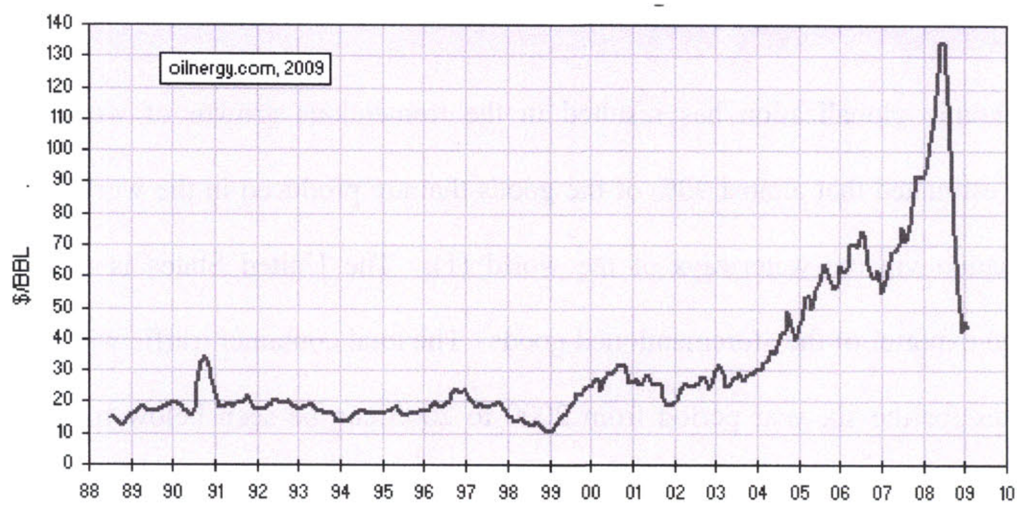

Figure 2: Average Cost of a Barrel of Crude Oil from 1988 to Present

Figure 2 shows that the cost of crude oil tripled from 2002 to 2006, skyrocketed to record highs during the summer of 2008, and then dropped back to pre-2006 prices as the year 2008 came to an end. The rising cost of diesel fuel, which is the refined product of crude oil, has resulted in shipping companies either operating their fleet of ships at lower speeds to keep costs down or making fewer transoceanic transits. Both of these choices have the obvious effect of decreasing the speed at which goods ultimately make it to the consumer.

It is important to note that shipping also releases pollutants into the atmosphere as the ships burn the fuels needed for their propulsion. It has been estimated that shipping is responsible for approximately 14 percent of the emissions of nitrogen (NO_x) from fossil fuels and 16 percent of the emissions of sulfur (SO_x) from petroleum uses into the atmosphere worldwide(3). It is therefore not surprising that countries are passing legislation that will require ships to reduce their emissions. The cost of reducing these emissions is being paid by the shipowners, meaning that the costs to shipowners to operate their fleet of containerships could rise even further. Other restrictions are also set to go into effect at some of the major shipping ports in an effort to clean up the air around these ports. For example, in 2008, the ports of Long Beach and Los Angeles mandated that the top speed of advance for all shipping either coming into or out of the ports should be no more than 12 knots whenever the vessel is within 40 nautical miles of the port. Furthermore, these same ports require all ships to burn cleaner fuels when within the same land limits, namely 0.2% sulfur marine gas oil. The previous land limit was only 20 nautical miles from land. Taken together, these issues make the search for a cleaner means of ship propulsion very important.

One such solution to these problems is to design, build, and operate a nuclear-powered merchant vessel or a fleet of such merchant vessels between worldwide shipping ports. Nuclear energy is considered by some to be a "green" solution to air pollution. The objective of this thesis is to evaluate the various aspects of such an undertaking. This thesis will identify the type of merchant ship and the powering requirements for this ship, and will propose a preliminary reactor concept design for this ship. The thesis will also analyze and propose solutions to various non-technical issues that currently stand in the way of building and operating a nuclear-powered cargo vessel. Finally, this thesis will assess whether or not a nuclear-powered commercial ship operating alone or within the context of a fleet of ships can be economically profitable. The analysis will consider not only the direct economic costs associated with the construction, operation, and maintenance of these ships, but will also consider the impact of the costs associated with making the current fleet of non-nuclear commercial ships comply with the various clean air acts that currently exist, or are likely to be introduced in the future.

The fundamental objective of this conceptual design is to show through simplified engineering analysis that a nuclear reactor can be used to propel a modern day cargo vessel without significantly affecting the cargo carrying capacity of the vessel and also to investigate the economic validity of nuclear propulsion for merchant vessels. Once the specific powering requirements have been determined, the reactor core will be validated via CASMO-4 with an eye towards maximizing core life within the confines of required classification survey timeframes. This thesis will also discuss the licensing process, both in regards to the nuclear reactor via the United States Nuclear Regulatory Commission and the ship itself via the American Bureau of Shipping classification society.

1.2 Previous Applications of Nuclear Power for Ship Propulsion

1.2.1 Military Applications

The United States Navy has been using nuclear power to propel its submarines and aircraft carriers since the USS Nautilus first signaled "underway on nuclear power" in 1955. Since that time, the United States Navy has used nuclear power for propulsion on submarines, aircraft carriers, and cruisers. A total of 215 nuclear-powered military vessels have been built and operated. These ships have accumulated almost 6,000 reactor-years of total operational time while steaming over 136 million miles without any significant reactor safety issues. The United States Navy's nuclear propulsion program currently operates 103 nuclear reactors. A simplified submarine reactor plant can be seen below in Figure 3(4). United States Naval Reactors use highly enriched uranium in their reactors. The enrichment level typically exceeds 90%. The reactor thermal power output varies between the different ship types, but the range is between 70 MW for a submarine and 550 MW for an aircraft carrier.

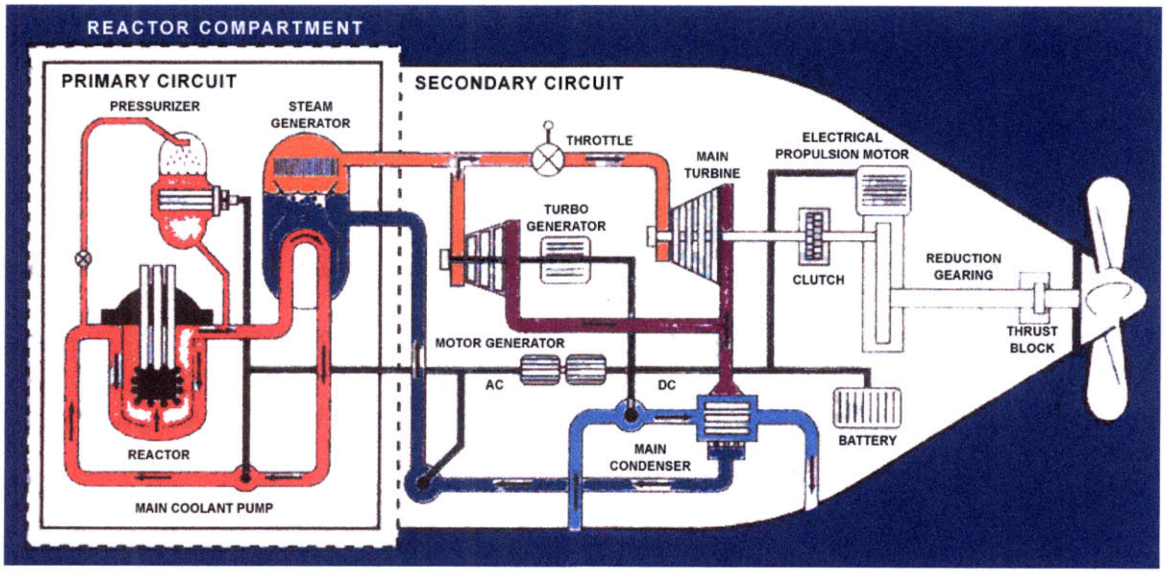

Figure 3: Simplified Submarine Reactor Plant

In addition to the United States, four other countries currently operate nuclear-powered warships and submarines: Great Britain, France, Russia, and China. Additionally, it is estimated that India will have a nuclear-powered submarine by 2009. Specific details about the nuclear-powered ships from these foreign countries are difficult to obtain and the open source information that is available is generally inaccurate. Therefore, no further discussion about foreign military nuclear combatants will be conducted.

1.2.2 Merchant Cargo Ships

If we look at the commercial merchant marine ships operated in the United States, only one nuclear-powered ship has ever been designed, built, and operated. This ship, the NS Savannah, was authorized by the Congress of the United States in July of 1956. The ship was to be the first of several nuclear-powered merchant vessels under President Dwight D. Eisenhower's Atoms for Peace initiative. The NS Savannah was to be a joint venture between the Maritime Administration (MARAD) and the Atomic Energy Commission (AEC). The keel of the ship was laid on May 22, 1958 and the ship was christened on July 21, 1959. The ship was acquired on May 1, 1962 and finally embarked on her maiden voyage on August 20, 1962(5). Since extensive information is readily available for NS Savannah, it served as a model for much of this project.

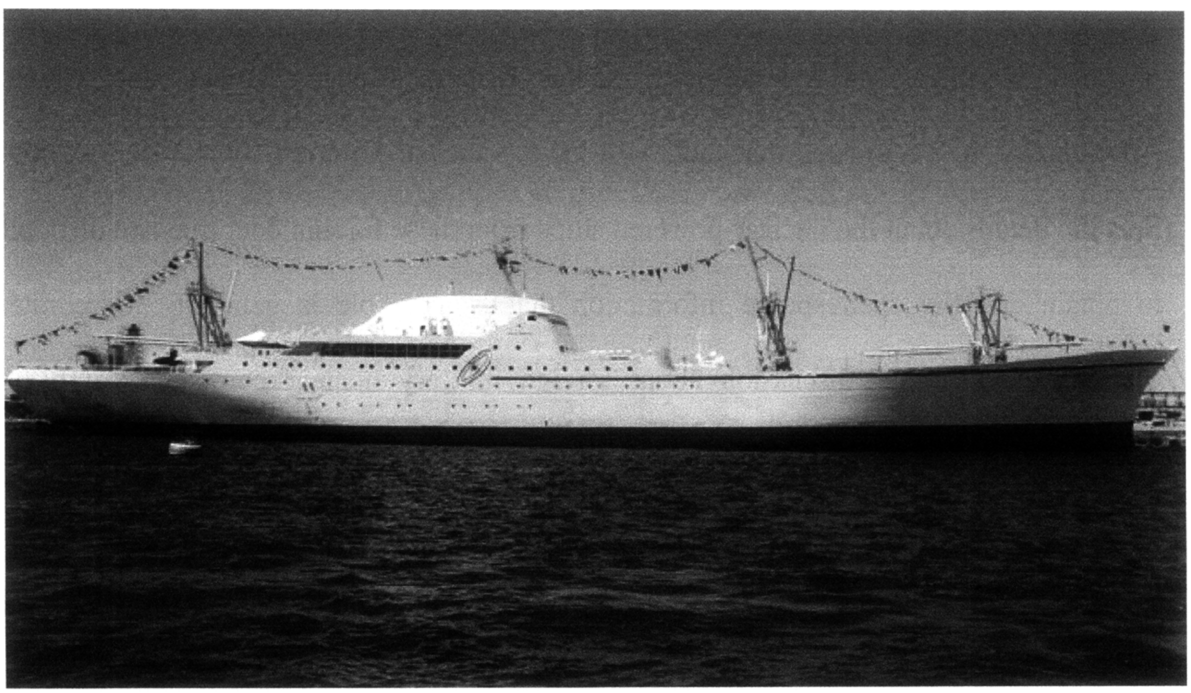

Figure 4: NS Savannah[1]

[1] http://www.globalsecurity.org/military/systems/ship/savannah-pics.htm

LOA	595.5 feet
Beam	78 feet
Draft	29.5 feet
Displacement	21,800 LT
Cargo Capacity	10,000 tons
Passengers	60
Crew	~ 110
Cruising Speed	21 Knots
Reactor Thermal Power	74 MW
Reactor Type	PWR

Table 1: Pertinent Naval Architectural Data for NS Savannah

The world's second civilian nuclear-powered merchant ship was built in Germany. The NS Otto Hahn was a 15,000 long ton displacement cargo and research vessel, powered by a 38 MW_{th} reactor, and was operated for the ten-year period from 1969 to 1979, steaming 650,000 nautical miles. But, as in the case of NS Savannah, the NS Otto Hahn proved to be economically unviable to continue operations and the vessel was ultimately converted to a diesel-propelled vessel and was renamed.

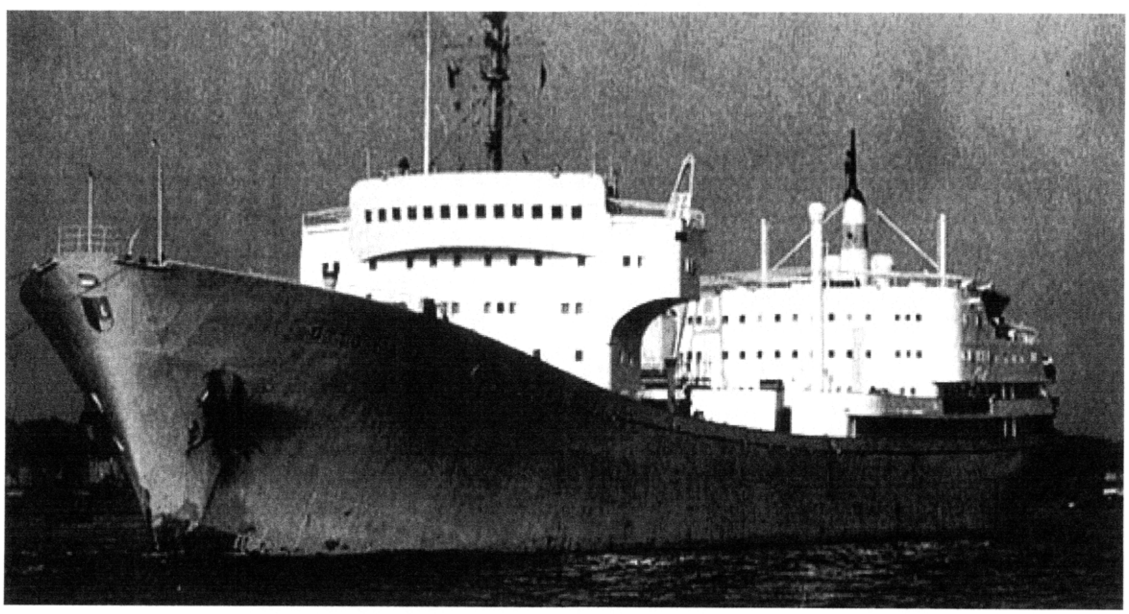

Figure 5: NS Otto Hahn[2]

[2] http://www.histarmar.com.ar/InfGral/Barcos-Nucleares/Fotos/NSOttoHahnorecarrier.jpg

LOA	172.05 meters
Beam	23.4 meters
Freeboard	5.3 meters
Displacement	25,790 LT
Cargo Capacity	14,000 tons
Research Personnel	35
Crew	~ 60
Cruising Speed	17 Knots
Reactor Thermal Power	38 MW
Reactor Type	PWR

Table 2: Pertinent Naval Architectural Data for NS Otto Hahn

The third civilian merchant ship was built in Japan. Similar to the NS Otto Hahn, the NS Mutsu was to be a research vessel as well as a cargo vessel. However, the NS Mutsu was plagued with problems beginning in the construction phase. Commissioning of the vessel was schedule to occur in 1972, but as a result of problems with the ship's primary radiation shielding and several other nuclear related issues, the ship was not actually commissioned until 1990. The vessel did complete four short research voyages from 1990 to 1992, but never carried cargo. The ship ceased operations and was finally decommissioned in 1995.

Figure 6: NS Mutsu[3]

[3] http://img401.imageshack.us/img401/7608/nsmutsuoy1.gif

LOA	130 meters
Beam	19 meters
Draft	7 meters
Displacement	25,790 LT
Cargo Capacity	8,242 tons
Cruising Speed	17 Knots
Reactor Thermal Power	38 MW
Reactor Type	PWR

Table 3: Pertinent Naval Architectural Data for NS Mutsu

The fourth civilian merchant ship was built in Russia and was commissioned in 1988. NS Sevmorput is a lash-carrier cargo ship that is also equipped with an ice breaking bow. It has been refueled once in 2003, and is currently still in service.

LOA	260 meters
Beam	32 meters
Freeboard	12 meters
Displacement	61,880 LT
Cargo Capacity	33,980 tons
Cruising Speed	20 Knots
Reactor Thermal Power	135 MW
Reactor Type	PWR

Table 4: Pertinent Naval Architectural Data Data for NS Sevmorput

1.2.3 Russian Nuclear-Powered Ice Breakers

Russia also operates a fleet of nuclear-powered ice breakers. These ice breakers began operation in 1959 with the ship NS Lenin. Since NS Lenin, eight other nuclear-powered ice breakers have been built and operated by Russia. Of these eight ships, six are still in operation today, with the most recent one, the NS 50 Let Pobedy, beginning operations in 2007.

Figure 7: Russian Nuclear-powered Ice Breaker[4]

LOA	148 to 159 meters
Beam	30 meters
Draft	11 meters
Displacement	~ 24,000 LT
Maximum Speed	22 Knots
Number of Reactors	2
Reactor Thermal Power	171 MW per Reactor
Reactor Type	PWR

Table 5: Pertinent Naval Architectural Data for Russian Ice Breakers

1.3 Thesis Outline

This thesis is organized into five chapters. Chapter 2 discusses the specific ship that was identified for the study, as well as stating the basic assumptions that were made during the study. Chapter 3 is the heart of the thesis. In this chapter, the various types of nuclear reactors and propulsion plant configurations are discussed and analyzed. The end result of Chapter 3 is that the nuclear reactor and the propulsion plant for the nuclear-

[4] http://gcaptain.com/maritime/blog/wp-content/uploads/2007/09/nuclear-icebreaker.jpg

powered variant are selected. Chapter 3 also addresses some of the licensing issues that will need to be overcome in order to make the project possible, and offers a solution to those problems. In Chapter 4, the economics surrounding the project are analyzed in order to determine the commercial feasibility of the conceptual design. Finally, Chapter 5 contains the conclusion of the thesis and identifies areas that could be expounded on for future follow-on work.

2. Preliminary Design Considerations and Assumptions

2.1 Overall Design Philosophy

The design philosophy employed to develop the conceptual design was multi-faceted. Consideration was given to proven as well as unproven propulsion technology. The starting assumption, however, was that the ship would be nuclear-powered. Therefore, both proven and unproven maritime reactor technology was also extensively researched and evaluated. Robert Munton, the technical director of the British Commonwealth Shipping Company, made the following statement in 1966 in regards to how shipowners view new technology:

> "The owner's consideration of any difference in ship design must essentially be concerned with the effect of that difference on the economics of operation throughout the ship's life. He is concerned with the total balance of earning power, amortized capital cost and operating cost. General experience indicates that in changing from a satisfactory

design to a new design of any item of machinery brings the risk of loss in availability time and unexpected costs for maintenance."(6)

One can conclude from Mr. Munton's statement that a shipowner is generally hesitant to change from a known good design to an unknown design, even if the unknown design has significant merit. In short, shipowners are averse to taking any kind of risk that is going to affect their profitability. For that reason, risk mitigation was considered as well. Since the starting argument for this study was that the ship was going to be powered by a nuclear reactor, every other design decision was based on mitigating future risk in the design. Therefore, the ultimate design philosophy for this project was based on mitigating risk to the maximum extent practical to the shipowner, while also striving to keep total costs as low as possible in order to ultimately maximize profitability for the shipowner.

2.2 The Proposed Ship

The baseline ship used for this project is the Emma Maersk, which can be seen below in Figure 8.

Figure 8: The Emma Maersk[5]

The principle naval architectural dimensions of the ship are listed below in Table 6(7).

LOA	397 meters
Beam	56 meters
Depth (molded)	30 meters
Displacement	120,000 LT
Cargo Capacity	11,000 + TEU
Crew	~ 13
Cruising Speed	25 Knots
Maximum Speed	31 Knots
Propulsion Power	110,000 SHP Maximum
Construction Cost	US $145,000,000
Shipbuilder	Odense Steel Shipyard Ltd

Table 6: Pertinent Naval Architectural Data for Emma Maersk

The Emma Maersk is the largest container ship ever built. It was built for the Maersk Shipping Company by the Odense Steel Shipyard located in Odense, Denmark. The Emma Maersk, along with the other ships that have been built to the same design, is the current state of the art container ship and therefore was the obvious choice for this

[5] http://gcaptain.com/maritime/blog/wp-content/uploads/2007/09/emma-maersk-underway.jpeg

analysis. The Emma Maersk is powered by a single 14-cylinder Wärtsilä diesel engine from Doosan Engine Co. developing 110,000 BHP or 80,080 kW at 102 revolutions per minute. This engine can be seen below in Figure 9(8).

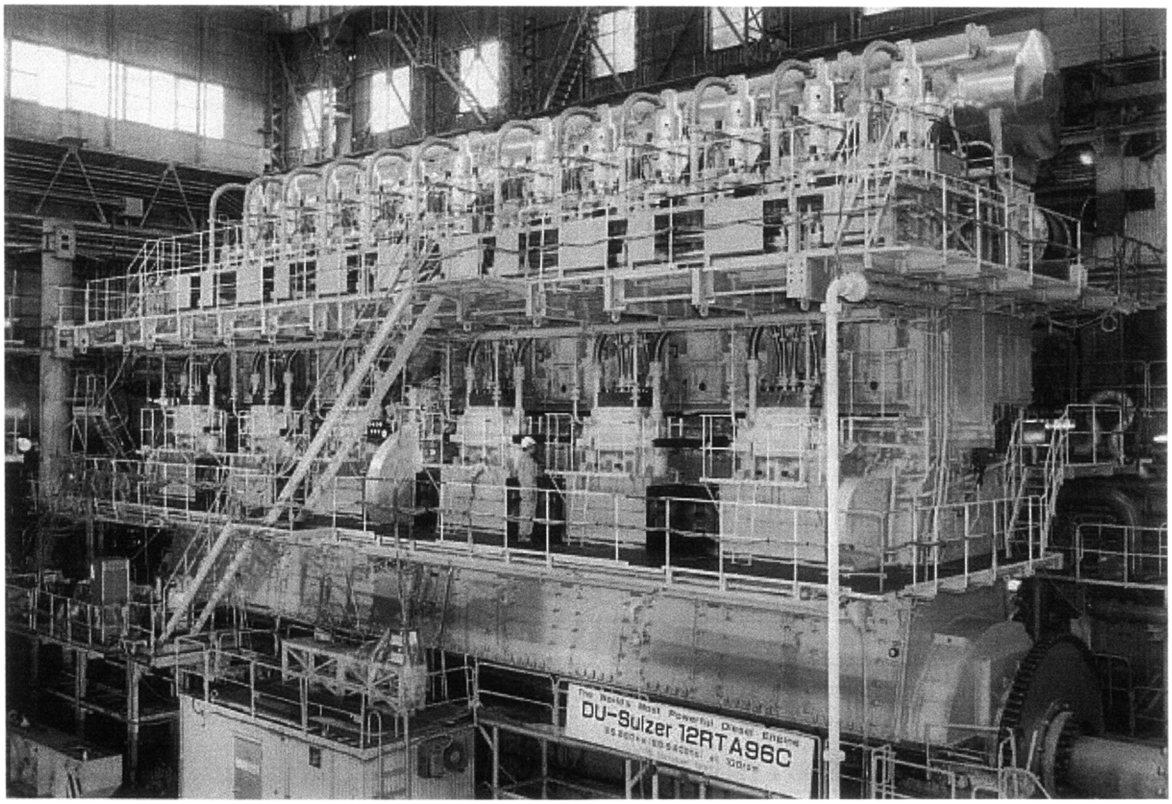

Figure 9: Emma Maersk's Propulsion Diesel Engine

Also, five diesel generators with a combined power of 20,700 kW and one combined gas/steam turbine generator of 8,500 kW driven by the main engine exhaust are installed on the ship in order to supply the required cruise electrical load. Together, these generators provide the Emma Maersk with the possibility of producing 29.2 MW of electrical power. The ship is designed to be operated by 13 merchant mariners; however, accommodations are already provided for 30 total merchant mariners(7). The Maersk company lists the cargo capacity of the Emma Maersk as 11,000 TEU. However, most shipping industry experts believe that the actual cargo carrying capacity of the ship is significantly more than what the Maersk company is willing to publicly acknowledge.

Figure 10 shows one such estimate conducted by the marine industry data agency AXS-Alphaliner. AXS- Alphaliner estimates the actual cargo carrying capacity of the ship to be 15,212 TEU, as shown below in Figure 10(9).

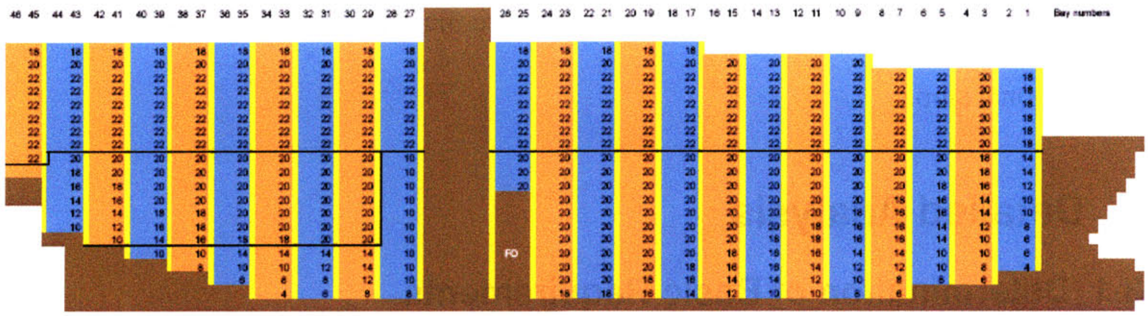

Figure 10: Estimated Cargo Capacity of the Emma Maersk

The cargo carrying capacity of the ship is an important item, since that is how the ship earns money for the shipowner. This study will assume the initial actual cargo carrying capacity of the Emma Maersk to be 15,212 TEU, as calculated by AXS-Alphaliner.

2.3 Other Assumptions

The Maersk company declined my request for specific information about their ship. Therefore, many of the ship characteristics had to be estimated using sound engineering principles and judgement.

The trade route selected for this analysis was a route that runs from Shanghai, China to Los Angeles, California. This trade route is estimated to be 6,000 nautical miles in length. This two-port trade route was selected because it was considered to be the most viable route since it would minimize the number of ports that would have to be upgraded to in order to provide the necessary husbandry services for the design vessel. Furthermore, these two ports are among the largest and most modern shipping ports in the entire world. Since ports-of-call of a nuclear-powered vessel are going to be required to provide services that a conventional port-of-call would not, the assumption was made that only the largest of ports would be willing to make the required accommodations. For example, a nuclear-powered ship is going to require more in-port security then a standard conventional ship.

3. Detailed Analysis

3.1 Determination of Basic Requirements

Based on publically available data, a propulsion analysis was performed on the Emma Maersk, and a speed versus power curve was developed. This curve can be seen below in Figure 11. This curve was developed using Equation 1 below.

$$P_{eff} = C_1 v_s^3 \qquad \text{Equation 1}$$

Where:

P_{eff} is the effective shaft horsepower
C_1 is a constant
v_s is ship's speed in knots

Despite the fact the C_1 is a function of many factors (ship speed, ship size, hull geometry sea state, water depth, fouling, etc.), it generally does not vary significantly over the range of operations. Therefore, it was assumed to be equal to a constant value for the purposes of this analysis. The purpose of developing this curve was to determine the required reactor thermal power output.

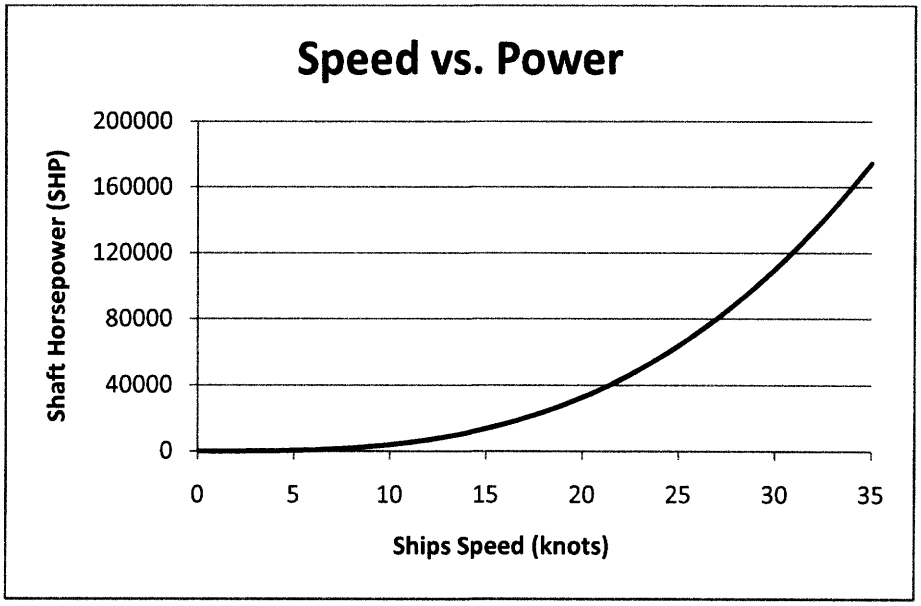

Figure 11: Speed vs. Power Curve for the Emma Maersk

The required reactor electrical power output and the required reactor thermal power output is not the same. The difference between the electrical power requirement and the thermal power requirement of the nuclear reactor is based on the assumption of a 33% efficiency for the baseline nuclear reactor. This is a very conservative assumption for a modern nuclear reactor. For example, the United States Advanced Pressurized Water Reactor (US-APWR) has a thermal efficiency of 39%(10).

As Equation (1) and Figure 11 show, the ship's speed and the required shaft horse power needed to develop that speed are related to one another via a cubic relationship. There is a tremendous amount of additional power required to propel a ship of this size at a relatively high rate of speed. This is exactly as one would expect. As can be seen in Figure 11, the ship needs 63,647 SHP to go 25 knots, and it requires 110,000 SHP to go 31 knots. Thus, simply to increase the ship's speed from 25 knots to 31 knots requires almost double the SHP. Also worth noting is the fact that the fuel consumption of a marine engine also follows a very similar cubic relationship. This is evident as seen below in Figure 12(11).

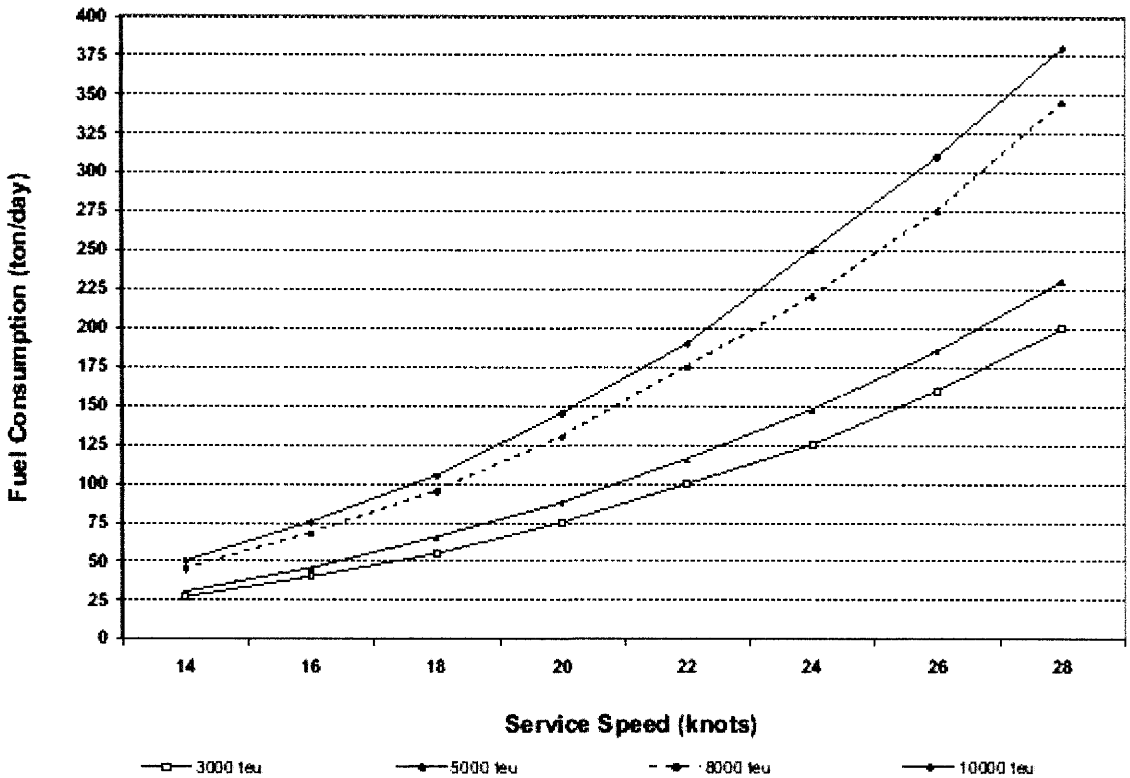

Figure 12: Daily Fuel Consumption of Various Container Ships at Various Service Speeds

Therefore, it becomes obvious that higher speed ships require bigger engines to propel them, and these engines consume fuel at a much higher rate when they operate at higher speeds. Also, bigger engines occupy more space and weigh more. This of course results in a loss of cargo carrying ability for the cargo ship, which in turn will decrease profitability to the shipowner. For the purposes of this conceptual study, it is assumed that the cruising speed of the nuclear-powered ship variant will be the same as for the conventionally-powered ship, namely 25 knots. Therefore, as mentioned previously, we need to develop approximately 63,647 SHP to propel the ship at its cruising speed. Cruising speed is defined as the speed a ship can go when its propulsion motor is operated at 85% of its maximum continuous rating. As will be discussed in Section 3.3, this power will be provided by two 36.5 MW_e propulsion motors. This alone corresponds to a required reactor thermal power output of approximately 219 MW_{th}. The ship also has electrical loads needed for additional reactor support systems as well as for refrigerated cargo and hotel services. The various estimated values for these are shown in Table 7 below. Therefore, the total reactor thermal power output proposed for this design is 350 MW_{th}.

	Electrical Power	**Thermal Power**
Propulsion Motors	73 MW	219 MW
Refrigeration	20.7 MW	62 MW
Hotel Loads		
Reactor Auxiliary Loads	14 MW	42 MW
Margin	9 MW	27 MW
		350 MW Total

Table 7: Reactor Power Basis Breakdown

The margin load takes into account the transmission losses associated with the propulsion motors. The Refrigeration and Hotel load was estimated based on the available installed power of the actual Emma Maersk. The reactor auxiliary load was estimated based on the study done by Stroud and Sawyer in (1). A discussion of the benefits and drawbacks associated with producing a larger reactor to propel the ship faster is discussed below.

One of the aspects considered during this design was the speed requirement. It is obvious from a cursory analysis that a faster speed would be more desirable then a slower speed. Consider a fleet of ships operating on the proposed trade route. If a shipping company had a fleet of six 10,000 TEU cargo ships operating on this route traveling at an average speed of 25 knots, then it could move 60,000 TEUs every 240 hours (every 10 days). If the speed of the fleet were increased to 35 knots, then the same amount of cargo could be moved every 171 hours (every 7.14 days). This would translate to 11 more port visits per year for the higher speed fleet, which means that 660,000 more TEUs would be transported by the faster fleet each year. Or, if looked at in terms of the number of ships in the fleet, the same amount of cargo that is carried by a fleet of six ships travelling at an average speed of 25 knots could be carried by a fleet of only 4 ships if those ship travelled at an average speed of 35 knots on our proposed trade route. However, as is evident from Figure 11, there is a penalty to be paid in terms of powering for this increase in speed. This extra power comes in the form of extra weight and space needed for larger propulsion equipment and associated systems, which in turn reduces the amount of cargo that the ship is able to ultimately carry. In the case of a nuclear-powered vessel, this would also result in a larger nuclear reactor, which in turn would further reduce the amount of cargo that a ship could carry from port to port. Furthermore, the higher the speed of a ship, the higher the dynamic forces that the ship will be exposed to as it transits the open ocean. While a well-designed ship will be able to withstand these forces without experiencing any structural problems, the cargo that is being carried above the deck might not be able to. This phenomenon, called slamming, is something that must not be overlooked when considering the actual need for speed in the design of a cargo vessel. Certainly, it is logical to assume that a shipowner would prefer that his ship arrive in port later with none of the cargo damaged then earlier with a significant amount of cargo damaged. Therefore, in keeping with the design philosophy of minimizing risk to the shipowner, the decision was made to keep the cruising speed for the nuclear-powered variant the same as the actual Emma Maersk.

3.2 Reactor Design

3.2.1 Choosing the Type of Reactor

Once the required thermal output of the reactor was determined, efforts shifted to developing a conceptual design for the reactor core that would meet this requirement. The starting point for this part of the project was to research and subsequently select the type of reactor that would be used for the ship. There are major differences between a reactor that is going to go on a ship and one that is going to be land based. Some of these basic considerations are as follows:

1. The design must consider the possible adverse effects of flooding.
2. The design must consider watertight integrity between compartments.
3. The design must take into account the constraints of being on a ship; namely volume and area constraints.
4. The design must consider the weight of the reactor and the placement on the ship, as this will essentially be a point load which could potentially affect the bending moment of the ship.
5. The design must take into account the increased likelihood of seawater corrosion of the various structural elements of the ship.
6. The design must take into account that the ship and therefore the reactor will be subjected to 6 different types of motions. A shipboard reactor will be subjected to

the same external motions as the ship that it is installed on (12). These six different types of motions can be seen below in Figure 13.

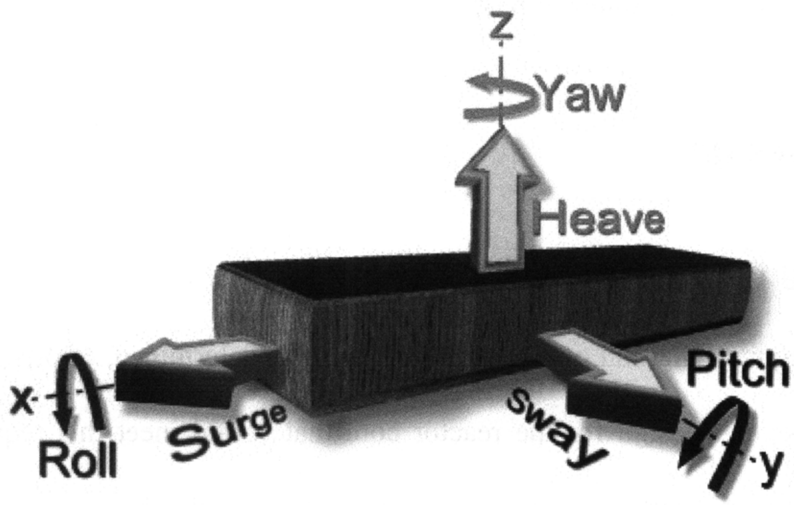

Figure 13: Motions of a Ship[6]

Surge Motion is the movement of the ship in the forward direction.

Sway is the lateral translational motion of a ship.

Heave is the up or down vertical translational motion of the ship.

Roll is transverse angular motion of the ship.

Pitch is oscillatory (teeter-tooter) motion of the ship.

Yaw is the weaving motion of the ship to port or starboard(13).

Four different reactors types were investigated and analyzed for application to this project. The first reactor type analyzed was the pressurized water reactor (PWR). The PWR has the advantage of being the reactor of choice for all but one US Navy nuclear-powered vessel, and also being the reactor of choice for all previously attempted commercial nuclear-powered vessels. The PWR has proven to be technically feasible in

[6] http://www.worldwideflood.com/ark/basic_hull_design/degrees_of_freedom.jpg

all maritime endeavors thus far. A schematic of a PWR was shown previously in Figure 3 above. In PWR designs, the nuclear reactor produces heat which is transferred to primary coolant circulated via a reactor coolant pump. This primary coolant then transfers its heat to a secondary system via a steam generator. In the steam generator, feedwater absorbs sufficient heat from the primary system to become steam which in turn drives steam turbines which produce the required electrical power needed and also the required thrust required for shaft propulsion power. Exhaust steam from the turbines is condensed in a condenser, and is subsequently pumped back into the steam generator as feedwater, where the cycle repeats. The primary system and the secondary system are not the same.

The next reactor type considered for this project was the Boiling Water Reactor (BWR). A schematic of a BWR can be seen below in Figure 14.

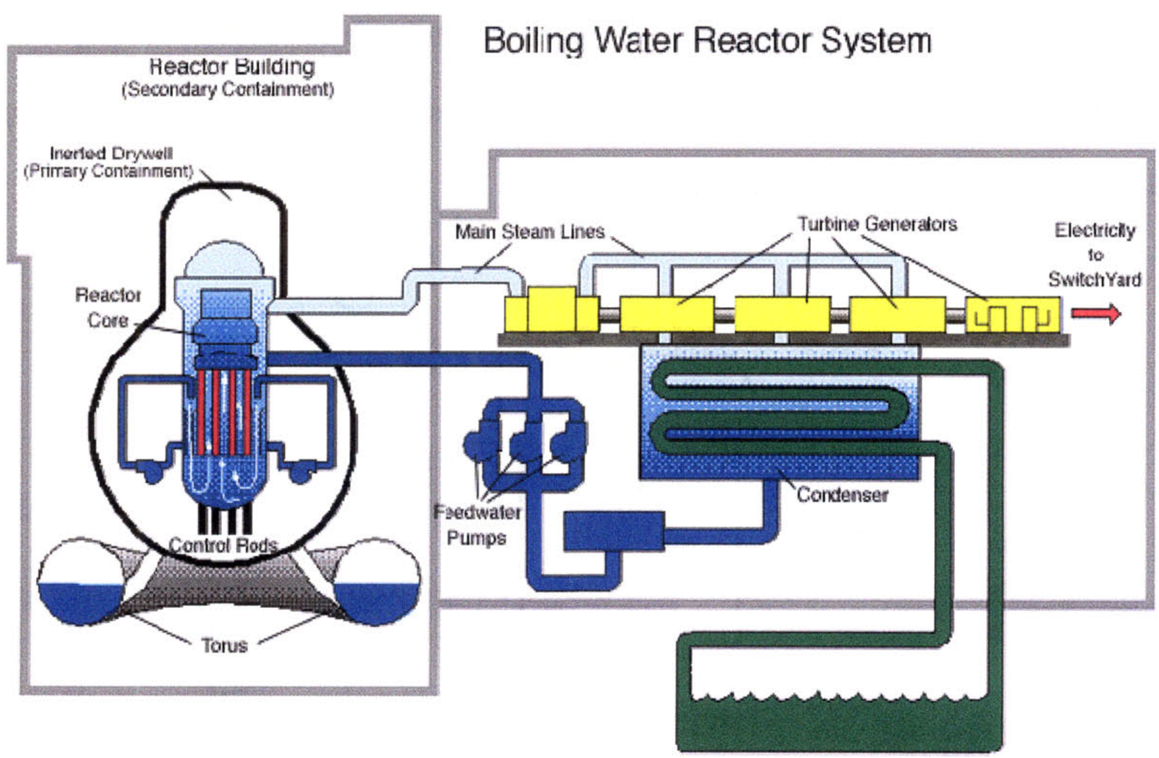

Figure 14: Typical Boiling Water Reactor Plant

A BWR power cycle is essentially a Rankine cycle. In a boiling water reactor, the heat necessary to make the steam for the turbines is still generated in the core. However, unlike in the PWR, the steam that is used to turn the turbine which makes the required electrical power is also produced in the core. Thus, there essentially is no secondary system, and the steam potentially contains radioactive impurities as a result. Some preliminary developmental work on marine BWRs has been conducted in Europe. However, this work has generally focused on the reactor's response to ship motions instead of focusing on reducing the required volume of the plant. Generally speaking, BWRs have a much lower power density then a typical PWR, and therefore the reactor plant tends to be larger. This lower power density does not make its physical size particularly compatible with ship dimensions at high power ratings(14).

The third type of reactor considered for this project was the Sodium Cooled Reactor (SCR). Liquid sodium has superior heat transfer characteristics, making it an almost perfect reactor coolant choice. The SCR consists of three separate circulating loops, as can be seen below in Figure 15(15).

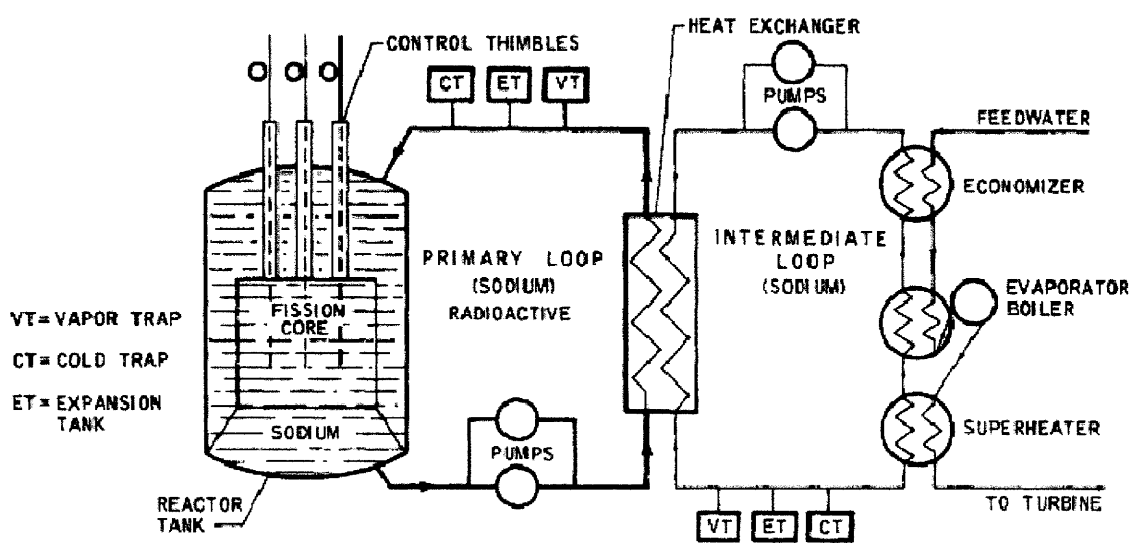

Figure 15: Sodium-Cooled Reactor Arrangement

In the primary loop, liquid sodium is pumped through the reactor where it removes the heat generated from fission. The sodium coolant temperature leaving the reactor is about 950F. The coolant then flows through a second heat exchanger where it transfers heat to liquid sodium in the intermediate loop. The sodium coolant pressure in the intermediate loop is higher than the sodium coolant pressure in the primary loop so that if a leak were to develop, no radioactive sodium would leak into the intermediate loop. Finally the sodium coolant of the intermediate loop transfers its heat to water in the boiler of the secondary loop in order to make the steam that drives the turbines.

This type of reactor was actually built and operated by the US Navy on the USS Seawolf (SSN-575). The reactor was only operated for three years before it was replaced with a pressurized water reactor due to technical problems(16). The major problem associated with the USS Seawolf's SCR was in the superheaters of the secondary system. The technology of the time simply was not up to par for the design.

The fourth type of reactor considered for this project was the Marine high temperature gas cooled reactor (MGCR). This reactor was studied extensively in the 1970s, and is considered to be a very good design. A detailed design of such a plant was even proposed by several companies, including Westinghouse and the General Atomics Corporation. The reactor was designed to be moderated by BeO and contained fuel that was enriched to a level of 10.5% and was cooled with helium gas(14). The high temperatures that are produced in the cycle require advanced materials in many of the components that will be discussed below. A schematic representation of the MGCR is shown below in Figure 16(15).

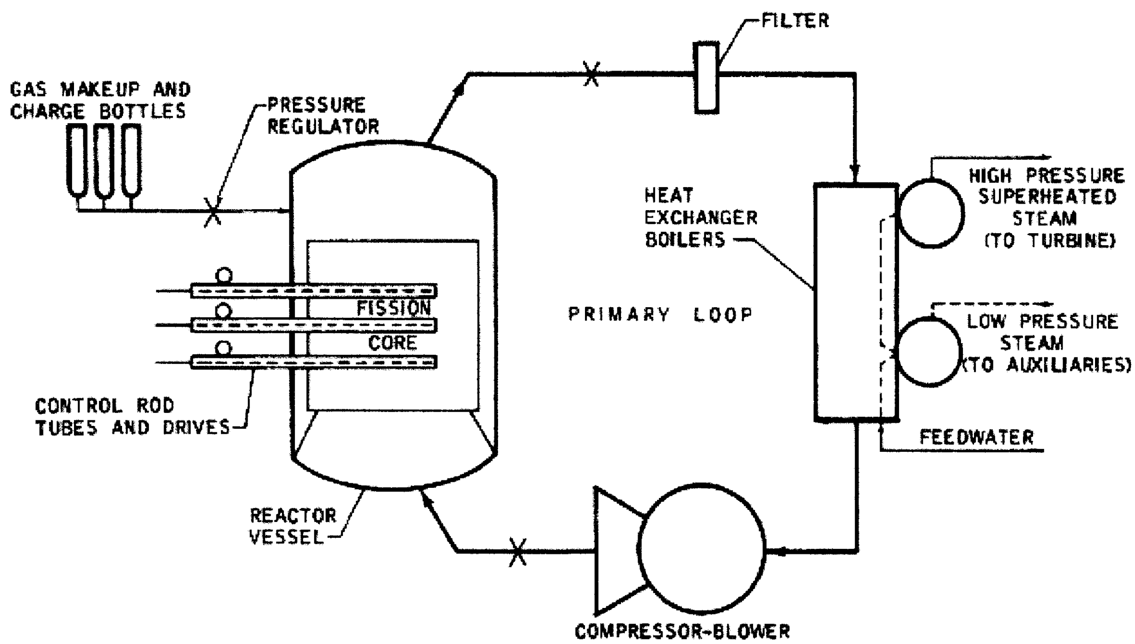

Figure 16: MGCR Concept Cycle Diagram

In the MGCR, helium leaves the reactor at very high temperatures (1700 F) and flows into the high pressure turbine. The HP turbine drives the low pressure compressor and high pressure compressors. Helium leaving the high pressure turbine then flows through the low pressure turbine, which is the power generating turbine, and is then directed into a recuperator. Helium from the compressor outlet is pre-heated prior to being returned back to the reactor by the helium flowing from the low pressure turbine. This has the obvious effect of increasing the overall cycle efficiency, which can be as high as 40% for a well designed plant. After passing through the recuperator, the helium flows through a pre-cooler prior to flowing through both of the compressors to raise the pressure of the helium back up to around 1500 psi before it completes the cycle and returns back to the reactor.

The MGCR has a number of advantages, though it has not been installed and operated on any ship, either civilian or military. For starters, the specific weight of the reactor plant itself is 1/5 the specific weight of a PWR(17). This means that the plant would be significantly smaller then a PWR for the same output power. Obviously, a smaller propulsion plant would translate to more cargo carrying space for a ship. It also is estimated to be around the same cost of a similar power producing PWR(17). This estimate is based on the thought that the cost reduction that would be seen from the reduction in material requirements needed for the plant would just about offset the cost addition caused by the requirement for advanced materials. The estimate also assumes that the cost of the uranium fuel in the reactor is approximately the same for a PWR and the MGCR(18).

In order to ensure that the best choice was made in regards to reactor type, a method of analysis called the Pugh Method was employed. This selection method was developed by Stuart Pugh during the 1980s. The Pugh Method concept selection seeks to narrow the number of concepts quickly and provides a unique way to incorporate strengths of rejected concepts into the dominant design, potentially generating a stronger overall concept. The process has two primary components, concept screening and concept scoring. The concept screening component has five steps. In the end, a broad variety of concepts are evaluated with respect to customer needs through converging on strengths and, at times, diverging to combine existing or inspire new concepts at different steps in overall concept selection. The first step is to prepare a selection matrix. An example of a generic Pugh matrix is presented below in Table 8(19).

	Datum	Concept 1	Concept 2	Concept 3
Need 1	**D**	-	+	-
Need 2	**A**	S	+	+
Need 3	**T**	+	S	-
Need 4	**U**	S	+	S
Sum +'s	**M**	1	3	1
Sum –'s		1	0	2

Table 8: Example Pugh Method Matrix

The left most column of the matrix contains selection criteria obtained by focusing on primary customer needs. Concepts that have been identified for analysis are listed across the top of the matrix. The next step is to rate the concepts. A datum or reference concept is selected for comparison. Each concept is then compared to the datum. For example, the question would be asked if concept 1 is better or worse at meeting need 1 than the datum. If the concept is better a "+" is entered in the respective cell. If the concept is as good as the datum a "S" is entered. If it is worse a "-" is entered. Once the entire Pugh chart is filled out, the first round is complete. The next step is to calculate the net score by summing the results. After determining the best concept, design work can then begin on that concept(19).

The Pugh Matrix for the reactor selection is shown below in Table 9. The PWR was chosen as the Datum, since it has been the reactor of choice for all previous ships. The categories that each reactor was scored on were developed after consulting with several individuals with significant shipboard reactor experience.

	PWR	BWR	SCR	MGCR
Risk	D	-	-	-
Safety	A	S	S	S
Cost	T	-	-	-
Size	U	-	+	+
Complexity	M	-	-	-
Sum +'s		0	1	1
Sum -'s		4	3	3
Overall Score		-4	-2	-2

Table 9: Reactor Selection Matrix

The original design philosophy called out for this project required that financial risk be minimized to the shipowner. The best possible way to mitigate the risk to the shipowner in regards to reactor choice is to select the PWR, therefore the BWR, SCR and the MGCR were given negative scores for the Risk category. In the Safety category, all reactors were determined to be the same, since any reactor built would have to ultimately meet the licensing requirements of an external agent. In the cost category, the BWR, SCR and MGCR were evaluated as worse than the PWR due to the fact that additional Research and Development funds would need to be spent before any of these reactors could be built. In the Size category, both the BWR and the SCR were evaluated as worse than the PWR, and the MGCR was evaluated as better than the PWR. Finally, in regards to complexity, the BWR, SCR, and the MGCR were evaluated as being worse than the PWR. After evaluating the results obtained from the Pugh Matrix, the PWR was the reactor type that was selected for this project. Despite the choice of a PWR for this endeavor, the author believes that the MGCR is the reactor that would ultimately be the most suitable for this application. However, until a prototype reactor is built, operated, and analyzed extensively, it will not be a suitable choice for a shipowner.

3.2.2 Core Design

Once the reactor type had been selected, a preliminary core analysis could be conducted. The design of the reactor core was performed under the following constraints, which were consistent with the previous analysis:

- The reactor selected for the ship was a pressurized water reactor (PWR). The PWR was selected because it is a proven reactor type that has been used extensively in naval applications.
- The core was to be limited to a maximum enrichment level of 20%. This is based on the fact that 20% is the highest enrichment level available to non-government entities.
- The total operating lifetime of the reactor core was to be either five years or ten years. This decision was made to ensure that a reactor refueling could be performed in conjunction with the required ABS dry-docking inspections in order to minimize the down-time of the ship.
- The final constraint was that the level of discharge burn-up was limited to 60,000 MW-day per kilogram. This is the highest fuel burn-up that has been seen in modern nuclear reactors.

Also, the decision was made to design the core using standard nuclear fuel assemblies. Again, this decision was made in order to adhere to the original design philosophy. Therefore, the type of fuel assembly selected was a standard 17x17 Westinghouse design. A picture of this assembly can be seen below in Figure 17 and Figure 18 (20).

The standard assembly is 21.5 cm in width, and 366 cm in height. The volume of the assembly (V_a) was determined as shown below:

$$V_a = W^2H = (21.5)^2(366) = 169{,}183.5\ cm^3 = 169.2\ Liters$$

There are 289 pins per assembly, and of those, 264 are fuel pins (represented by the gray circles).

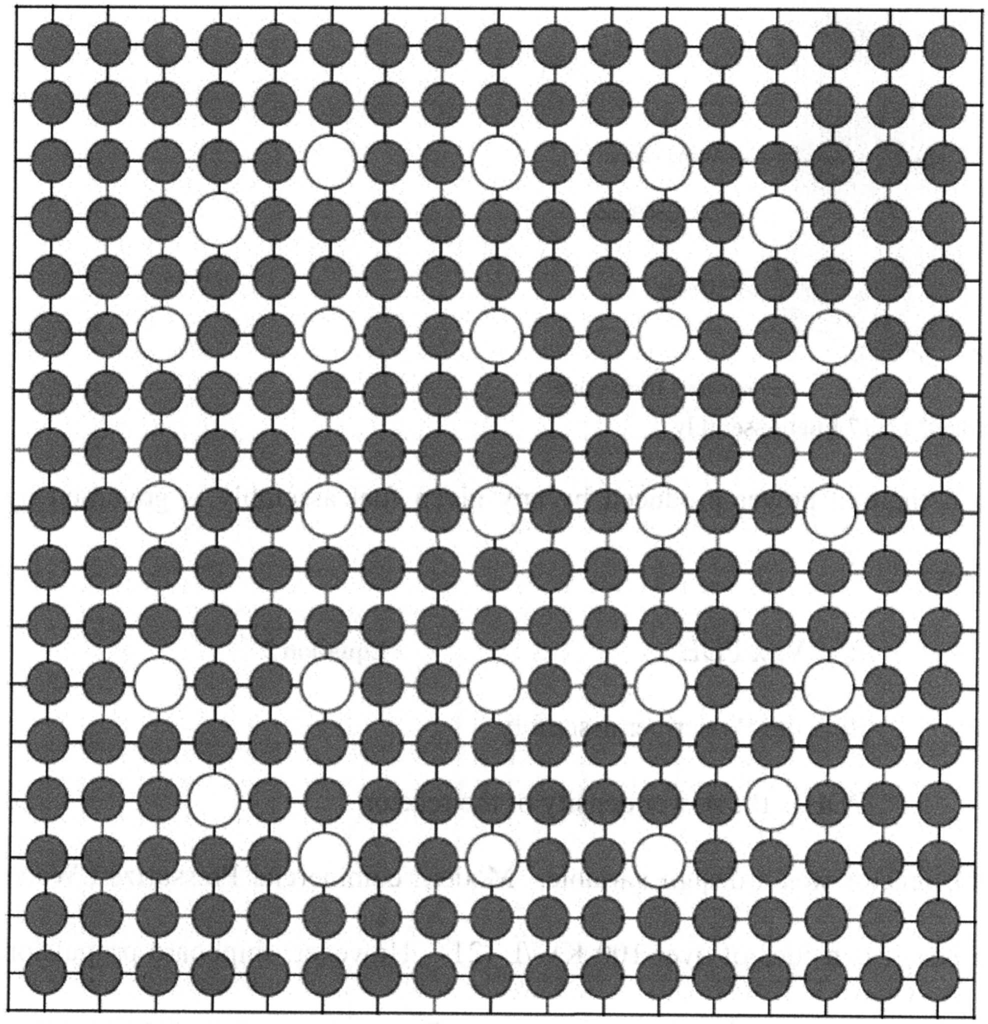

Figure 17: Cross-Section of a Standard 17x17 Fuel Assembly

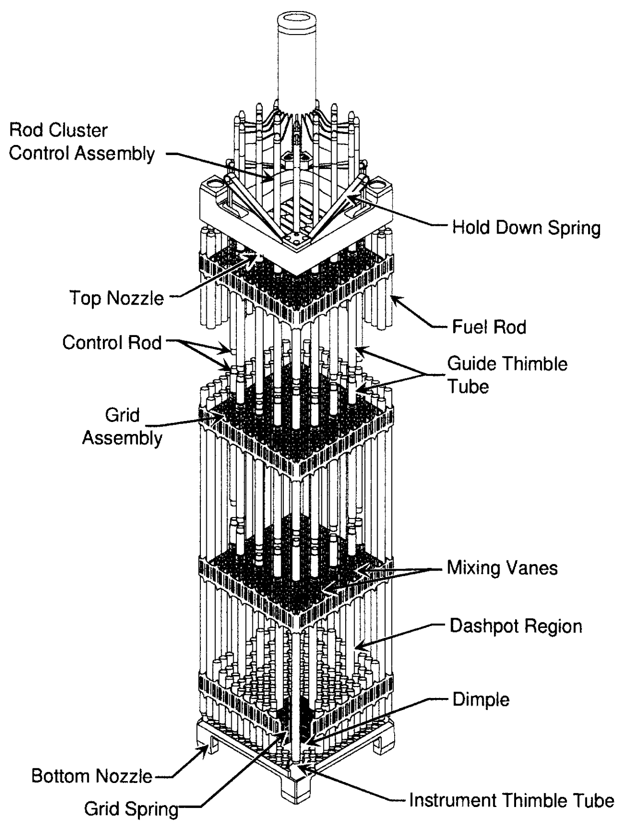

Figure 18: Standard 17x17 Fuel Assembly

The total thermal power produced by any given fuel assembly is governed by Equation 2 below:

$$P_a = V_a \times PDE \qquad \textbf{Equation 2}$$

Where: P_a is the Power per assembly

PDE is the power density of the reactor

The PDE of the reactor was a design variable. Modern commercial Pressurized Water Reactors have power densities of over 100 KW/L (21). However, shipboard propulsion reactors typically have a much lower power density. Since power density for a propulsion reactor is a measure of its size and weight, it is desired to have as high a power density as is practical. But, as PDE gets bigger, the total core operating lifetime gets smaller. After several iterations, the PDE for this design was determined to be 55.9 KW/L. This resulted in a P_a of 9458.28 KW per assembly.

Once the power per fuel assembly was known, the total number of fuel assemblies required to be installed in the core could be calculated. This calculation is governed by Equation 3 below:

$$\overline{} \qquad \textbf{Equation 3}$$

Using Equation 3, the total number of fuel assemblies needed for this design was calculated to be 37. Once the total number of fuel assemblies required for the core was known, the actual core could be arranged. Reactor cores are designed to be axis-symmetric. Therefore, the core proposed for this design is as shown below in Figure 19.

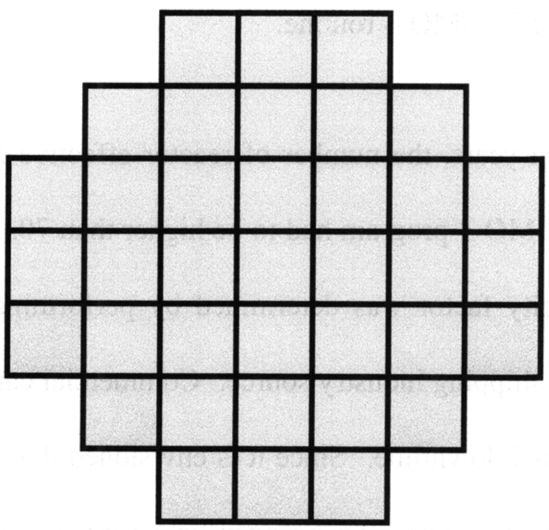

Figure 19: Proposed Concept of Core Design

In order to validate the early concept design for the reactor core, a computer program called CASMO-4 was used. CASMO-4 is a fuel assembly burn-up program. CASMO-4 is a multi-group two-dimensional transport theory code for burn-up calculations on BWR and PWR assemblies or simple pin cells. The code handles a geometry consisting of cylindrical fuel rods of varying composition in a square pitch array with allowance for fuel rods loaded with gadolinium, burnable absorber rods, cluster control rods, in-core instrument channels, water gaps, boron steel curtains, and cruciform control rods in the regions separating fuel assemblies(22).

The required input cards for CASMO-4 were varied in order to produce the maximum core-life possible with the highest PDE, within the constraints imposed by the required periodicity of ship classification society inspections. As stated earlier, it was the entering desire to have a core that would last for either five or ten years. The ultimate computer model used for CASMO-4 and the final output can be viewed in Appendix A.

Bo Feng, a PhD candidate from the Department of Nuclear Science and Engineering, provided assistance in the development of the CASMO-4 routine.

In order to achieve a core life of ten years, the number of reactor effective full power hours (EFPH) determined by the CASMO-4 program had to be higher than 70,000 EFPH. Note that this value for the capacity factor was determined by performing a conservative analysis on data provided by a shipping industry source. Commercial cargo ships operate continuously, with very minimal downtime. Since it is envisioned that the reactor will operate at close to maximum power rating during open-ocean transits, and then at reduced power during piloting and while in port offloading and onloading cargo, the 80% value used in this analysis is a solid estimate.

This value of ten years for the core lifetime was arrived at as shown below:

$$Core\ Life = \left(\frac{Number\ of\ EFPH}{Capacity\ Factor}\middle|\frac{Year}{8760\ hours}\right) = \left(\frac{70{,}000\ EFPH}{0.8}\middle|\frac{Year}{8760\ hours}\right)$$

$$= 10\ years$$

The CASMO-4 output results clearly shows that a ten year core life is possible with a capacity factor of 80%. This conclusion was made after a careful review of the pertinent output results from CASMO-4. Specifically, by reviewing the generated values for K-infinity and ensuring that its value never dropped below the critical value, we are sure that the reactor will be capable of being critical for its entire design life. K-infinity, the infinite multiplication factor, is defined as the ratio of the neutrons produced by fission in one generation to the number of neutrons lost through absorption in the preceding generation(23). It is defined mathematically by Equation 4 below:

$$K_{\infty} = \frac{neutron\ production\ from\ fission\ in\ one\ generation}{neutron\ absorption\ in\ the\ preceding\ generation} \qquad \textbf{Equation 4}$$

In order for a nuclear reactor to maintain criticality, at least one neutron from fission in the previous generation must go on to produce a fission event in the next generation. What K-infinity does not take into account is the effect of neutrons leaking out of the core. Therefore, another parameter known as the effective multiplication factor (K_{eff}) must be determined. K_{eff} is defined mathematically below in Equation 5.

$$K_{eff} = K_{\infty} £_{th} £_{f} \qquad \textbf{Equation 5}$$

Where: $£_{th}$ is the thermal neutron non-leakage probability
$£_{f}$ is the fast neutron non-leakage probability

In order for a nuclear reactor to be capable of sustained operations, K_{eff} must be greater than one. However, CASMO-4 outputs the value of K_{inf} that it determines will be required to have a value for K_{eff} that is equal to one. A typical value of neutron leakage from a large reactor is approximately 3%. More neutrons leak from a smaller core than they do from a larger core. For conservatism, the assumption was made that our reactor should be able to sustain 10% neutron leakage. Therefore, in order to account for this neutron leakage, the critical value needed for K_{inf} at the end of core life was determined to be 1.10. A plot of the end of core life value of K_{inf} taken from CASMO-4 versus the percentage of Uranium-235 enrichment is shown below in Figure 20.

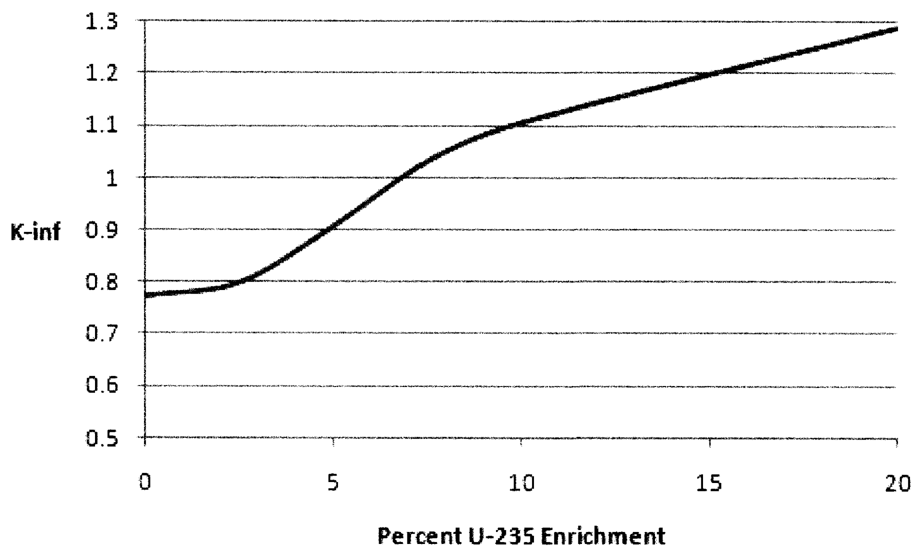

Figure 20: Graph of the Infinite Multiplication Factor vs. U-235 Percent Enrichment

Figure 20 clearly shows that the proposed reactor core will be sufficient at a Uranium-235 enrichment level of 10%.

3.2.3 Basic Concept of Reactor Operations

The general concept of reactor operations is based on that employed in a commercial power reactor. Namely, it is desired to operate the reactor at as close to the maximum rated power level as possible while seeking to minimize power transients. This will likely be possible only during the open-ocean transit between the two ports-of-call.

3.2.4 Refueling

Since the reactor is designed to have a ten-year core lifetime, it will only be necessary to refuel the core once. Therefore, unlike for a commercial nuclear power reactor that requires refueling about every eighteen months, no special refueling systems were incorporated into the design. It is envisioned that the reactor will be refueled using technology that already exists. The general refueling plan is quite simple and is as follows:

1. Disconnect the control rods and their drive mechanisms.
2. Remove the reactor vessel head from the reactor vessel.
3. Install extension sleeve on top of the reactor vessel.
4. Remove reactor internals.
5. Install lead-lined handling casket on top of extension sleeve.
6. Open the coffin.
7. Lift spent fuel elements one at a time into the handling casket.
8. Close the casket.
9. Lift casket off of reactor vessel and transfer it to the location where the spent fuel is going to be stored.
10. Unload fuel from casket into the transfer storage cart.
11. Repeat steps 6 through 9 until all spent fuel assemblies have been removed.
12. Inspect reactor internals and make repairs as needed.
13. Install new fuel elements into the reactor.
14. Install reactor internals.
15. Remove extension sleeve.
16. Install reactor vessel head and reconnect control rods and their drive mechanisms(15).

Obviously, each step mentioned above requires an extensive amount of planning and work. However, refueling is a process that certain American shipyards, such as Northrop Grumman Newport News, are familiar with and fairly proficient at. Therefore, the author of this thesis believes that the refueling of the reactor will not be an overly taxing evolution in the life of the ship.

3.3 Propulsion Plant Selection

In order to select the machinery needed to propel the ship, a careful analysis of the various propulsion systems and their associated configurations was conducted. This was an important analysis because even in modern ships, propulsion systems are so large and heavy that in many applications they force the rest of the ship to be constructed around them. Machine sizes and their locations also reduce the space available for cargo(24). Putting in the right configuration is vital to maximizing economic profitability. Therefore, in order to propel the ship, three separate propulsion configurations were researched and evaluated.

The first type of configuration analyzed was the direct drive configuration. In the direct drive configuration, the prime mover is directly coupled through a shaft to the propulsor. This is the current configuration that exists on the Emma Maersk, and is the configuration that exists on the majority of large conventionally-powered cargo ships. This configuration has the obvious advantage of minimizing the number of pieces of equipment in the propulsion train, as well as offering fairly high efficiencies when compared to other propulsion configurations. However, it would not be compatible with a nuclear reactor unless the propulsion turbine had an excessive amount of stages in order to reduce its speed to that compatible with the propulsor. For this reason, direct drive systems were not considered for further analysis in this project.

The second configuration investigated was the standard gear-driven assembly configuration. An example of this type of propulsion train can be seen below in Figure 21(25).

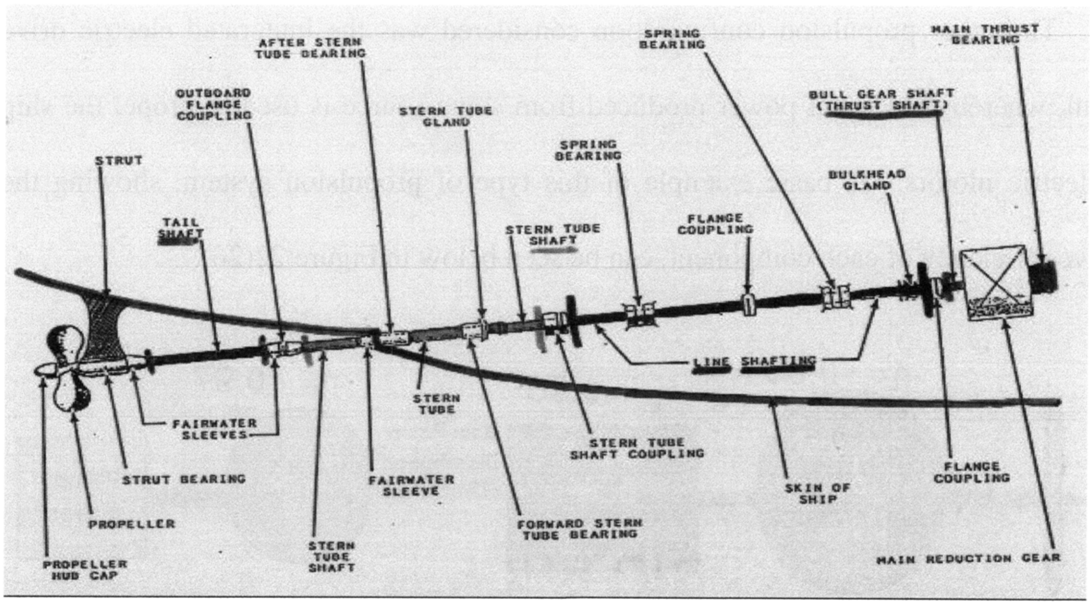

Figure 21: Standard Propulsion Train

The prime mover, a steam turbine for the case of a nuclear-powered vessel, would be connected directly forward of the main reduction gear. The high rotational speed of the steam turbine gets reduced to the lower rotational speed required by the propulsor. This propulsion configuration has been used for many years and is extremely reliable and is generally very efficient. From the figure, one can see that the propeller would ultimately be driven by a shaft that is directly coupled to the reduction gears via several other shaft line components. The major disadvantage of this type of arrangement is that it takes up a large amount of space and also requires the complete straight line alignment of the shaft in order to propel the ship through the water. For the Emma Maersk nuclear variant of this project, the standard main engine configuration would consist of separate main engine turbines and their associated reduction gear and shaft line components. This configuration was not selected because of the weights associated with the configuration as well as the space lost as a result of the required shafting and associated shaft line components.

The other propulsion configuration considered was the integrated electric drive system, whereby electrical power produced from some source is used to propel the ship via electric motors. A basic example of this type of propulsion system, showing the relative efficiency of each component, can be seen below in Figure 22(26).

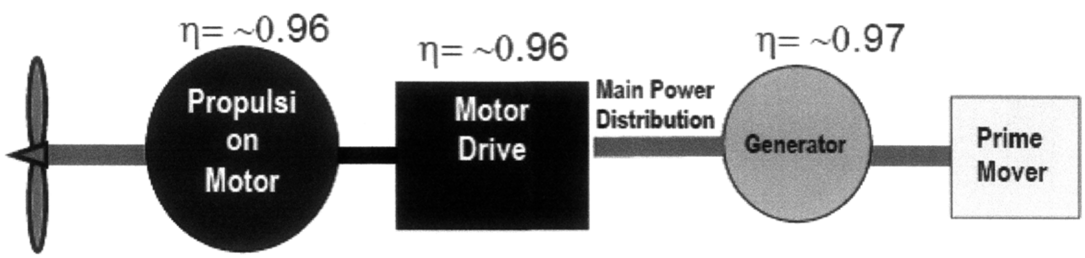

Figure 22: Simplified Electric Propulsion System

Similar to the other propulsion arrangement, this configuration has also been used for many years and is also highly efficient. However, the electric propulsion configuration offers the naval architect / ship designer almost unlimited flexibility in propulsion arrangement. This is because the large shaft line seen in Figure 21 is essentially eliminated and is replaced with power cable runs which are easily placed wherever necessary. The length of the shaft line is reduced significantly in electrical propulsion arrangements, and could even become zero if the decision was made later on to use a podded propulsor. Furthermore, the requirement to maintain strict alignment over very long lengths from the prime mover to the propeller is also eliminated. Another advantage of electrical propulsion systems is that they give the ship operators' much needed flexibility through the ability to only use the minimum amount of electricity generating equipment for their required operational need (24). Because of the better arrangeability given by the electric propulsion system, it is a superior system for this application. Ultimately, an integrated electric motor propulsion system was selected. This was also in keeping with the spirit of the original design philosophy. These electrical motors are coupled directly to a gearing system which in turn propels the ship through the water via the propellers. This decision proved advantageous for another reason, in that it enabled the elimination of steam turbines for propulsion. Instead, this design decision only requires steam turbines for electrical power generation. Granted these steam turbines, henceforth referred to as Ship's Service Turbine Generators (SSTGs), are now going to have to be larger than if they were only used to produce electrical power. However the elimination of turbines for propulsion reduces the overall footprint of the engineroom by eliminating additional turbine support systems.

After settling on the choice of propulsion system, it was then necessary to select the major components that were to be included in this design. First, it was necessary to see if there existed a suitable electric motor that would be able to propel a ship the size of the Emma Maersk Nuclear variant of this project. If a suitable motor was unable to be found, then the previous design decision would have to be re-evaluated. Currently there are few motors on the market that are capable of producing the required thrust needed for our ship. However, after significant research, a suitable motor was found. This motor, designed and manufactured by the American SuperConductor Company, is capable of producing 36.5 MW (48,927 SHP) of thrust to a propeller shaft. The specification for this motor, along with a picture of the motor relative to older propulsion motors is shown below in Figure 23.

SPECIFICATIONS	
Output:	36,500 kW
Speed:	0-120 rpm
Efficiency:	>97%
Pole Pairs:	8
Voltage:	6 kV
Stator Full Load Current:	1270 A rms
Weight:	<75 metric tons
Dimensions (l x w x h)	3.4m x 4.6m x 4.1m
Stator Cooling:	Liquid

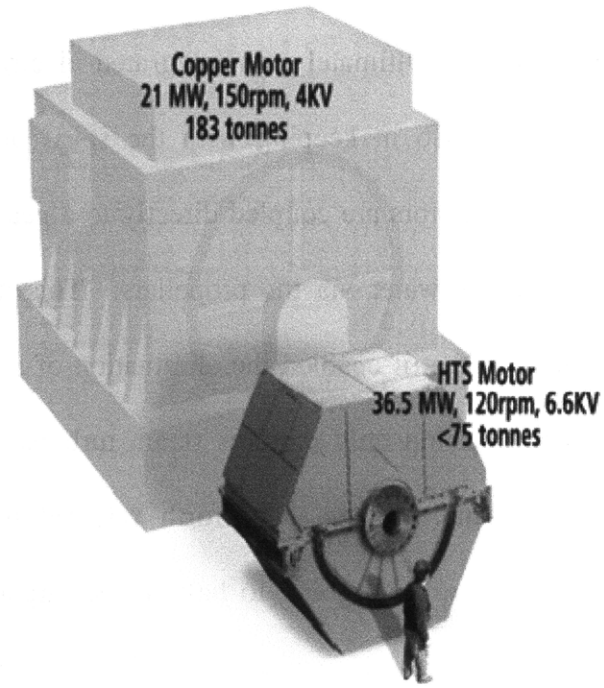

Figure 23: American Superconductor's HTS Propulsion Motor[7]

Since one motor can only produce about 50,000 SHP it was determined that two separate motors would be needed in order to produce the required shaft horsepower needed for the ship. There has been a significant amount of technological advancement in recent years in regards to high power ship propulsion motors. In the future, these motors will likely be more powerful than the ones chosen for this project. However, in keeping with the overall design philosophy of minimizing the risk to the shipowner, the decision was made to choose already-existing motors versus theoretical motors, even though it is likely that the latter will be available within the timeframe of this project. Since the choice was made to go with all electric propulsion, alternate sources of power had to be chosen as well. The general idea behind any component selection was to provide redundancy.

[7] http://www.amsc.com/products/motorsgenerators/shipPropulsion.html

With that in mind, Ship's Service Turbine Generators (SSTGs), and Auxiliary and Emergency Diesel Generator sets were subsequently selected based on the electrical powering requirements. A schematic of the proposed electrical distribution system for this ship is shown below in Figure 24. Information on the specific generator sets chosen can also be seen below in

Table 10.

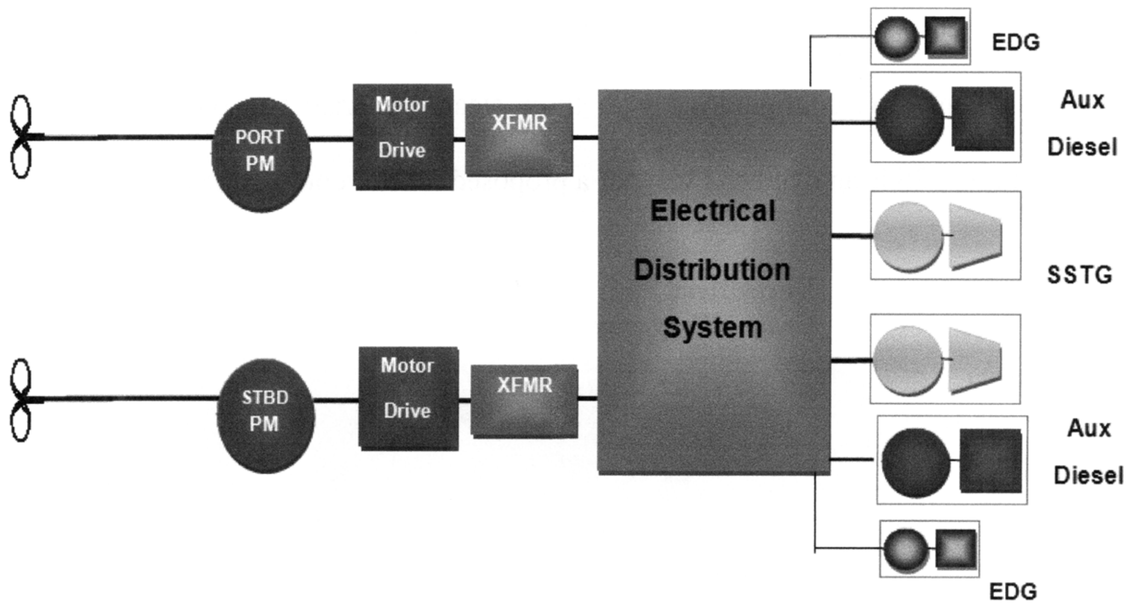

Figure 24: Proposed Electrical Distribution System

Type	Manufacturer	Model	Maximum Rating
SSTG	Siemens	SST-500	100 MW
ADG	Caterpillar	CAT 16CM43	14.4 MW
EDG	Caterpillar	CAT 3616C	2.5 MW

Table 10: Electrical Distribution System Specifics

The specific diesel generator models selected for this project were so chosen because the Caterpillar Corporation has a proven history of manufacturing diesel generators for the United States Navy. Therefore, it is reasonable to assume that they have the technical know-how to modify their components for seagoing vessels.

3.4 Reactor and Engineroom Location

Once the concept selection of the nuclear reactor and the propulsion plant was complete, attention was shifted towards determining the basic layout and location for these areas.

The ultimate design layout of the reactor compartment and containment portion envisioned for this project is very similar to the design proposed by Stroud and Sawyer. Based on the analysis of required core size and other component size restrictions, a three primary coolant loop configuration with three steam generators is proposed. Shown below in Figure 25 is an overhead view of a proposed reactor compartment (1).

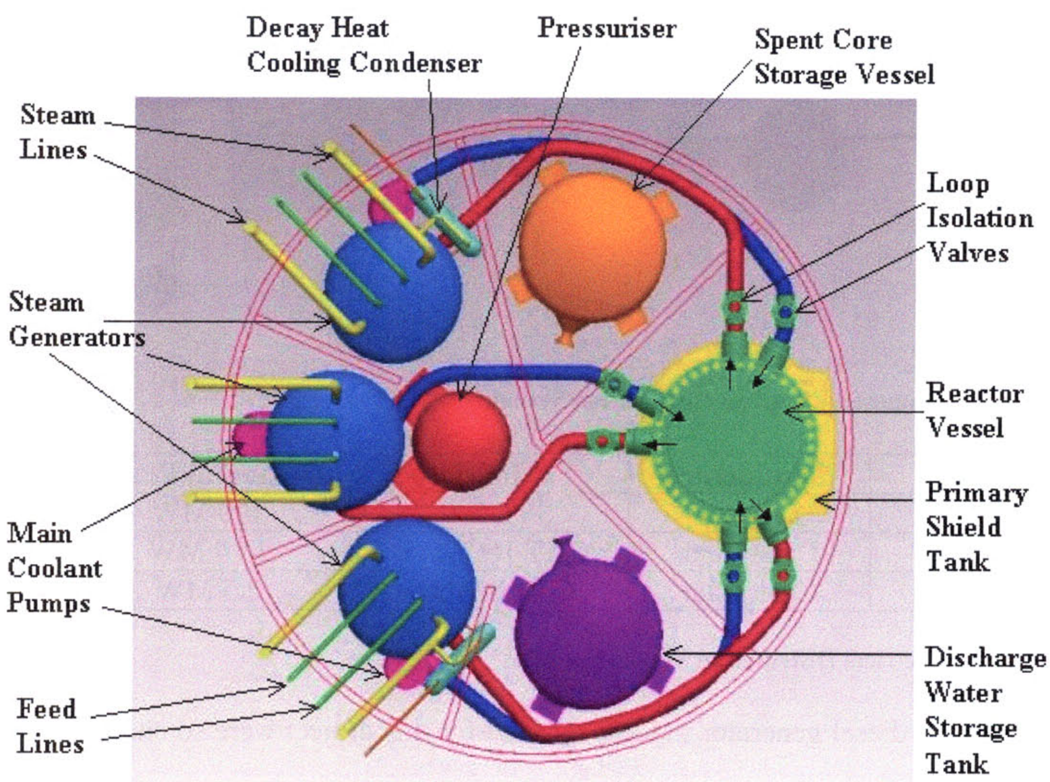

Figure 25: Overhead View of the Reactor Compartment

The entire reactor compartment is located in a portion of the ship that is known as the containment. The overall function of the containment, as its name implies, is to prevent the release of radiation to the environment. The containment serves as the final barrier before radioactivity would be released. Therefore, it is obvious that it is one of the most important structures that will be needed for the project. A generic containment vessel for a land-based power reactor alongside the containment of the ship-based reactor of the NS Savannah can be seen below in Figure 26 (27).

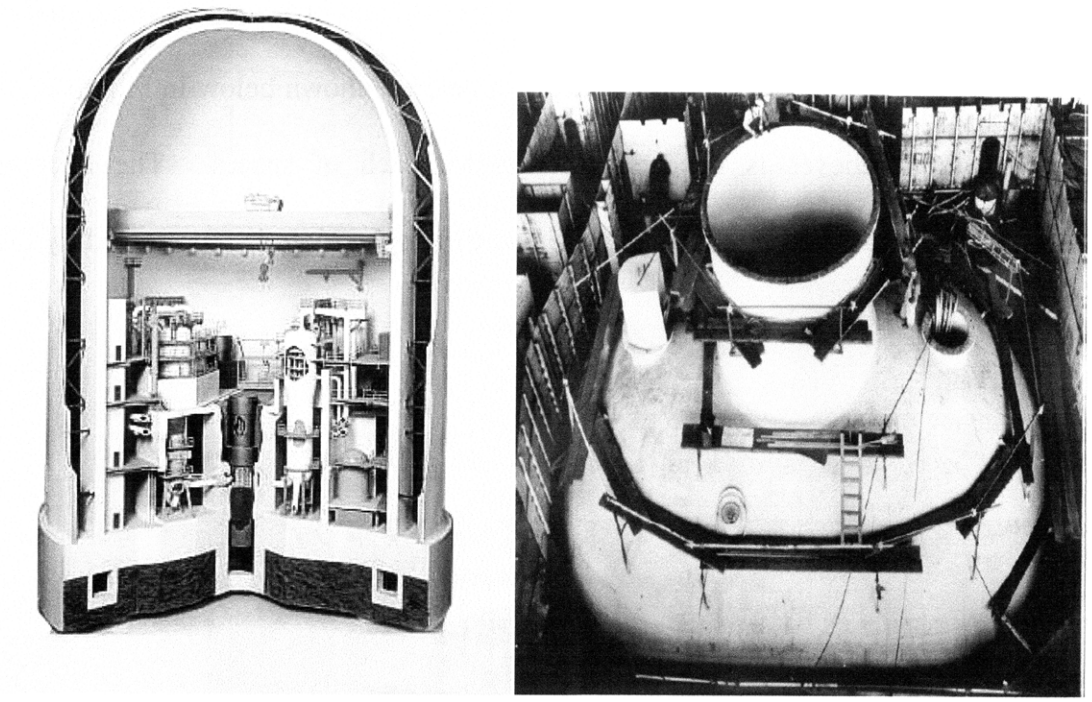

Figure 26: Typical Containment Vessel of a Land-Based Reactor and Ship-Based Reactor

In the event of a serious reactor accident, the containment will be counted on to withstand the pressures developed and prevent the release of fission products and radioactivity to the environment. Since the worst-case reactor accident would be a core meltdown, the final containment of the nuclear-powered variant is envisioned to be built with a core-catcher as part of the design. A core-catcher will prevent the nuclear reactor from melting through the hull of the ship, thereby eliminating the possibility of extensive environmental damage in the unlikely event of a reactor accident.

Next, it was necessary to pick suitable locations for reactor and propulsion spaces. In order to do this, the proposed engineroom volume and reactor compartment volume had to be determined. As mentioned previously, the Maersk Company was unwilling to provide detailed engineering related information in regards to any of its ships. Therefore, these volumes had to be estimated. This estimate was performed using the TEU layout drawing previously shown in Figure 10 as a reference. Actual placement of these spaces is a very important step, as will be discussed more below. Shown below in Figure 27 is where the author believes is the best location for each of spaces. The Reactor Compartment is represented by the red square and the Engineroom is represented by the green square.

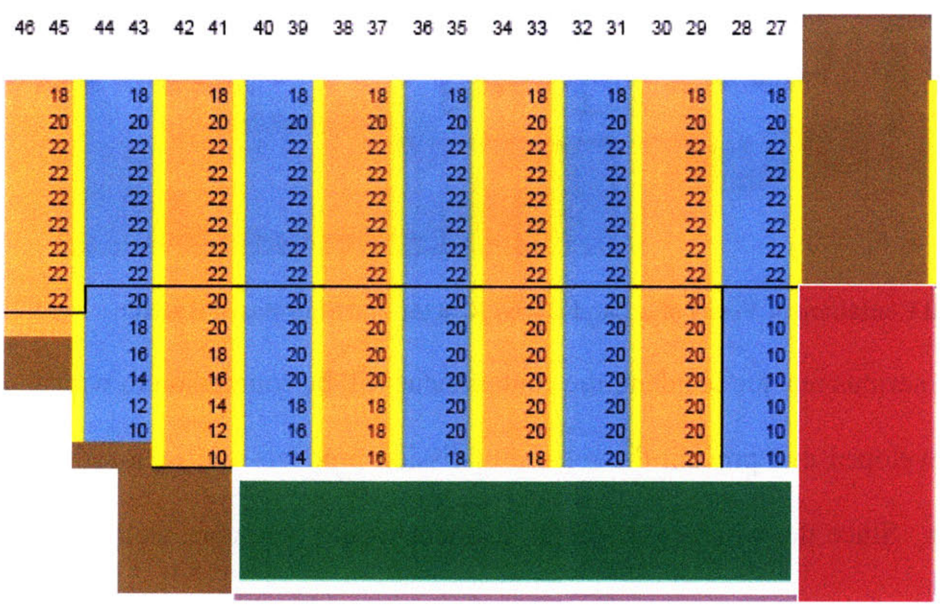

Figure 27: Estimated Engineroom Volume

The dimensions of the reactor compartment and containment space are as follows:

Length = 60 ft
Width = 180 ft
Height = 98.42 ft

Using the dimensions listed above, the proposed reactor compartment and containment volume of this ship is estimated to be approximately 1,062,936 ft^3. Likewise, the following dimensions were assumed for the determination of the engineroom volume calculation:

Length = 280 ft
Width = 180 ft
Height = 35 ft

Using the dimensions listed estimated above, the proposed engineroom volume of this ship is estimated to be approximately 1,713,000 ft^3. This area has the capacity to have four separate decks for the arrangement of equipment. This area provides more than enough space to house all the equipment and systems that will be necessary for the nuclear variant. This estimate was made based on an assumption of the location and length of the engineroom and the known beam and draft of the ship.

It is important to note that the proposed placement of the reactor is very close to the amidships position of the ship. This is advantageous for several reasons. First, this area is one of the safest locations on the ship in regards to collisions and groundings. Second, the amidships position is the strongest position structurally on the ship. Bending moments produced by the weight of the reactor are minimized by putting the reactor here(15). It is also important to note that the placement of the engineroom in the location selected results in the elimination of an estimated 220 equivalent TEUs. Therefore, using the AXS-Alphaliner estimate previously discussed in Section 2.3 as the basis, the cargo carrying capacity of the nuclear-powered variant is reduced from 15,212 TEUs to 14,998 TEUs.

For comparison purposes, the relative location of the containment and machinery space of the NS Savannah is shown below in Figure 28(28). The choice of location for the Engineroom and Containment of the Emma Maersk nuclear-powered variant is consistent with this proven design.

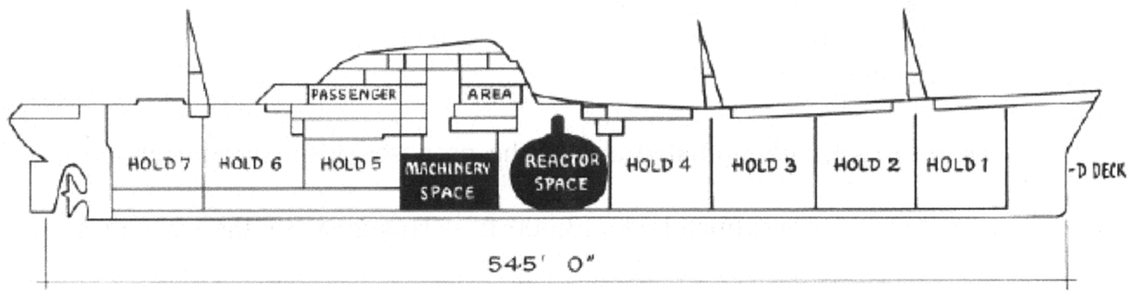

Figure 28: Location of Containment and Machinery Space on the NS Savannah

3.5 Licensing

In order for a nuclear reactor to be able to operate in the United States, it must be licensed by the Nuclear Regulatory Commission (NRC). The NS Savannah's nuclear reactor was licensed by the Atomic Energy Commission, the precursor organization to the modern day NRC. The documentation used by AEC to license the NS Savannah is outdated and is not sufficient to allow for the operation of a new nuclear-powered cargo vessel. The licensing of the nuclear reactor presents a problem. This is because there are currently no worldwide commercial cargo ships that are nuclear-powered. So the question arises as to who will license the reactor and who will provide the oversight. Even if we make the assumption that the reactor will be licensed in the United States, we are still left with the question as to what happens to the ship once it reaches international waters. Given that a cargo ship will operate in international waters, and subsequently make port calls all over the world, it is hard to determine how many nuclear regulating bodies will actually be involved. The World Nuclear Association lists thirty-five nuclear regulatory bodies that currently exist worldwide (29). This is perhaps the greatest single issue that needs to be overcome in order to operate a single nuclear-powered cargo vessel or a fleet of nuclear-powered cargo ships.

In addition to the licensing of the nuclear reactor, in order for a ship to sail and subsequently be permitted to enter foreign ports, it must be approved by one of the classification societies that currently exist. The major class organization that exists in the United States is the American Bureau of Shipping (ABS). The ABS was the classification society which granted class status to the NS Savannah, so they already have some documentation dealing with nuclear-powered cargo vessels. Unlike for the case of reactor licensing, classification by any one of the major classification societies of the world is generally sufficient for a merchant vessel to go anywhere it wants to go in the world.

3.5.1 Licensing via the NRC

The standard procedure for a new nuclear reactor to be licensed by the NRC is not a fast process. It is governed by 10 CFR Part 50 and 10 CFR Part 52 of United States Code. It takes on average about 12 years for a new reactor design to be certified, given permission to build on a specific site, and then be certified to operate. The general approval steps and timeline is shown below in Figure 29.

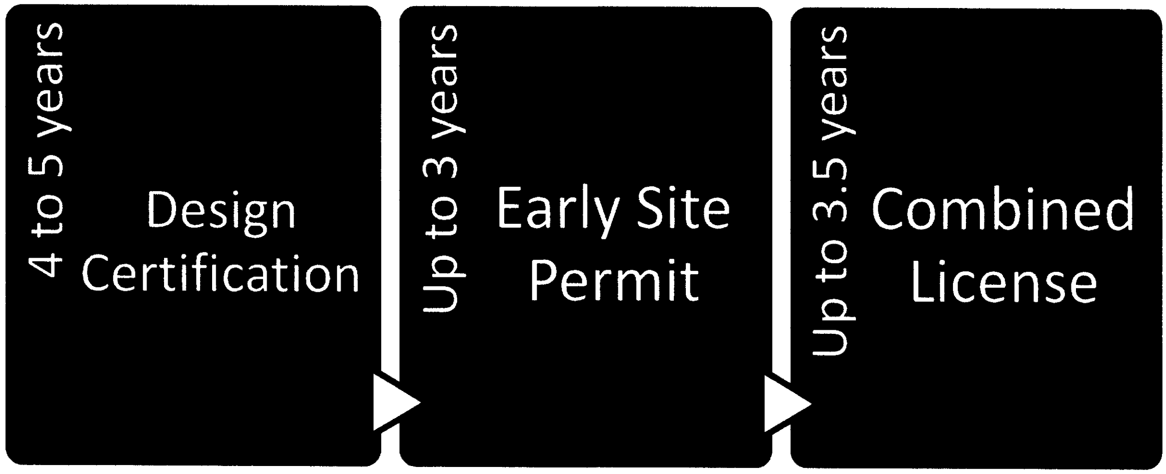

Figure 29: Typical NRC Approval Steps and Timeline

The first part of the NRC licensing process is the Design Certification phase. The reviews conducted during the Design Certification phase ensure that any new nuclear reactor design meets the safety requirements of the NRC. There is a public hearing that is a part of this phase. The second part of the NRC licensing process is the Early Site Permit phase. During this phase, there are several safety and environmental reviews. Essentially, this phase determines whether a proposed location is suitable to support a nuclear power plant. The applicant is required to submit an environmental impact statement during this phase of the process. As in the case of the design certification phase, there are public hearings which are a part of this phase. The third and final phase of the NRC licensing process is the Combined License phase. The Combined License phase determines whether building a specific reactor design at a specific site meets all the requirements delineated by the NRC. Approval in this phase actually authorizes construction of the reactor and allows for it to be operated after construction (38).

By considering that a ship is not a stationary object, one can see where the problem of licensing the reactor under the current framework gets difficult. Current NRC regulations are not sufficient to grant an operating license to an ocean-going vessel. In order to overcome this significant issue, regulations will have to be changed. By law, the NRC only licenses nuclear reactors that operate in the United States. So, if our ship were to stay within the waters of the United States, there would not be a licensing issue. However, when the nuclear-powered vessel sails into international waters is when the problems arise. Edward Baker, the Director of Advanced Reactor Programs within the Office of New Reactors of the NRC adamantly stated in a telephone interview that the oversight of a nuclear reactor operating in international waters is currently not within the jurisdiction of the NRC, even if the reactor itself had been licensed by the NRC. Overcoming this issue would require a change in the legislation that governs the NRC, or the development of an international maritime agency that would provide oversight of nuclear reactors that are installed on commercial ships. Neither of these options is likely to be welcomed by the maritime industry.

Another problem is that the NRC is likely to take significantly longer to approve a shipboard nuclear reactor then the estimated 12 years it takes to approve a new reactor design for a land-based plant. There are several reasons for this. First, a nuclear reactor used on a ship is fundamentally different from a commercial nuclear reactor used to produce electrical power. For example, a commercial nuclear reactor is typically operated at or near 100% power capacity all the time, with minimal power transients. A shipboard reactor has to be capable of operating over a wide range of power levels, especially during the ingress and egress to ports. Rapid power transients can also be anticipated as the ship is transiting close to land. Once on the open ocean, a shipboard reactor will essentially be the same as a commercial reactor, operating at maximum capacity in order to propel the ship at its top speed to the next port. A shipboard nuclear reactor has to be more robust in its design then a land based nuclear reactor.

The shipowner will be the entity that applies for a license. In the case of the NS Savannah, the reactor was licensed by the Atomic Energy Commission, which was the precursor organization to the modern day NRC. The shipowner was granted the license, and the shipowner in turn contracted out for the operators of the reactor. There were two separate companies which were responsible for the operation of the NS Savannah. It is the opinion of this author that that is how a future nuclear powered ship should be manned. There should be a company that is contracted to provide operator training and subsequently licensed reactor operators that will operate and maintain the nuclear reactor that is on the ship. This will help alleviate the risk undertaken by the shipowner.

The United States Navy has an organization known as Naval Reactors that has comprehensive responsibility for the design and safe operation of all the nuclear reactors that are on naval vessels. Naval Reactors also oversees the training of all nuclear operators in the navy. Naval Reactors falls under the United States Department of Energy and is the sole entity that "licenses" a naval vessel to operate its nuclear reactor. If nuclear-powered commercial shipping is to become a reality, an organization such as this will need to be established for the commercial shipping world. This organization could be another department within the NRC itself, or could be another separate organization altogether under the Department of Energy.

In an effort to facilitate a marine nuclear propelled ship, alternate solutions to the current process should be considered. One such alternate solution to the licensing issue is to create a new licensing organization that could be totally dedicated to nuclear merchant ships. As mentioned above, the United States Navy has its own nuclear agent known as Naval Reactors (NR). Naval Reactors was founded by Admiral Hyman G. Rickover in 1948. Naval Reactors is under the Department of Energy. If Naval Reactors were to initiate a civilian branch, the long licensing process of the NRC could be reduced. As was mentioned previously in this thesis, Naval Reactors have overseen the operation of sea-going nuclear reactors that have accumulated almost 6,000 reactor-years total operational time while steaming over 136 million miles without any significant reactor safety issues. Obviously, their designs are very robust and are beyond reproach when it comes to nuclear safety. If NR could be convinced to de-militarize their reactors, this could be extremely beneficial to the commercial nuclear shipping industry as well as the United States Navy as a whole. By de-militarization of a naval reactor the author means instead of having reactors that contain fuel that is highly enriched, the reactors would contain fuel that is only enriched to the maximum level permissible to a civilian firm of 20%, as well as removing some of the other redundant systems that are required for a vessel of war that would not be needed for a commercial cargo ship. The proposed solution would consist of the following:

1. Naval Reactors would establish a Civilian Reactors Branch that would be responsible for all aspects pertaining to a nuclear reactor on a commercial cargo ship.

2. Naval Reactors would sell to a commercial shipping company a safe, de-militarized reactor design that would be suitable for the powering and propulsion of its cargo vessel.
3. The shipping company would build their ship in a United States shipyard that is nuclear certified.
4. Naval Reactors would provide the necessary oversight of the reactor, just as they currently do for all nuclear-powered ships of the United States Navy.
5. The shipping company would sub-contract out to a firm the operations and maintenance of the nuclear reactor and its associated systems.
6. The nuclear power plant operating firm would have all their nuclear plant operators trained at the Naval Nuclear Power School in Goose Creek, South Carolina. The firm would be responsible for ensuring that each operator had the appropriate security clearance prior to them attending the training.

There are many benefits to this proposed solution to the United States Navy. First, if this solution were to be adopted, it would result in the broadening of the shipyard nuclear workforce that currently exists in the United States. Currently, the United States Navy builds new submarines in two different shipyards (Northrop Grumman Newport News in Newport News, Virginia and at Electric Boat in a combination of Groton, Connecticut and Quonset Point, Rhode Island). Both shipyards build about half of the submarine and the two halves are assembled after sailing the half from one of the shipyards to the other shipyard. This arrangement was set up to ensure that the industrial base and knowledge base that currently exists would not atrophy, so that in the future if it becomes necessary to build more nuclear-powered vessels, money will not have to be spent to revitalize the workforce. However, maintaining two shipyards that essentially do the same thing has resulted in new Virginia class submarines being extremely expensive. If one of the shipyards were to be able to maintain its nuclear proficiency doing other work, such as in the building a commercial nuclear-powered vessel, the cost of building submarines could drop significantly. Another advantage to doing this would be that it would generate revenue for the United States Navy as a whole, revenue that could be spent building more warships or aircraft or maintain the current fleet of warships and aircraft. The reactor design would be sold to the shipping company. The firm responsible for operations and maintenance would have to pay for the training and certification of its operators.

This proposed solution is advantageous to the shipowner seeking to develop a commercial nuclear-powered cargo vessel as well. Since a naval nuclear reactor has already been designed and operated, the design costs to the shipowner will be lower than if he has to pay a company to design a reactor for his ship from scratch. Further cost savings are realized when one considers the costs associated with the licensing process of the NRC. Furthermore, because of the outstanding safety record of naval nuclear reactors, the shipowner knows he is getting a robust and safe design that will propel his ship from port to port.

There are some disadvantages to this proposal. Naval Reactors would likely be unwilling to take on the burden of essentially being the regulatory body for civilian commercial nuclear-powered cargo ships without being forced to do it by Congress. Another disadvantage lies in the area of national security. Naval nuclear reactor technology is classified at the Confidential level as a minimum. It would likely be difficult for Naval Reactors to demilitarize a reactor to the point that it could be used by a civilian shipping company without potentially jeopardizing Naval Nuclear Propulsion Information (NNPI). Furthermore, the training that all operators receive is classified at the Confidential level. This proposal could be potentially infeasible in the interest of national security. However, this proposed solution does alleviate many of the licensing problems, and, based on the superb track record of naval reactors, would likely cause more countries to be willing to allow the nuclear-powered cargo ship to enter their ports.

It is important to note that this licensing concept is simply a proposed alternate solution to the licensing problem facing a commercial nuclear-powered cargo ship, as the author does not speak for the United States Navy or Naval Reactors.

Another alternate solution could involve any of the worldwide maritime organizations working in conjunction with a worldwide nuclear agency, like the International Atomic Energy Association. These organizations would be responsible for licensing and providing the oversight for reactors that are used on non-military nuclear-powered shipping vessels. This partnership is even more unlikely then the other proposed alternate solution, since there would have to exist many nuclear-powered cargo vessels to make such an organization cost effective. As there currently is not a large interest in nuclear-powered cargo vessels by the shipping industry, an organization like the one suggested would not be possible. It will not be until a significant majority of shipping is done via nuclear-powered cargo vessels that this solution would be viable.

3.5.2 Ship Classification via the ABS

Regardless of how the nuclear reactor is ultimately licensed, there does exist another aspect of "licensing" that is unique to ships. This "licensing" is known as classification. Classification of a ship consists of a representation of the level of compliance of a ship, vessel or offshore structure to the rules set up by a classification society. This is established following plan approval and surveys carried out by the society's experts, as provided for in the rules. Ship classification provides a point of reference on ship safety and reliability to shipbuilders, ship repairers, shipbrokers, charterers, Flag Administrations, insurers and the financial community. It is represented by a class, entered on classification certificates and transcribed in the register of ships published periodically by the society(30). Ships that do not have class status are not permitted to enter many foreign ports around the world. There are several classification societies that exist today. The major ship classifications societies in the world are the American Bureau of Shipping (ABS), Germanischer Lloyd, Det Norske Veritas, Llyod's Register, China Classification Society, Korean Register of Shipping and Bureau Veritas. If a ship has class status with one of the major classification societies, then it usually does not have any problems being allowed to enter foreign ports. There are other smaller class societies as well. For the purpose of this project, the assumption is made that the ship will be classed by The American Bureau of Shipping. ABS was responsible for the classification of the NS Savannah, and therefore already has a set of rules that exist for classing a nuclear-powered merchant vessel. These rules are summarized below(31).

A reactor must operate satisfactorily under the following conditions:

Vessel Accelerations: Vector sum of the maximum accelerations from heave, pitch and roll

Athwartships Accelerations: Same as Vessel Accelerations

Fore and Aft Accelerations: Not less then 1g

Roll Motion: 30 degrees to each side

Pitch Motion: 10 degrees up and down

Permanent List: 15 degrees to port or starboard

Permanent Trim: 5 degrees down by bow or stern

The reactor safety system must operate under the following conditions:

Roll Motion: 45 degrees to each side

Pitch Motion: 12 degrees up and down

Permanent List: 45 degrees to port or starboard

Permanent Trim: 10 degrees down by bow or stern

Classification societies mandate that ships be inspected at regular intervals during their service lives. Some of these inspections require that the ship be placed in a drydock in order to facilitate inspection of certain hull systems. These special survey drydocking inspections are usually conducted every five years, as was discussed previously. However, drydocking of the ship may still be required every 2.5 years.

The case of a nuclear-powered cargo vessel will be unique. In the case of a nuclear-powered cargo vessel, it will require that the classification society and the reactor licensing organization work together to ensure that a ship is in compliance with their specific rules. For example, a classification society requires surveyors to be on hand at various times during the construction of a vessel. The NRC also has inspectors on-site at various times during construction of nuclear reactors. For this reason, it will be necessary to ensure that there is agreement between regulating agencies in regards to construction techniques and processes. Also, the American Bureau of Shipping already has established rules for a shipboard nuclear reactor. This added level of bureaucracy will undoubtedly result in significant delays during the construction phase of the ship, as the two organizations agree on a common set of requirements.

4. ECONOMICS AND LOGISTICS

4.1 General Discussion

Shipping experts point out that all the previous attempts at operating a nuclear-powered commercial cargo ship were generally considered to have been unsuccessful in terms of economic profitability. That is why none of the previous nuclear-powered vessels actually operated for the duration of their design life. Upon closer inspection, however, the point can be made that these ships were not designed to be economically viable. For example, the NS Savannah was both a passenger vessel as well as a cargo ship. Space that would have been valuable for cargo was instead used for staterooms and other comforts for the ship's passengers. Supporters of the NS Savannah note that the ship was built with five goals in mind:

1. To demonstrate to the world the employment of nuclear power in an instrument of peace for the benefit of mankind.
2. To bring the power of the atom into the market places of the world in peaceful trade and commerce.
3. To enlighten the public to the fact that nuclear-powered ships are entirely dependable and safe.
4. To stimulate early solutions to such problems as international liability and indemnification, and to win acceptance for nuclear ships in the world's ports.

5. To give MARAD and the Atomic Energy Commission the opportunity to assess the possible contributions of nuclear power to the progress of the American Merchant Marine in providing shipping services on routes essential for maintaining the flow of the foreign commerce into the United States(25).

Obviously, none of these aforementioned goals were focused on making the ship an economic success. Therefore, it should not come as a surprise that the NS Savannah was not as economically successful as she could have been.

4.2 Logistical Assumptions

The economics of this project are what ultimately is going to determine the viability of a nuclear-powered cargo ship. Unlike the NS Savannah, this variant is being designed with the overall profitability to the shipowner as one of the primary objectives. In order to perform this analysis, three major assumptions had to be made concerning the logistics of the project. These assumptions are as follows:

1. The baseline nuclear ship is going to continue to be built in a foreign shipyard, such as the Odense Steel Shipyard where all other Emma Maersk class ships have been built. The author envisions some subtle differences between the baseline nuclear variant and the conventionally powered line of ships. The baseline nuclear ship consists of all the non-nuclear systems of the ship. It includes all the navigation equipment, all the cargo bays and associated cargo storage and handling equipment, the berthing spaces, the diesel engines, the fuel tanks for the auxiliary diesels and emergency diesel generators. It will also include the installation of the propulsion motors. It does not include the propulsion diesel or

any of the electrical diesels that are installed on the actual ship. The cost for this baseline ship is equal to the cost of the as-built Emma Maersk.

2. The nuclear reactor is going to be installed in the United States at one of the public shipyards. The most likely location is the Northrop Grumman shipyard in Newport News, Virginia (NGNN). NGNN is a nuclear-certified shipyard that has the facilities and the expertise within their workforce to get this task done. NGNN is where the United States Navy builds its nuclear-powered aircraft carriers.
3. The baseline nuclear ship will be towed to NGNN from Odense Steel Shipyard in order to facilitate the reactor plant installation. After the reactor plant is installed and subsequently tested, the nuclear variant will be ready to be put into service.

4.3 Economic Analysis

Determining actual costs is an extremely difficult task, especially for a project that has no real predecessor such as this one. Therefore, an economic model was developed that the author believes to be an accurate depiction of costs. The goal was to develop a model that would show the breakeven point in which the nuclear-powered variant was competitive with the conventionally-powered variant in terms of the Present Value (PV) of the lifecycle costs for each of the different ships. The PV for each cost was calculated using the equation 6 below:

$$NPV = \sum_{t=1}^{20} \frac{CE_t}{(1 + DR)^t} \qquad \text{Equation 6}$$

Where: t is the service year
CE_t is the cash expenditure at time t
DR is the discount rate

The discount rate was set equal to 10% for the entire economic analysis. In order to develop this economic model, two separate economic studies that dealt with nuclear-powered ships were extensively analyzed. The first economic study analyzed was conducted by Manalytics International in (1). This economic study was also for a nuclear-powered cargo vessel, so it seemed like the logical starting point. This study was conducted on a fleet of nuclear-powered cargo vessels and was based on a smaller ship (the OOCL Shenzhen) with a larger nuclear reactor. Their premise was a smaller fleet of nuclear-powered vessels traveling at a higher speed then a larger fleet of conventionally-powered vessels travelling at a slower speed.

The next economic study analyzed was conducted by the United States Navy. This study focused on the costs of putting nuclear reactors onboard surface combatant ships of various sizes compared to the costs of keeping those same ships conventionally-powered (32). Despite the fact that there are fundamental differences between military combatant vessels and commercial cargo ships, several aspects of the US Navy's study proved to be useful to this thesis. By marrying portions of this study with the previously discussed study, and then subsequently using sound engineering judgment, an improved economic model was developed for this thesis that allows for a suitable conclusion to be drawn. The model developed also was able to determine at what bunker fuel cost a nuclear-powered vessel would be more cost effective then a conventionally-powered vessel.

There are several economic similarities between the proposed nuclear-powered variant and the actual Emma Maersk. For example, the costs associated with Classification Society membership as well as for General Management and Administration are estimated to be the same. Also, the arrangement analysis clearly shows that both the nuclear-powered variant and the actual Emma Maersk have roughly the same estimated cargo-carrying capacity, so the profitability of each ship based on hauling cargo is roughly equivalent. The main difference in the economics comes from the actual day-to-day operations of the two different ships. The nuclear-powered variant has significantly higher upfront costs but lower actual operating costs while the actual Emma Maersk has a higher operating cost but lower upfront costs. A summary of all costing data is shown below in Table 11 and is discussed extensively is Sections 4.3.1, 4.3.2, and 4.3.3.

Costing Data	Nuclear-Powered Vessel	Emma Maersk
Ship Acquisition Cost	$1.2 billion	$145 million
Maintenance and Repair	$1.6 million per year $2 million every 5 years for turbine overhaul & reactor maintenance	$800,000 per year
Dry-docking/Class Inspections	$1.25M every 2.5 yrs. $1.75M every 5 yrs	$1.25M every 2.5 yrs $1.75M every 5 yrs
Fossil Fuel Burn Rate	4,000 metric tons/yr	350 metric tons/day
Nuclear Refueling	$115 million to replace Reactor Core	N/A
Spent Fuel Disposal	$3 million/yr beginning 10th year	N/A
Manning	$25,000 per day (35 crew)	$10,000 per day (20 crew)
Security	$3 million per year	$1 million per year
Insurance	1% of value of the vessel per year	1% of value of the vessel per year
Scrap Value	$20 million steel and copper	$10 million steel only
Decommissioning	$20 million	None
Slot Charter Expense Refueling/Dry-docking	$71.1 million per 5 year period	$19.5 million per 5 year period

Table 11: Costing Data

4.3.1 Acquisition Costs

The acquisition cost is the cost that the shipowner must pay in order to acquire the ship. For the actual Emma Maersk, this cost was easily obtainable from several sources. The Maersk company website lists this cost as $145M. The nuclear-powered variant's acquisition cost was not so easily determined. Using the information from (32), a nuclear premium of $1.05B was added to the initial baseline ship cost, bringing the total acquisition cost of the nuclear-powered variant to $1.2B. This costing number for the nuclear premium was derived from the nuclear premium of $800M taken from the US Navy study. However, the $800M premium was based on the fifth ship in a class of ships. Therefore, in order to determine the actual nuclear premium for the first ship in the class, as would be the case for our nuclear-powered variant, additional analysis was required. The US Navy uses a learning curve when determining costs. A typical learning curve is shown below in Figure 30 (33).

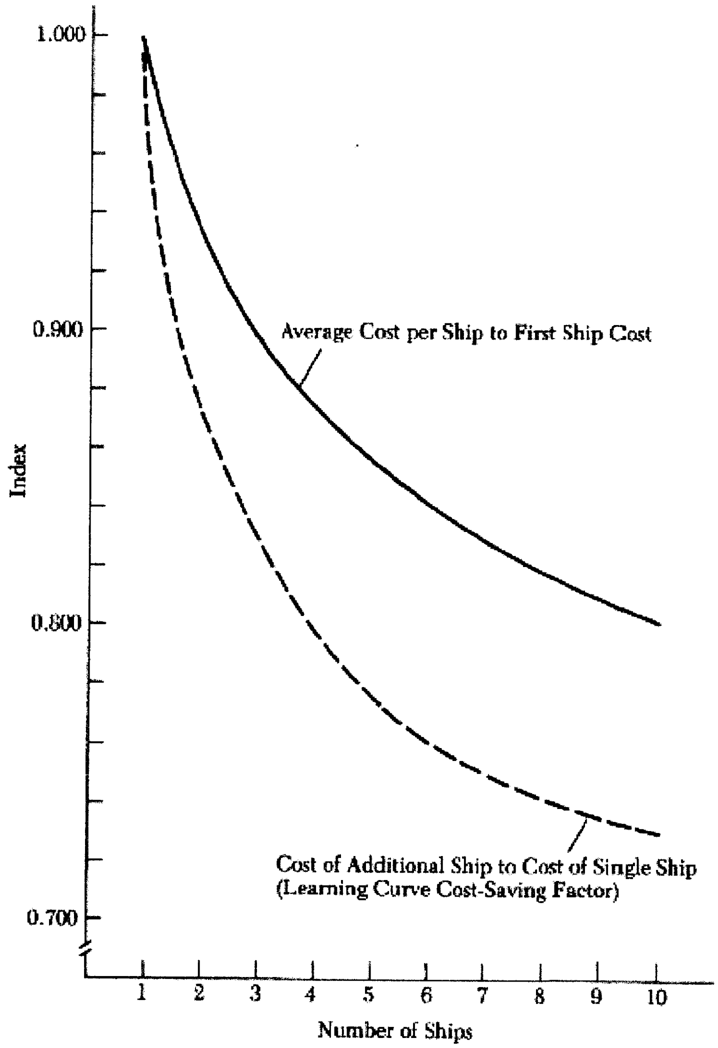

Figure 30: Example of a Learning Curve

As previously mentioned, one of the assumptions in (32) is that the costs reported are for the fifth ship in the class. So, in order to determine the first ship cost, it was necessary to back-out the savings associated with learning. This was accomplished by taking the nuclear premium of $800M and subsequently dividing it by the learning curve factor of

0.76 taken from Figure 30. After doing this, the final acquisition cost of the nuclear-powered variant was estimated to be \$1.2B.

Once the cost of the two variants had been determined, the assumption was made that this cost would be financed over the 20 year operational life of the ship. A yearly loan payment was subsequently determined based on level payments and a constant loan interest rate of 6%. The PV of the acquisition cost was then calculated using the yearly loan payment as the cash expenditure.

4.3.2 Marine Insurance

There are several different kinds of insurance that a commercial cargo ship is required to have. These categories of insurance include but are not limited to cargo insurance, hull and machinery insurance, freight insurance, and builder's risk insurance. For the purpose of this economic analysis, the total yearly insurance premium cost was calculated based on 1% of the value of the vessel. This was consistent with the economic analysis done by Manalytics in (1). The value of the vessel for each year was calculated using the straight-line depreciation method as shown below by Equations 7 and 8:

$$\boldsymbol{d} = \frac{(\boldsymbol{B}-\boldsymbol{BV_N})}{\boldsymbol{N}} \qquad \text{Equation 6}$$

$$\boldsymbol{BV_k} = \boldsymbol{B} - \boldsymbol{dk} \qquad \text{Equation 7}$$

Where:

d is annual depreciation deduction
N is the service life, and is equal to 20 years
B is the cost basis and is equal to the acquisition cost
BV_N is the salvage value at the end of service life
k is the deduction year $(1 \leq k \leq N)$
BV_k is the book value at the end of service year k

The salvage value at the end of the ship's service life (BV_N) was set equal to 10% of the initial acquisition cost. As mentioned above, the depreciation was calculated using he straight-line method. Both of these decisions were made after reviewing various tax codes.

Once the yearly book value (BV_k) was known for each vessel, the insurance premium for each year was calculated. Then, the PV of each of the yearly insurance premiums was determined.

4.3.3 Manning

The manning costs for each ship over the lifetime of each ship were calculated based on the numbers reported in Table 11. Then, the PV of each of the yearly manning costs was subsequently calculated for use in future analysis. It was estimated that the nuclear-powered variant would have 15 additional crew members over the conventionally-powered vessel. It was estimated that these crew members would be specially trained in reactor operations and therefore would rate a higher wage then the other crew.

It should be noted that the NS Savannah had significant issues in regards to crew pay. Just as suggested here, the NS Savannah's nuclear trained crew was allocated extra pay. However, the deck officers cited a maritime tradition which required them to receive more pay than the engineer officers. Ultimately, this dispute was settled by an arbitrator who ruled in favor of the deck officers. The arbitrator's decision caused the nuclear engineers to shut down the reactor and refuse to start it back up (5).

4.3.4 Other Lifecycle Costs

There are other costs that were used to estimate the final lifecycle costs for the nuclear-powered variant and the actual Emma Maersk. Again, the PV of each of these other lifecycle costs was subsequently calculated. These costs are as listed in Table 11.

4.3.5 Operational Costs

The operational costs associated with each ship essentially come from the burn rate of fuel used onboard the ship. In the case of the nuclear-powered variant, it was estimated that the ship will burn 4,000 metric tons of fuel each year. This estimate was consistent with the economic analysis conducted in (1). In the case of the actual Emma Maersk, the burn rate was estimated to be 350 metric tons per day. This value for the burn rate was interpolated from Figure 12, and subsequently validated by Eric Wilhelm in (34). The PV of the yearly operating fuel costs was subsequently calculated for the Final Cost Analysis.

4.4 Final Cost Analysis

4.4.1 Base-case Analysis

A summary of the PV of the various lifecycle costs, except for the operating expenses, are presented below in Table 12. A complete listing of the PV of the various lifecycle costs can be found in Appendix C for the nuclear-powered variant and Appendix D for the conventionally-powered variant. The operating expenses for the base-case vary with the cost per metric ton of the fuel. For the base-case analysis, the yearly cost of fuel was assumed to be constant over the operating life of the ship.

Costs	Nuclear-Powered Vessel	Emma Maersk
Ship Acquisition Cost	$895.3M	$109.9M
Insurance	$72.2M	$12.1M
Manning	$74.5M	$29.8M
Other Lifecycle Costs	$202.6	$48.8M

Table 12: Summary of the PV of Ship Lifecycle Costs

A careful review of all economic data reveals that the final lifecycle cost of the nuclear-powered variant is dominated by the acquisition cost of the ship while the final lifecycle cost of the Emma Maersk is dominated by the burn rate and the cost of bunker fuel. This is fairly obvious by looking at the slope of each line in Figure 31 below.

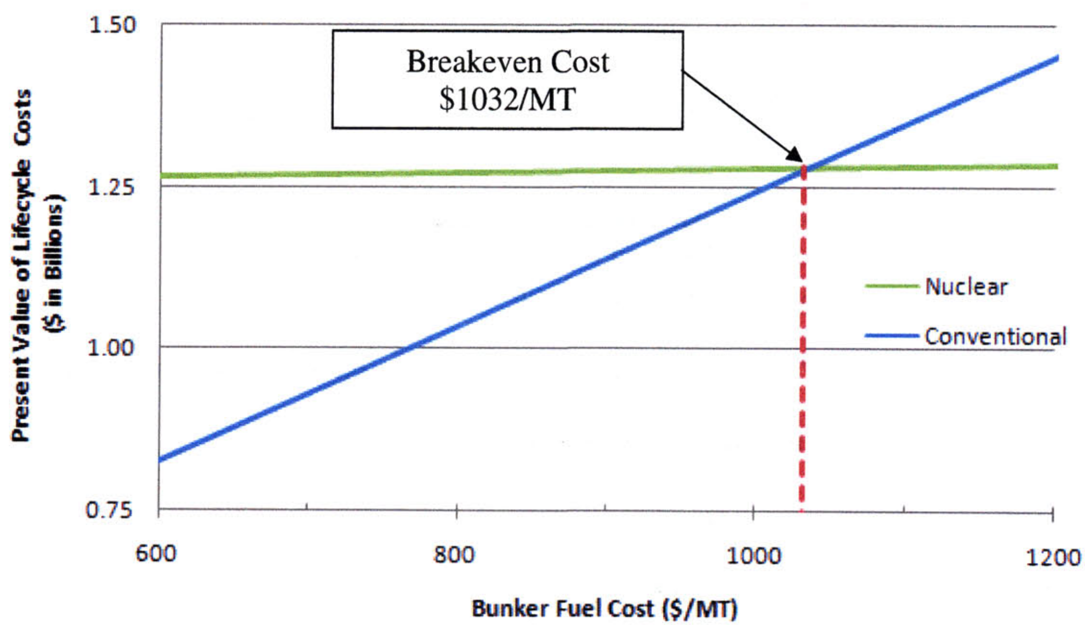

Figure 31: Net Present Value Lifecycle Cost Comparison

Figure 31 also shows that the breakeven cost at which the nuclear-powered variant becomes competitive with the non-nuclear variant is when the bunker fuel cost is approximately $1032 per metric ton. This corresponds to a cost of crude oil of approximately $206 / barrel. It should be noted that even during the summer of 2008 when bunker fuel prices reached their peak value, its cost of $590 per metric ton was still significantly less than the breakeven cost determined by this economic analysis.

4.5.2 Sensitivity Analysis

Sensitivity analysis is a technique for investigating the effect of changes in project variables on the base-case (35). In order to do the sensitivity analysis, several key variables affecting the lifecycle costs of the individual variants were determined. After estimating the most likely change in the key variables, the economic model was then run again and the corresponding results were evaluated. Then a Sensitivity Indicator Fraction was calculated as shown below in Equation 9.

$$SI = \frac{B_o - B_f}{B_o} \times 100\% \qquad \text{Equation 9}$$

Where:

SI is the sensitivity indicator fraction
B_o is the breakeven cost of the base-case model
B_f is the breakeven cost of the current model

A complete listing of the PV of the various lifecycle costs used for the sensitivity analysis can be found in Appendix E through Appendix G.

CASE ONE

The first variable investigated was the yearly cost of fuel. As stated above, the base-case assumed that the yearly cost of fuel was constant over the life of the ship. A regression analysis conducted on the bunker fuel costing data depicted in Figure 2 shows that the cost of fuel has been increasing at a rate of approximately 5% per year since 2001. So, an additional analysis was conducted assuming that the yearly fuel cost increased by 5%. The result of this analysis is shown below in Figure 32.

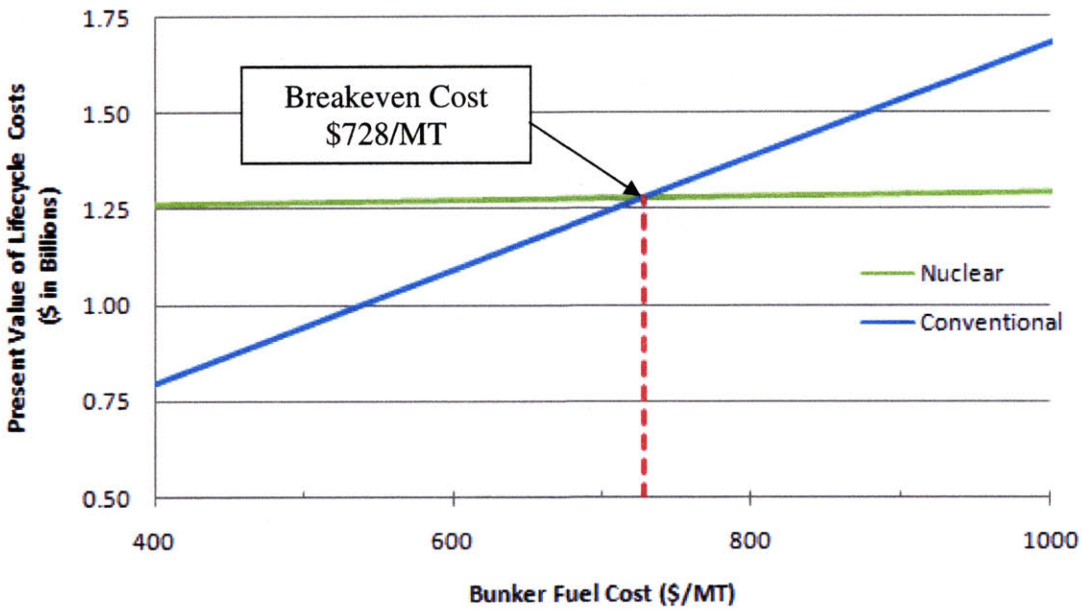

Figure 32: PV Lifecycle Cost Comparison Assuming a 5% Increase in Fuel Costs

Figure 32 clearly shows that the breakeven cost has decreased from $1032/MT to $728/MT. This results in a SI value of 29.45%. Qualitatively, this analysis shows that as the yearly cost of fuel increases, the breakeven cost decreases.

CASE TWO

The second analysis was conducted on the acquisition cost of the nuclear-powered variant. I wanted to examine the effect on the breakeven cost if the government offered a subsidy on the cost of the nuclear reactor to a shipowner in order to get him to purchase the nuclear-powered variant. Two subsidies, one at a level equal to 25% of the cost of the reactor and the other at a level equal to 50% of the cost of the nuclear reactor were analyzed. The result of this analysis is shown below in Figure 33.

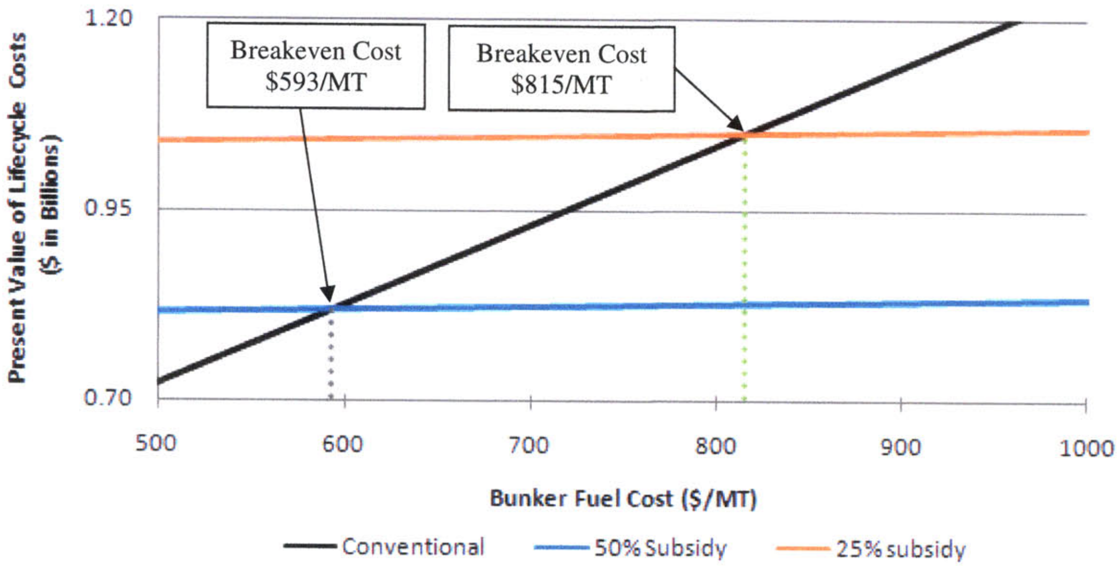

Figure 33: PV of Lifecycle Costs Assuming a Government Subsidy

Figure 33 clearly shows that the breakeven cost has decreased to $593/MT if the government offers a 50% subsidy on the cost of the nuclear reactor, and to $815/MT if the government gives a 25% subsidy on the cost of the nuclear reactor. This results in a SI value of 68.7% for the 50% subsidy and a SI value of 21.02% for the 25% subsidy. Qualitatively, this analysis shows that as government subsidy levels increases, the breakeven cost decreases.

CASE THREE

The third analysis was also conducted on the acquisition cost of the nuclear-powered variant. I wanted to examine the effect on the breakeven cost if the government were to guarantee the loan needed to purchase the nuclear-powered variant. This would allow for the shipowner to get a loan at a lower interest rate than would otherwise be possible. For the purpose of this analysis, the assumption was made that the interest rate would be reduced from 6% to 3%. The result of this analysis is shown below in Figure 34.

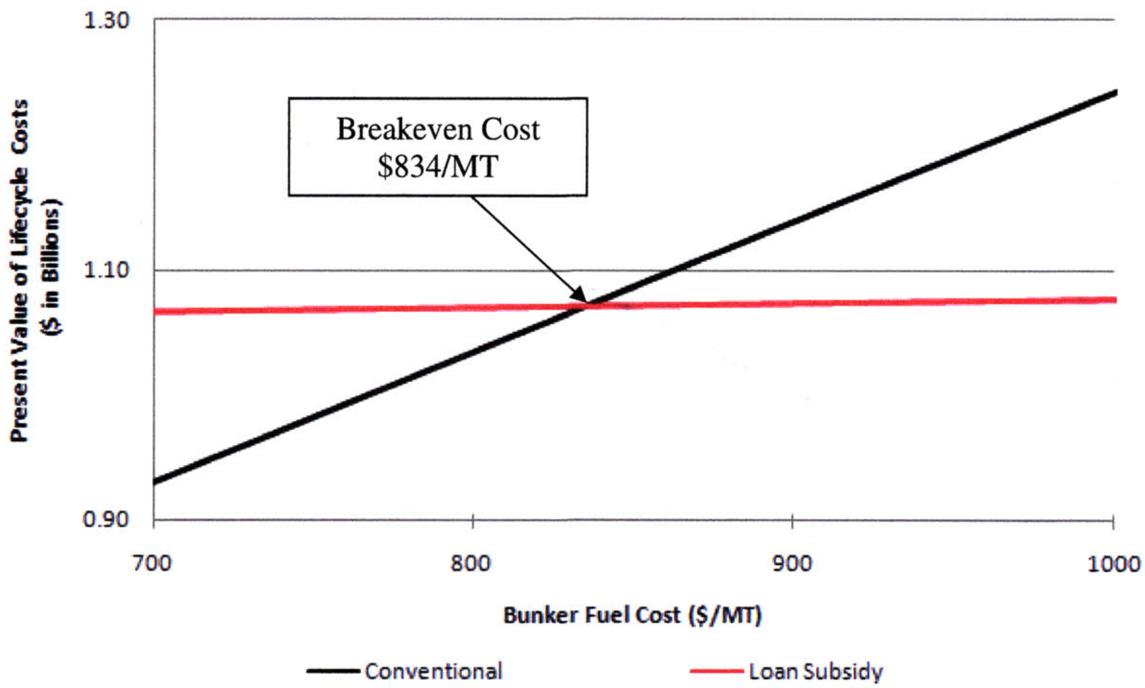

Figure 34: PV of Lifecycle Costs Assuming a Government Loan Subsidy

Figure 34 shows that the breakeven cost has decreased from $1032/MT to $834/MT if the government offers a loan guarantee to the nuclear shipowner. This results in a SI value of 19.18%. Qualitatively, this analysis shows that as government loan subsidy levels increase, the breakeven cost decreases.

CASE FOUR

A fourth case is probably the most likely. It is possible that both the cost of fuel will continue to increase each year and that the government could provide some sort of subsidy to promote nuclear-powered shipping. For this analysis, a 5% yearly increase in the cost of fuel was assumed along with a government subsidy similar to the ones previously analyzed for. The results of this analysis can be seen below in Figure 35.

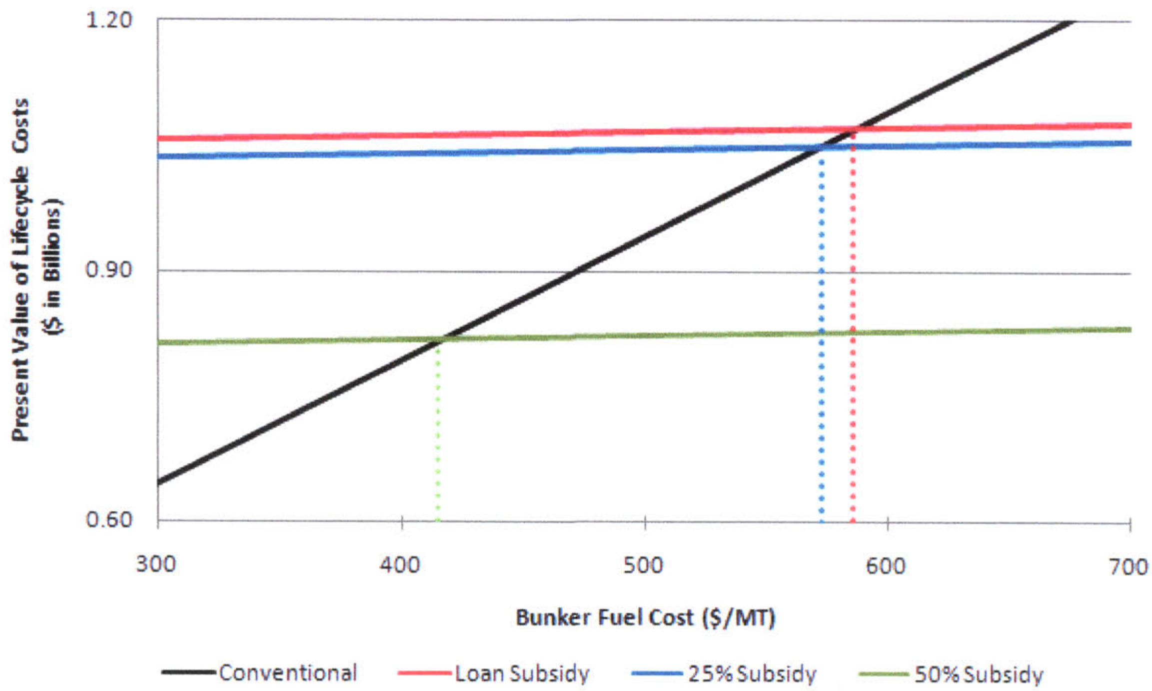

Figure 35: PV of Lifecycle Costs Assuming a Subsidy and Increasing Fuel Costs

Figure 35 clearly shows that the breakeven costs for this case are lower than for any other single case. The breakeven cost for the 50% government subsidy is now $415/MT, while the breakeven costs for the 25% government subsidy and the loan subsidy are now $573/MT and $586/MT respectively.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The ultimate result of this research is that nuclear-powered commercial cargo ships are technically feasible. This conclusion is nothing new, as there have been four such cargo vessels built and operated prior to this study. However, what this thesis has done is to identify the licensing issues, classification society issues, and construction issues and to provide some proposed solutions to these problems. This thesis has also shown that the financial aspects of a nuclear-powered cargo vessel are too difficult to be overcome without government intervention. This government intervention could come in the form of the subsidies already discussed in Section 4.5.2 of this thesis, or could come in the form of environmental legislation. The United States Environmental Protection Agency recently proposed legislation to the United Nation's International Maritime Organization that, if approved, would require ships to burn low sulfur fuel when operating within 230 miles of United States' coastline (36). The cost of low sulfur marine fuel at the Port of Los Angeles is shown below in Figure 36 (37). These fuel prices represent a 40% increase over the conventional fuel price.

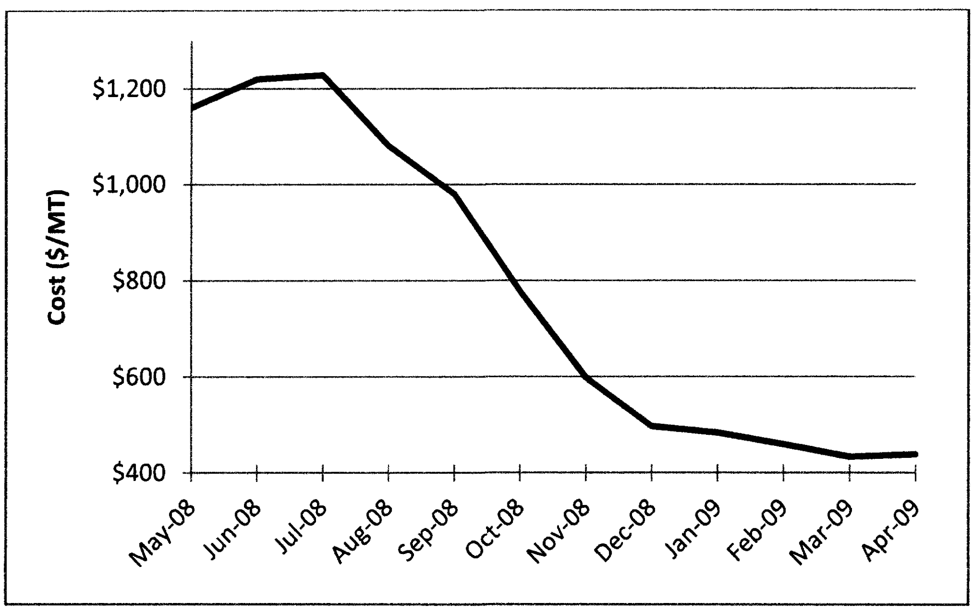

Figure 36: Cost of Fuel with a Low Sulfur Content at the Port of Los Angeles

Therefore, this legislation would have the effect of increasing the cost of fuel to conventional shipowners and would help make the nuclear-powered variant more attractive. If other nations were to follow suit on this type of legislation and require ships to burn low sulfur fuel, nuclear-powered cargo ships could potentially become competitive instantly.

It is the conclusion of this research that nuclear-powered cargo vessels are still too expensive in the short-term to compete financially with conventionally-powered cargo vessels despite the rising costs of conventional fuels and the additional costs associated with forced compliance of local port clean air initiatives. During the timeframe of this project there has been a large amount of volatility in the cost of fuel oil, rising to all-time high levels and subsequently dropping back to "normal" levels. A closer look at Figure 2 indicates just how volatile the oil market has been in recent months, as the cost of a barrel of oil has dropped from a high value of $145/barrel in July of 2008 to less than $40/barrel at the close of 2008. It is unlikely that shipowners will even consider the prospect of a nuclear-powered vessel unless the cost of fuel oil is at a high level for a sustained period of time. However, in the long-term, the nuclear-powered cargo ship does appear to have significant promise. The cost of fuel will undoubtedly continue to rise. It is also likely that environmental concerns will cause the government to intervene by legislation or subsidy, or both. Furthermore, as time passes, the public perception of nuclear power is likely to become more favorable. Therefore, the final conclusion of this research is that nuclear-powered cargo vessels, given the right circumstances, will be economically feasible in the near future. How quickly this happens depends on the rate at which fuel costs increase as well as the timeframe of government action.

5.2 Recommendations for Future Research

There are several areas of this preliminary conceptual design that could easily be expanded as part of the detailed design phase. The following are areas that the author believes could be looked at in greater detail:

- A more thorough analysis of reactor core physics will need to be completed in order to ensure the results obtained during the preliminary analysis are valid. It would likely be necessary to model the core completely using a suitable software package in order to accomplish this task to the level of detail that would be necessary for the detailed design phase.
- A Probabilistic Risk Assessment (PRA) is part of the Nuclear Regulatory Commission's certification process for any new reactor design. This assessment would be somewhat different than that required for a land-based reactor. For example, a PRA for a land-based reactor requires the analysis of the consequences of an earthquake. This event could probably be replaced with an analysis for a rogue wave in the case of the shipboard reactor. As there are several other events that would be different between land-based and shipboard reactors, this area could easily warrant a thesis by itself.
- A more thorough structural analysis of the ship should be performed. It was assumed that all areas of the ship were still within the limits and specifications of the American Bureau of Shipping, the organization that the author believes will classify the ship. This assumption was made based on the location of the major components necessary for the nuclear-powered variant, as well as the assumption that there will be the ability to increase the scantlings of the ship if needed in order to comply with the rules.
- Since the rules for the classification of the ship by the American Bureau of Shipping were written in 1962 using very conservative approaches, it would likely be necessary to review these rules and determine whether or not they are still

adequate and complete as written. This endeavor would likely require both model testing and theoretical investigations using appropriate software packages. Since computing power has increased significantly since 1962, more detailed analysis of motions and stresses can be done today. Therefore, this author believes that it is possible that the limits that were written into the rules back in 1962 could be relaxed. This task would certainly be suitable for a thesis.

- NuScale Power is a company specializing in the design of small-scale nuclear reactors for a variety of applications. If the company is able to produce a design that is approved by the NRC, then it would be interesting to do a feasibility study using their technology for smaller commercial vessels. Perhaps those reactors could be the key to the nuclear renaissance for commercial shipping.

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Appendix A: CASMO-4 Routine

```
 LIST OF USER FILES
    ******************
NEUTRON DATA LIBRARY FILE     /codes/CMSCODES/CasLib/library/j2lbb70.970702
INPUT FILE                 beaver10.inp
OUTPUT LIST FILE           beaver10.out
CARD IMAGE FILE (SEG1)     beaver10.cax
HOST AND WORKING DIRECTORY    mightyalph/dsk2/users/jbeaver

    LIST OF CASMO INPUT CARDS
    *************************
      TTL * NS ROCKY BEAVER

      ***** STATE POINT PARAMETERS *****
      TFU=900.0 TMO=583.1 BOR=0.0 VOI=0.0
      **SIM 'ROCKYBEAVER'

      ***** OPERATING PARAMETERS *****
      PRE 155.1296  * CORE PRESSURE, bars
      PDE 55.9 'KWL'  * POWER DENSITY, kW/liter

      ***** MATERIAL COMPOSITIONS *****
      FUE 1 10.4/10
      FUE 2 10.1435/4.8 64016=7
      SPA 10.81934 0.1800E-4,,8.154/718=84.59 347=15.41

      ***** GEOMETRY SPECIFICATION *****
      PWR 17 1.26 21.5
      PIN 1 0.4096 0.4178 0.4750/'1' 'AIR' 'CAN'
      PIN 2 0.4096 0.4178 0.4750/'2' 'AIR' 'CAN'
      PIN 3 0.5690 0.6147/'COO' 'BOX'  * GUIDE TUBE
      PIN 4 0.5690 0.6147/'COO' 'BOX'
      PIN 4 0.4331 0.4369 0.4839  0.5690 0.6147/'AIC' 'AIR' 'CRS' 'COO' 'BOX'
         //1 'RCC' 'ROD'
      LPI 3
        1 1
        2 1 1
        4 1 1 4
        1 1 1 1 2
        1 1 1 1 1 4
        4 1 2 4 1 1 1
        1 1 1 1 1 1 1 1
        1 1 1 1 1 1 1 1 1
      DEP -60
      STA
      END
```

Appendix B: CASMO-4 End of Core Life Output (10% Enrichment)

```
1* C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 79 PAGE = 325
 *  NS ROCKY BEAVER
 *  BURNUP =    60.000 V= 0.0  TF= 900.0  TM= 583.1  BOR=   0.0

PREDICT NUMBER DENSITIES OF BURNABLE NUCLIDES AT  60.000 MWD/KGU

STATE POINT DATA WRITTEN ON RESTART FILE NAMED=(FILE NOT NAMED - STATUS=SCRATCH)
EXPOSURE= 60.000 PASSWORD=/081022/1905         (SEQUENCE NUMBER ON RESTART FILE=0080)
1* C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 80 PAGE = 326
 *  NS ROCKY BEAVER
 *  BURNUP =    60.000 V= 0.0  TF= 900.0  TM= 583.1  BOR=   0.0

K-INF FROM THE MICRO GROUP CALCULATIONS = 1.11827 (AVERAGE PIN CELL)  SEGMENT NO  1
  (SPECTRA CALCULATION NUMBER 1- 4)    = 1.11818 1.12233 1.06701 1.12233
K-INF FROM THE MACRO GROUP CALCULATION  = 1.10825     TOTAL TIME OF SOLUTION =  0.06 CPU-SEC.

C H A R A C T E R I S T I C S   S O L U T I O N

          -------TIMINGS------    INNER ITERATIONS PER OUTER (* = NOT CONVERGED)
 ITER   EIGEN  COARSE  FINE  TOTAL      1A  2B  3B  4B  5C  6C  7C  8C

  1 1.10733   0.01  0.03  0.04     1*  1*  1*  1*  1*  1*  1*  1*
  2 1.10624   0.01  0.03  0.04     1*  1*  1*  1*  1*  1*  1*  1*
  3 1.10624   0.01  0.03  0.04     1*  1*  1*  1*  1*  1*  1*  1*
  4 1.10626   0.01  0.03  0.04     1*  1*  1*  1*  1*  1*  1*  1*
  5 1.10627   0.01  0.03  0.04     1*  1*  1*  1*  1*  1*  1*  1*
  6 1.10627   0.01  0.03  0.04     1   1*  1*  1   1*  1   1*  1*
  7 1.10627   0.00  0.02  0.02     0   1   1*  0   1*  0   1   1*
  8 1.10627   0.00  0.01  0.02     0   0   1   0   1   0   0   1
TOTALS          0.08  0.20  0.30

*****************************************************************************************************
* K-INF = 1.10627  K-EFF = 1.00000  B2G =  0.000E+00  B2M =  1.829E-03  M2 =   58.09          *
*****************************************************************************************************
1* C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 80 PAGE = 327
 *  NS ROCKY BEAVER
 *  BURNUP =    60.000 V= 0.0  TF= 900.0  TM= 583.1  BOR=   0.0

BURNUP IN MWD/KG                                  WEIGHT PER CENT OF  U-235 X 1.E+00
 0.00                                      0.00
63.52 61.78                                   3.87  4.02
39.47 61.71 61.97                                1.94  4.02  4.00
 0.00 63.69 63.89  0.00                           0.00  3.85  3.83  0.00
63.53 61.75 62.06 64.36 39.68                         3.87  4.02  3.99  3.80  1.93
63.36 61.56 61.79 64.26 65.32  0.00                    3.88  4.04  4.02  3.80  3.72  0.00
 0.00 63.15 39.21  0.00 64.47 63.09 59.79                 0.00  3.90  1.96  0.00  3.79  3.91  4.19
62.24 60.59 60.45 62.46 60.43 58.80 57.76 57.26             3.98  4.12  4.14  3.96  4.14  4.27  4.37  4.41
59.44 59.23 59.34 59.41 58.94 58.20 57.74 57.39 58.21          4.22  4.24  4.23  4.22  4.27  4.33  4.38  4.41  4.34

WEIGHT PER CENT OF  U-236 X 1.E+00                      WEIGHT PER CENT OF  U-238 X 1.E+00
 0.00                                      0.00
 1.15  1.13                                 86.96 87.00
 0.56  1.13  1.13                             92.02 87.01 87.00
 0.00  1.15  1.15  0.00                          0.00 86.97 86.96  0.00
 1.15  1.13  1.14  1.16  0.56                       86.96 87.01 87.00 86.95 91.99
 1.15  1.13  1.13  1.16  1.17  0.00                    86.96 87.00 87.00 86.95 86.90  0.00
 0.00  1.15  0.55  0.00  1.16  1.14  1.11                 0.00 86.96 92.02  0.00 86.91 86.96 87.02
 1.14  1.12  1.12  1.14  1.12  1.10  1.09  1.09             86.98 87.01 87.02 86.97 87.02 87.06 87.08 87.08
 1.11  1.11  1.11  1.11  1.10  1.10  1.09  1.09  1.10          87.04 87.05 87.04 87.04 87.04 87.06 87.06 87.06 87.03

WEIGHT PER CENT OF Pu-239 X 1.E+01                      WEIGHT PER CENT OF Pu-240 X 1.E+01
 0.00                                      0.00
 8.07  8.27                                  2.27  2.28
 8.26  8.24  8.28                               2.46  2.28  2.27
```

```
 0.00 8.09 8.08 0.00                        0.00 2.27 2.27 0.00
 8.15 8.31 8.28 7.99 8.30                    2.26 2.27 2.28 2.29 2.53
 8.20 8.36 8.28 8.02 8.00 0.00                2.26 2.27 2.28 2.28 2.32 0.00
 0.00 8.19 8.38 0.00 8.20 8.31 8.71            0.00 2.27 2.46 0.00 2.30 2.26 2.23
 8.37 8.53 8.51 8.33 8.59 8.73 8.91 9.01        2.25 2.25 2.25 2.25 2.25 2.19 2.17 2.16
 8.72 8.69 8.70 8.70 8.81 8.91 9.03 9.11 9.07    2.21 2.21 2.21 2.21 2.20 2.19 2.18 2.17 2.19

WEIGHT PER CENT OF Pu-241 X 1.E+01             WEIGHT PER CENT OF Pu-242 X 1.E+02
 0.00                                  0.00
 1.74 1.71                              4.13 3.80
 1.86 1.70 1.71                          4.65 3.78 3.79
 0.00 1.74 1.74 0.00                      0.00 4.11 4.12 0.00
 1.74 1.70 1.71 1.75 1.86                  4.06 3.75 3.80 4.24 4.67
 1.75 1.71 1.71 1.75 1.78 0.00              4.04 3.74 3.79 4.21 4.41 0.00
 0.00 1.75 1.86 0.00 1.78 1.75 1.69          0.00 4.05 4.59 0.00 4.24 3.99 3.44
 1.74 1.70 1.70 1.74 1.70 1.67 1.65 1.65      3.86 3.59 3.59 3.90 3.54 3.29 3.14 3.07
 1.69 1.68 1.69 1.69 1.68 1.67 1.67 1.67 1.70  3.41 3.37 3.39 3.40 3.33 3.21 3.15 3.11 3.23

AVERAGED NUMBER DENSITIES OF BURNABLE NUCLIDES
U-234 = 1.02513E+19 U-235 = 9.04960E+20 U-236 = 2.49621E+20 U-237 = 3.05906E+17 U-238 = 1.97314E+22 U-239 =
4.66464E+15
Np-236= 1.49097E+14 Np-237= 2.29253E+19 Np-238= 2.16210E+16 Np-239= 6.73717E+17 Pu-238= 8.47246E+18 Pu-239=
1.90339E+20
Pu-240= 5.05700E+19 Pu-241= 3.83639E+19 Pu-242= 8.33605E+18 Pu-243= 7.67441E+14 Am-241= 3.72234E+18 Am-242=
2.63265E+15
Am-243= 1.68034E+18 Am-244= 5.52784E+14 Am242m= 6.70440E+16 Cm-242= 4.54143E+17 Cm-243= 1.12350E+16 Cm-
244= 5.40866E+17
Cm-245= 3.46477E+16 Cm-246= 1.88750E+15 Cm-247= 1.95765E+13 Cm-248= 9.84228E+11 Cm-249= 4.56568E+06 Bk-249=
1.01641E+10
Bk-250= 3.32720E+06 Cf-249= 4.54191E+09 Cf-250= 2.61675E+09 Cf-251= 1.20178E+09 Cf-252= 3.54578E+08
Kr-83 = 5.74163E+18 Rh-103= 3.65689E+19 Rh-105= 2.57376E+16 Ag-109= 3.71452E+18 I-135 = 1.07507E+16 Xe-131=
2.90429E+19
Xe-135= 1.03989E+16 Cs-133= 7.86428E+19 Cs-134= 6.82252E+18 Cs-135= 6.58836E+19 Cs-137= 8.01048E+19 Ba-140=
4.64009E+17
La-140= 6.26351E+16 Nd-143= 6.38768E+19 Nd-145= 4.74172E+19 Pm-147= 7.33831E+18 Pm-148= 1.68690E+16 Pm-149=
2.02804E+16
Sm-147= 1.01356E+19 Sm-149= 2.05823E+17 Sm-150= 1.55223E+19 Sm-151= 1.21548E+18 Sm-152= 6.27416E+18 Eu-153=
6.52443E+18
Eu-154= 1.98259E+18 Eu-155= 2.36879E+17 Eu-156= 5.18649E+16 Gd155F= 1.27989E+16 LFP1 = 1.68690E+21 LFP2 =
4.01651E+20
EXTFP = 2.68535E+20
Gd-152= 4.86842E+17 Gd-154= 3.59728E+19 Gd-155= 3.45599E+17 Gd-156= 7.76314E+20 Gd-157= 3.50565E+17 Gd-158=
9.49678E+20
Gd-160= 5.00060E+20
1* C A S M O - 4 UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 80 PAGE = 328
 * NS ROCKY BEAVER
 * BURNUP= 60.000 V= 0.0 TF= 900.0 TM= 583.1 BOR= 0.0 EFPH= 79030 ECH= 0.000

     -------------------- C A S M O - 4   S U M M A R Y ----------------------
     BURNUP = 60.000 MWD/KG  K-INF = 1.10627  M2 = 58.09  B2 = 1.829E-03
     ----------------------------------------------------------------------------

 * POWER DISTRIBUTION   PEAK: LL = 1.066 ( 92.7 W/CM), HSF = 1.066 ( 31.0 W/CM2)
 0.000
 1.057 1.038
 0.764 1.037 1.032
 0.000 1.047 1.047 0.000
 1.042 1.027 1.032 1.060 0.767
 1.039 1.027 1.035 1.056 1.066* 0.000
 0.000 1.044 0.758 0.000 1.047 1.028 0.992
 1.023 1.012 1.015 1.027 1.003 0.981 0.966 0.957
 0.993 0.991 0.992 0.991 0.983 0.972 0.964 0.958 0.965

 * TWO GROUP DATA                    K-INF XE, NO XE 1.10706   1.12357
  DIFF1   , DIFF2      1.4782E+00 3.2219E-01  M2    ", "   5.8675E+01 5.8718E+01
  ABS1    , ABS2       1.3507E-02 1.6379E-01  XE2 MIC, MAC  1.1003E+06 3.4590E-03
  NUFISS1 , NUFISS2    8.9122E-03 2.6011E-01  SM2   ", "   3.4946E+04 2.1804E-03
  REMOV1  , NU         1.2559E-02 2.6090E+00  BOR1  ", "   8.0532E+00 4.7385E-24
  KAPPA   , XE-YIELD   3.2991E-11 6.8146E-02  BOR2  ", "   4.1594E+02 2.4474E-22
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* NEUTRON BALANCE        GROUP 1    GROUP 2     TOTAL
  FLUX .......      7.4398E-02  5.6821E-03  8.0080E-02
  ABSORPTION ....   4.6938E-01  4.3471E-01  9.0409E-01
  FISSION ......    1.1943E-01  2.6388E-01  3.8331E-01
  NUFISSION .....   3.0970E-01  6.9036E-01  1.0001E+00
  LEAKAGE ......    9.3973E-02  1.7435E-03  9.5716E-02
  OUTSCATTER ....   4.4440E-01  7.9751E-03  4.5238E-01
  K-INF (2-GROUP).. 3.4191E-01  7.6515E-01  1.1071E+00
  ETA*F, P .....    6.5981E-01  1.5881E+00  4.8181E-01
  INV VELOCITY ...  4.7012E-08  2.2555E-06
  FLUX DET/CELL ... 9.7357E-01  1.3829E+00

* NEUTRON DETECTOR     2.2353E+11  GAMMA DET  0.0000E+00  PR LIFE TIME  1.0464E-05
  INTEGRATED ABS ..  4.0894E+23  INT NUFISS  5.0557E+23  INT LEAKAGE   9.6467E+22
  FAST FLUENCE   ..  1.3849E+22  POWER (W/G) 1.8221E+01  NORM FACTOR   1.7971E+15
  CONV RATIO     ..  4.7582E-01  FISS/TOT U% 3.9525E+00  FISS/TOT PU%  7.7195E+01

* NUCLIDE  WT(%)    CAPTURE     FISSION     INT CAPT    INT FISS       MWD/KG
  U-234    0.045    1.8071E-03  6.5794E-05  1.0563E+21  4.0621E+19      0.012
  U-235    3.952    5.7638E-02  2.1913E-01  3.9505E+22  1.4753E+23     43.919
  U-236    1.095    1.4062E-02  8.4399E-04  4.0773E+21  2.3137E+20      0.069
  U-238   87.281    1.7858E-01  2.6162E-02  8.0649E+22  1.2268E+22      3.732
  Pu-238   0.037    1.4147E-03  1.9538E-04  1.7680E+20  2.5562E+19      0.008
  Pu-239   0.845    6.2407E-02  1.1175E-01  1.9597E+22  3.4715E+22     10.789
  Pu-240   0.226    4.8014E-02  3.8507E-04  1.2385E+22  8.4814E+19      0.026
  Pu-241   0.172    8.0042E-03  2.4241E-02  1.4955E+21  4.5202E+21      1.421
  Pu-242   0.037    2.3183E-03  4.7090E-05  3.1888E+20  6.3399E+18      0.002
  Am-241   0.017    2.7919E-03  4.1968E-05  4.2603E+20  6.5077E+18      0.002
  TOT U   92.374    2.5216E-01  2.4620E-01  1.2530E+23  1.6007E+23     47.731
  TOT PU   1.318    1.2216E-01  1.3662E-01  3.3974E+22  3.9352E+22     12.246
  FISSILE  4.970    1.2805E-01  3.5515E-01  6.0598E+22  1.8676E+23     56.130
  FERTILE 87.593    2.2992E-01  2.6820E-02  9.4277E+22  1.2420E+22      3.778
  TOT GD   5.957    3.4906E-03              7.5255E+21
  Gd-155   0.001    2.4510E-04              3.0236E+21
  Gd-157   0.001    1.0380E-03              3.5310E+21

* DELAYED NEUTRON DECAY  0.0128 0.0315 0.1229 0.3249 1.4082 3.8436        TOTAL
         YIELD*E3  0.1840 1.2189 1.0881 2.3034 0.8626 0.2099         5.8670
   EFFECTIVE YIELD*E3  0.1754 1.1617 1.0371 2.1954 0.8222 0.2001     5.5919

1* C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 80 PAGE = 329
 *  NS ROCKY BEAVER
 *  BURNUP =   60.001 V= 0.0  TF= 900.0  TM= 583.1  BOR=  0.0

 PREDICT NUMBER DENSITIES OF BURNABLE NUCLIDES AT  60.001 MWD/KGU
1* C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22 19:05:34 STATE POINT = 81 PAGE = 330
 *  NS ROCKY BEAVER
 *  BURNUP =   60.001 V= 0.0  TF= 900.0  TM= 583.1  BOR=  0.0
 END                                        INPUT CARD

 STATE POINT DATA WRITTEN ON RESTART FILE NAMED=(FILE NOT NAMED - STATUS=SCRATCH)
 EXPOSURE= 60.001 PASSWORD=/081022/1905        (SEQUENCE NUMBER ON RESTART FILE=0081)
1  * C A S M O - 4  UNIVRSY 99/02/26 STUDSVIK * EXECUTION 08/10/22  19:05:34  JOB=UNIV        PAGE =  331

  ** C A S M O - 4  SUMMARY  **

  NS ROCKY BEAVER

  HVOI=  0.0 HTFU=  900.0 HTMO=  583.1 HTCO=  583.1 HBOR=   0.0

  NO VOID   TFU   TMO   TCO   BOR ROD  BURNUP  K-INF  K-INF    M2    PIN  U-235 FISS PU  TOT PU
                                       MWD/KG         TWO-GROUP  PEAK  WT %  WT %   WT %

  1  0.0  900.0  583.1  583.1   0.0    0.000 1.37532 1.37656 59.30  1.112  9.713  0.000  0.000
  2                                    0.100 1.35798 1.35938 59.12  1.112  9.700  0.002  0.002
  3                                    0.500 1.35331 1.35473 59.08  1.112  9.651  0.016  0.016
  4                                    1.000 1.34907 1.35051 59.05  1.111  9.589  0.035  0.035
  5                                    1.500 1.34593 1.34739 59.04  1.111  9.528  0.053  0.054
  6                                    2.000 1.34342 1.34488 59.02  1.110  9.467  0.071  0.072
  7                                    2.500 1.34127 1.34274 59.02  1.110  9.407  0.088  0.090
```

8	3.000	1.33934	1.34081	59.01	1.109	9.347	0.105	0.108
9	3.500	1.33754	1.33900	59.01	1.109	9.287	0.122	0.125
10	4.000	1.33579	1.33725	59.01	1.108	9.228	0.139	0.143
11	4.500	1.33405	1.33551	59.01	1.107	9.168	0.155	0.160
12	5.000	1.33230	1.33376	59.01	1.107	9.109	0.171	0.177
13	5.500	1.33055	1.33201	59.01	1.106	9.051	0.187	0.194
14	6.000	1.32878	1.33024	59.01	1.106	8.992	0.203	0.211
15	6.500	1.32701	1.32847	59.01	1.105	8.934	0.218	0.227
16	7.000	1.32523	1.32669	59.00	1.104	8.876	0.233	0.244
17	7.500	1.32345	1.32491	59.00	1.104	8.819	0.248	0.260
18	8.000	1.32167	1.32314	59.00	1.103	8.762	0.262	0.276
19	8.500	1.31991	1.32137	59.00	1.102	8.705	0.277	0.292
20	9.000	1.31815	1.31961	59.00	1.102	8.648	0.291	0.308
21	9.500	1.31639	1.31785	59.00	1.101	8.591	0.305	0.323
22	10.000	1.31465	1.31610	59.00	1.100	8.535	0.318	0.339
23	10.500	1.31292	1.31438	59.00	1.099	8.479	0.332	0.354
24	11.000	1.31122	1.31268	59.00	1.099	8.423	0.345	0.369
25	11.500	1.30954	1.31100	59.00	1.098	8.368	0.359	0.384
26	12.000	1.30789	1.30934	59.00	1.097	8.313	0.371	0.399
27	12.500	1.30625	1.30770	59.00	1.096	8.258	0.384	0.413
28	13.000	1.30465	1.30609	59.00	1.096	8.203	0.397	0.428
29	13.500	1.30306	1.30451	59.01	1.096	8.148	0.409	0.442
30	14.000	1.30150	1.30294	59.01	1.096	8.094	0.422	0.456
31	14.500	1.29995	1.30140	59.01	1.096	8.040	0.434	0.470
32	15.000	1.29844	1.29988	59.01	1.096	7.986	0.446	0.484
33	15.500	1.29696	1.29839	59.02	1.096	7.933	0.457	0.498
34	16.000	1.29551	1.29694	59.02	1.096	7.879	0.469	0.512
35	16.500	1.29408	1.29551	59.03	1.096	7.826	0.480	0.525
36	17.000	1.29268	1.29410	59.03	1.096	7.773	0.491	0.539
37	17.500	1.29130	1.29272	59.04	1.096	7.720	0.503	0.552
38	18.000	1.28994	1.29135	59.04	1.096	7.668	0.513	0.565
39	18.500	1.28860	1.29001	59.05	1.096	7.616	0.524	0.578
40	19.000	1.28729	1.28870	59.05	1.096	7.564	0.535	0.591
41	19.500	1.28600	1.28740	59.06	1.096	7.512	0.545	0.604
42	20.000	1.28473	1.28613	59.06	1.096	7.460	0.556	0.616
43	20.500	1.28348	1.28487	59.07	1.096	7.409	0.566	0.629
44	21.000	1.28225	1.28363	59.08	1.096	7.358	0.576	0.641
45	21.500	1.28104	1.28241	59.08	1.096	7.307	0.586	0.653
46	22.000	1.27985	1.28122	59.09	1.096	7.256	0.595	0.665
47	22.500	1.27868	1.28004	59.10	1.096	7.206	0.605	0.677
48	23.000	1.27752	1.27888	59.11	1.096	7.155	0.614	0.689
49	23.500	1.27637	1.27772	59.11	1.096	7.105	0.623	0.701

** C A S M O - 4 SUMMARY **

50	24.000	1.27523	1.27657	59.12	1.096	7.055	0.633	0.713
51	24.500	1.27408	1.27542	59.13	1.096	7.005	0.642	0.724
52	25.000	1.27293	1.27425	59.14	1.096	6.956	0.650	0.735
53	25.500	1.27174	1.27306	59.15	1.096	6.907	0.659	0.747
54	26.000	1.27051	1.27182	59.15	1.096	6.857	0.668	0.758
55	26.500	1.26922	1.27052	59.16	1.096	6.809	0.676	0.769
56	27.000	1.26785	1.26915	59.17	1.096	6.760	0.684	0.780
57	27.500	1.26641	1.26770	59.17	1.096	6.711	0.693	0.791
58	28.000	1.26487	1.26616	59.17	1.096	6.663	0.701	0.801
59	28.500	1.26324	1.26453	59.18	1.096	6.615	0.709	0.812
60	29.000	1.26152	1.26280	59.18	1.096	6.567	0.716	0.822
61	29.500	1.25971	1.26098	59.18	1.095	6.519	0.724	0.833
62	30.000	1.25780	1.25907	59.18	1.095	6.472	0.732	0.843
63	30.500	1.25581	1.25707	59.17	1.095	6.424	0.739	0.853
64	31.000	1.25372	1.25498	59.17	1.095	6.377	0.746	0.863
65	31.500	1.25154	1.25280	59.17	1.094	6.330	0.754	0.874
66	32.000	1.24929	1.25054	59.16	1.094	6.283	0.761	0.883
67	32.500	1.24696	1.24821	59.16	1.093	6.237	0.768	0.893
68	33.000	1.24456	1.24581	59.15	1.093	6.190	0.775	0.903
69	33.500	1.24212	1.24336	59.14	1.093	6.144	0.781	0.913
70	35.000	1.23451	1.23575	59.12	1.091	6.006	0.801	0.941
71	37.500	1.22149	1.22271	59.07	1.089	5.781	0.832	0.987
72	40.000	1.20836	1.20956	59.02	1.087	5.560	0.861	1.030
73	42.500	1.19529	1.19646	58.98	1.084	5.343	0.887	1.072
74	45.000	1.18231	1.18344	58.93	1.082	5.131	0.912	1.112

75	47.500	1.16943	1.17051	58.89	1.079	4.924	0.934	1.150
76	50.000	1.15663	1.15767	58.84	1.077	4.721	0.954	1.187
77	52.500	1.14393	1.14491	58.80	1.074	4.522	0.973	1.222
78	55.000	1.13130	1.13223	58.76	1.071	4.328	0.989	1.255
79	57.500	1.11875	1.11961	58.72	1.069	4.138	1.004	1.287
80	60.000	1.10627	1.10706	58.68	1.066	3.952	1.017	1.318

NORMAL TERMINATION

Appendix C: Nuclear Ship PV Analysis→Base-Case

Year	Acquisition	maintenance	repair	DDCI	refueling	spent fuel	manning	security	insurance	decomm	slot charter
1	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$12,000,000	$0	$0
2	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$11,460,000	$0	$0
3	$105,165,160	$1,600,000	$0	$1,250,000	$0	$0	$8,750,000	$3,000,000	$10,920,000	$0	$0
4	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$10,380,000	$0	$0
5	$105,165,160	$1,600,000	$2,000,000	$3,000,000	$0	$0	$8,750,000	$3,000,000	$9,840,000	$0	$71,100,000
6	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$9,300,000	$0	$0
7	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$8,760,000	$0	$0
8	$105,165,160	$1,600,000	$0	$1,250,000	$0	$0	$8,750,000	$3,000,000	$8,220,000	$0	$0
9	$105,165,160	$1,600,000	$0	$0	$0	$0	$8,750,000	$3,000,000	$7,680,000	$0	$0
10	$105,165,160	$1,600,000	$2,000,000	$3,000,000	$115,000,000	$3,000,000	$8,750,000	$3,000,000	$7,140,000	$0	$71,100,000
11	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$6,600,000	$0	$0
12	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$6,060,000	$0	$0
13	$105,165,160	$1,600,000	$0	$1,250,000	$0	$3,000,000	$8,750,000	$3,000,000	$5,520,000	$0	$0
14	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$4,980,000	$0	$0
15	$105,165,160	$1,600,000	$2,000,000	$3,000,000	$0	$3,000,000	$8,750,000	$3,000,000	$4,440,000	$0	$71,100,000
16	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$3,900,000	$0	$0
17	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$3,360,000	$0	$0
18	$105,165,160	$1,600,000	$0	$1,250,000	$0	$3,000,000	$8,750,000	$3,000,000	$2,820,000	$0	$0
19	$105,165,160	$1,600,000	$0	$0	$0	$3,000,000	$8,750,000	$3,000,000	$2,280,000	$0	$0
20	$105,165,160	$1,600,000	$0	$3,000,000	$0	$3,000,000	$8,750,000	$3,000,000	$1,740,000	$20,000,000	$71,100,000
NPV	$895,330,287	$13,621,702	$2,491,713	$6,292,683	$44,337,478	$8,263,620	$74,493,683	$25,540,691	$72,243,032	$2,972,873	$99,148,971

Fuel Costing Data		NPV
200	800000	$6,810,851
210	840000	$7,151,394
220	880000	$7,491,936
230	920000	$7,832,479
240	960000	$8,173,021
250	1000000	$8,513,564
260	1040000	$8,854,106
270	1080000	$9,194,649
280	1120000	$9,535,191
290	1160000	$9,875,734
300	1200000	$10,216,276
310	1240000	$10,556,819
320	1280000	$10,897,362
330	1320000	$11,237,904
340	1360000	$11,578,447
350	1400000	$11,918,989
360	1440000	$12,259,532
370	1480000	$12,600,074
380	1520000	$12,940,617
390	1560000	$13,281,159
400	1600000	$13,621,702
410	1640000	$13,962,245
420	1680000	$14,302,787
430	1720000	$14,643,330
440	1760000	$14,983,872
450	1800000	$15,324,415
460	1840000	$15,664,957
470	1880000	$16,005,500
480	1920000	$16,346,042
490	1960000	$16,686,585
500	2000000	$17,027,127
510	2040000	$17,367,670
520	2080000	$17,708,213
530	2120000	$18,048,755
540	2160000	$18,389,298
550	2200000	$18,729,840
560	2240000	$19,070,383
570	2280000	$19,410,925
580	2320000	$19,751,468
590	2360000	$20,092,010
600	2400000	$20,432,553
610	2440000	$20,773,095
620	2480000	$21,113,638
630	2520000	$21,454,181
640	2560000	$21,794,723
650	2600000	$22,135,266
660	2640000	$22,475,808
670	2680000	$22,816,351
680	2720000	$23,156,893
690	2760000	$23,497,436
700	2800000	$23,837,978
710	2840000	$24,178,521
720	2880000	$24,519,064
725	2900000	$24,689,335
730	2920000	$24,859,606
740	2960000	$25,200,149
750	3000000	$25,540,691
760	3040000	$25,881,234
770	3080000	$26,221,776
780	3120000	$26,562,319
790	3160000	$26,902,861
793	3172000	$27,005,024
800	3200000	$27,243,404
810	3240000	$27,583,946
820	3280000	$27,924,489
830	3320000	$28,265,032
840	3360000	$28,605,574
850	3400000	$28,946,117
860	3440000	$29,286,659
870	3480000	$29,627,202
880	3520000	$29,967,744
890	3560000	$30,308,287
900	3600000	$30,648,829
910	3640000	$30,989,372
920	3680000	$31,329,914
930	3720000	$31,670,457
940	3760000	$32,011,000
950	3800000	$32,351,542
960	3840000	$32,692,085
970	3880000	$33,032,627
980	3920000	$33,373,170
990	3960000	$33,713,712
1000	4000000	$34,054,255
1010	4040000	$34,394,797
1020	4080000	$34,735,340
1030	4120000	$35,075,883
1040	4160000	$35,416,425
1050	4200000	$35,756,968
1060	4240000	$36,097,510
1070	4280000	$36,438,053
1080	4320000	$36,778,595
1090	4360000	$37,119,138
1100	4400000	$37,459,680
1110	4440000	$37,800,223
1120	4480000	$38,140,765
1130	4520000	$38,481,308
1140	4560000	$38,821,851
1150	4600000	$39,162,393
1160	4640000	$39,502,936

Appendix D: Conventional Ship PV Analysis→Base-case

Year	Acquisition	maintanence	DDCI	manning	security	insurance	slot charter
1	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
2	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
3	$12,913,606	$800,000	$1,250,000	$3,500,000	$1,000,000	$1,450,000	$0
4	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
5	$12,913,606	$800,000	$3,000,000	$3,500,000	$1,000,000	$1,450,000	$19,500,000
6	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
7	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
8	$12,913,606	$800,000	$1,250,000	$3,500,000	$1,000,000	$1,384,750	$0
9	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
10	$12,913,606	$800,000	$3,000,000	$3,500,000	$1,000,000	$1,384,750	$19,500,000
11	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
12	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
13	$12,913,606	$800,000	$1,250,000	$3,500,000	$1,000,000	$1,450,000	$0
14	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
15	$12,913,606	$800,000	$3,000,000	$3,500,000	$1,000,000	$1,450,000	$19,500,000
16	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,384,750	$0
17	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
18	$12,913,606	$800,000	$1,250,000	$3,500,000	$1,000,000	$1,384,750	$0
19	$12,913,606	$800,000	$0	$3,500,000	$1,000,000	$1,450,000	$0
20	$12,913,606	$800,000	$3,000,000	$3,500,000	$1,000,000	$1,384,750	$19,500,000
NPV	$109,940,810	$6,810,851	$6,292,683	$29,797,473	$8,513,564	$12,080,139	$27,192,756

Fuel Costing Data		NPV	440	53900000	$458,881,084	690	84525000	$719,608,973	910	1.11E+08	$949,049,516
200	24500000	$208,582,311	450	55125000	$469,310,200	700	85750000	$730,038,089	920	1.13E+08	$959,478,631
210	25725000	$219,011,427	460	56350000	$479,739,316	710	86975000	$740,467,205	930	1.14E+08	$969,907,747
220	26950000	$229,440,542	470	57575000	$490,168,431	720	88200000	$750,896,320	940	1.15E+08	$980,336,862
230	28175000	$239,869,658	480	58800000	$500,597,547	725	88812500	$756,110,878	950	1.16E+08	$990,765,978
240	29400000	$250,298,773	490	60025000	$511,026,662	730	89425000	$761,325,436	960	1.18E+08	$1,001,195,093
250	30625000	$260,727,889	500	61250000	$521,455,778	740	90650000	$771,754,551	970	1.19E+08	$1,011,624,209
260	31850000	$271,157,004	510	62475000	$531,884,893	750	91875000	$782,183,667	980	1.2E+08	$1,022,053,325
270	33075000	$281,586,120	520	63700000	$542,314,009	760	93100000	$792,612,782	990	1.21E+08	$1,032,482,440
280	34300000	$292,015,236	530	64925000	$552,743,125	770	94325000	$803,041,898	1000	1.23E+08	$1,042,911,556
290	35525000	$302,444,351	540	66150000	$563,172,240	780	95550000	$813,471,013	1010	1.24E+08	$1,053,340,671
300	36750000	$312,873,467	550	67375000	$573,601,356	790	96775000	$823,900,129	1020	1.25E+08	$1,063,769,787
310	37975000	$323,302,582	560	68600000	$584,030,471	793	97142500	$827,028,864	1030	1.26E+08	$1,074,198,902
320	39200000	$333,731,698	570	69825000	$594,459,587	800	98000000	$834,329,245	1040	1.27E+08	$1,084,628,018
330	40425000	$344,160,813	580	71050000	$604,888,702	810	99225000	$844,758,360	1050	1.29E+08	$1,095,057,133
340	41650000	$354,589,929	590	72275000	$615,317,818	820	1E+08	$855,187,476	1060	1.3E+08	$1,105,486,249
350	42875000	$365,019,044	600	73500000	$625,746,933	830	1.02E+08	$865,616,591	1070	1.31E+08	$1,115,915,365
360	44100000	$375,448,160	610	74725000	$636,176,049	840	1.03E+08	$876,045,707	1080	1.32E+08	$1,126,344,480
370	45325000	$385,877,276	620	75950000	$646,605,165	850	1.04E+08	$886,474,822	1090	1.34E+08	$1,136,773,596
380	46550000	$396,306,391	630	77175000	$657,034,280	860	1.05E+08	$896,903,938	1100	1.35E+08	$1,147,202,711
390	47775000	$406,735,507	640	78400000	$667,463,396	870	1.07E+08	$907,333,053	1110	1.36E+08	$1,157,631,827
400	49000000	$417,164,622	650	79625000	$677,892,511	880	1.08E+08	$917,762,169	1120	1.37E+08	$1,168,060,942
410	50225000	$427,593,738	660	80850000	$688,321,627	890	1.09E+08	$928,191,285	1130	1.38E+08	$1,178,490,058
420	51450000	$438,022,853	670	82075000	$698,750,742	900	1.1E+08	$938,620,400	1140	1.4E+08	$1,188,919,173
430	52675000	$448,451,969	680	83300000	$709,179,858	910	1.11E+08	$949,049,516	1150	1.41E+08	$1,199,348,289

APPENDIX E: Nuclear Ship PV Data for Increasing Fuel Costs

Fuel Costing Data		NPV
450	1800000	$21,801,751
460	1840000	$22,286,235
470	1880000	$22,770,718
480	1920000	$23,255,201
490	1960000	$23,739,685
500	2000000	$24,224,168
510	2040000	$24,708,651
520	2080000	$25,193,135
530	2120000	$25,677,618
540	2160000	$26,162,102
550	2200000	$26,646,585
560	2240000	$27,131,068
570	2280000	$27,615,552
580	2320000	$28,100,035
590	2360000	$28,584,518
600	2400000	$29,069,002
610	2440000	$29,553,485
620	2480000	$30,037,968
630	2520000	$30,522,452
640	2560000	$31,006,935
650	2600000	$31,491,419
660	2640000	$31,975,902
670	2680000	$32,460,385
680	2720000	$32,944,869
690	2760000	$33,429,352
700	2800000	$33,913,835
710	2840000	$34,398,319
720	2880000	$34,882,802
725	2900000	$35,125,044
730	2920000	$35,367,285
740	2960000	$35,851,769
750	3000000	$36,336,252
760	3040000	$36,820,736
770	3080000	$37,305,219
780	3120000	$37,789,702
790	3160000	$38,274,186
793	3172000	$38,419,531
800	3200000	$38,758,669
810	3240000	$39,243,152
820	3280000	$39,727,636
830	3320000	$40,212,119
840	3360000	$40,696,602
850	3400000	$41,181,086
860	3440000	$41,665,569
870	3480000	$42,150,053
880	3520000	$42,634,536
890	3560000	$43,119,019
900	3600000	$43,603,503
910	3640000	$44,087,986
920	3680000	$44,572,469
930	3720000	$45,056,953
940	3760000	$45,541,436
950	3800000	$46,025,919
960	3840000	$46,510,403
970	3880000	$46,994,886
980	3920000	$47,479,370
990	3960000	$47,963,853
1000	4000000	$48,448,336
1010	4040000	$48,932,820
1020	4080000	$49,417,303
1030	4120000	$49,901,786
1040	4160000	$50,386,270
1050	4200000	$50,870,753
1060	4240000	$51,355,236
1070	4280000	$51,839,720
1080	4320000	$52,324,203
1090	4360000	$52,808,686
1100	4400000	$53,293,170
1110	4440000	$53,777,653
1120	4480000	$54,262,137
1130	4520000	$54,746,620
1140	4560000	$55,231,103
1150	4600000	$55,715,587
1160	4640000	$56,200,070

APPENDIX F: Conventional Ship PV Data for Increasing Fuel Costs

Fuel Costing Data		NPV
450	55125000	$667,678,634
460	56350000	$682,515,937
470	57575000	$697,353,240
480	58800000	$712,190,543
490	60025000	$727,027,846
500	61250000	$741,865,149
510	62475000	$756,702,451
520	63700000	$771,539,754
530	64925000	$786,377,057
540	66150000	$801,214,360
550	67375000	$816,051,663
560	68600000	$830,888,966
570	69825000	$845,726,269
580	71050000	$860,563,572
590	72275000	$875,400,875
600	73500000	$890,238,178
610	74725000	$905,075,481
620	75950000	$919,912,784
630	77175000	$934,750,087
640	78400000	$949,587,390
650	79625000	$964,424,693
660	80850000	$979,261,996
670	82075000	$994,099,299
680	83300000	$1,008,936,602
690	84525000	$1,023,773,905
700	85750000	$1,038,611,208
710	86975000	$1,053,448,511
720	88200000	$1,068,285,814
725	88812500	$1,075,704,465
730	89425000	$1,083,123,117
740	90650000	$1,097,960,420
750	91875000	$1,112,797,723
760	93100000	$1,127,635,026
770	94325000	$1,142,472,329
780	95550000	$1,157,309,632
790	96775000	$1,172,146,935
793	97142500	$1,176,598,126
800	98000000	$1,186,984,238
810	99225000	$1,201,821,541
820	1E+08	$1,216,658,844
830	1.02E+08	$1,231,496,147
840	1.03E+08	$1,246,333,450
850	1.04E+08	$1,261,170,752
860	1.05E+08	$1,276,008,055
870	1.07E+08	$1,290,845,358
880	1.08E+08	$1,305,682,661
890	1.09E+08	$1,320,519,964
900	1.1E+08	$1,335,357,267
910	1.11E+08	$1,350,194,570
920	1.13E+08	$1,365,031,873
930	1.14E+08	$1,379,869,176
940	1.15E+08	$1,394,706,479
950	1.16E+08	$1,409,543,782
960	1.18E+08	$1,424,381,085
970	1.19E+08	$1,439,218,388
980	1.2E+08	$1,454,055,691
990	1.21E+08	$1,468,892,994
1000	1.23E+08	$1,483,730,297
1010	1.24E+08	$1,498,567,600
1020	1.25E+08	$1,513,404,903
1030	1.26E+08	$1,528,242,206
1040	1.27E+08	$1,543,079,509
1050	1.29E+08	$1,557,916,812
1060	1.3E+08	$1,572,754,115
1070	1.31E+08	$1,587,591,418
1080	1.32E+08	$1,602,428,721
1090	1.34E+08	$1,617,266,024
1100	1.35E+08	$1,632,103,327
1110	1.36E+08	$1,646,940,630
1120	1.37E+08	$1,661,777,933
1130	1.38E+08	$1,676,615,236
1140	1.4E+08	$1,691,452,539
1150	1.41E+08	$1,706,289,842
1160	1.42E+08	$1,721,127,145

APPENDIX G: Nuclear Ship PV Acquisition Data for Various Subsidies

25% Subsidy	50% Subsidy	3% Loan
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$79,009,792	$52,854,425	$81,403,163
$672,654,902	$449,979,518	$693,031,017