Strategies for the Success of Nuclear Powered Commercial Shipping

by

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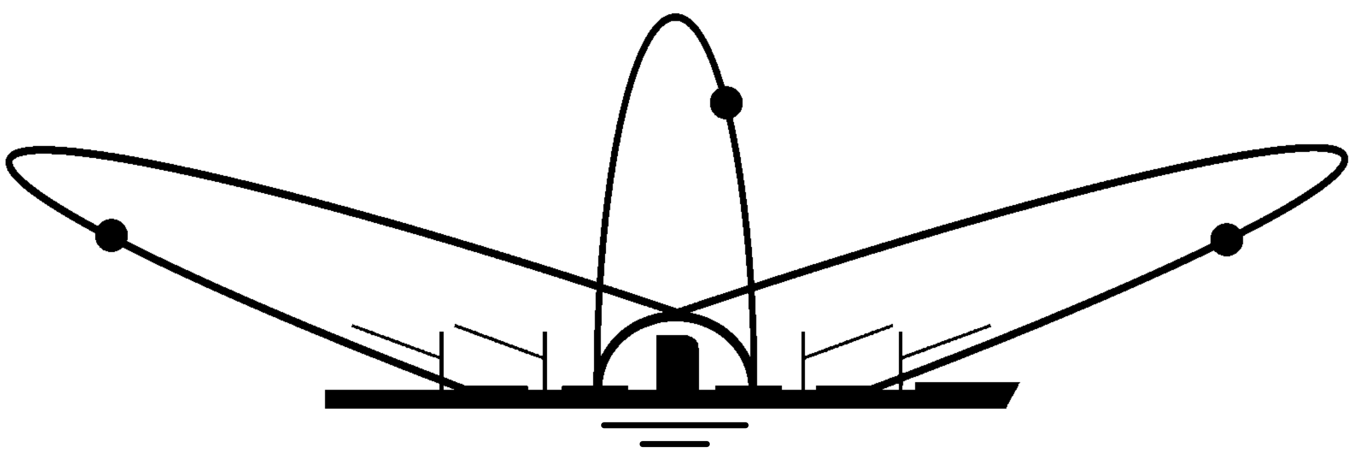

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GENERAL COMMENTS

The majority of this paper's content comes from a variety of sources accumulated by the author from digital files, web articles, blog posts, and conversations with various individuals on the discussed topics. The purpose of this paper is to provide a qualitative discussion of various topics relevant to achieving commercial success with nuclear powered merchant ships.

ABSTRACT

The development of nuclear powered commercial ships has taken on greater importance beyond transporting cargo cheaper. Increasing limitations on Sulfur Oxide emissions from ships has put the global maritime industry on a search for economical ways to meet current and future environmental regulations. With the inevitable development of trans-Arctic shipping, nuclear power is the only means of preventing the phenomenon of "graying of the ice", which is the deposition of black carbon soot particles on snow and ice from oil and natural gas burning engines, leading to increased heat retention and melting. However, unless these next generation nuclear powered ships are cost-effective and can achieve an acceptable level of safety, they will not be deployed and their environmental advantages not realized. This paper discusses in qualitative terms methods for the cost-effective and safe development of nuclear powered commercial ships for world trade, specifically by a United States initiated program. Discussed are changes to the nuclear regulatory model that can alleviate certain economic burdens that ship-sized nuclear reactors may face, and recommendations are made for how industry can actively lower nuclear power's high upfront costs. Emphasis is placed on the development of an inherently safe, wide-market application reactor that can achieve these cost and safety goals.

INTRODUCTION

Conversations about the use of nuclear power for the propulsion of commercial ships are susceptible to knee-jerk reactions regarding safety and economics. In order to move these conversations forward, a modern perspective of these issues and their accompanying solutions is needed. More detailed and informed discussions of nuclear power for commercial ships will help generate enthusiasm and genuine interest by answering peoples' questions, providing exposure to a broad range of topics, and revealing the magnitude of nuclear power's economic potential. This paper is written from the standpoint of a United States initiated nuclear shipping program and is meant to give the reader a starting point for discussing nuclear propulsion. The success of nuclear propulsion will depend on the understanding and utilization of the topics in this paper.

What Nuclear Power Offers the Shipping Industry

The cost of nuclear fuel is low and stable, which means speed is not an economic limitation for nuclear powered ships. While slow-steaming for fossil-fueled ships can reduce costs for the ship owners through lower fuel consumption, the benefits are not necessarily felt by cargo owners unless those lower fuel costs translate into lower freight rates. While time sensitive cargo does not go on ships, there is a certain benefit to getting cargo to the buyers as quickly as possible. Nuclear power can achieve these higher speeds for much lower costs than fossil-fueled powered vessels. Based on the low cost of fuel, the economics of nuclear powered ships will tend towards higher speeds such as 20 knots for bulk carriers, or 30 knots for container ships. Slow steaming is a strategy that evolved relatively recently to lower fuel costs and absorb excess capacity by reducing the number of vessels available at any given time as they are locked up in longer transit times (Jorgensen, 2013). It is not necessarily ideal for the containerized cargo market (Kloch, 2013).

Future environmental regulations concerning fossil fuel emissions place constraints on the types of fuels vessels can burn, raising costs through limited availability (Lloyd's, 2012). Nuclear reactors do not produce these emissions and do not have the same limitations on fuel supply. While radioactive wastes are produced, these are contained within the reactors and are not released into the environment. Nuclear power's most significant environmental advantages is that it will allow for total compliance to atmospheric emissions regulations, and will allow for environmentally responsible transarctic shipping.

Trans-Arctic Shipping

The steady decline of polar sea ice over the last few decades has led to predictions that the North Polar regions will be open to regular marine traffic by at least the middle of the century (sooner if specially constructed ice-breaking vessels are built). This has generated a lot of excitement in maritime industry circles as it provides shorter distances compared to current trade routes, alternatives to the Panama and Suez canals, and represents a new frontier for exploration and development. However, there are challenges and environmental aspects that must be considered.

The production of soot from oil and gas burning engines will be caught in the circumpolar winds of the Arctic atmosphere and eventually be deposited on the snow and ice (Femenia, 2008). Research has shown that seemingly miniscule amounts of soot can increase the heat retention of snow and ice, leading to increased melting (Hansen & Nazarenko, 2003). **This is an issue independent from CO2 emissions.** Ice loss in the arctic is prone to being a positive feedback loop where as more ice is loss, the region warms up due to the increase in absorbed sunlight, which results in more ice loss and the situation is worsened (Hansen & Nazarenko, 2003). The presence of hundreds, if not thousands of hydrocarbon burning vessels in the Arctic region would lead to substantial ice loss **independent from concerns regarding anthropogenic CO2 emissions.** (Arctic Marine Shipping Assessment, 2009)

The use of natural gas is not a silver bullet for this issue because the lubricating oil in the cylinders of diesel engines will be burned and also produce soot (Femenia, 2008). It does not take a lot of soot to increase the heat retention of ice. Nuclear power is the only way to avoid this potential environmental damage while still remaining economical.

Another aspect of utilizing nuclear power for transarctic vessels is the disproportionately lower fuel cost of nuclear fuel compared to liquefied natural gas and fuel oil, allowing for higher powers and operating speeds. There is a considerable amount of extra power needed to break through several feet of ice. Because the transarctic ships will be susceptible to bad weather that can delay their voyages, higher open-ocean speeds will be needed to make up the lost time. Nuclear power can achieve these speeds much more cheaply due to its lower fuel costs.

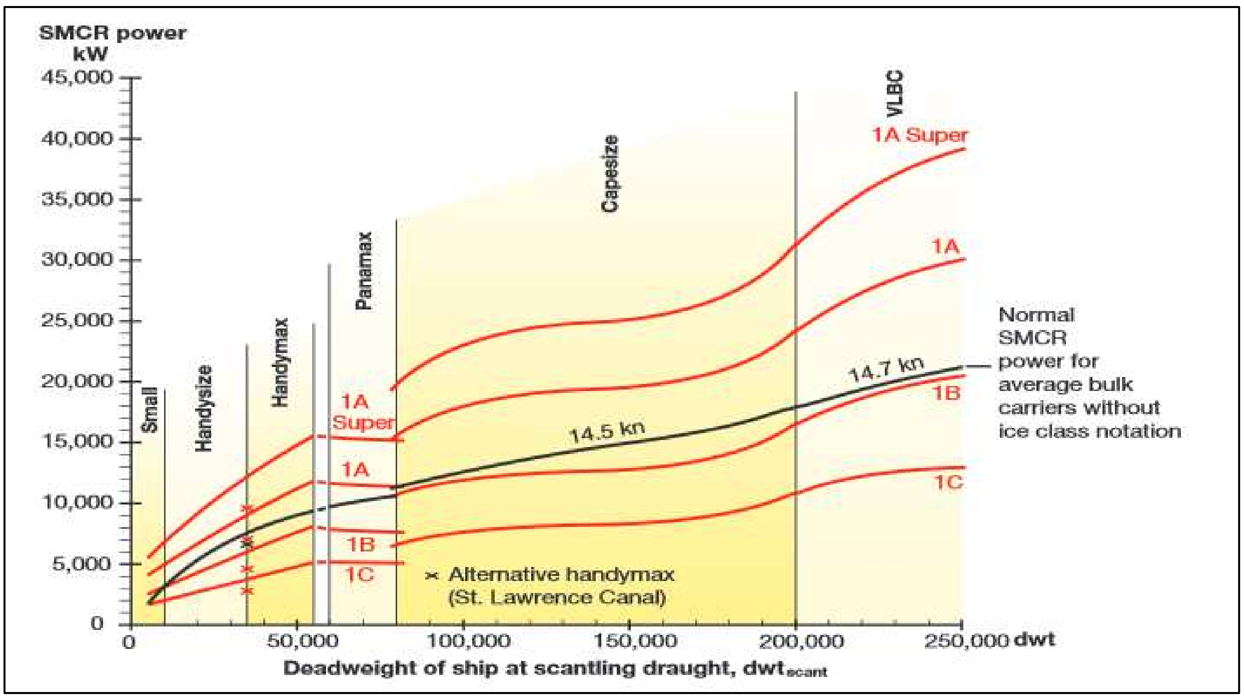

Figure 1 - Minimum required propulsion SMCR power for average size bulk carriers with Finnish-Swedish ice-class notation for Controllable Pitch propellers (Fixed Pitch propellers add +11%). The red lines represent the power requirements of ice-class vessels. Generally, ice-class vessels generally require more power than standard vessels, in some cases, twice as much. Graph taken from MAN Diesel's *Propulsion Trends in Bulk Carriers.*

Hazards of Nuclear Power for Ships

Nuclear power has its own safety and environmental considerations. These are mostly tied to worst case scenarios where some part of the reactor is compromised, leading to the release of radioactive materials into the environment. Our current experience with "meltdowns" is not an inherent feature of nuclear power, but of fundamental reactor design. It is possible to design reactors so the release of radioactive materials in the worst types of accidents are minimized and even prevented (Horstman, 2007).

For a brief discussion of radiation health effects, see Appendix A.

Safety considerations with nuclear powered commercial ships are primarily focused on reactor design and safety systems. Key topics are safety of the reactor during accident situations and what happens to the reactor if the vessel sinks. Meltdowns and radioactive emissions can be averted through proven reactor designs. Current practices for protecting the engine spaces during cargo fires will likely suffice for marine reactors, especially since nuclear reactors do not contain flammable hydrocarbons. If a ship is fetched up on the rocks with a broken back, as long the engine space is still intact, a properly designed reactor will not pose any greater threat than the hazardous cargo the ship is already carrying (which may have already spilled into the ocean). The exact behavior of a ship's nuclear reactor after a sinking, however, is a topic that requires further research. Recovery of the cores may have to be factored into the design and arrangement of the reactors aboard vessels, but the world's marine salvage industry has proven itself up to such a task (Titan Salvage, 2013). Safety is paramount in any industrial operation and further research into modern nuclear powered commercial ship safety will likely yield encouraging results.

Boundaries to Progress – Economic, Technical, and Regulatory

The first nuclear powered cargo vessel was launched in 1962 by the United States of America. This ship, the *NS Savannah*, was not meant to be economical, but a technology demonstrator for the new method nuclear marine propulsion and a way of developing the port-entry protocols for subsequent series of economical nuclear powered cargo ships (Adams, 2011). The *Savannah* was a success in this respect; it did exactly what was intended and once its mission was complete, there was no longer an economic reason to operate a first-of-a-kind technology demonstrator (Koehler, 2013). Germany and Japan each built a nuclear powered commercial ship of their own and achieved similar results. The exception is Russia who has been operating a series of highly successful nuclear powered ice breakers in the arctic for the past few decades and a nuclear powered LASH carrier which has been operating since 1988. The Russians' use of nuclear power for their icebreakers reflects the demands imposed by their arctic operating environment, but their ships are restricted to Russian territorial waters, so the Russian experience does not represent true commercial nuclear shipping.

The NS *Savannah* was a demonstration success that laid the foundation for future nuclear powered ships, but the year is now 2014 and the amount of nuclear powered cargo vessels plying the world's oceans today is effectively the same as it was 40 years ago; none. If nuclear power is economical and safe for ships, and if a wide range of countries did accept the *Savannah* into its ports, why has there been so little progress? There are four reasons why nuclear power for commercial ships has made almost no material grounds:

1. The nuclear industry up until now has built itself into a small corner of the market by only building gigantic utility plants. Ships have power requirements many times smaller than this, so there have been no available reactors to purchase, let alone to do the full design and safety analysis needed for ships. While some marine nuclear reactors have been proposed in a multitude of studies, with at least one being fully designed in the 60s as a standardized marine nuclear propulsion plant[1], building a specifically sized reactor with a small production volume is economically prohibitive.

[1] This was the Consolidated Nuclear Steam Generator designed by Babcock & Wilcox in the 1960's.

2. The cost of fuel is nuclear power's key advantage, but only relatively recently has the cost of oil has only become significantly higher than nuclear fuel. This widens the number of ship types nuclear power can be economical for compared to in the past. For example, this lack of fuel price differential, and the corresponding lack of availability of nuclear reactors, likely discouraged the use of nuclear propulsion for the SL-7 class of high-speed fuel oil burning container ships that were built in the early 70s, whose economics were destroyed by the OPEC oil embargo in 1973.

3. Lack of confidence in investors that any nuclear related project will be protected from political opposition or clever public delays, such as was the case for the Shoreham nuclear power plant debacle (Cohen, 2004). And finally;

4. Most studies have focused on high-speed applications in which the transit times are well above industry standard. Such low transit times may not have strong enough customer bases that will pay the higher premiums, even if a nuclear powered service is significantly cheaper than a fossil-fueled equivalent. Such high-speed services are able to absorb the costs of purpose-built maritime nuclear reactors, but only if there is demand for such services, which remains to be determined.

Figure 2 – The SL-7, as depicted above, would have been a good candidate for nuclear power. Nuclear propulsion probably was considered for this class of high-speed container ships, but conventional propulsion was ultimately selected, likely due to the lack of price differential between nuclear fuel and oil at the time. The class's economics were destroyed by the rise of oil prices in the 1970's following the OPEC oil embargo and the ships were sold to the U.S. Navy. The stability of nuclear fuel prices would have prevented this outcome.

With current fossil-fuel prices, it is possible to devise economic scenarios where nuclear power is competitive against industry standard ships. This requires overcoming nuclear power's higher capital costs, which in some cases can eliminate the fuel cost advantage that makes nuclear propulsion attractive in the first place. This is why most studies have focused on high-performance services.

Nuclear reactors will probably always have higher upfront costs compared to diesel engines, but these costs do not need to be prohibitively so. Technical factors make nuclear reactors more expensive, but there are also regulatory forces at work, namely those of nuclear quality controls and the costs of licensing the design.

American Opportunities in Nuclear Power

Nuclear powered vessels have inherently lower operating costs compared to conventional vessels. The United States cannot build a conventionally powered ship that is cheaper than one built in a foreign shipyard because there is no operating cost advantage for the U.S.-built ship. There is, however, a significant operating cost advantage to nuclear power, which may be enough to make American shipyards competitive. There are several areas where the U.S. could gain the upper hand in the development of nuclear powered commercial vessels, which no other countries at present seem to be pursuing at all. They are:

Construction of marine reactors,
Refueling and maintenance of nuclear powered ships,
Manning and training of nuclear merchant ship crews, and
Construction of nuclear powered commercial ships.

The first two areas will always require detail and expertise and are activities that cannot be offshored for cheaper labor. The United States' current experience with the refueling of nuclear reactors in shipyards will allow U.S. shipyards to gain the productivity they need to reduce their costs and achieve competitiveness in that area. The latter potential, that of building nuclear powered commercial ships in U.S. shipyards, requires further elaboration.

The reason for America's uncompetitive, surprisingly overpriced shipbuilding costs compared to foreign shipyards is not just higher labor and materials costs (Bureau of Labor Statistics, 2011). It is a combination of lack of productivity and inefficiencies in the corporate and labor structures (Hansen M., 2012). In some cases, the maintaining of high overheads to acquire complex naval contracts may also negatively affect certain shipyards abilities to perform commercial work.

Nuclear powered ships could potentially be built in U.S. shipyards and carry the U.S. flag because their operating costs are inherently lower compared to fossil fueled vessels. Along with this, there is an environmental advantage associated with nuclear power in the arctic for which a premium could be paid. By making the most of these cost advantages, a series of nuclear powered ships could be designed and built in order to give American shipyards enough orders to increase their productivity and reduce their costs, allowing subsequent nuclear powered vessels, ranging from bulk carriers to container ships, to be even more competitive against their foreign counterparts.

Costs must be Lowered

Nuclear power cannot rely on the costs of fossil fuels alone. Although fuel price is the primary economic advantage, nuclear power has to actively seek measures to reduce its capital costs. This can be accomplished through a combination of technology, manufacturing practices, and changes to current nuclear regulations (Hopf, Jan 2013; July 2013). The application of a passively safe (cannot meltdown), wide market reactor that can be factory built can help achieve the needed cost reductions and safety goals necessary to make nuclear power economical against conventional propulsion.

The following sections discuss in qualitative terms strategies for achieving safe and economical nuclear powered commercial ships.

NUCLEAR REACTOR CONSIDERATIONS

Safety

The first step towards nuclear powered commercial ships is having available nuclear reactors that can be used on ships. There are none currently for commercial use. The first consideration for these marine usable reactors is safety.

Any ship must be able to be abandoned by its crew. Regardless of cargo or the propulsion plant, provided the crew has put the ship into a situation where more people will not be harmed, Safety of Life at Sea must always have priority. When the safety of nuclear commercial ships is discussed, it is the health of the public and environment at large that are of concern and not the crews of the ships. This is not correct for judging the safety of a ship. A higher standard needs to be set and that is the characteristics of the reactor are such that if any nuclear powered commercial ship has a collision or cargo fire, the first question we ask is not, "What of the reactors," but, "Is the crew safe?" The crew of any nuclear powered ship must be able to shut down the reactors and abandon the vessel in a state in which the world never has to worry about a meltdown or nuclear accident. This is possible through the proven concept of passive safety, where the reactor does not need active cooling to prevent meltdowns. It is possible for radioactive materials to be released under exceptional circumstances, such as prolonged military bombardment or intentional, elaborate destruction of the reactors, but these are situations that do not occur for commercial ships.

Current pressurized water technology, as the world's nuclear navies uses on their submarines and as used in current electricity generating plants, does not allow passive safety in the case of meltdowns. A meltdown is where the temperature of the nuclear fuel elements becomes high enough so that damage to the core begins to occur and fission products begin to be released. Upon shutdown of these reactors, there is sufficient decay heat to heat up the fuel elements. Unless this heat is removed through active means, such as using diesel engine-driven pumps on a ship, a meltdown will result. Where these land based utility reactors have the advantage is that people can return to them rather easily in the event of an accident; they do not roll-over, disappear beneath the waves, or fetch up on the rocks beneath a storm beaten cliff. Emergency equipment cannot be brought to a ship very easily. Wrecked ships can spend days before emergency services arrive, or weeks before any serious salvage attempt can be made. It is not likely that a nuclear powered commercial ship will be able to sustain such active cooling for so long, or that the public and regulators will accept such unnecessary risk to its mariners when better, passively safe options exist for marine nuclear reactors. Therefore, **only reactors that <u>cannot</u> meltdown should be considered for marine nuclear propulsion.**

Figure 3 - Photographs of the MOL *Comfort,* the container ship that broke in half off the coast of India in 2013. Such a situation is generally avoidable through proper materials and construction, but it will have to be considered for nuclear powered ships. A nuclear powered container ship could one day face a similar situation as the MOL *Comfort* and so the reactor onboard needs to be incapable of a meltdown. Only reactors that cannot meltdown should be considered for commercial nuclear shipping.

Suitable Reactor Types

Several types of reactor technologies exist that can achieve the necessary safety goals while still being appropriate for installation aboard ships. They are the High-Temperature Gas-Cooled reactor and the Molten Salt reactor. While it may be possible to design other reactor types, such as Pressurized Water reactors or Liquid Metal-

Cooled reactors, to achieve passive safety in a shipboard setting, the necessary features might not be suitable or economical for ships, if the features of the passively safe NuScale pressurized water reactor, or the Toshiba 4S liquid metal-cooled reactor are any indication (NuScale, 2014; Toshiba 2013). Those reactors are intended for land based electricity generation and not for any use at sea. In this case, the time honored maxim applies, “What works well at sea works well on land,” but not the other way around (Crommelin, 2013).

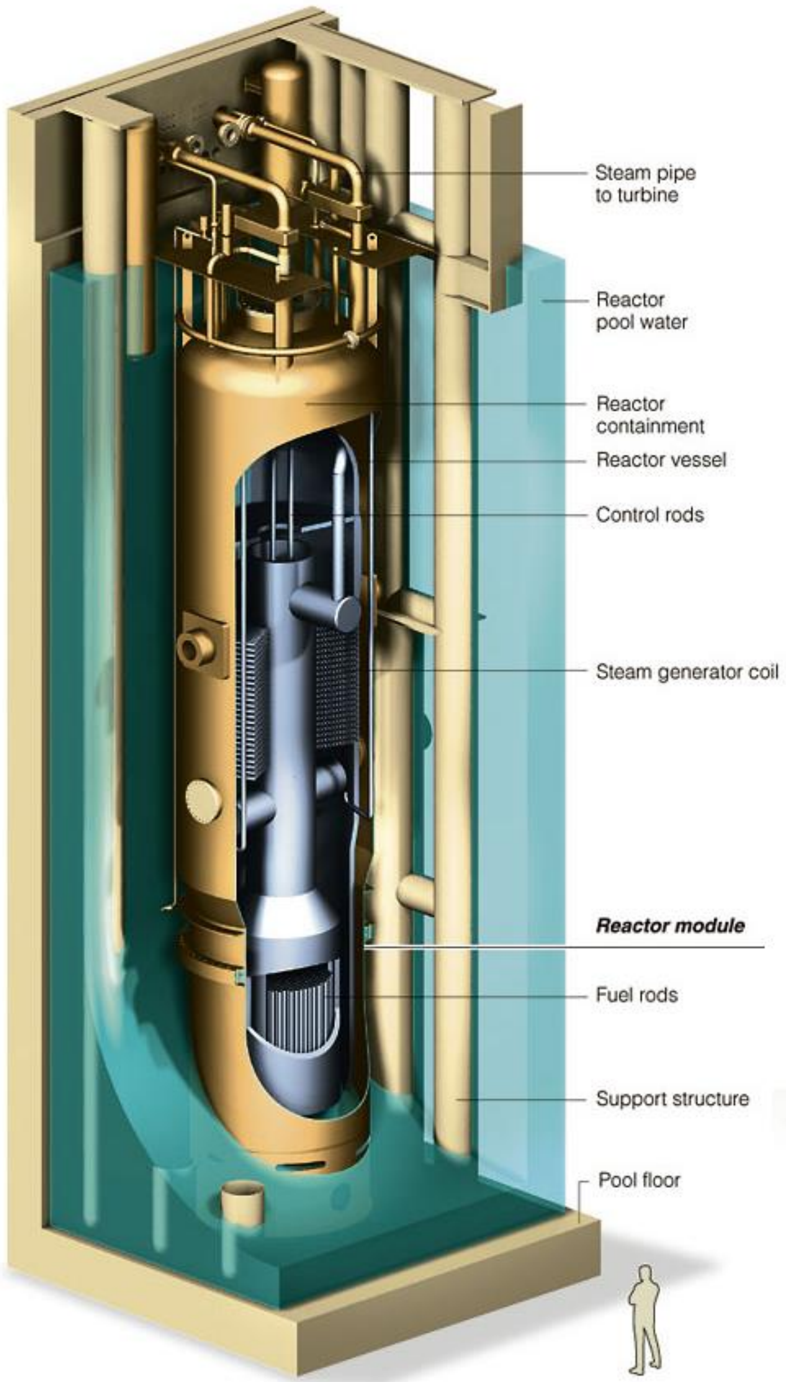

Figure 4 - The NuScale pressurized water reactor. Despite receiving funding from the Department of Energy, many of its characteristics make it unusable for ships, such as its “in ground” construction, immersion in a column of water for passive removal of decay heat, its height, and its use of passive circulation of the coolant water, which could be interrupted by the rolling motions of a ship.

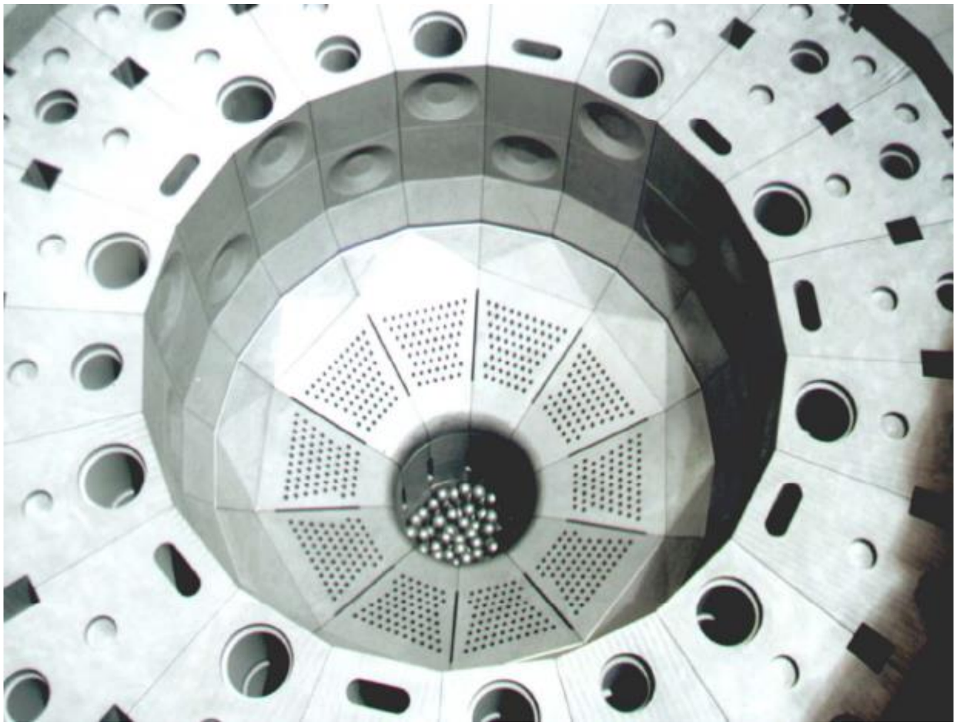

Figure 5 – A partially fueled core of a High-Temperature, Gas-Cooled, Pebble Bed reactor. The fuel elements are graphite spheres which are stacked to form a porous “bed”, as is partially shown in the image above. The perimeter of the pebble bed is some form of neutron reflector, allowing the fission reaction to sustain itself. The passive safety features of gas-cooled reactors make them suitable for marine use. Image above courtesy of the HTR-10 project from Tsinghua University, China.

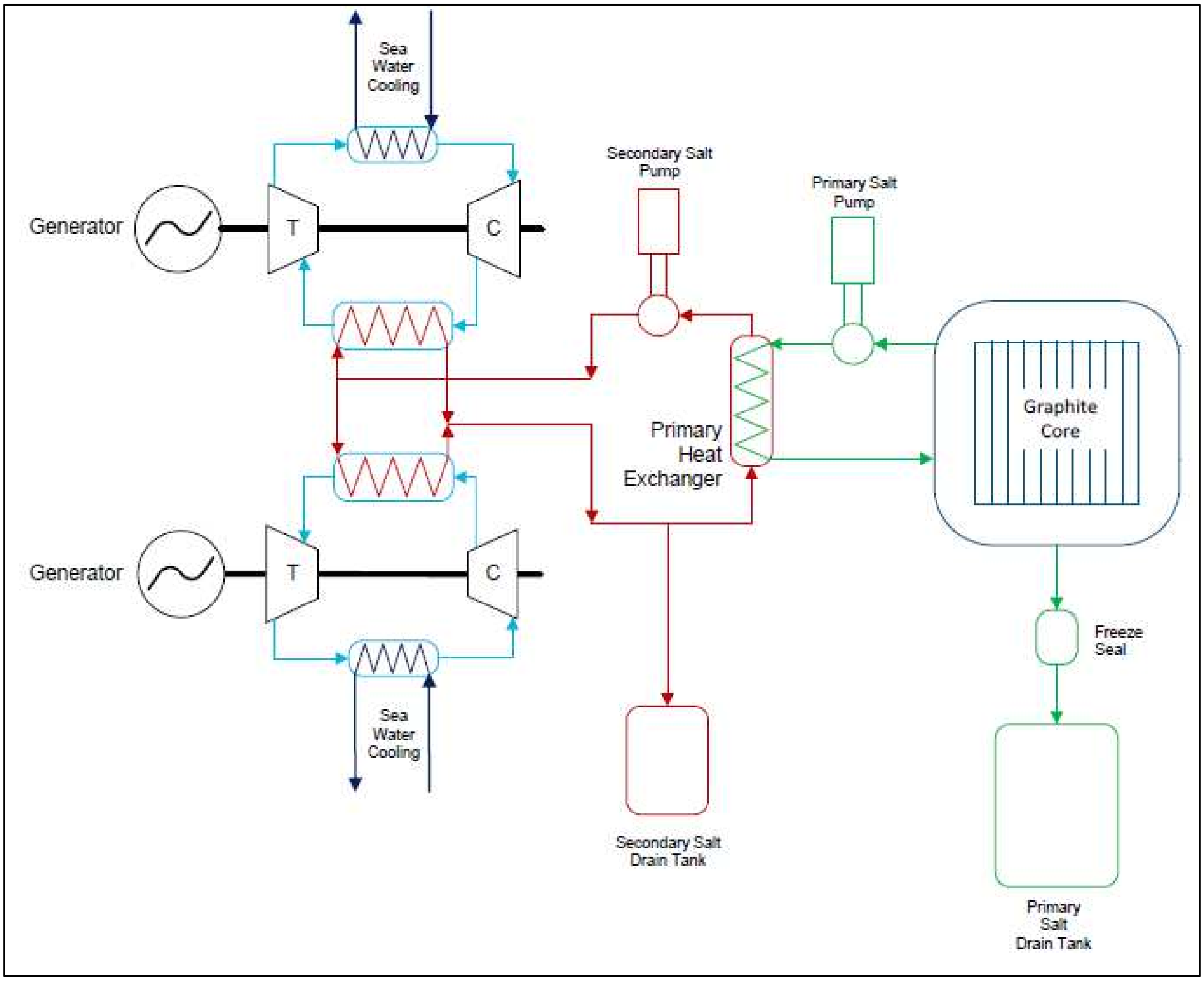

Figure 6 - Diagrammatic view of a marine Molten Salt Reactor plant. The machinery can either be steam or gas turbine, as depicted. The nuclear fuel atoms are dissolved into a "salt" that becomes liquid when heated. The liquid fuel-coolant mix is driven by pump through the core where it becomes critical, whereby it then leaves the core and no longer fissions until it passes through the core again. The fission products are contained within the salt coolant. In the event of an emergency, the liquid coolant is drained into a tank where it solidifies and expels its decay heat through natural means (surface area of the tank, integrity of the fuel). Image taken from BMT Defense Services *The Potential of the Molten Salt Reactor for Warship Propulsion* (Hill et al., 2012)

Passive Safety

Gas-cooled reactors achieve passive safety through size and surface area of the core. Depending on their design, it is impossible for gas-cooled reactors to meltdown upon shut down because natural means are all that are needed to remove the decay heat from the core. Molten salt reactors achieve the same passive safety through similar means. In both cases, the fuel elements are also able to maintain integrity at very high temperatures, so while the temperatures of the cores of molten salt reactors and gas-cooled reactors may become very high in accident conditions, fission products will not be released (Adams, September 2013). The crews of ships powered by these reactors can abandon their ships and no dangerous nuclear related events will occur.

Power excursions (loss of control of the fission reactions) are prevented by designing the cores so that a rise in temperature results in a decrease in power (Sorensen, 2006). This happens because as the fuel elements increase in temperature, they expand, so neutrons have a greater chance of missing fuel atoms (the neutrons are absorbed by the non-fuel components in the core, the biological shielding, or simply escape the reactor).

The gas-cooled reactor in particular is most suited for the first iteration of modern nuclear commercial ships due the relative simplicity of their systems and pre-existing foundation of research. Molten salt reactors have their own advantages, but will be realized in later generations of ships once the technology has matured.

Economics

Both gas-cooled reactors and molten salt reactors have the potential to be the most economical types of small reactors (Nordhaus et al., 2013). While gas-cooled reactors do require pressure vessels and high-temperature materials, these pressures are concurrent with typical steam boilers and the relative simplicity of their safety systems offset the additional costs. Molten salt reactors are able to operate at near atmospheric pressure, eliminating the need for heavy, pressurized components altogether. Further research, however, must be done on molten salt reactors in terms of their operating and maintenance since the coolant will eventually contain a large diversity of elements (the fission products) and, if cooled down, will solidify inside the pumps and pipes. The coolant of a molten salt reactor must first be drained out of the system, or reheated back to liquid. Both molten salt reactors and gas-cooled reactors are able to operate at high thermal efficiencies, leading to lower fuel costs compared to current light-water technology.

But nuclear reactors are already expensive. Just being “cheaper” than current costs, which are already high, is not enough. In order to make these passively safe marine nuclear reactors cheaper, let alone get them developed at all, certain economic strategies must be employed. These strategies are: developing a marine reactor for a wide-market, standardizing the design, and factory construction and testing. This means the size of the reactors need to be based on finding a medium between the power requirements of ships and the demands of the other available markets. Commercial ships will most probably have to utilize pre-existing reactors because developing a limited range of appropriately sized reactors for a select few ships is not economically feasible. What diesel engine manufacturer, for instance, bases their business model on purpose building custom diesel engines? None.

Ships may have to install multiple smaller reactors to achieve their economical service speeds because a small reactor might have the greatest chance of actually being realized. There are advantages and disadvantages to this concept. **However, the clear advantage of such a scenario, that of adapting a wide-market land based reactor to maritime use, is that the reactor exists at all.** Nuclear commercial shipping, and all the safety and risk analysis needed to achieve it, depends on having a suitable nuclear reactor.

ECONOMICS

Empirical Case for a Wide-Market, Small Reactor

Nuclear reactors and their fuel elements are manufactured products, so the cost control practices used in the manufacturing industries also apply to the construction of marine nuclear reactors. These practices include large production runs, centralized manufacturing, and appealing to as wide a market as possible.

The following section will discuss strategies for achieving an economical marine nuclear reactor based on developing a product that can compete with the diesel engine.

Case Study – Diesel Engine Manufacturing

The marine diesel engine manufacturer Wartsila is a leader in its field. It is currently establishing considerable market share in the land side power generation market where close variants of its marine diesel engines are being used to generate electricity ashore (Wartsila, 2013). This is not necessarily a required market for Wartsila's business model because they already have access to the entire maritime industry, which is tens of thousands of ships strong. Marine nuclear reactors, on the other hand, will not initially have access to the complete maritime market, so it will be *necessary* for marine nuclear reactors to appeal to the land market as well. The designs of these marine reactors and their companies' business models must achieve wide market potential to gain interest from private investment.

Figure 7 - Wartsila engines manufacturing incorporating line and centralized assembly. These practices can be applied to construction of marine nuclear reactors and their associated machinery. Image courtesy of Gcaptain.com

The manufacturing of marine diesel engines utilizes the full range of cost control practices that can also be applied to marine nuclear reactors. The author has personally been to one of the major diesel engine manufacturer's factories and witnessed these techniques in action. One of the more significant aspects of the manufacturing of diesel engines that must be applied to marine nuclear reactors is factory testing of the fully built engines. If necessary, marine nuclear reactors will be loaded with a core and tested at the factory before being transported to the shipyard for installation on the ship.

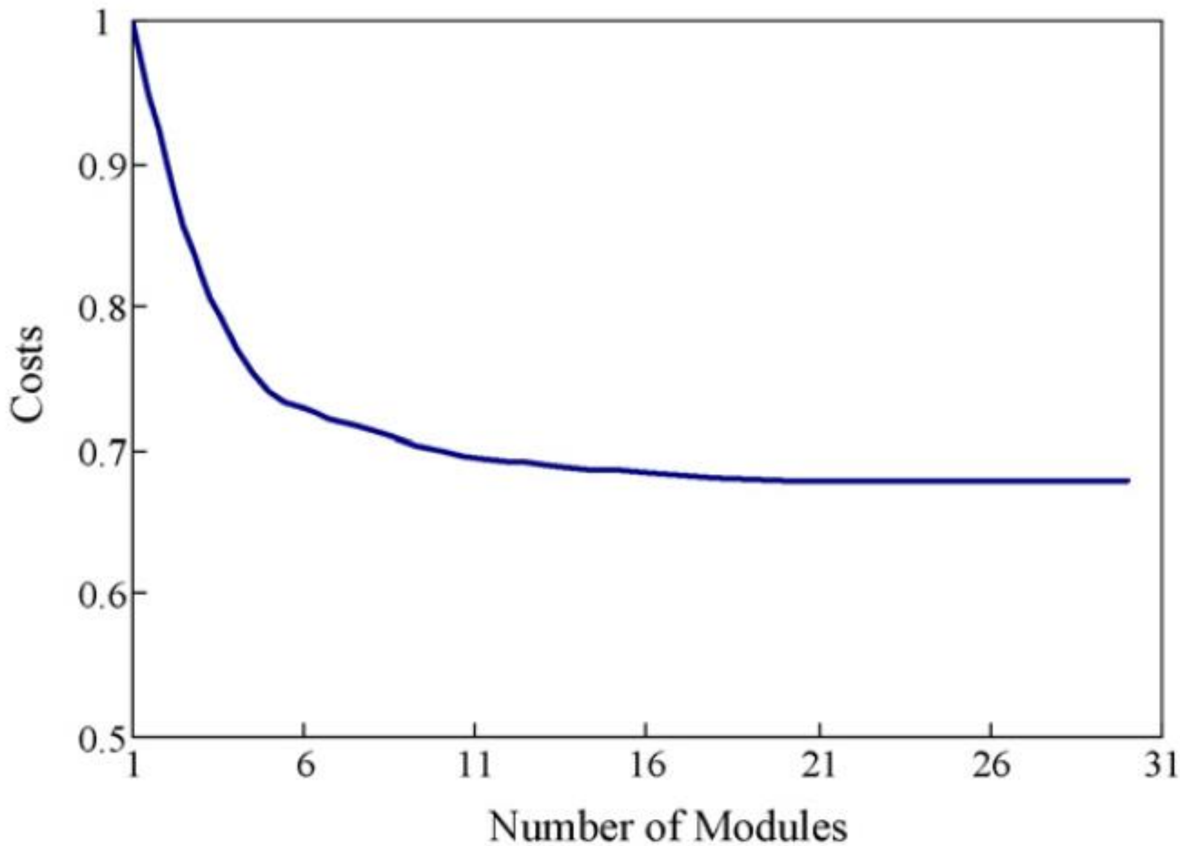

Figure 8 - Typical learning curve, which is a form of economy of scale. The curve represents that costs are reduced with each subsequent construction, so large production runs are very important for achieving Nth-of-a-Kind costs for manufactured goods. The cost of the first item is usually the "First-of-a-Kind" cost. This is how marine nuclear reactors will achieve economies of scale.

To what extent efficient production practices will reduce the costs of small nuclear reactors is currently unknown, **but centralized fabrication, standardized production, and wide-market availability must be utilized for the production of small nuclear reactors.**

Non-Maritime Targeted Markets

Markets where oil and natural gas are the primary source of power generation would be the focus of sizing a wide-market marine reactor that can also be used on land. This is because the key economic advantage of nuclear power is the dramatically lower fuel cost, and in some cases, its minimal infrastructure to support its operation. These are the precise markets which the diesel engine and gas turbine manufacturers appeal to. The relatively high cost of fossil fuels in these markets makes nuclear power ideal because oil and natural gas throughout the World are currently much higher in price than nuclear fuel. Another advantage of nuclear power in these applications is the minimal infrastructure needed to support its operation, compared to regular truck deliveries of diesel fuel or natural gas pipelines.

The objective should be to develop marine reactors that can also replace the diesel engine and gas turbine in shore based applications. Some of these other applications, other than electricity generation, include local power production for industrial sites such as mines, chemical plants, and water desalinization facilities. High-temperature gas-cooled reactors can be well suited for these isolated industrial sites because of their lack of use of water for their cooling or power cycles.

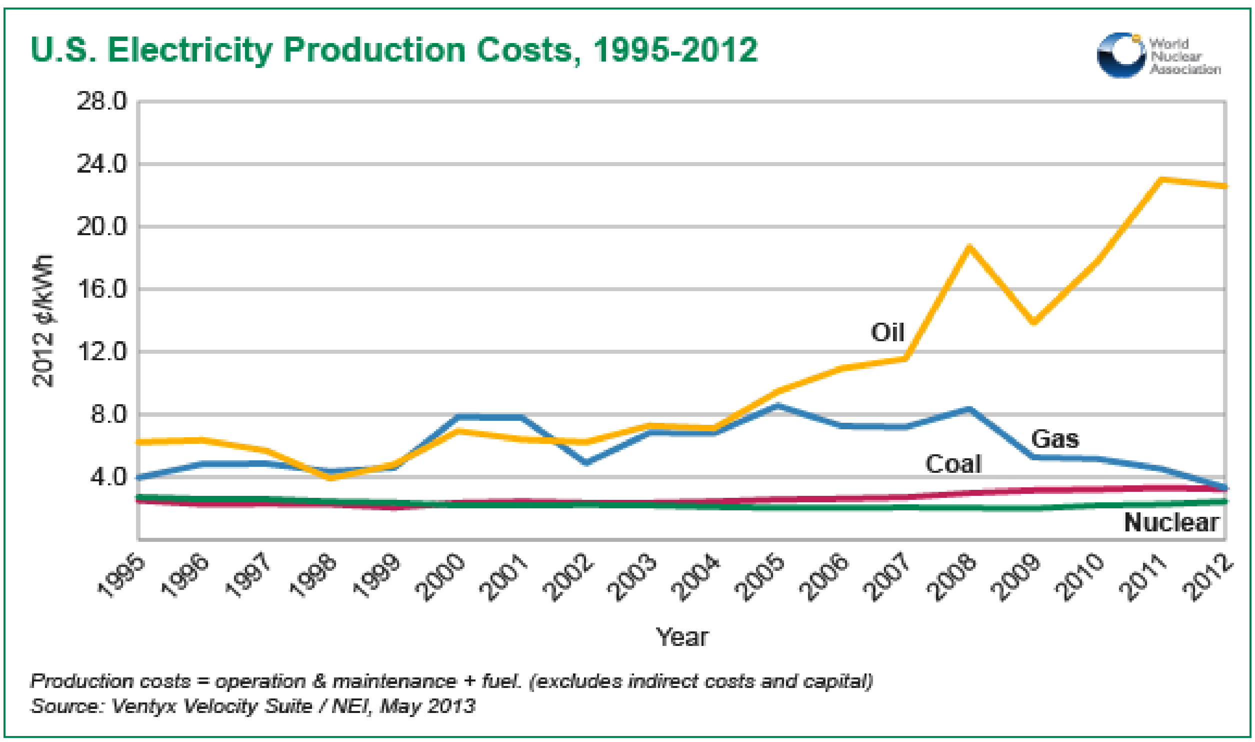

Figure 9 - U.S. Electricity Production Costs (excluding indirect costs and capital). The operating cost of oil based electricity generation in the United States greatly exceeds all other forms of power generation.

Figure 10 - Cost of Natural Gas overseas in $ USD/mmBTU. The price of natural gas throughout much of the world is on par with that of oil, making nuclear power potentially competitive.

Examples of Small Reactor Applications

Wartsila provides several examples of where its diesel engines are being used for the purpose of electricity generation using oil and natural gas (Wartsila, 2013). Small ship-sized nuclear reactors could be used in these applications, in which case the annual fuel costs savings for each were calculated based on the estimated costs of oil and gas in their regions. The first example is from Indonesia, which generates a significant portion of its electricity from burning oil and natural gas. The annual savings in fuel for the small power plant presented below was estimated to be **$10 million USD** for a natural gas price of $15/mmBTU, a nuclear fuel price of $2.2/mmBTU, and a capacity factor of 90%.

Figure 11 - Small power plant in Indonesia running on natural gas. A small, ship-sized nuclear reactor could be used instead. The annual fuel cost savings could be upwards of $10 million USD per year.

The second example is from the Dominican Republic showing a floating, barge mounted power generation plant using six small diesel engines. Floating nuclear power plants are directly related to a nuclear shipbuilding program. The annual fuel cost savings from nuclear power were estimated to be **$75 million USD.**

Figure 12 - A floating power generating station in the Dominican Republic where multiple small nuclear reactors could be used instead of diesel engines. Such a construction is directly related to a nuclear shipbuilding program. The annual fuel cost savings from nuclear power are estimated to be $75 million USD.

REGULATORY COST REDUCTIONS

Even with the above manufacturing and economic strategies in place, cost reductions from the regulators will likely still be needed to compete with the diesel engine.

Regulatory Needs

The need for regulation comes from the understanding that, in order to attain the benefits of a technology, it must be executed safely and economically. Because nuclear power is not an inherent hazard to public health or the environment, as made apparent by its miniscule waste volume, lack of emissions, and economic opportunities, it has certain benefits that *should* be realized. Nuclear regulations, like all other regulated industries, needs to achieve a balance between cost and safety. Nuclear regulations must be in place in order to ensure the safe use of nuclear technology because repeated accidents, even if small, can lead to a loss in public confidence in the technology, which negatively impacting its acceptance in the market place. Even with safety realized, however, the benefits of nuclear power will never be realized if it is too expensive. **The subject of cost for nuclear powered ships is just as important as safety, so the influence of nuclear regulations on the cost of nuclear power must be considered.**

Influence of Regulations on the Cost of Nuclear Power

Nuclear regulations contribute a significant cost to the deployment of new nuclear technologies (Bullis, 2013). In the area of “permits, licenses, amendments, renewals...” the U.S. Nuclear Regulatory Commission (NRC) publishes that the costs for those services will be calculated using a “professional staff-hour rate of $272 per hour”. This includes the costs for approving the design of a marine nuclear reactor and likely elements of the design of the nuclear powered ships. These costs are heavily time dependent, so the licensing, approval, inspection, etc. processes must be streamlined and minimized.

In the case of the construction of nuclear reactors, the greatest influence is from nuclear specific quality controls. An example of these regulatory influences is the sharp rise of the cost of constructing a nuclear power plant in the United States following the Three Mile Island accident in 1979. This cost escalation, while also affected by inflation and rising costs in general, can be greatly attributed to the increase in labor costs associated with quality control engineers needed to meet the additional regulations following the U.S. NRC’s response to Three Mile Island (Cohen, 2004).

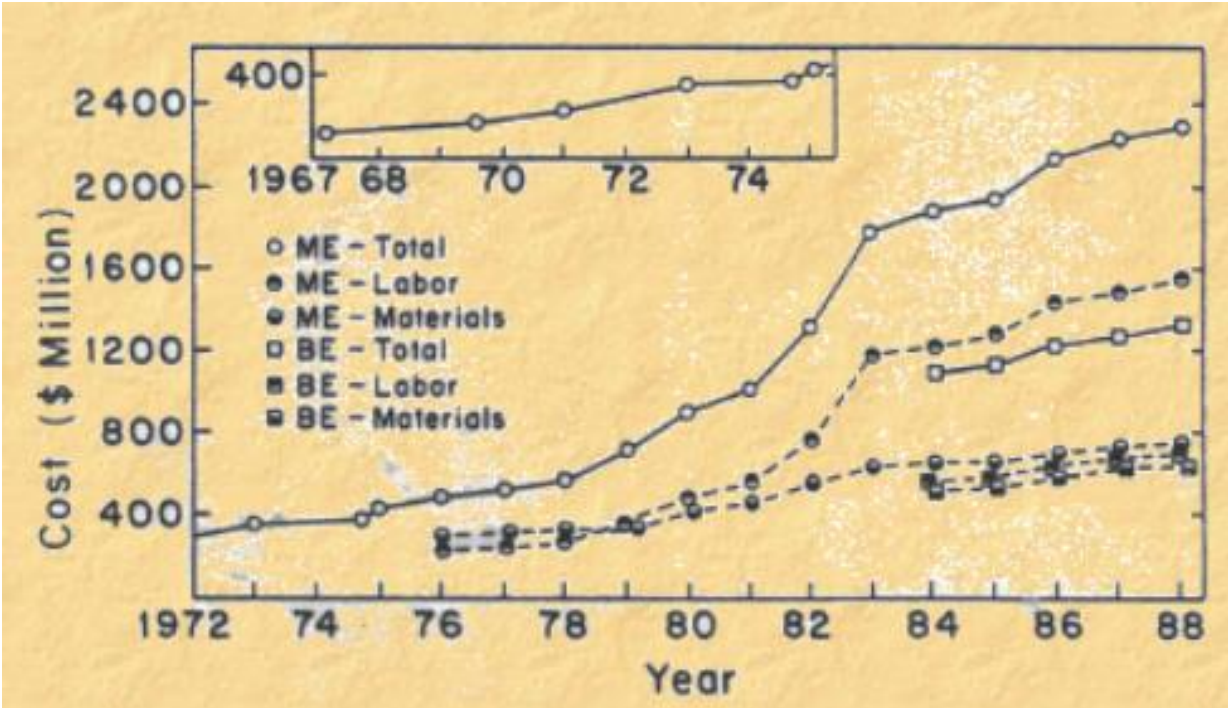

Figure 13 - Graph taken from Bernard L. Cohen's book *The Nuclear Energy Option*. The EEDB cost (the actual cost if the plant were built in a very short time) of a 1,000,000 kW nuclear power plant as estimated by United Engineers in various years. M.E. is median experience; B.E. is best experience; Total is labor plus materials (see text for explanation). These costs do not include escalation or interest on funds used during construction (Cohen, 2004).

Nuclear regulations are significantly a matter of quality controls and documentation, which are attached to labor costs. An example of this in the modern era are the delays faced by the current construction of two nuclear reactors in South Carolina caused by missing documentation for the manufacturing of certain components. The documentation was to have been provided by a subcontractor who was new to the nuclear field and unfamiliar with the requirement to document every step (Jones & Pavey, 2012). The delays in South Carolina caused by missing paper work may amount to the reactors being 12-18 months behind schedule and a reduction in economic benefit to the area by $1 billion dollars, because of the delay (Jones & Pavey, 2012).

Having the right business model and the most efficient production practices may not be enough to ensure the economical adoption of nuclear powered commercial ships. The area of nuclear quality controls also needs to be a source of cost reductions.

Nuclear Quality Controls

The author cannot provide specific values for the influence of nuclear quality assurance on the construction of current nuclear reactors. It is likely that the construction of nuclear powered commercial ships will, at least for the machinery spaces, be considered to require similar oversight to the construction of a land based nuclear reactor building. Despite this, anecdotal evidence can be provided to give an idea on these costs and potential solutions for reducing them.

In an article about Small Modular Reactors (SMR's), a frequent writer for the American Nuclear Society wrote in a comment that a co-worker informed him that nuclear-grade carbon steel costs about five times more than equivalent steel for other non-nuclear applications (Hopf, March 2013). Paper work and lack of suppliers were cited as the reasons for this cost differential. This steel is apparently used extensively throughout nuclear power plants.

The recommendation from that article is that a research program should be funded to determine what is making nuclear power's construction and capital costs so high, and then act on reducing them. The results from such a study would have major implications for the quality control requirements of marine reactors, their installation aboard vessels, and the quality controls needed for the shipyards. The following quotation explains the writer's plan:

"*There should be a significant area of research devoted to what is making nuclear construction/capital costs so high and what can be done to reduce them. This, after all, is the biggest issue the industry faces. Technology advances would be considered, but more importantly, all current policies, practices, regulations and requirements would be put on the table and subject to a fresh, objective, bottoms-up review to determine their cost effectiveness. Non-cost-effective requirements would be discarded. New requirements would be considered, if cost-effective.*

In the specific area of component fabrication QA requirements, the use of more typical industrial or commercial QA requirements (as opposed to the nuclear-unique NQA-1 program) would be thoroughly evaluated. Instead of just assuming that non-NQA-1 (e.g., commercial-grade) components WILL fail, the evaluation would study historical failure rates for components fabricated under different (more common) QA regimes. Also, the evaluation would fully consider the nature of the component failures, based (again) on historical records and statistics of how (non-nuclear-grade) components have failed. I've seen evaluations that not only assume that any component that is not verified (by nuclear QA program or dedication) will fail, but will fail completely in a totally non-realistic way (e.g., simply vanish). We must do better than this.

A detailed Probabilistic Risk Assessment evaluation would consider the use of non-NQA-1 or non-dedicated components, based on non-nuclear industry component failure rates and failure modes. The effects of such component failures on the magnitude and likelihood of releases would then be calculated, and those results would be plugged into a cost/benefit analysis. Such an evaluation may allow the use of more common industrial or commercial component fabrication QA requirements for some or most of the components of a reactor (perhaps SMRs in particular, given their very low potential releases). That, in turn, could result in significant cost reductions with little impact on public safety or the risk of financial losses from a release (Hopf, March 2013)."

REGULATORY STRATEGY

NS *Savannah* Experience

Regulation is a significant fraction of the cost and time needed to green light nuclear related projects and so it cannot be glossed over for nuclear shipping. Providing the regulatory agencies with a framework for the nuclear powered vessels is just as important as coming up with an economic scenario (Koehler, 2013). This framework is necessary for expediting the regulatory process and reducing the associated costs. It is also important for giving investors and other interested parties a time frame for the availability of the technology, as well as confidence the project will be accepted. While there is uncertainty regarding *modern* nuclear powered vessels and their entrances to port, there does exist regulatory precedents for nuclear powered ships as created by the nuclear merchant ships *Savanna* (U.S.), *Otto Hahn* (Germany), and *Mutsu* (Japan). For the United States, the experience of the NS *Savannah* is considered the most relevant and should be the foundation for future U.S. flagged nuclear powered vessels. Because this paper takes an American perspective, some of the following ship type strategies were developed based on the *Savannah* experience.

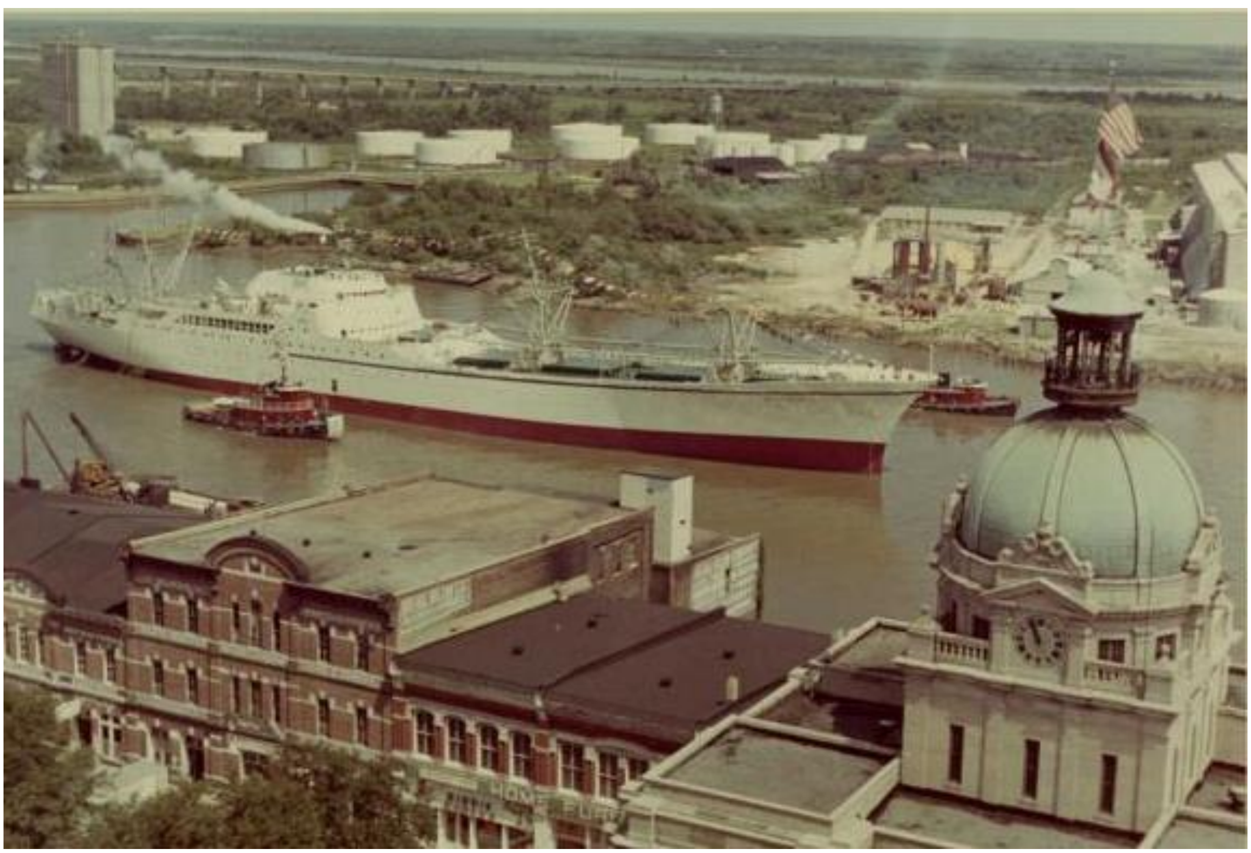

Figure 14 - The Nuclear Ship *Savannah* in the port of Savannah, Georgia. In more general terms, the photograph above represents the acceptance of a nuclear powered merchant ship in close proximity to a major urban center. The reactor of the *Savannah* was capable of a meltdown, but passively safe marine reactors would eliminate that safety concern for future nuclear ships.

EARLY SHIP TYPES

Some of these options do not incorporate the concepts of using a wide-market reactor, or the regulatory experience of the *Savannah*, but these scenarios are useful in showing the areas in which nuclear power could have the greatest economic potential. In general, vessels with high power requirements or those that require cleaner burning fuels by sailing in Emissions Control Areas present the best initial economic opportunities.

Coast Guard Ice Breaker

The United States Coast Guard currently has no experience boarding and inspecting nuclear powered ships. Trade in the Arctic is bound to increase and so a corresponding increase in the area's emergency services will be needed. Nuclear powered ice-class vessels with high-power and long endurance are therefore a possibility and perhaps a necessity for increased trade in the Arctic. America could design and build a nuclear powered ice breaker for the U.S. Coast Guard (Koehler, 2013). The reactor could be designed and built by Naval Reactors, versus depending on commercial availability. This would mean a pressurized water reactor, electric propulsion, and diesel auxiliaries, like a contemporary nuclear power plant. While a meltdown is possible with these types of reactors, the Nuclear Regulatory Commission has considerable experience with this arrangement and so the short term availability of a U.S. Coast Guard icebreaker is very high (Koehler, 2013).

The United States and Canada could work together on such a project because Canada has a strong interest in having effective emergency services available in its Arctic waters. The combined effort would give both the United States and Canadian Coast Guards experience with nuclear power. It would also provide a modern framework for multiple countries working together to regulate nuclear powered vessels.

The key advantages to this concept are providing the nuclear regulators, coast guards, and marine classification societies contemporary experience with nuclear power and potentially improving the United States and Canadas' presence in the arctic.

Ice-Breaking Oil Tanker

The profitability of oil and natural gas will remain for decades to come. Oil will still remain a valuable feed stock for manufactured materials, a machine lubricant, and as transportation fuel. As oil and gas prices rise, reserves in the Arctic regions are starting to become potentially economical. This has led to significant interest in exploitation of these hard-to-reach resources and will, in some cases, require the use of specially constructed ice-class vessels.

In order to avoid graying of the ice from fossil fuel soot, nuclear power is an environmental necessity for the Arctic region. Nuclear power can also be economical due to the higher power requirements that ice-class vessels need to power through ice. Therefore, ice-breaking nuclear powered oil and natural gas carriers are potential early adopters of marine nuclear propulsion.

Figure 15 - The World's first ice-breaking, arctic oil tanker, the SS *Manhattan*. Built in the United States in 1962, the voyage was successful, but the environmental hazards and uncertainties of the route discouraged further developments. The Trans-Alaska pipeline was built instead. Another example of America's ability to achieve technical success when there is an economic incentive. Image above courtesy of Marine Exchange Alaska.

At least one study was performed on this topic in 1978 for a nuclear powered, icebreaking oil tanker service between Alaska, Canada, and the East Coast (Levine & Winall, 1978). Whether or not the study still has relevance today, the design called for 150,000 kW of shaft power to allow for icebreaking at up to 7 feet of ice at its economic speed, and a vessel over 1000 feet in length. Other vessel and route options cannot be provided at this time, but it is likely that the power requirements for such vessels will be rather large to enable icebreaking at economic speeds.

Trans-Arctic Container Ship

Another potential early adopter of nuclear propulsion are trans-arctic container ships, as explored in the paper *Trans Arctic Shipping Using Nuclear Power.* The Arctic region represents an alternate route to the Panama Canal and Suez Canals, as well as potentially faster transit times for the Asia-Europe and Asia-America routes (Femenia, 2008). Graying of the ice must be avoided through the use of nuclear power. Nuclear power is potentially economical in this situation for the United States due to the considerably lower fuel costs compared to conventional propulsion; trans-Arctic shipping has higher power requirements that will be needed for ice-breaking and harsh weather, as well as for the higher open-ocean speeds that will be needed to maintain schedule if delays are faced during the Arctic voyage.

Trans Pacific, High Speed Container Ship

Nuclear power's economics favor vessels that make more round trips, which translate to higher service speeds. High-speed nuclear powered container ships on the Asia-Pacific routes could transport double the amount of cargo per year compared to current vessels. A study was done in 2008 that concluded that a 35 knot New-Panamax container ship on the China to Long Beach run was economically feasible (Sawyer et al., 2008). However, certain issues would have to be addressed for such high-speed nuclear ships. These issues are:

1). Availability of the reactor due to the large power requirements. Such large power requirements are currently beyond anything in the diesel engine market and so the choice of nuclear reactor, or reactors if two or more need to be installed, will not be applicable to the oil and gas power production markets. Either a purpose-built reactor will have to be designed and constructed, or multiple scaled up units will have to be installed.

2). Availability of deck officers with High Speeds Vessel endorsements. While this is not a barrier, the availability of deck officers in the United States with the High-Speed Vessel endorsements (30 knots or more) is currently very limited.

3). China is part of the trade route. China is currently aggressively expanding its nuclear power program and is researching and developing passively safe nuclear technology that could be used on ships, such as the gas-cooled reactor, **but the gas-cooled reactor that China is developing is not usable on ships.** China is a competitor to the United States and since nuclear power is already so much of a political football with great economic and industrial potential, it is not likely that China will passively allow the United States to take the lead in nuclear powered commercial ships without the intention of following suit. This issue is elaborated on in the subsequent section *Building the Ships?*

They key economic advantage in this option is that the nuclear powered container ship is practically doubling its yearly revenue compared to a conventional fossil fueled vessel. It also has a significantly lower transit time, which is a useful service characteristic because shipping errors can be corrected more quickly, which is good for the cargo owners and so can help create an interested customer base.

A high-speed, trans-Pacific nuclear container ship using a single, large pressurized water reactor may have the characteristics presented in Table 1 below (Sawyer et al., 2008).

Table 1 - Summary of principal characteristics for a high-speed, trans-Pacific nuclear container ship servicing California and China. The study was done by the Center for Commercial Deployment of Transportation Technology in California.

SHIP CHARACTERISTICS		
Length Over All	feet	1198
Beam	feet	141
Draft	feet	43
Displacement	tonnes	121,100
Container Capacity	TEU	9,200
Reefer Plugs	No.	700
Speed - Sustained	knots	35
Port Turnaround Time	hours	33
PROPULSION & POWER		
Propulsion Power	SHP	273,000
Number of Shafts	No.	3
Total Installed Power	MWe	280

Nuclear Thermal Power	MWt	1000
Refueling Outtage	days	35 to 40
Refueling Interval	years	5.2

Trans-Atlantic Container Ship Using Multiple Small Reactors

There are two advantages of a trans-Atlantic nuclear shipping service between the United States and Europe: the size of ship is smaller compared to other trade routes, which enables smaller reactors to be used, and all major European merchandise ports were visited by the NS *Savannah.* This precedent means that the protocols already exist for the entrance of nuclear powered ships into all major the ports of Europe, such as Rotterdam, Le Havre, and Southampton, all of which were visited by the *Savannah.*

N.S. SAVANNAH
PORT DEMONSTRATION VISITS
1962 - 1965

Port	Visitors Aboard	Date of Visit
States Marine Operation		
Yorktown	4,613*	2-1 to 8-21-62
Savannah	38,268	8-22 to 8-28
Norfolk	18,394	8-30 to 9-4
Panama Canal	134	9-18
Seattle	55,999	10-1 to 10-21
San Francisco	39,957	11-18 to 11-26
Long Beach	25,867	11-27 to 12-10
Los Angeles	16,494	12-11 to 12-17
Honolulu	21,581	12-22 to 12-28
Portland	34,915	1-4 to 1-10-63
San Diego	42,378	1-14 to 1-22
Balboa, C.Z.	8,292	1-29 to 1-31
Galveston	37,736	2-5-63 to 5-17-63
Subtotal	344,628	
AEIL Operation		
Galveston	7,342	3-21-64 to 5-4-64
Houston	40,894	5-5 to 5-10
New Orleans	14,883	5-14 to 5-16
Baltimore	28,792	5-20 to 5-24
Boston	21,286	5-26 to 6-1
New York	36,030	6-1 to 6-8
Bremerhaven	30,390	6-18 to 6-23
Hamburg	49,919	6-23 to 6-29
Dublin	40,585	7-2 to 7-6
Southampton	32,742	7-7 to 7-12
Hoboken	33,001	7-20 to 7-30
Providence	38,871	7-31 to 8-4
Portland	33,066	8-5 to 8-9
Oslo	30,874	8-18 to 8-24
Copenhagen	44,956	8-25 to 9-1
Halsingborg	22,964	9-1 to 9-4
Malmo	30,401	9-4 to 9-8
New York	3,106	9-17 to 9-22
Rotterdam	50,929	9-30 to 10-6
Antwerp	50,578	10-6 to 10-12
LeHavre	11,090	10-13 to 10-19
Brooklyn	38,842	10-26 to 11-3
Philadelphia	42,575	11-4 to 11-8
Lisbon	35,389	11-17 to 11-23
Barcelona	25,454	11-25 to 12-1
Naples	22,616	12-2 to 12-8
New York	219	12-18 to 12-22
Wilmington	13,919	12-23 to 12-29
Charleston	17,195	12-30 to 1-3-65
Jacksonville	47,460	1-4 to 1-14
San Juan, P.R.	15,381	1-17 to 1-21
Piraeus-Athens	38,976	2-2 to 2-7
Hoboken	258	2-18 to 2-23
Pt. Everglades	48,535	2-25 to 3-3
Mobile	18,597	3-5 to 3-9
Galveston	27,037	3-10 to 8-20-65
Subtotal	1,045,152	

Total Visitors All Ports - 1,389,780

*Includes Demonstration Run Passengers.

Figure 16 - Table showing the ports of call for the NS *Savannah*. A United States – Europe nuclear container ship service would utilize the full precedent of the NS *Savannah* and include all major European merchandise ports. The added advantage of such a service is that a number of the countries which the *Savannah* visited also have considerable experience with nuclear power. The Panama Canal was also transited by the *Savannah*.

To create the most overlap between the land side and maritime markets, an appropriately sized reactor for both will need to be developed. This will not result in ships having one appropriately sized reactor, as the industry currently accomplishes with single, large slow speed diesel engines, rather multiple units will have to be installed to achieve the needed power. It is possible to scale nuclear reactors, but it is not as easy compared to the diesel engines. Initially, there will not be much flexibility in reactor size.

Based on Wartsila's *Power Plant Solutions*, a marine reactor that could also replace the diesel engine in land based applications would be within the range of 10 MW to 20 MW of electrical output. The author and several colleagues performed a study on a 10 MW, passively safe gas-cooled reactor and its application to a container ship on the trans-Atlantic trade route. The conclusion was that U.S. shipyards need to reduce their costs in order for such a service to be competitive.

While a small reactor may be suitable for its intended land based market, multiples on the order of 3 to 6 would have be installed depending on the initial size of the reactor that is licensed. This is not technically infeasible, but it leads to complex machinery arrangements and higher costs compared to fewer, bigger reactors. Any technology needs a starting point, however, and larger versions could eventually be built. Initiating a nuclear shipping program with multiple reactors also leads to rapid gains in experience of installation, maintenance, and refueling, all of which lead to faster Nth-of-a-Kind costs for the next iteration of vessels.

An economical nuclear powered liner service between America and Europe would likely have a 3-week turnaround time and be modeled off of current trade routes. To compare, the lowest turnaround time on the Atlantic route is currently 4 weeks, which means the nuclear powered ships can carry 33% more cargo per year at a much lower fuel cost. The service speed of the vessels would be between 22 – 23 knots with a design speed of 25 knots. TEU capacity is currently very flexible on the Trans-Atlantic route, but installed power would probably not exceed 60 MW.

AMERICAN OPPORTUNITIES

According to a recent study done by MARAD in 2013 on the impact of America's shipbuilding and repair industry on the U.S. economy (the author will simply use the term "shipbuilding industry"), each direct job creates 2.7 other jobs indirectly in other parts of the U.S. economy (MARAD, 2013). While the Gross Domestic Product of America's shipbuilding industry is small compared to the national overall, it does employ a considerable amount of people for its size. U.S. shipbuilding and repair employs over 400,000 workers directly and indirectly, and the average income of a shipbuilding industry worker was $73,630 in 2011, which is 45 percent higher than the national average (MARAD 2013).

Nuclear power is a potential way for the United States to expand its shipbuilding industry beyond reliance on Jones Act and Naval contracts. The foreign revenue generated from providing services for nuclear powered ships could be considerable once their place in the world market becomes widespread.

Not all segments of the U.S. shipbuilding industry are suitable for nuclear propulsion, but there would be a clear benefit to the various shipbuilding States' economies for U.S. involvement in nuclear powered shipping, whether it is in building and repairing the nuclear powered ships, providing training services for operators, or building the marine reactors.

Building the Reactors

In order to reduce quality control costs and ensure efficient factory production, only countries with an experienced nuclear regulatory agency and nuclear manufacturing base should construct and install marine reactors. The U.S. Nuclear Regulatory Commission is considered to be the gold standard for nuclear regulations and so it follows that the manufacture and installation of marine reactors should take place in the

United States (Harding, 2012). Such an arrangement is possible if the reactor is designed and tested in the United States.

Training of the Crews

The engineering departments of nuclear powered commercial ships will need to be trained in the proper handling of radioactive materials and in the operation of their reactors. Different types of reactors vary considerably compared to the standard diesel engine and so this training cannot be standardized in the same manner as has been done for conventional propulsion. The operation of a pressurized water reactor, for example, is very different from that of a high-temperature gas-cooled reactor, which is very different from a molten salt reactor. The training of these reactor operators will be specific to the technology and so will have to be performed on working test reactors on land. These reactors will be owned and operated by the manufacturing companies and will need operating licenses from the Nuclear Regulatory Commission. This arrangement can be easily accomplished in the United States if it is already building the reactors. In fact, the U.S. Nuclear Regulatory Commission, in its “New Reactor Licensing” branch, actually has a streamlined procedure for approving the construction of demonstration and research reactors called “Class 104” (10 CFR 50.21). This licensing path can be doubly utilized for building both the test reactors during the research and development phase, and for building the training reactors. In order to expedite the research and development phase further, the test reactors could be built by the Department of Energy on their own land because the Department of Energy has the right to build nuclear reactors without NRC licenses (Adams, December 2013).

Maintaining the Ships

The refueling of ship borne nuclear reactors in a shipyard is not trivial work and so cannot be outsourced. Neither can reactor specific maintenance as it deals with unique hazards and quality controls. Small accidents involving the highly radioactive fuel elements, even if there are no injuries, can cause costly problems relating to the accumulation of radioactive materials in the shipyard and the ensuing concerns from the regulators about the ability of the shipyard to safely conduct the work. The refueling of marine reactors should only be performed at shipyards familiar with the process. An example of such a shipyard in the United States that can handle deep-draft vessels, versus exclusively submarines, is Newport News in Virginia. In order to gain enough experience with the merchant nuclear reactors, multiple and repeated refuelings by these teams and shipyards must be made, even though nuclear reactors only require refueling once every several years. **The refueling and nuclear specific maintenance of nuclear powered commercial ships should initially only be conducted at a limited number of shipyards in order for them to gain experience through productivity.**

America's decades long experience refueling nuclear powered naval ships is directly applicable to the commercial sector as the materials and hazards are identical, although the secrecy of the procedures (naval vs. commercial) are starkly different. This training and experience could be transferred to servicing commercial vessels and would give America the detail and expertise to refuel the World's nuclear merchant ships. This means the United States will also be storing and managing the spent fuel from these ships, which would be another source of foreign revenue.

Building the Ships?

Whether or not any more stringent standards need to be enforced for the construction of nuclear powered ships remains to be determined. It can be argued that, in order to avoid stringent documentation of quality assurance, there needs to be confidence that what quality assurance is in place will be followed closely and so can be subject to standard industry oversight. The United States already has decades of experience installing naval nuclear reactors aboard ships, whereas the present dominant shipbuilding nations have zero experience in this area. A study should be performed as to how this unique American experience can be adapted for commercial ships.

The United States currently cannot build ships for the same price as European and Asian shipyards, but the United States does not have to match their prices in order to still build commercial ships. The use of nuclear power on commercial ships results in certain annual cost savings that can offset America's higher shipyard costs. These lower fuel costs and higher service speeds that result from nuclear power can allow for higher construction costs, even after including the capital investments of the reactors.

The United States may still have to reduce its shipyard costs in order to make nuclear powered ships competitive with foreign-built, conventional vessels, but such cost reductions should be possible through modernization, productivity, and increased labor efficiency.

However, once nuclear powered ships are accepted by a wide range of countries, what would prevent other shipbuilding nations with inherently lower costs from building their own nuclear powered ships? The answer to this question will be known when the final regulatory requirements for nuclear powered ship construction are decided. The answer may initially be a matter of who is building the marine reactors and who has the necessary nuclear quality control base for following the new regulations. Quality and longevity of the ship construction may also be important for reducing the life-cycle costs stemming from the capital investment. It may come down to whether or not American shipyards can truly build higher quality, longer lasting products. The United States' decades long experience with nuclear regulations and naval nuclear propulsion puts it in the position to build quality nuclear powered commercial ships from the outset of a new program, whereas other countries may have to climb the learning curve.

The United States should try to get back into building commercial ships for foreign trade through the use of nuclear power. Whether it is in maintenance or construction, shipyard work employs hundreds of well-paid workers per vessel and is a significant source of foreign capital for a country, making it desirable for the national economy.

For example, South Korea understood the value of commercial shipbuilding in the 1970's when it sought to create its' own shipbuilding industry from the bottom up. The genesis of South Korean shipbuilding was not privately funded, but heavily supported by the government due to its importance to the country's national economy (Walker, 1999). Today, South Korea's shipbuilding industry employs tens of thousands of workers per major shipyard and has the secondary economic effect of utilizing many of the country's domestic materials and manufacturing industries.

While part of South Korea's success comes from its lower labor and material costs compared to the United States, their shipyards are also assisted in large part by their productivity and large revenue streams, both of which allow cost control through learning and investment in modern technology. Nuclear power may be able to achieve the productivity needed to create a sustainable shipbuilding program.

The United States will likely have to reduce its shipyard costs. Based on the author's research of one U.S. shipyard that currently builds deep-draft vessels for the Jones Act, that shipyard may have to reduce its construction costs (labor + materials + auxiliary machinery) by as much as 70 percent if it were to build U.S. flagged nuclear powered container ships for regular foreign trade. More research, however, is needed for America's other shipyards.

IMPLEMENTATION STRATEGIES

Public Acceptance

The public, policy makers, and other interested parties need to be given a modern understanding of ionizing radiation's effects on human health and the environment. Radiobiology (the study of ionizing radiation's effects on biological function), epidemiological studies, and modern cancer treatment prove that current radiation protection standards and policies are significantly over-precautious and give adults and children the wrong impression about the real hazards from radiation exposure (NUREG, 1995; Health Physics Society, 2004). This is not to say that the public has been intentionally mislead, rather it has only been until relatively recently that the science of ionizing radiation exposure has matured (Allison, 2009). It is now recognized and understood that plants and animals repair DNA damage caused by ionizing radiation, such as which comes from nuclear power plant accidents, and that there is a threshold of such radiation induced ailments (Calabrese, 2013). There is no laboratory or empirical evidence for human health effects caused by ionizing radiation exposure, either external or internal, for doses below 100 miliSieverts of radiation (Allison, 2009; Health Physics Society, 2004). It has been suggested that a maximum allowable chronic radiation exposure for children and adults should be 100 miliSieverts per month and the same value for single, short term doses (Allison, 2009). In order to account for potential cumulative radiation effects that are not presently known, a maximum lifetime dose of 5,000 miliSieverts (500 Rem life time) is also suggested (Allison, 2009).

Any risk assessment for nuclear powered commercial vessels will include dispersals of radioactive material in whatever types of events that can cause them. Temporary evacuations for the public will have to be made in some cases, but a modern understanding of radiation health effects, as described above, reveals that the risks to human health and the magnitude of financial loss associated with the meltdown of a nuclear powered ship in port are well below what current radiation protection standards would imply.

To illustrate this, the Port-Operating-Plan for the NS *Savannah* for Le Havre, France will be used. Using the predicted average 24-hour radiation doses to the Le Havre area in the event of a meltdown of the NS *Savannah* in port, which had a 74 MW-thermal reactor, it can be seen that there would be over one week of time for people within three miles of the *Savannah* to evacuate until radiation levels decayed to below the suggested value of 100 miliSieverts per month (10 Rem per month), at which point they would be able to return. People beyond three miles would have to be aware there was a meltdown so as to take precautions to protect their Thyroid glands from Iodine-131 exposure, but in general, no short or long term health effects would be incurred from this population if they stayed where they were.

Table 1. Potential Radiation Dose to Le Havre Population

Affected distance, feet	Number of persons	Average dose (24-hour), rem	
0 - 946	20,000[a]	25.0[b]	
946 - 5,000	15,000	0.90	10 Days to evacuate
5,000 - 10,000	25,000	0.760	
10,000 - 15,000	30,000	0.275	
15,000 - 20,000	40,000	0.150	No health risk
20,000 - 25,000	30,000	0.100	
25,000 - 50,000	50,000	0.070	
50,000 - 100,000	50,000	0.025	

(a) Maximum number of persons to be permitted in the 24-hour controlled zone at any particular time.

(b) Maximum dose arbitrarily assigned to persons within the 24-hour controlled zone.

Figure 17 - Estimated 24-hour radiation exposures to the public for a Design Basis Accident for the NS *Savannah* at the port of Le Havre, France. A modern understanding of radiation health effects reveals the true magnitude of health risk from the meltdown of a small marine nuclear reactor in port. The figures above are short term doses and do not describe the long term doses from the longer lived isotopes, such as Caesium-137 and Strontium-90, both of which have half-lives of roughly 30 years. The long term doses resulting from these isotopes would be far below the short term values above.

Figure 18 - Visual depiction of a 3-mile temporary evacuation radius for the NS *Savannah,* based on the Port Operating Plan for Le Havre, France, if a modern understanding of radiation health effects is used. All of Manhattan is avoided. While some bridges and highways are within the radius, drivers passing through will only receive limited radiation exposure since evacuees would have 10 days until they received the monthly dose limit. The radius is centered over the Port Newark channel. Meltdowns take many hours to days to develop, so there is plenty of time to tow the vessel out to sea or begin making preparations if the vessel cannot be moved. Larger nuclear reactors will have larger radii, probably up to 5 miles, excluding uniquely high-powered vessels. Image courtesy of Google Maps.

Protection and Indemnity

Current protection and indemnity insurance for nuclear reactors in the United States follows the Price-Anderson Act, a law enacted in 1957 at the beginning of commercial nuclear power to ensure that adequate compensation existed for the public in the event of nuclear or radiological accidents, regardless of who might be liable (American Nuclear Society, 2005). This was to ensure that members of the public *would* be compensated, versus getting bogged down in legal battles. In short, all nuclear reactors in the U.S. are required to purchase a certain amount of coverage based on criteria published by the NRC, but if damages exceed a reactor's individual coverage, *all* reactors pay into a pool to cover the costs (up to $12 billion currently). Beyond that, Congress can appropriate additional funds if deemed necessary. In essence, all reactor operators have responsibility, so an accident for one is an accident for all.

The Price-Anderson Act is an appropriate model for insuring future nuclear powered commercial ships and was, in fact, used by the NS *Savannah.* While the Price-Anderson Act gave the *Savnnah* the liability coverage it needed to be accepted into many ports, the technology of the *Savannah* was relatively new and did not have the passive safety features recommended for future marine reactors (Femenia, 2012). At least for the first generation of modern nuclear ships, the Price-Anderson Act should be used to guarantee that coverage *will* exist for accidents, but the true risks will only be known when actual reactors and completed ship designs are available, and a modern understanding of radiation health effects is adopted.

The Price-Anderson Act also applies to non-reactor operations, such as fuel fabrication facilities, waste disposal sites, and the transport of spent nuclear fuel, which could one day include shipyards performing refueling work (American Nuclear Society, 2005). For further details on the Price-Anderson Act, see the paper *The Price-Anderson Act, 2005* published by the American Nuclear Society.

Competing Commercial Interests

The success of nuclear powered commercial shipping ultimately depends on the success of nuclear fission in general; the technologies are similar, as are the economics, and the expanded use of fissile materials either on land or at sea includes the topics of radiation protection and proliferation. The economics are most important, however, because the success of nuclear power is also the decline in market share of oil and natural gas. Every nuclear powered commercial ship that is built is a fossil-fueled ship that was not built, and subsequently large volumes of oil and gas that were not purchased. The rise of nuclear marine propulsion, therefore, is the decline of fossil-fueled propulsion.

The hydrocarbon industry is one of the most lucrative industries in the world and so has the money to pay for lobbyists and has the influence to speak to people in positions of public power. To what extent nuclear power can replace fossil-fueled propulsion remains to be determined, but ultimately, nuclear fission in whatever form is a direct competitor to fossil fuels. Nuclear powered shipping will face opposition from the hydrocarbon industries. This does not imply conspiracy or “hidden dealings”, rather it will lobby officials, the public, and spend its resources on consistently making the case *against* the widespread use of fission.

A clear example of this competition comes from an advertisement in a Long Island newspaper, likely from 1979 during the start of public outcry over the construction of the Shoreham nuclear power plant in Long Island, New York. A portion of the advertisement is presented below, showing an oil industry organization sponsoring an ad against nuclear power vicariously through the use of solar energy. Regardless of the factuality of the advertisement’s criticisms, which focused on emergency core cooling and inadequate insurance coverage for the plant, the advertisement represents the hydrocarbon industry (oil heating) funding public protest of nuclear power (electric heating). The operation of the Shoreham power plant would likely have allowed Long Island residents to switch over to electric heating for their homes and water instead of oil. Any reduction in market share for the hydrocarbon industry which results from the entry of a competitor is the potential for further competition. It is not in the interest of the hydrocarbon industries to allow nuclear powered commercial shipping to become accepted, or else nuclear power will become accepted in more places.

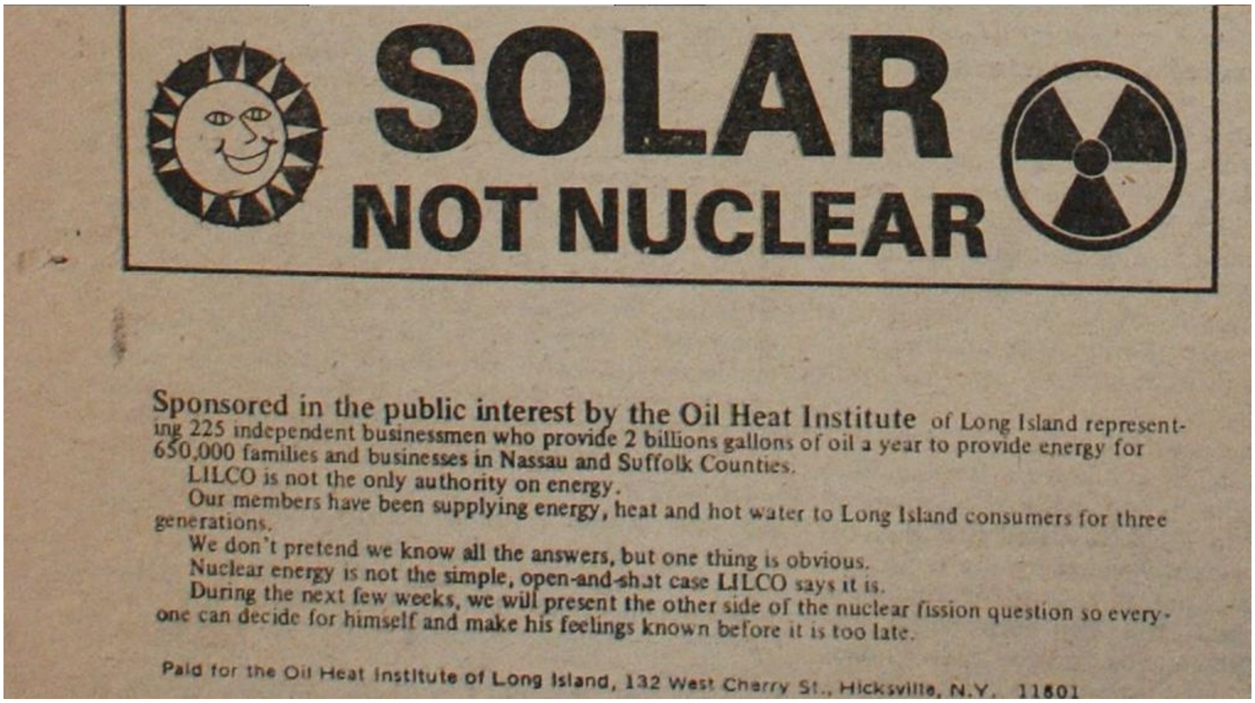

Figure 19 - Advertisement showing a combination of hydrocarbon and renewable energy industry funding against nuclear power.

The strategy for dealing with this commercial opposition is to **make people aware of it. Policy makers will be influenced by their relationships with members of the hydrocarbon industries who they have become familiar, and so will be less inclined to side with their commercial competition when public opposition arises.** None of this is sinister, it is just business.

Opposition will also be faced from the wind and solar industries as nuclear power is a direct competitor in the area of electricity generation. In a similar vein to replacing oil and gas, every nuclear reactor that is built is a field of wind turbines or solar panels that was not.

Research and Development

A nuclear powered commercial shipping program in the United States, whether it is a combination of designing the reactors, building the ships, or training the crews, will require political protection with strong leadership (Crommelin, 2013). This political protection will need to engender a national interest in having a nuclear shipping program and must know how to communicate clearly about the real risks and benefits of nuclear power. Economics need to be the focus of such a program in order to garner support from industry and investors, from which the money for research and development will be supplied. Not all ship types will be economical for U.S.-built nuclear propulsion, so a study should first be performed that seeks to determine:

1. What is the full range of economical ship types for U.S.-built nuclear power, their speeds, and trade routes, followed by:
2. Determining the most economical sizes of reactors for those designs as well as the other applicable markets, along with accurate cost estimates, to determine:
3. If American shipyards can construct the hulls at a low enough price, and finally:
4. If shipbuilding costs are currently too high, how American shipyards can reduce their costs to the target levels.

Such a study would yield the design and construction objectives of a U.S. nuclear shipbuilding program and determine its economic feasibility.

If the economics are positive and the necessary shipyard cost reductions are possible, then lobbying of industry and government can begin. Representatives from interested parties such as shipping, combined heat and power, electricity generation, and interested manufacturers for the reactor components would act as the lobbying base and protection for the fledgling program (Crommelin, 2013). The shipbuilding and repair states would also provide support for bringing nuclear shipping to their regions. These interested parties would need to have a clear understanding of the hazards and benefits of nuclear energy in order to communicate clearly to politicians and the public.

In order to improve the manufacturing aspects of the reactors, the interested manufacturing parties will provide input during the design process in order to make the most use of pre-existing components (Crommelin, 2013). The reactors would also be designed to serve both the land and maritime markets, allowing the countries of the nuclear ships' trade routes to also benefit from the U.S. program. The benefits of using small nuclear reactors in the developing world need to be emphasized. Groups interested in producing fresh water and electricity for the developing world would also have an interest in the success of a nuclear reactor suitable for those purposes.

CONCLUSION

Nuclear power favors vessels with high power requirements, so container ships and icebreaking vessels are suitable for early adoption of nuclear propulsion. Expanding nuclear propulsion to other ship types, such as slower-going bulk carriers, will generally require higher service speeds than the industry is currently used to. To avoid soot induced melting of Arctic ice from increased shipping in that region, nuclear power will need to be used on a large scale.

Nuclear shipping is only possible if there are nuclear reactors available for ships, so the development of passively safe, wide market marine reactors is critical for future developments. Applying the principles of large production runs and factory construction will help lower the costs of these reactors, as well as changes to nuclear quality control requirements through cost-benefit analysis of current regulations.

Discussions about the safety of nuclear powered ships are ultimately about reactor design and radiation. A modern understanding of ionizing radiation health effects reveals that the true risks from radioactive materials are far below what current regulations imply. Reactors can also be built so meltdowns are impossible, eliminating that concern for nuclear ships in port.

The success of nuclear propulsion ultimately is tied to the success of nuclear fission in general. Focused opposition will be faced from the hydrocarbon and renewable energy industries, as well as any other lucrative industries which stand to lose out from the acceptance and widespread use of nuclear energy. Protests, lobbying, and advertising against nuclear fission will likely be funded by these commercial entities and nuclear propulsion for commercial ships is just as much their competition as a utility-sized nuclear power plant.

There are opportunities for the United States in nuclear powered commercial shipping. The technical and regulatory familiarity with nuclear power puts the United States in a position to lead the world in the development of modern nuclear ships, but only if there is a national interest to do so. Building the reactors, training the crews, or performing maintenance and repair on nuclear powered ships are ways to grow the United States maritime industry, as well to increase the United States' influence in global maritime matters. America will likely still have to reduce the costs of its shipyards if it wants to build nuclear powered ships for foreign trade, but nuclear power is a way to overcome the price differential.

APPENDIX A

Radioactivity is not an inherent health hazard. Like most materials, its danger is a matter of dose. Our bodies contain many thousands of radioactive decays per second in the form of radioactive isotopes of carbon, hydrogen, and potassium atoms we consume in the food we need to live. If animals and plants receive too high of a dose of radiation in too short a time, then deleterious effects occur, but if the dose is spread out over a period of time in which their bodies can repair the damage, no effects result (Calabrese, 2013). The Sulfurous and Nitrous emissions from diesel engines are similar; the problem is not the mere presence of Sulfur Oxides and Nitrogen Oxides, but too many of these compounds accumulating in the air so that people begin to experience problems, starting with those with greatest sensitivity.

Some animals and plants have higher thresholds for radiation exposure than others, and certainly there are people who are more sensitive than the average, but the operation of nuclear reactors do not produce radioactive emissions on the same order that fossil fuel burning produces air pollution in ports and cities.

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