Feasibility Analysis for a Nuclear-Powered Commercial Merchant Ship

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of
Naval Engineer
and
Master of Science in Mechanical Engineering
at the
Massachusetts Institute of Technology
May 2022

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May 6, 2022

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ABSTRACT

This thesis evaluated advanced reactor designs to determine the best option for installation onboard a civilian container ship in support of the IMO's strategy for reducing greenhouse gas emissions from ships. Greenhouse gas reduction has been a major challenge within commercial maritime shipping as the industry has recently expanded significantly. Although the industry continues to grow, these emissions must be greatly lowered beyond current values by 2030 for climate change to be meaningfully combated.

Concurrently, the global nuclear power industry has made tremendous advancements in developing new technologies throughout the last two decades, and at the forefront of these efforts are seven Generation IV reactor designs. These designs were created to improve economics, increase passive safety measures, and expand fuel cycle control, and so far, research efforts have been so successful that the idea of incorporating these designs into the overall climate change solution has been met with significant support from both public and private organizations throughout the world.

Therefore, Generation IV reactor designs were evaluated based on their technical feasibility and projected commercial readiness to determine the best option to supply propulsive and electrical power onboard a commercial container ship. Related to commercial shipping, a nuclear-powered container ship has been considered and analyzed thoroughly in the past, but the introduction of Generation IV technology presents an interesting opportunity to revisit the concept and determine if using these designs would increase real-world implementation feasibility.

To fully understand the research space, past nuclear-powered maritime applications as well as previously conducted research related to this topic were reviewed to validate this concept's feasibility. The licensing and regulatory process was also analyzed to understand the feasibility of final commercialization, and from this analysis, liquid metal reactors (specifically, Sodium Cooled Reactors, Molten Salt Fast Reactors and Lead-cooled Fast Reactors) were selected as optimal solutions for implementation onboard container ships.

Thesis Supervisor: Paul Sclavounos
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Acknowledgments

First and foremost, I would like to thank my husband, Danny, for his unwavering love and assurance throughout every aspect of our relationship. I will never be able to fully express how much it means to me that we get to spend our lives together, and without his support, none of what I have accomplished would have been possible.

Second, I want to thank my advisor, Professor Paul Sclavounos for his unending patience, wisdom, guidance and support. Professor Sclavounos always encouraged me to push the boundaries of what we believe to be possible and shine a light into the unknown. This project is a strong reflection of his optimism for what society can achieve in the future, and I am beyond grateful to have had the opportunity to work with him.

Third, I would like to thank my classmates within the MIT 2N program. More than once, their help and encouragement pushed me to work harder and helped me continue moving forward, and I could not have made it to this point without them.

Lastly, I would like to thank the US Navy and MIT for providing this amazing educational and professional opportunity to study within the 2N program. I have learned so much throughout my time in Boston, and my life has been forever changed by this experience.

Thank you again to all.

Contents

List of Abbreviations

2N: Naval Construction and Engineering

ABS: American Bureau of Shipping

ADS: Accelerator Driven System

AEC: Atomic Energy Commission

AHTR: Advanced High Temperature Reactor

aLEU: Advanced Low Enriched Uranium

ALFRED: Advanced Lead Fast Reactor European Demonstrator

ARD: Advanced Reactor Design

ARDP: Advanced Reactor Demonstration Program

ARPA-E: Advanced Research Project Agency-Energy

BOA: Beam Overall

BUSHIPS: Bureau of Ships

BV: Bureau Veritas

BWR: Boiling Water Reactor

CCS: China Classification Society

CEA: French Alternative Energies and Atomic Energy Commission

CFR: Code of Federal Regulations

CH_4: Methane

Class NK: Nippon Kaiji Kyokai

CMNP: Commercial Maritime Surface Vessel Nuclear Propulsion

CO_2: Carbon Dioxide

CRS: Croatian Register of Shipping,

DNV: Det Norske Veritas

DOE: Department of Energy

EBR-I: Experimental Breeder Reactor-I

Euratom: European Atomic Energy Communit

FBR: Fast Breeder Reactor

FHR: Fluoride salt-cooled High-temperature Reactor

FNR: Fast Neutron Reactor

ft: Feet

GAIN: Gateway for Accelerated Innovation in Nuclear

GE: General Electric

Gen IV: Generation IV

GHG: Greenhouse Gas

GL: Germanischer Lloyd

HEU: Highly Enriched Uranium

HTGR: High-Temperature Gas-cooled Reactor

IACS: International Association of Classification Societies

IAEA: International Atomic Energy Agency

IMO: International Maritime Organization

INL: Idaho National Laboratory

JAEA: Japan Atomic Energy Agency

Kr: Krypton

KR: Kean Register

kts: Knots

LBE: Lead-Bismuth Eutectic

LEU: Lowly Enriched Uranium

LFR: Lead-cooled Fast Reactor

LMR: Liquid Metal Reactor

LNG: Liquid Natural Gas

LOA: Length Overall

LR: Lloyd's Register

LT: Long Ton

LWBR: Light Water Breeder Reactor

m: Meters

MARAD: Maritime Administration

MCFR: Molten Chloride Fast Reactor

MGCR: Marine High Temperature Gas Cooled Reactor

MOX: Mixed Oxide

mrem: Millirem

MSFR: Molten Salt Fast Reactors

MSR: Molten Salt Reactor

MWe: Mega-Watts electric

MWt: Mega-Watts Thermal

MYRRHA: Multi-Purpose Hybrid Research Reactor for High-Tech Applications

N_2O: Nitrous Oxide

NEICA: Nuclear Energy Innovation Capabilities Act

NEIMA: Nuclear Energy Innovation and Modernization Act

nm: Nautical Miles

NNPP: Naval Nuclear Propulsion Program

NPMS: Nuclear-Powered Merchant Ship

NRC: Nuclear Regulatory Commission

NRIC: National Reactor Innovation Center

NSS: NS Savannah

ORNL: Oak Ridge National Laboratory

PLAN: People's Liberation Army Navy

PRC: People's Republic of China

PRISM: Power Reactor Innovative Small Modular

PRS: Polish Register of Shipping

Pu: Plutonium

PWR: Pressurized Water Reactor

RINA: Registro Italiano Navale

RS: Russian Maritime Register of Shipping

SCWR: Supercritical Water-Cooled Reactor

SFR: Sodium Fast Reactor

SME: Subject Matter Experts

SOLAS: Safety of Life at Sea

T: Draft

TEU: Twenty-Foot Equivalent Unit

Th: Thorium

TRISO: Tri-structural Isotropic Particle

TRL: Technology Readiness Level

U: Uranium

UC: Uranium Carbide

UMS: Unattended Machinery Spaces

UN: United Nations; Uranium Nitride

UO_2: Uranium Oxide

VHTR: Very High Temperature Reactor

Xe: Xenon

μSv: Micro-Sievert

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1.0 Background and Motivation

1.1 Motivation

Interest in nuclear power has increased over the last decade due to concerns surrounding climate change. These concerns have been driven by environmental changes observed around the world. For example, 2010-2019 was the warmest decade on record, and the global community has not been on track to meet the temperature targets established within the Paris Agreement [1].

In an effort to combat these alarming trends, the International Maritime Organization (IMO) released the, "Initial IMO Strategy on Reduction of GHG Emissions from Ship," in 2018. This strategy outlined goals to mitigate and reduce both carbon dioxide (CO_2) and greenhouse gas (GHG) (which include carbon dioxide, methane (CH_4), and nitrous oxide (N_2O)) emissions within the international shipping industry. The IMO Strategy also aligned with the United Nation's (UN) Sustainable Development Goal 13 which addressed climate change through urgent action to combat it and its impacts, and its main goals were to:

- Reduce CO_2 emissions per transport work (as an average across international shipping) by:
  - At least 40% by 2030 (compared to 2008).
  - Pursue efforts towards 70% by 2050 (compared to 2008).
- Peak GHG emissions as soon as possible, and reduce the total annual GHG emissions by at least 50% by 2050 (compared to 2008).
  - Additionally, pursue efforts towards phasing out GHG (as part of the CO_2 emission reductions). [2]

The IMO Strategy is a direct response to the international shipping industry's contribution to global carbon emissions. Within the Third IMO GHG Study of 2014, it was estimated that GHG emissions from international shipping in 2012 accounted for some 2.2% of all global CO_2 emissions [3]. While this value conveys how international shipping has been responsible for only a relatively small portion of total emission contributions, it was also estimated that these emissions could grow by 50-250% by 2050 based on projections for increased demand of maritime shipping within the global supply chain [3]. These trends were later confirmed by the

Fourth IMO GHG Study of 2020 where the shipping industry's global GHG contributions had risen to 2.89% in 2018, and emissions were again anticipated to increase by 90-130% by 2050 [4]. Additionally, large merchant ships account for the greatest contributions to these emissions within the international shipping industry.

To meet these goals established by the IMO, both operational changes and new technology implementations are necessary. Thus, the Fourth IMO GHG Study of 2020 also specifically recommended the use of alternative low-carbon and zero-carbon fuels moving forward [4]. In attempting to identify the best zero-carbon fuel options, nuclear power is one of the few energy sources that has reached the necessary technological maturity and development required to replace fossil fuels and produce significant energy without carbon emissions. While renewable energy is another key part of the overall solution for reducing carbon emissions, these energy sources represent an incomplete solution due to their intermittent nature. As a result of this inherent fact surrounding renewable energy, the full extent of its contributions are also stunted by a dependency upon energy storage technology. While fully developing energy storage technology represents another key component within the overall solution, the academic community generally agrees that this industry is still in its infancy, and much more investment is needed to utilize renewable energy to its fullest extent [5]. As a result, nuclear energy is a key energy option capable of meeting global energy demands while renewable energy and energy storage capabilities continue to grow.

Therefore, a Nuclear-Powered Merchant Ship (NPMS) could supply the necessary power for the increasing international shipping demand while also meeting the zero-carbon goals established by the IMO over the upcoming decades. Consequently, this project explored the overall feasibility of implementing a NPMS into the international shipping industry. Areas of focus within this project included:

1. Review of previous nuclear-powered marine applications within the military, public and private sectors (both domestically within the US and internationally).
2. Synthesis of past academic research which were related to this project's efforts.
3. Investigation into concerns surrounding the regulatory and licensing framework.

4. Analysis into modern reactor technologies to select the best option for the NPMS and maximize this project's real-world feasibility.

1.2 Background on Nuclear Power

Nuclear power has been a commercially viable power source since the 1950s, and now, it is widely utilized for power generation around the world. As of 2020, 32 countries operate nuclear reactors, and 50 countries utilize the energy produced [6]. From the World Nuclear Association, these power generation capabilities (as of 2020) are as follows:

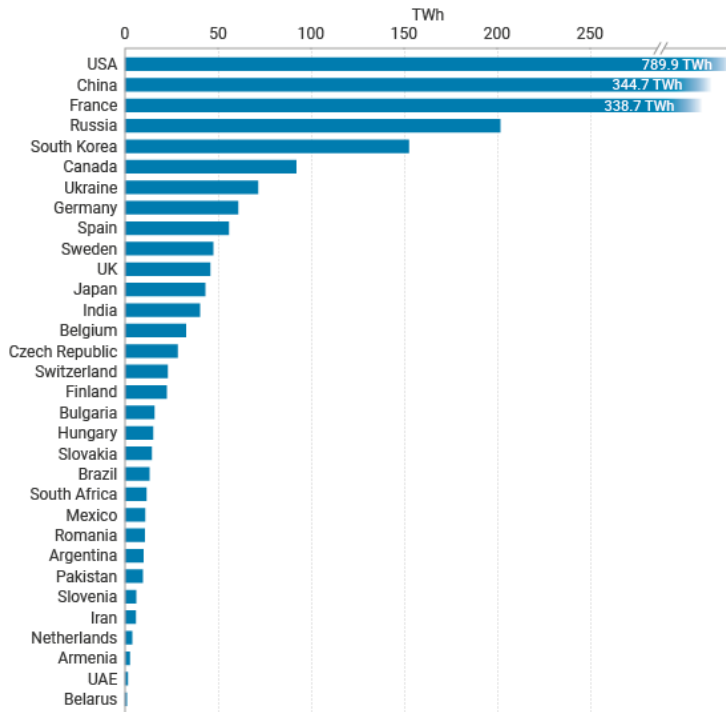


Figure 1: 2020 Breakdown of Nuclear Generation by Country [6]

Nuclear power is also the second-most widely used form of carbon-free energy following hydroelectric power, and it is the fourth most common energy source after coal and natural gas. The specific breakdown of types of energy used around the world (as of 2018) is shown below:

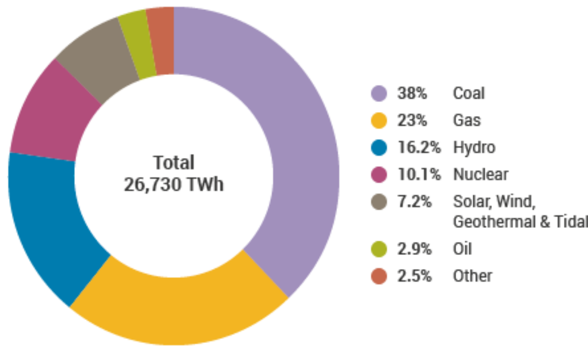


Figure 2: 2018 World Energy Production Breakdown [6]

Although specific trends and future projections vary for each country, these statistics show how the developed world has overall accepted nuclear power. Therefore, nuclear power represents a highly feasible solution for meeting the increasing global power demand while concurrently reducing carbon emissions.

Additionally, many of the same countries who operate the largest amounts of nuclear power are also main players within the commercial shipping industry. Shown below are the top ten largest shipping countries ranked with respect to ship ownership (top) and tonnage capacity (bottom), and countries in the top-half of worldwide nuclear power production have been highlighted:

Vessels
(Number of vessels)

Economy of ownership (Ranked by number of ships owned)	Flag of registration (Ranked by number of ships registered)							
	Panama	China	Liberia	Marshall Islands	Singapore	China, Hong Kong SAR	Indonesia	World
China	617	4 569	113	75	75	921	6	6 869
Greece	469	0	1 021	1 023	29	22	2	4 648
Japan	2 024	0	210	210	155	56	8	3 910
Singapore	288	1	235	139	1 493	138	90	2 861
Germany	30	0	607	119	75	19	0	2 504
Indonesia	18	0	7	2	7	1	2 132	2 208
Norway	43	0	90	129	86	46	4	2 043
United States of America	70	0	93	347	8	43	0	1 933
Russian Federation	36	0	125	0	2	1	0	1 742
China, Hong Kong SAR	297	20	44	65	48	883	3	1 690
World	6 528	4 603	3 686	3 592	2 613	2 425	2 293	52 961

Sources: UNCTADstat (UNCTAD, 2020a); Clarksons Research.
Note: Commercial ships of 1000 gt and above.

Tonnage
(Thousands of dead-weight tons)

Economy of ownership (Ranked by tonnage owned)	Flag of registration (Ranked by tonnage registered)							
	Panama	Liberia	Marshall Islands	China, Hong Kong SAR	Singapore	Malta	China	World
Greece	26 375	85 396	77 629	1 372	1 832	64 332	0	363 867
Japan	133 322	19 208	13 148	2 947	9 715	573	0	233 195
China	22 970	7 472	4 009	78 238	7 287	2 614	100 269	229 247
Singapore	11 302	16 942	9 689	7 734	74 773	2 243	2	137 396
China, Hong Kong SAR	11 344	5 403	3 399	72 505	4 485	785	149	101 035
Germany	857	33 876	6 235	1 304	3 750	6 723	0	89 412
Korea, Republic of	35 500	1 468	26 208	1 123	10	356	0	80 595
Norway	2 061	5 146	7 840	7 505	4 570	1 370	0	63 985
Bermuda	1 784	6 744	18 156	7 492	1 043	423	0	60 414
United States of America	1 240	6 763	25 884	3 091	335	643	0	57 688
World	328 566	274 842	261 919	201 297	140 145	115 852	100 467	2 051 019

Sources: UNCTADstat (UNCTAD, 2020a); Clarksons Research.
Note: Commercial ships of 1000 gt and above.

Find the data on UNCTADstat

Figure 3-4: Top Ten Shipping Countries Based on Ships Owned (Top) and Tonnage Capacity (Bottom)

Within these rankings, only Singapore and Bermuda have no prior experience with operating or utilizing nuclear power. Although Greece does not use nuclear power for electricity, it has established the Greek Atomic Energy Commission and has one operational research reactor [7]. Norway's experience with nuclear power is similar to Greece in that it has a regulatory framework for nuclear power and has been home to some research reactors in the past, but Norway has never used nuclear power (though some political parties and industry leaders have expressed support for it in the future to combat climate change) [8]. Hong Kong also does not operate any nuclear power, but nuclear power is imported into the area from the People's Republic of China (PRC) [9]. Therefore, almost all the main countries within the international shipping industry already use nuclear power to some extent.

1.3 Concerns for Nuclear Power

Despite its prominent use throughout the world, a few key concerns have also surrounded nuclear energy and historically stunted its growth as a commercial energy source. Those areas of concern are:

- Economics
- Safety
- Waste Management

To make nuclear power a truly feasible energy option moving forward, all three concerns must be addressed. With respect to implementing nuclear power into the international shipping industry, there is also elevated emphasis on the economic hurdles. Specifically, the maritime shipping industry has typically preferred a well-understood status quo compared to implementing new technology. While this trend is not a negative factor (in fact, the industry's firmly established stability is likely derived from many years of operating with consistency), it is important to understand the nature of the industry to which a NPMS is being suggested, and knowing that the industry is resistive to change helps better develop a solution that will be accepted. Thus, a main reason for this preference for the status quo relates to the high cost of implementing new technology. Therefore, economics must be especially prioritized while investigating the feasibility of a NPMS to increase the likelihood that the concept will be well-received by the international shipping industry.

In addressing these three main concerns, it was important to note that pressurized water reactors (PWRs) (which use Uranium-235 (U-235) as the fissile material and light water as a coolant) have dominated the nuclear energy market. Although each individual system may vary slightly, PWRs are the most widely used reactor design throughout commercial power generation and naval warship applications. While this technology has proven itself to be both functional and highly reliable, nuclear energy could better meet the three areas of concern in the following ways:

Economics. As mentioned before, PWRs mainly use U-235 as the reactor's fuel, and U-235's global availability is inherently limited due to the small amount which exists in nature (which is mainly mined from the ground but can also be extracted from seawater) [10]. Although Uranium is as common in the Earth's crust as tin and tungsten, only 0.7% of naturally occurring Uranium is the specific isotope U-235 [10]. With this said, experts agree the global supply of U-235 is not an issue for the future of power generation, and there have not been any major issues with using U-235 as a fuel source in the past. However, U-235 is more expensive (both financially and in terms of energy consumption requirements) compared to other nuclear fuels due to the significant enrichment process required to extract U-235 from Uranium ore and concentrate it to higher, usable quantities. There is also widespread disdain for continued Uranium mining due to the negative environmental impact during the mining process, and this public opposition is the greatest in Australia where a large portion of the world's Uranium mining occurs [10] [11]. As a result, other nuclear fuel sources have the potential to be more economically desirable and widely available in comparison. These fuels provide low-cost alternatives in attempting to plan and use nuclear energy to solve wide-scale power demands to decrease carbon emissions.

Also related to economics, PWRs require a costly certification process before beginning to operate. As a result, the initial capital costs associated with designing and constructing a new PWR is often too high to justify the investment. As mentioned before, this fact is especially important when attempting to create an energy solution for the international shipping industry.

Safety. PWRs are highly pressurized systems which also operate at high temperatures. While these systems have developed a strong track record for safety and have proven to be fully controllable, nuclear reactors could be generally improved (from a safety perspective) if they could achieve the same (or improved) power output and efficiencies while operating at atmospheric pressure. At lower operating pressure, these systems would require less oversight during operation, and a loss of coolant casualty would become a less severe event (because it would no longer involve steam escaping a highly pressurized system).

PWRs also require that the reactor core remain “covered” by coolant. Additionally, a constant coolant flow must always be maintained through the core to continuously remove heat generated by the fuel and prevent excessively high temperatures. This flow through the core is especially necessary immediately following a reactor shut down when the coolant must continue to remove decay heat which results from spontaneously decaying fission fragments. To further highlight the importance of decay heat removal, one of the three major nuclear accidents (Fukushima Daiichi) resulted from an inability to sustain decay heat management (among other contributing factors). While modern PWRs can remove decay heat without assistance from pumps over substantial periods of time using natural convection through the core (a design feature which adds significant passive safety to the reactor’s design), nuclear reactors could achieve increased passive safety if the core did not require the continued presence of coolant within the reactor and/or coolant flow while shut down.

In summary, reactor safety could generally be improved by:

- Operating at atmospheric pressure.
- Not requiring the constant presence of coolant.
- Not requiring continuous coolant flow.

Waste Management. It is important that all future nuclear reactors are designed with included consideration for waste management. Most current commercial reactors require a refuel annually which results in a high rate of waste production. Future reactors could attempt to follow a refuel schedule similar to naval reactors (which only refuel every 25 years or not at all throughout the ship’s 30-45 year service life span). However, these long spans between refuels are accomplished by highly enriching U-235 fuel (above eighty percent), and as previously discussed, other fuel options now exist which may be preferrable to U-235. Therefore, future reactors must better manage waste production by:

- Extending the time duration between refuels.
- Developing new reactors whose waste can be repurposed or reused.
- Developing new reactors that can utilize the currently existing waste from previous reactors as repurposed fuel.

1.4 Generation IV Technology Solutions

Having expanded on the main areas of concern surrounding nuclear power, advanced Generation IV (Gen IV) reactor designs are currently attempting to address all these concerns. Compared to PWRs (which is considered a Generation III technology), these technologies represent the most promising reactor designs for the future. Some of these designs also stem from older technology that has been revisited and is now more feasible following assistance from modern supercomputing and advancements in materials technology. There are seven types of Gen IV reactors, and their main discernable features are shown below:

	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - advanced high-temperature reactors	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

* high = 7-15 MPa
\+ = with some U-235 or Pu-239
** 'battery' model with long cassette core life (15-20 yr) or replaceable reactor module.

Figure 5: Gen IV Reactors and Their Main Features [12]

Therefore, a NPMS equipped with either a Gen IV reactor design or other Advanced Reactor Design (ARD) (which is a more general term used to describe reactor technologies that have implemented improvements compared to the traditional Generation III PWR) could substantially reduce carbon emissions both within the international shipping industry and global community. There have been attempts in the past by four different countries to develop a NPMS, but these attempts utilized PWRs and resulted in varying levels of success. There has also been substantial research efforts and application examples of PWRs implemented into marine vessels (which is reviewed in greater depth later), but not as much research into implementing a Gen IV design. Lastly, there has been a noteworthy increase in interest for Gen IV technology development within the commercial sector, and these efforts have been met and further supported by increased financial investments and overall support from various governments. All these factors indicate a potential solution for eliminating GHG emissions within the international shipping industry through the development of an economically viable NPMS with Gen IV reactor technology.

1.5 Thesis Outline

Having established this thesis' background and main motivations within Chapter 1, Chapter 2 reviews the history of the nuclear power industry and highlights how nuclear power has always been utilized within (and influenced by) naval ship applications. Past and present uses of nuclear power onboard commercial ships was also evaluated, and past research which most highly influenced this project was synthesized. From there, Chapter 3 discusses the process of licensing and classifying the NPMS based on recent advancements made within the regulatory community to support the new reactor technology progress. Chapter 4 then establishes the specific design framework and requirements which were needed later on to analyze and select a reactor technology for the NPMS. Lastly, Chapter 5 reviews the technical aspects of each reactor technology option and compares their various pros and cons. The final recommendations and conclusions are provided within Chapter 6.

2.0 Previous Research and Applications

2.1 The Birth of the Nuclear Power Industry

During the afternoon of December 2, 1942, the first nuclear power experiment, the Chicago Pile-1, achieved a self-sustained nuclear chain reaction [13]. The Chicago Pile's success initiated the nuclear age, and later that month on December 28th, the Manhattan Project was formed to further explore nuclear fission and its potential applications within World War II [13]. Following the war, the US Atomic Energy Act of 1946 created the Atomic Energy Commission (AEC) to provide government oversight and explore peaceful uses for nuclear energy [13].

2.2 The US Naval Nuclear Propulsion Program

While the AEC's main goal was to prove nuclear energy's commercial viability, the AEC also collaborated with the US Navy to continue exploring national defense applications. To that end, a group of naval officers and civilian representatives were sent to the AEC laboratory in 1946 in Oak Ridge, Tennessee, for a year to learn about reactor technology [14] [15]. One of these officers was Captain Hyman G. Rickover, a seasoned ship and submarine commander who had served as the Head of the Electrical Section within the Navy Bureau of Ships (BUSHIPS) during World War II [14]. During his visit, CAPT Rickover became convinced that nuclear power was the superior option for the future of submarine propulsion due to its increased stealth and unlimited range. Upon his return to Washington, DC in 1946, he spent the next decade establishing and leading programs within both BUSHIPS and the AEC which allowed for the cohesive development and oversight of the first nuclear-powered naval submarine [15]. These programs laid the foundation for the Naval Nuclear Propulsion Program (NNPP), and the following years included noteworthy achievements:

2.2.1 The USS Nautilus (SSN-571)

In 1949, CAPT Rickover spearheaded a contract with Westinghouse to develop a PWR design for use onboard a submarine [14]. In the subsequent years, President Truman authorized construction for the Navy's first nuclear-powered PWR submarine, the USS Nautilus, in 1950 [14]. From there, construction began in 1951, and the ship was then launched and commissioned in 1954 [14] [16]. On January 17, 1955, the USS Nautilus embarked for the first time, and the

Commanding Officer historically messaged, “Underway on Nuclear Power” [16]. The USS Nautilus operated with a perfect safety record for 25 years, and when it was finally decommissioned in 1980, it had:

- Become the first ship to fully cross the North Pole underwater [16].
- Broken multiple submerged speed and distance records [16].
- Traveled over half a million miles during its entire life span [16].
- Developed the technological foundation for all subsequent naval submarine designs.
    - The last conventional submarine was decommissioned in October 1990, and today, all active and planned US submarines are nuclear-powered with a PWR [17].

2.2.2 The USS Seawolf (SSN-575)

To identify the best solution and establish industrial competition, CAPT Rickover also contracted with General Electric to develop a Liquid Metal Reactor (LMR) (which in this case can be more specifically referred to as a Sodium Fast Reactor (SFR)) design for submarine propulsion, and design work for the USS Seawolf began in 1950 [14]. Construction began in 1953, and the ship was launched in 1955 with a corresponding commission in 1957 [14] [18]. Both the USS Seawolf and USS nautilus are shown in the figure below:

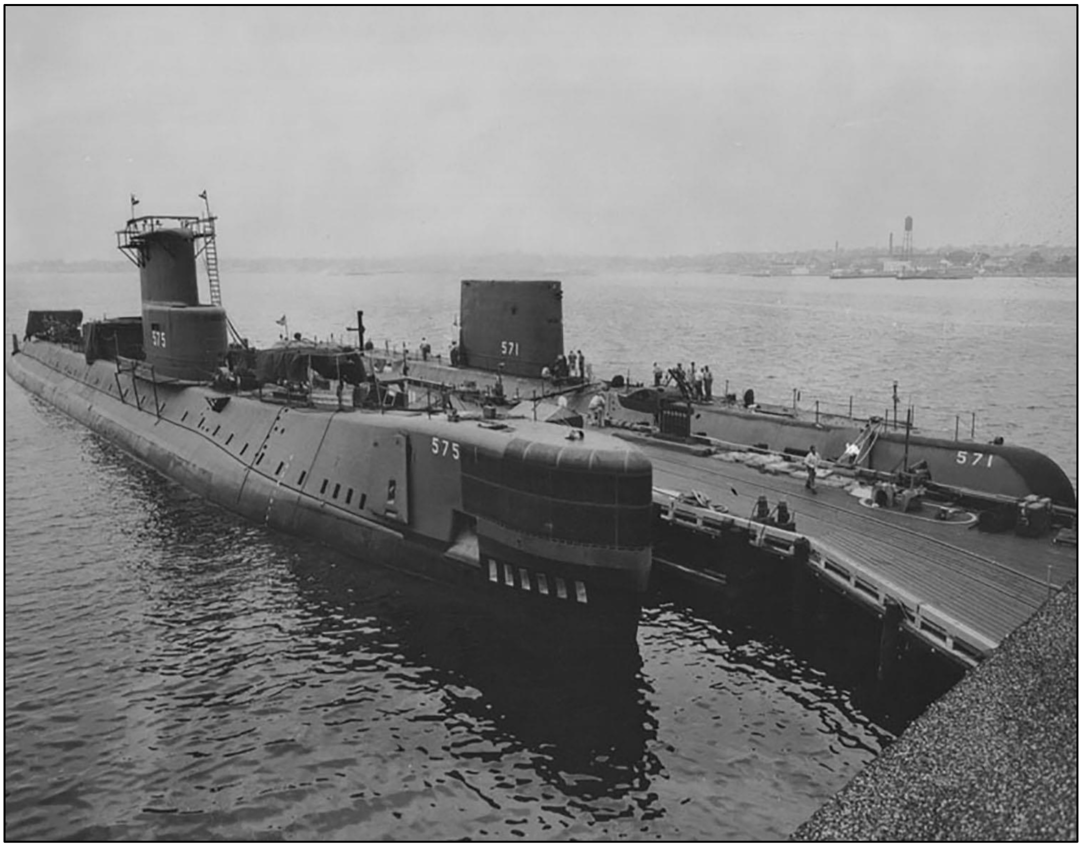


Figure 6: The USS Seawolf (SSN-575, Left) Alongside the USS Nautilus (SSN-571, Right) [19]

Despite a perfect safety record, the USS Seawolf was converted to a PWR in 1958 after having operated with a SFR for two years, and while this next detail may not have been realized at the time, this decision shaped the future of nuclear technology development within both the Navy and commercial nuclear power industry [14].

In trying to discern the reason why the USS Seawolf was converted to a PWR, historical recollections were somewhat inconsistent. The various recounts of the circumstances were as follows:

- One reference cited an overlooked detail within the reactor's design as the cause for the PWR's superiority. Specifically, Sodium reacts poorly with a certain type of stainless steel, and that material was used for the system's superheaters [20]. As a result, the decision was made to limit the reactor's operation to saturation conditions (which did not require these superheaters) [20]. However, this decision also meant that the reactor would only achieve approximately 80% of its highest possible power [20]. Therefore, the reactor's fuel was not depleted as efficiently, so the Seawolf was later converted to a PWR (which was also a slightly more mature technology at the time whose testing had advanced further) [20].

- A second reference credited aspects of the USS Seawolf's overall design as the cause for preference for PWRs over LMRs. Mainly, the reactor's use of the intermediate neutron spectrum raised coolant temperatures and provided superheated steam (for reference, the outlet temperature was 454°C compared to the Nautilus' 305°C) [21]. While this design was highly efficient, large electric heaters were required to keep the plant warm when the reactor was down to avoid the sodium freezing [21]. Additionally, the sodium became highly radioactive (with a half-life of 15 hours), so the entire reactor system had to be more heavily shielded than a water-cooled plant. Furthermore, the reactor compartment couldn't be entered for many days after shutdown [21].

Thus, the Naval Nuclear Program proceeded into the future using exclusively PWRs, and LMRs were mainly abandoned by both the Navy and commercial industry until recent decades when the technology was revisited as part of the development for Gen IV reactor designs. In total, the USS Seawolf operated for 30 years and traveled over 473,000 miles before being decommissioned in 1987 [14].

2.2.3 The Shippingport Atomic Power Station

The initial success of the NNPP directly impacted the initial development of commercial nuclear power plants. On December 8, 1953, President Eisenhower delivered his, "Atoms for Peace," speech before the United Nations General Assembly where he compelled the international community to forgo atomic weapons and shift efforts towards peaceful nuclear power applications [22]. In response to this speech, CAPT Rickover (who was serving as the chief of the Naval Reactor Branch within the AEC at the time) was directed to develop the first full-scale, commercial nuclear power plant [15]. Since PWR testing for submarine propulsion was more advanced at the time compared to LMRs, a PWR design was chosen for the Shippingport Atomic Power Station. The station began operation in 1957, and from there, it operated for 25 years and produced 7.4 thousand gigawatt-hours of electrical power [14] [23]. Other noteworthy aspects of the Shippingport Station include:

- The NNPP remained responsible for the Shippingport Station throughout its entire life span and decommissioning [14].
- The Shippingport Station was designed with future experimentation and flexibility in mind. While the first reactor installed was a PWR, that reactor was later replaced with a Light Water Breeder Reactor (LWBR) [14] [23]. This reactor was designed to produce power by "breeding" fissile material as other fissile material was consumed, and end-of-life testing confirmed that the breeding rate was higher than expected [14].
- It is widely agreed that the site was built, prepared, and tested very quickly. Initial construction began in 1954, and the site was operational by the end of 1957 [24].
- The Shippingport Station represents a success story in decommissioning. Following the Three Mile Island disaster in 1979, the Shippingport Station was selected for decommission in 1982 due to rising public concerns surrounding nuclear power safety [23]. This decommission process was completed in 1989, and the site was completely returned to its "green-field" condition [14].

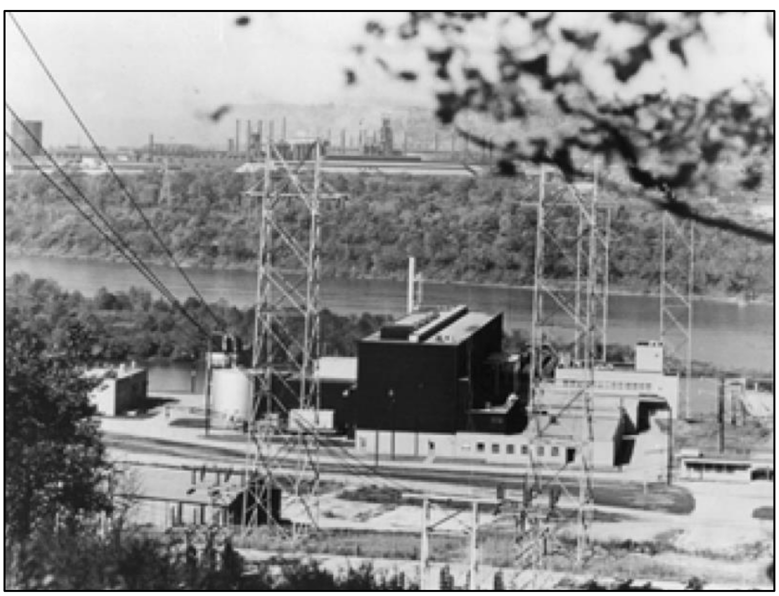


Figure 7: The Shippingport Atomic Power Station [14]

Figure 8: The Decommissioned Shippingport Site [14]

2.2.4 The USS Enterprise (CVN-65)

Following the successful implementation of nuclear-powered submarines, focus shifted towards applying the same solution to aircraft carriers. Even before the implementation of nuclear submarines, it was believed that carriers would be an especially good fit for nuclear power due to their high electrical and propulsive power requirements. As a result, construction for the first nuclear-powered aircraft carrier, the USS Enterprise, was authorized by Congress in 1954 (one year after President Eisenhower's, "Atoms for Peace," speech, and the same year as the USS Nautilus' commissioning) [25]. From there, the ship was launched in September 1960, and it was commissioned in November 1961 [25].

Throughout its service life, the USS Enterprise used eight reactors to power the ship and spin four propellers (compared to the one reactor used to spin one propeller onboard submarines) [25]. In addition to its increased endurance, the ship also possessed a major advantage compared to oil-fueled carriers in that more space was available onboard for aviation fuel, ordnances and other stores due to the elimination of diesel storage, air intakes, exhaust ducts and smokestacks [26]. Furthermore, the USS Enterprise was active and operated for over 50 years despite being originally intended to operate for 25 years [25]. Finally, it was decommissioned in December

2012, but the ship's overall success led to the elimination of conventionally fueled aircraft carriers, and today, all US aircraft carriers are nuclear-powered [25].

2.2.5 The USS Long Beach (CGN-09)

Alongside the USS Enterprise, the US Navy also explored nuclear-powered cruisers to determine if nuclear power was also a good fit for other surface combatant crafts. Therefore, the keel was laid for the USS Long Beach in December 1957, and the ship was launched in July 1959 [14]. The USS Long Beach was commissioned in September 1961 (a few months before the USS Enterprise), and it became the first of nine total nuclear-powered cruisers [14]. The USS Long Beach was powered by two reactors that supported two propellers, and it operated for 34 years until it was decommissioned in May 1995 as part of the US Navy's downsizing efforts following the end of the Cold War [27] [14]. The ship's major accomplishments include its participation in Operation Sea Orbit in 1964. During this mission, the USS Long Beach completed the first around-the-world cruise without replenishments over 64 days alongside the USS Enterprise and fellow nuclear-powered cruiser, the USS Bainbridge [28]. An image from this operation is provided below:

Figure 9: Operation Sea Orbit, From Left to Right: USS Bainbridge, USS Long Beach, USS Enterprise [27]

2.3 Naval Nuclear Propulsion Today

Similar to its original organization, the modern US Navy continues to apply a cradle-to-grave approach to nuclear power by overseeing every part of the ship and its corresponding reactor's lifecycle. This oversight includes design, construction, crew training, vessel operation, ship maintenance, refuels, decommissioning and eventually, waste management and disposal. The NNPP also still works in conjunction with the Department of Energy, so as a result, it operates with overall cooperation and general support from its governing body. Furthermore, the US Navy has been empowered by the US government to act as a self-regulating organization due to its strict internal requirements and flawless safety record. This approach is very different from the commercial nuclear-power industry where lengthy licensing processes can sometimes completely derail a potential project. Therefore, many experts agree that the NNPP's success was at least partially due to the overall support provided throughout the US Government system.

As previously stated, all active and planned US submarines and aircraft carriers are powered using a PWR. Figures related to currently active nuclear submarines are shown below:

Figure 10: USS Michigan, Ballistic Missile Submarine [29]

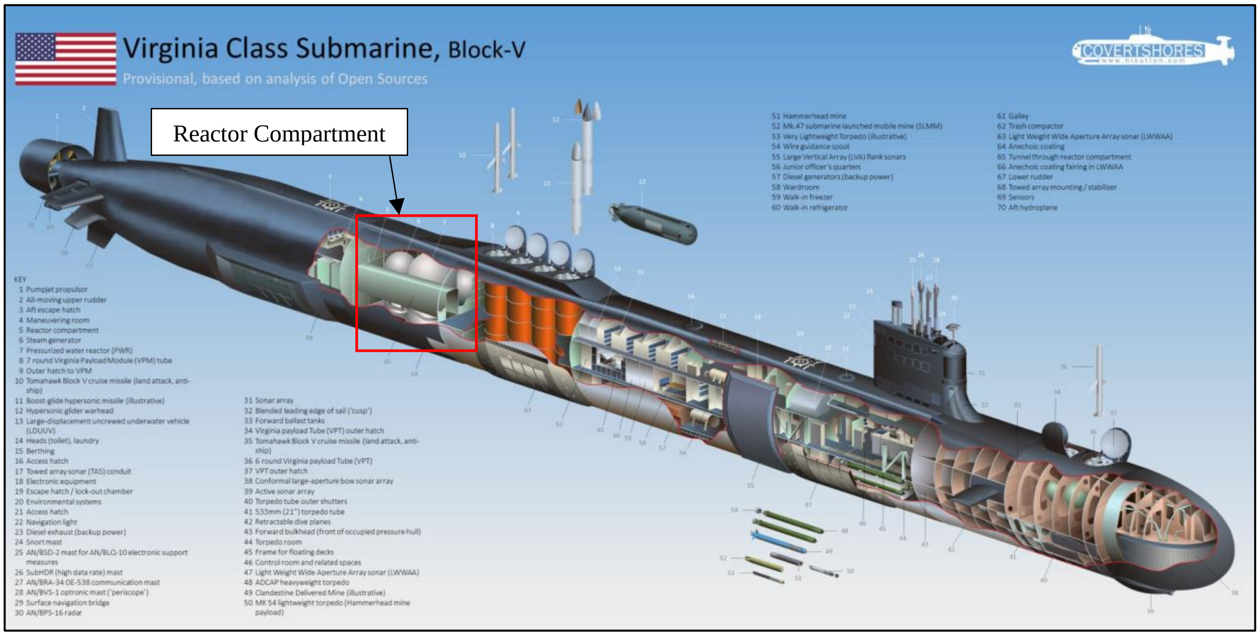


Figure 11: US Navy Attack Submarine [30]

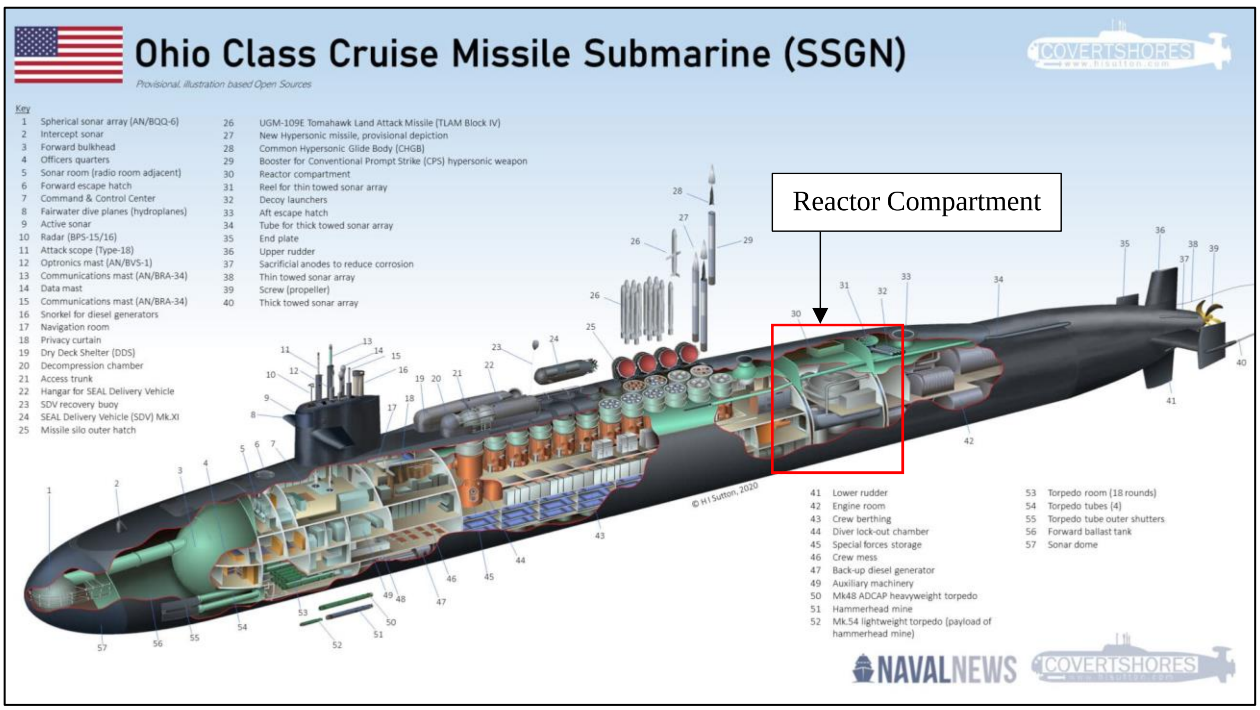


Figure 12: US Navy Ballistic Missile Submarine [31]

As of 2020, the US Navy currently operates 50 attack submarines, 14 ballistic missile submarines and 12 aircraft carriers (for a total of 76 nuclear-powered vessels) [14]. A publicly available figure showing the typical layout of a naval nuclear propulsion system is provided below:

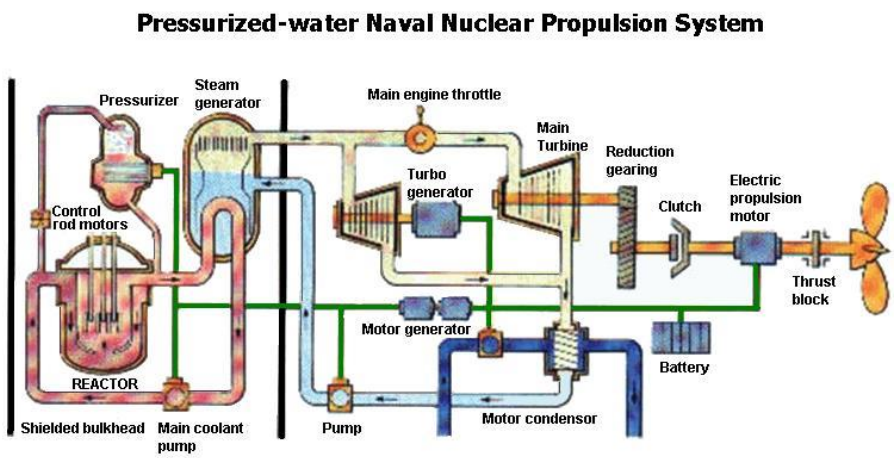


Figure 13: Engine Room Layout Onboard a Naval Nuclear-Power Vessel [32]

Related to this propulsion system, three key design aspects include:

1. Highly Enriched Fuel. The reactor uses highly enriched uranium (HEU) for fuel. For vessels operated by the US and the United Kingdom (UK), this HEU is enriched to greater than 93.5% [33]. This fuel is significantly more enriched (and therefore, more expensive) compared to fuel used in the civilian nuclear-power industry. For reference, commercial uranium is enriched to 3-5%, and research reactors use fuels enriched to 12-19.75% [34]. Uranium is also typically classified as HEU and "weaponized" above 20% enrichment (and in contrast, fuels enriched below 20% are considered lowly enriched uranium (LEU)) [33] [34]. These reactors are fueled with HEU to support:

- Higher power requirements (compared to commercial ships). US submarine reactors reach max powers of about 220 Mega-Watts Thermal (MWt), and US aircraft carrier reactors reach max powers of approximately 700 MWt [21]. These high-power ratings support high electrical outputs required for military systems such as:
  - Communications equipment.
  - Navigation sensors and equipment.
  - Weapons systems.

    - Onboard Nimitz-class aircraft carriers (which make up the majority of currently operated US carriers, but the Nimitz class is also currently being phased out by Ford-class aircraft carriers), the reactors onboard also supply auxiliary steam needed during flight operations.
- Longer endurances between refuels. Unlike commercial nuclear power plants (which are typically refueled annually), the US Navy's nuclear vessels are either only refueled once during the ship's life (as is the case for aircraft carriers), or alternatively, the reactor core is capable of lasting throughout the ship's life without the need for a refuel (as is the case for submarines) [21]. This increased range provides key strategic advantages in that the ship's global positioning and overall operation time is less constrained by the reactor's power availability and maintenance schedule.
    - For reference, aircraft carriers are refueled after twenty-five years of operation at the halfway point within the ship's life, and submarines can operate 30-40 years without needing to refuel [21].

2. Increased Engine Room Manning. Operating a naval nuclear-powered engine room requires 24/7 monitoring performed by larger quantities of people (compared to operating a conventional engine room of similar size). This requirement stems from the use of an intricate secondary steam system which requires constant oversight as well as daily chemical monitoring to detect issues and prevent corrosion.

For reference, the approximate number of engine room operators needed for a conventional containership is 4-6 people [35]. These lower values are partially due to the use of Unattended Machinery Spaces (UMS) which utilize automation and alarm systems to allow for lower manning requirements within engine room spaces.

3. Significant Over-Engineering. Naval nuclear-powered vessels and their corresponding nuclear propulsion system are highly over-engineered so that they can:

- Satisfy higher fuel integrity standards.
- Protect against wartime attacks and battle shock.
- Accommodate the crew's living spaces within close proximity to the reactor.
- Support rapid and frequent changes in power to accommodate tactical ship maneuvering.

- Reduce noise and the potential for detection.
- Minimize life-cycle costs by operating for many years without refueling.
- Be compact and cost-effective [36] [37].

This over-engineering is seen within the robust structures, redundancies and backup systems built into the ship and propulsion system's design. While these measures provide increased safety and operational capability, it is important to note that these design decisions also increase the vessel's overall cost. Additionally, not all these over-engineered capabilities would provide sufficient value when applied within the commercial shipping industry to justify the corresponding higher design and manufacturing costs.

2.4 Naval Nuclear Propulsion and Commercial Shipping

To summarize, the NNPP represents a success story in the wide-scale implementation of nuclear power into marine propulsion. However, the US Navy's use of nuclear power does not represent a perfect footprint for nuclear power applied within the commercial shipping industry. While many justifications for this conclusion exist, the main reason is due to the NNPP's high costs for design and operation. Additionally, the NNPP has developed a massive, all-encompassing structure over multiple decades built upon a foundation based on longstanding principles, and therefore, it would be extremely difficult to replicate a similar organization at the onset of implementing nuclear power into maritime shipping.

Nevertheless, many experts within both the nuclear power and maritime shipping fields recognize the NNPP as proof that a NPMS is technically feasible [38]. As a result, many lessons learned and key takeaways can be drawn from the NNPP's history and current operations as this project attempts to implement nuclear power into the commercial shipping industry. These takeaways include:

1. Collaboration and support from governments as well as licensing and regulatory bodies is crucial. Throughout the NNPP's initial years, CAPT Rickover facilitated significant cooperation between the AEC and BUSHIPS to eliminate barriers to entry and ensure that the regulators were involved alongside the Navy in developing these pioneering designs. Furthermore, the idea of a nuclear-powered Navy received strong support from both the legislative and executive branch at the time which helped progress the program

through its initial developmental years. In applying nuclear power to the commercial shipping industry, similar involvement and support from governmental and regulatory bodies could play a key role in the NPMS's implementation success.

2. Safety must be prioritized from the onset of the program. It is widely agreed that the Navy is allowed to operate independently and regulate itself due to their flawless safety record. This record is the result of harsh self-imposed standards and an overall concern for safety at every level of the program's design and operation. Furthermore, the NNPP's safety record has also resulted in high public approval (compared to other applications of nuclear power), and therefore, a similar prioritization of safety should be strived for in developing the NPMS.
3. The Navy's port-access model (which uses individual agreements with foreign nations) could serve as a potential initial example for handling port calls. Specifically, the US Navy's nuclear-powered vessels can access over 150 foreign ports in over 50 countries through individual, bilateral agreements [38] [14]. While this system seems infeasible across the entire commercial shipping industry, this system has worked for the NNPP across many decades and was important to acknowledge within this project.
4. Previous naval nuclear operators present a viable, well-trained workforce for the commercial shipping industry. The NNPP has established a complex training infrastructure which utilizes both classroom and simulated hands-on elements to ensure high-level nuclear operations proficiency for tens of thousands of sailors. While the NPMS will still require its own training program for any nuclear operators, hiring previous naval operators could encourage the NPMS' successful implementation by increasing the baseline levels of nuclear propulsion knowledge and experience.

With respect to the Navy's reactor technology, HEU PWRs like the reactors onboard US naval vessels are also not the most viable reactor technology option for the commercial shipping industry since the US ceased all HEU production in 1992 as part of the country's non-proliferation agenda [39]. As a result, all US nuclear-powered ships use fuel from an HEU stockpile generated from a combination of pre-1992 production and recycled Cold War-era warheads [39]. While this supply is expected to last until 2060, Congress has expressed interest since 1995 to shift away from using HEU in naval applications for the purpose of:

- Expanding non-proliferation efforts. So far, the goal of non-proliferation initiatives has been to reduce the use of HEU in weapons development and civilian applications (such as research reactors and medical equipment) [33]. However, removing HEU from US naval propulsion would:
  - Continue the US's historic trend of leading non-proliferation efforts.
  - Eliminate one of the largest non-weapons HEU uses worldwide.
  - Encourage other countries (such as the UK and Australia) to make similar changes.
  - Make it more difficult for other countries to justify HEU production for naval propulsion use.
  - Remove the chance of HEU theft or nefarious diversion from the naval fuel cycle [39] [33].
- Developing an alternative design option before the HEU stockpile is emptied.
- Preparing for future naval vessel designs. The NNPP recently completed construction of the first Ford-class aircraft carrier and began preparing for construction of the first Columbia-class ballistic missile submarine. Soon, the NNPP will also begin a replacement design for the Virginia-class fast attack submarine. With so much change and technological progression anticipated soon, an opportunity exists to consider new reactor designs which do not utilize HEU.

For these reasons, reports were submitted to Congress in 1995, 2014, 2016 and 2020 regarding the ability to implement LEU and other advanced fuel systems into naval nuclear reactor designs [33]. As an aside, these changes (if acted upon) would represent a major shift for the NNPP away from foundational technology which had been developed and refined over seven decades, and the hypothetical technology which was chosen as the replacement would represent a strong recommendation to the commercial shipping industry and other marine propulsion applications on promising future reactor designs. Conversely, any ARDs which were successfully implemented in the commercial maritime sector first could also potentially influence future naval efforts during the anticipated transitional upcoming years.

While earlier reports were clear that this technological change was not feasible due to cost increases and the reintroduction of refuels into the reactors' life-cycle, the 2016 report outlined a timeline and expected cost to develop and test an advanced fuel system which would enable the use of LEU in aircraft carrier [40]. However, these plans did not progress further at the recommendation of the Secretaries of Energy and the Navy [33].

The report submitted in 2020 was a collaboration between Idaho National Laboratory (INL), Oak Ridge National Laboratory and Argonne National Laboratory where technical reactor-design recommendations were made to support powering, "ship-borne systems and transportable systems to fixed locations, e.g., to a remote base or to a seawater desalination service location" [41]. Specifically, the goal was to initially investigate reactor designs which would:

- Assume an enrichment of 19.75% (which represented the highest enrichment value within the LEU classification) [41].
- Reach a target power rating of 350 MWt with an assumed efficiency of approximately 28.6% (which corresponded to a 100 MWe output) [41].
- Typically operate between, "approximately 5-30% of full power with excursions to 100%," which would result in an average lifetime power of 20% (or 20 MWe) [41].
- Have a single-batch core lifetime of 30 years [41].
- Overall prioritize:
    - Compactness.
    - The ability to achieve, "rapid and repeated load following capability from 0 to 100% power without rate or restart constraints due to Xe poisoning and other effects" [41].
    - Options with high Technology Readiness Level (TRL).

Within this report, different fuel systems and reactor technologies were evaluated to determine a smaller subset which were best for further evaluation as potential replacements for the NNPP's current reactor design. Following significant analysis, the recommended fuel systems were as follows:

Recommended Fuel Systems for an Advanced LEU (aLEU) Reactor Design			
Tier	**Fuel Type**	**Fuel Form**	**Strengths / Weaknesses**
Tier 1			

UO_2	Rod and plate[a]	Monolithic, dispersion or inert matrix[b]	Infrastructure, low swelling, power producing / low thermal conductivity, fuel cracking
U-xMo[c]	Rod and plate	Monolithic, dispersion or inert matrix	Some infrastructure, high TRL, undergoing qualification / lacks high temperature irradiation experience
U_3Si with alloy additions	Plate	Dispersion or inert matrix	Some infrastructure, reasonable TRL / fuel density lowered as dispersion
U-2Mo-1Si	Plate	Dispersion or inert matrix	Some infrastructure, thermal conductivity / little infrastructure
Tier 2			
U-10Zr	Rod	Monolithic	High TRL, thermal conductivity / infrastructure being reconstituted, porosity limits burnup to ~30%
UC	Rod and plate	Monolithic, dispersion or inert matrix	Reasonable TRL though not current, dense fuel, thermal conductivity / no infrastructure
UN	Rod and plate	Monolithic, dispersion or inert matrix	Uranium density, thermal conductivity / no infrastructure, difficult to fabricate

a. Benchmark systems are UO_2 as rods and plates with both H_2O and Na coolants.
b. Composite systems are considered inasmuch as the benefits of dispersion fuel properties are conferred on the UO_2 monolithic portion with minimal reduction of uranium density.
c. x = 7, 9, or 10 weight percent.

Table 1: Recommended Fuel Systems for an aLEU Reactor Design [41]

Equipped with an initial set of potential fuel systems, the report evaluated different reactor concepts using a two-stage down-selection process to identify the best options for further analysis. The associated down-selection stages were described as, “1) an overall qualitative screening based on a given concept’s prospects for meeting mission requirements, considering relevant information such as its history and relative maturity, allowing for innovative designs, and (2) a simple reactor physics and thermal-hydraulics analysis that provides insight into the relevant overall core characteristics” [41]. Following this analysis, the recommended reactor concepts included PWRs, SFRs and Lead-cooled Fast Reactors (LFRs) [41]. For primary coolants, water and liquid sodium were also specifically recommended due to their high TRL [41].

Overall, these conclusions provide valuable insights into potential reactor technology options for the NPMS. While the design objectives within the report varied greatly from the NPMS’ anticipated design goals (specifically with respect to the high power rating, dynamic operational profile and long core lifespan), the resultant conclusions provided key insights due to their relation to marine application and goal to implement designs with high TRL. Lastly, this report’s conclusion also gives a first look into a potential future direction for the NNPP which has historically influenced the direction of civilian and commercial nuclear power applications.

2.5 International Naval Nuclear Propulsion

Alongside the US, there are five other countries who also operate nuclear-powered warships: the UK, France, Russia, the PRC and India. In September of 2021, Australia also announced plans to develop a nuclear-powered submarine fleet over the next two decades using shared technology information from the US and the UK [42]. Additionally, Brazil has expressed interest since the 1980s in building nuclear-powered submarines, but the country has not yet operated nuclear vessels [43]. However, Brazil signed an agreement in November of 2021 with French ship builders to build its first nuclear-powered submarine by 2034 (which would also mean that this vessel would be anticipated before Australia's first nuclear submarines) [44]. An overview of each country's nuclear fleet is as follows:

2.5.1 PRC

The People's Liberation Army Navy's (PLAN) nuclear program began in the 1970s [21]. While these numbers aren't known with full certainty, it is believed that the PLAN has 15 nuclear submarines as of 2021 (6 ballistic missile submarines, and 9 attack submarines) [45]. Additionally, these quantities are projected to double by 2030 due to the PRC's interest in modernizing their submarine force [45]. Furthermore, the PRC has also expressed interest in developing nuclear-powered icebreakers [21]. Related to the reactor technology, it is believed the PRC utilizes PWRs with initial designs that strongly resembled Russian reactors due to assistance received from Russia [21]. However, it is also believed that the PRC uses LEU instead of HEU (which is an interesting differentiator in contrast with other navies) [33] [21].

2.5.2 France

The French nuclear navy began in 1964 with the construction of the Le Redoutable-class ballistic missile submarine [46]. As of 2021, France has 10 nuclear powered vessels (four ballistic missile submarines, five attack submarines and one carrier) [21] [47] [48]. All platforms use PWRs with LEU (between 5-7%), and among the different ships, the reactor design is either the same model or a slightly modified version. This reactor, the K15, is shown in the figure below:

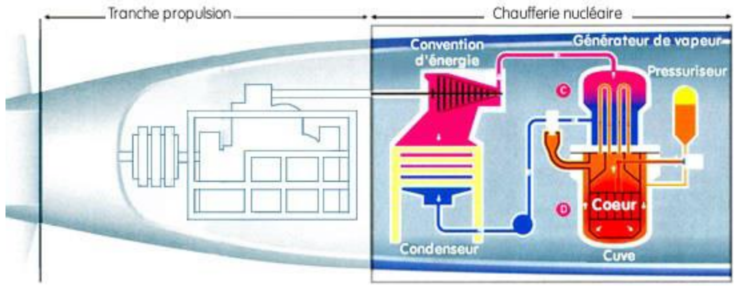


Figure 14: French Naval Nuclear Propulsion System [21]

Noteworthy aspects of this design include how the steam generator is located within the reactor pressure vessel. Additionally, the use of LEU allows for a more affordable design that more closely resembles civilian reactors, and as a tradeoff, the reactor must be fueled every 7-10 years (depending on the specific platform) [21]. Moving forward, France is in the process of constructing six new attack submarines as part of the Barracuda-class [21].

2.5.3 India

The Indian Navy's nuclear fleet is relatively new with its first ballistic missile submarine (the INS Arihant, a PWR with HEU) commissioned in 2016 [21]. From there, India has had a history of leasing nuclear vessels from Russia, and plans are in place to construct additional ballistic submarine in the future [21].

2.5.4 UK

The Royal Navy has developed its nuclear fleet through a strong partnership with the US since the 1950s [49]. As of 2021, the Royal Navy operates 12 nuclear submarines (4 ballistic missile and 8 attack) which are all powered with a PWR that uses HEU supplied by the US [49] [21].

2.5.5 Russia

Following the USS Nautilus' commissioning in 1954, the Russian Navy quickly developed its own nuclear submarine fleet, and throughout the Cold War, this country was one of the largest nuclear-powered forces on the seas [21]. While current vessels are all powered by PWRs, Russia's naval nuclear program also started by experimenting with both PWRs and LMRs which utilized lead-bismuth as the coolant (similar to how the NNPP began with both PWRs and an SFR) [21]. Also like the US, Russia operated nuclear-powered cruisers, and one remains in service [21]. In addition to this cruiser, Russia currently operates twenty-one submarines (8 ballistic and 13 attack), and plans exist to build more submarines as well as overhaul other nuclear cruisers in the future [21].

In summary, nuclear power is already highly implemented into the maritime setting through its use onboard submarines and within various navies. Related to the reactor technology, PWRs are the prevailing design, and this trend most likely stems from the US' original decision to utilize PWRs onboard their vessels (a design decision which also influenced the origin and future trends within the civilian nuclear power industry). However, deviations exist with respect to the fuel enrichment used within these PWRs (which also aligns with current research conducted by various national labs and submitted to Congress), and efforts are ongoing within certain countries to continue to lower the required enrichment level.

In contrast with the civilian nuclear industry, there is also a clear trend of growth for nuclear power within naval applications. All countries with nuclear-powered vessels have plans to build more, and aspirations exist to acquire nuclear-powered vessels among countries who have not yet entered this space. Although the operational profile and requirements for a naval warship are very different when compared to a merchant ship, this trend shows how nuclear power is well suited for the maritime industry.

2.6 Commercial Nuclear Propulsion Applications

Alongside the various military applications, four countries have also made attempts with varying success throughout history to implement nuclear power into various commercial industries. These countries include Germany, Japan, the US and Russia, and additionally, China has expressed interest since 2018 in developing a nuclear-powered "experimental platform" which some believe will be a commercial icebreaker [50] [51]. With respect to each country, the various nuclear-powered commercial ships include:

2.6.1 NS Savannah (NSS)

Following President Eisenhower's 1953 "Atoms For Peace" speech, this American cargo-passenger ship was the world's first nuclear-powered commercial ship. The NSS was first suggested in 1955 for the purpose of:

- Demonstrating the peaceful uses of nuclear power.
- Exhibiting the feasibility of nuclear-powered merchant ships.
- Developing the maritime infrastructure necessary for subsequent nuclear-powered merchant ships [52].

A figure of the NSS as well as a table of the ship's technical data are provided below:

Figure 15: NS Savannah

NS Savannah Technical Data	
Length Overall (LOA, ft)	595.5
Beam Overall (BOA, ft)	78
Draft (T, ft)	29.5
Displacement (Loaded, LT)	21,800
Power Rating (MWt)	74
Reactor Type	PWR
Reactor Fuel	UO_2, 4% enriched
Maximum Speed (kts)	21
Cargo Capacity (LT)	10,000
Officers	25

Crew	85
Passengers	60

Table 2: NS Savannah Technical Data [53]

The ship was initially a joint project between the Department of Transportation's Maritime Administration (MARAD), the AEC and the Department of Commerce [54]. After being launched in 1959, the ship was owned and operated by MARAD, and regulatory licensing and oversight was provided by the AEC (which was later replaced by the Nuclear Regulatory Commission (NRC)) [54] [55]. From there, the NSS completed its maiden voyage in 1962, and the ship remained in service with a flawless safety record until 1971 [55]. Additional figures related to ship's overall and engine room layout are provided below:

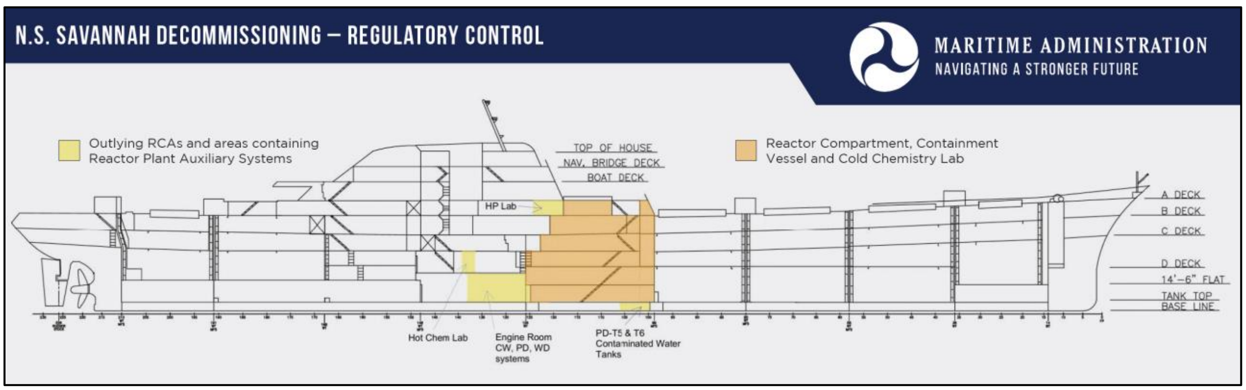


Figure 16: NS Savannah Layout [52]

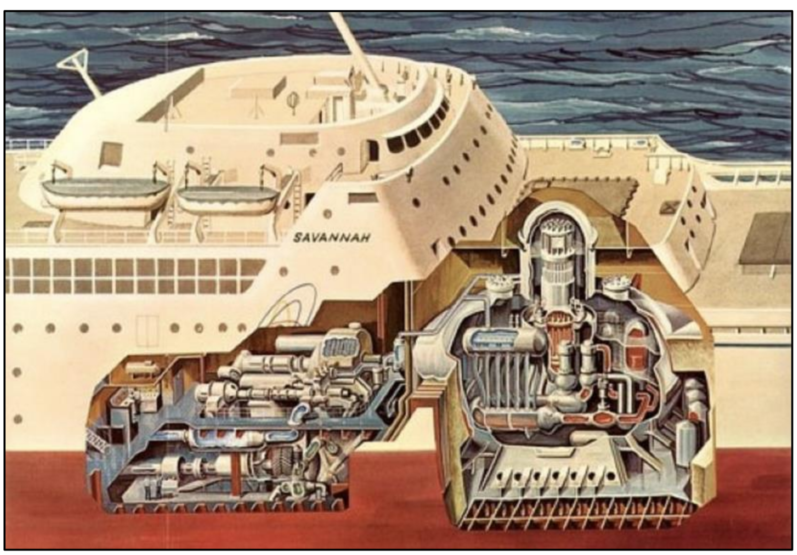


Figure 17: NS Savannah Engine Room [56]

Like other nuclear-powered ships, the NSS' engine room was located near the center of the ship where the reactor would be most secure from damage and experience the smallest response from wave motion. This engine room design was also not as compact as the nuclear-powered systems onboard naval vessels due to differences in design priorities and a purposeful lack of collaboration with the Navy throughout the NSS's development to further solidify the ship's peaceful agenda.

Related to oversight, regulations for nuclear-powered commercial vessels were developed to support this vessel, and although these regulations were written in the 1960s, it's possible that these requirements could serve as a starting point for developing current and future regulations for the NPMS. Additionally, the NSS helped secure some of the first agreements which granted access for nuclear-powered ships into foreign ports for the purpose of trade, and therefore, these agreements could potentially be revisited and serve as the initial foundation for port-access agreements within the current maritime industry [57].

Lastly, the NSS is often cited as an economic failure since it had higher construction and operational costs compared to a passenger ship or cargo ship at the time, and due to these high costs, the ship's service life was cut short due to economic unviability [58]. The NSS is also frequently perceived as a failed experiment since no additional nuclear-powered cargo ships were ever developed in the US (despite initial plans that the NSS would be the first of many similar ships). However, experts argue these failings are because the NSS was designed to achieve diplomatic goals (versus economic goals) [58]. To that end, the NSS was not economically optimal due to the ship's:

- Reduced cargo space and a larger crew compared to other cargo ships of the era.
- Reduced passenger space compared to cruise liners.
- Visually appealing hull design (versus a more functional shape like a bulk carrier) which resembled a streamlined yacht.
- Increased electrical loads to support a pool, lounges, significant HVAC loads and lavish staterooms [58].

Overall, the ship was designed to improve the US' international relationships, increase public opinion of nuclear power, and prove the overall feasibility of a nuclear-powered cargo ship (which experts agree the NSS successfully achieved) [58]. Therefore, its early decommissioning due to unmaintainable economics was more the result of misaligned design goals (versus the result of its specific use of nuclear power). Moving forward, these economic issues could be avoided using a more economically driven initial design philosophy.

2.6.2 NS Otto Hahn

After its launch in 1964, this German bulk carrier (and the world's second nuclear-powered cargo ship) made its first port call in 1970 and remained in service until 1979 when it was deactivated due to economic shortcomings [59] [60]. Following deactivation, the ship was converted to a conventional marine diesel vessel and continued to operate from 1983 to 2009 [59] [61]. During its time as a nuclear vessel, the NS Otto Hahn steamed 650,000 nautical miles (nm) and visited thirty-three different ports across twenty-two countries [59]. A figure of the NS Otto Hahn as well as a table of the ship's technical data are provided below:

Figure 18: German Otto Hahn [60]

NS Otto Hahn Technical Data	
Length Overall (ft)	564.46
Beam Overall (ft)	76.77
Freeboard (ft)	17.48
Draft (ft)	30.24
Displacement (LT)	25,790
Power Rating (MWt)	38
Reactor Type	PWR
Reactor Fuel	LEU, 3.5-6.6% enriched
Maximum Speed (kts)	17
Cargo Capacity (LT)	14,040
Crew	63
Research Personnel	35

Table 3: Otto Hahn Technical Data [59] [61]

This ship was very similar to the NSS in that it was designed to carry both passengers and cargo (specifically ore) [60]. The NS Otto Hanh also used a reactor design based on the reactor originally onboard the NSS. Lastly, the Otto Hahn operated without any major safety issues (like the NSS), and although other ships were planned to follow this ship, the NS Otto Hahn was the only German-made nuclear-powered cargo ship to be produced thus far.

2.6.3 NS Mutsu

The world's third nuclear-powered commercial ship was launched in Japan in 1969. Like the other nuclear-powered cargo ships, the NS Mutsu was initially intended to be the first of many nuclear-powered cargo ships [62]. Unfortunately, this ship never operated as a cargo ship following an incident in 1974 where neutron radiation leaked outside the protective shielding while initially testing the reactor [63]. From there, the ship underwent a significant repair period from 1978 to 1982, following which, the ship served as a research vessel until it was converted to conventional diesel power in 1995 [64] [62]. Figures of the NS Mutsu and its layout as well as a table of the ship's technical data are provided below:

Figure 19: NS Mutsu [62]

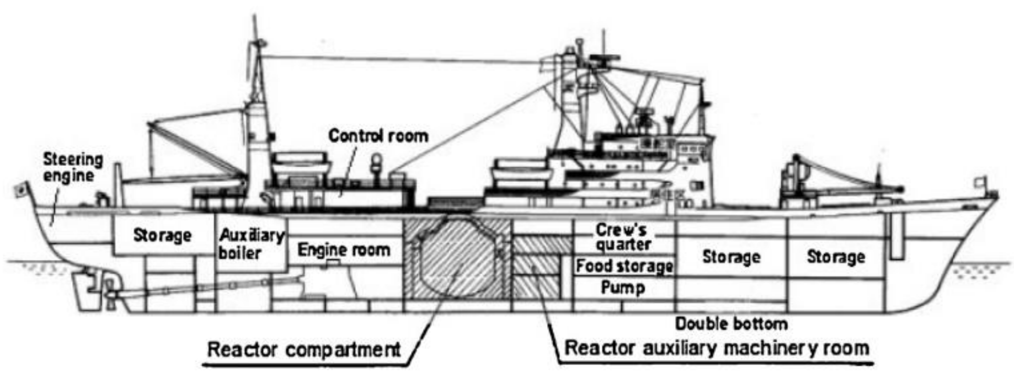


Figure 20: NS Mutsu Layout [65]

Mutsu Technical Data	
Length Overall (ft)	426.5
Beam Overall (ft)	62.3
Depth (ft)	43.3
Draft (ft)	22.6
Power Rating (MWt)	36
Reactor Type	PWR
Reactor Fuel	LEU, 3.24-4.44% enriched
Maximum Speed (kts)	17.2

Cargo Capacity (LT)	8,240
Crew	80

Table 4: Mutsu Technical Data [65]

Although the NS Mutsu did not operate as a cargo ship, lessons learned from this ship can be applied to the current project and planning for the NPMS. In hindsight, the reason behind the faulty shielding design was due to reduced experience with reactor design and poor communication between the companies selected to build the ship and reactor [63]. Specifically, the reactor and the ship were built by different companies, so although the shielding design was reviewed by the Westinghouse Electric Company, the shield was not designed with sufficient collaboration and integration between the involved parties [63]. This observation was important within the context of this project because the NPMS could be designed using a similar approach (where one company builds the ship while another provides the nuclear-powered systems within the engine room). Therefore, the history of the NS Mutsu highlights the importance of ensuring the proper amount of collaboration between the shipbuilder and reactor designers should the NPMS use a similar construction model.

2.6.4 Sevmorput

This Russian cargo-ship was the world's fourth nuclear-powered cargo ship when it was built in 1988, and after significant refits, it remains in service today [66]. Equipped with its high power capacity, the Sevmorput can travel through ice fields up to 1 meter thick [67]. A figure of the Sevmorput as well as a table of the ship's technical data are provided below:

Figure 21: Sevmorput [68]

Sevmorput Technical Data	
Length Overall (LOA, ft)	854.0
Beam Overall (BOA, ft)	113.5
Draft (T, ft)	38.7
Displacement (LT)	61,966
Power Rating (MWt)	135 MW
Reactor Type	PWR
Reactor Fuel	HEU, 30-40% enriched
Speed (kts)	20.5
Cargo Capacity (LT)	33,980

Table 5: Sevmorput Technical Data [66] [67] [69]

Other noteworthy details related to the Sevmorput's design include that the ship is equipped with both two standby diesel generators and two emergency diesel generators [67]. While these generators are not required alongside to the reactor to meet the ship's powering requirements during normal operations, these additional systems provide valuable redundancy in the event of a casualty or situation where the reactor cannot be utilized.

2.6.5 Russian Icebreakers

In addition to cargo ships, Russia has also deployed nuclear power onboard icebreaker ships. In fact, the Soviet Union was one of the first countries to deploy nuclear power onboard a surface ship for civilian use in 1959 through their nuclear-powered icebreaker Lenin [70]. Since then, these vessels have been recognized as a success in nuclear power implementation onboard surface ships since their reactor's high power output is very well suited to push through and break ice (which can be over 2.8 meters (m) thick) [71]. As of 2022, Russia currently operates six icebreaker ships, and eight more are either planned or under construction [72]. A figure and technical data related to the most recent ice breaker class, the Arktika, is provide below:

Figure 22: Arktika Icebreaker Ship [73]

Arktika Technical Data	
Length Overall (LOA, ft)	568.5
Beam Overall (BOA, ft)	111.5
Draft (T, ft)	34.4
Displacement (Loaded, LT)	33,530
Power Rating (MWt)	175
Reactor Type	PWR
Reactor Fuel	HEU, 20% enriched
Speed (kts)	22
Crew	53

Table 6: Arktika Technical Data [71] [74] [75]

2.7 Academic Research

A significant amount of academic research has already been conducted related to introducing nuclear power into various aspect of the maritime industry, and due to this high quantity, not all research related to this topic has been reviewed within the scope of this project (in fact, an attempt to synthesize this work in its entirety could be a future research effort of its own). Therefore, the bodies of work discussed below are those which most heavily influenced this project. Additional discussion of other academic research efforts is also covered in later sections related to the specific types of Gen IV reactor designs available for the NPMS.

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

In 2009, a thesis was conducted within the MIT Naval Construction and Engineering (2N) Program which developed an early conceptual design and overall feasibility of a nuclear-powered cargo vessel [76]. Due to the scope and similarity to the current project's topic, this thesis provided key insights and helped lay a foundation for this project's approach and methodology. However, this thesis was understandably limited by the available technology of its time, and as a result, the overall conclusion was that nuclear-powered cargo ships were not yet economically preferrable to their conventionally powered counterpart. Thus, it was possible that new conclusions could now be drawn as a result of the technological progress made surrounding ARDs and Gen IV reactors. It was also possible that a nuclear-powered cargo ship would be a preferrable design within the current market due to increased concerns surrounding GHG emission reduction (which would need to be met while maintaining economic viability).

In more technical detail, this thesis applied a risk-averse design philosophy and used the Emma Maersk as the baseline ship for analysis since it was the biggest container ship built at the time. Following an electric and propulsion analysis, the baseline ship's total power requirement was 350 MWt. This thesis also assumed that the baseline ship would be continued to be built at the same shipyard, and the nuclear engine room would be added by a civilian nuclear-certified shipyard in the United States (most likely the Newport News Shipyard in Virginia where both nuclear aircraft carriers and submarines are constructed). For the anticipated trade route, this thesis limited operational analysis to a single trade route from Shanghai, China to Los Angeles, California (6,000 nm total). This route was selected because:

- These two specific ports seemed like a viable route since they were among the largest and most modern ports at the time.
- By limiting the analysis to only two ports, the minimal number of ports would need to be upgraded to support a nuclear vessel.
- The author anticipated these larger ports would be most willing to implement the necessary changes to support a nuclear-powered ship.

For the reactor design, four different types of reactors were analyzed:

- PWR
- Boiling Water Reactor (BWR)
- SFR
- Marine High Temperature Gas Cooled Reactor (MGCR)

Using the Pugh method, a PWR was selected as the reactor type for this study. Additionally, the author believed the MGCR was the actual best option for this application, but this technology was not mature enough at the time (which was an especially valuable insight within the context of the current project).

Using a PWR, a specific reactor design was developed using a software called CASMO-4 to meet the baseline ship's power requirements. This analysis followed a logical progression since the author was pursuing a degree in nuclear science and engineering, and the author also had a professional background as a US Navy nuclear engineer. However, detailed design of a reactor was beyond the scope of this project since there was already a catalog of commercially developed designs which were both available and more technologically mature than any design which could be created within this project. Additionally, utilizing a commercial off-the-shelf solution helped:

- Reduce risk.
- Capitalize on knowledge and progress already made by experts in the nuclear engineering field.

- Improve this project's economic viability by eliminating the process of designing, testing and certifying a new reactor design.
- Increase the overall feasibility of this project's final solution by integrating tangible, real-world technology.

Returning to the 2009 thesis, the propulsion system used an electric motor to provide flexibility within the engine room, and both auxiliary and emergency diesel generators were included for redundancy. The figure below shows the proposed electrical distribution:

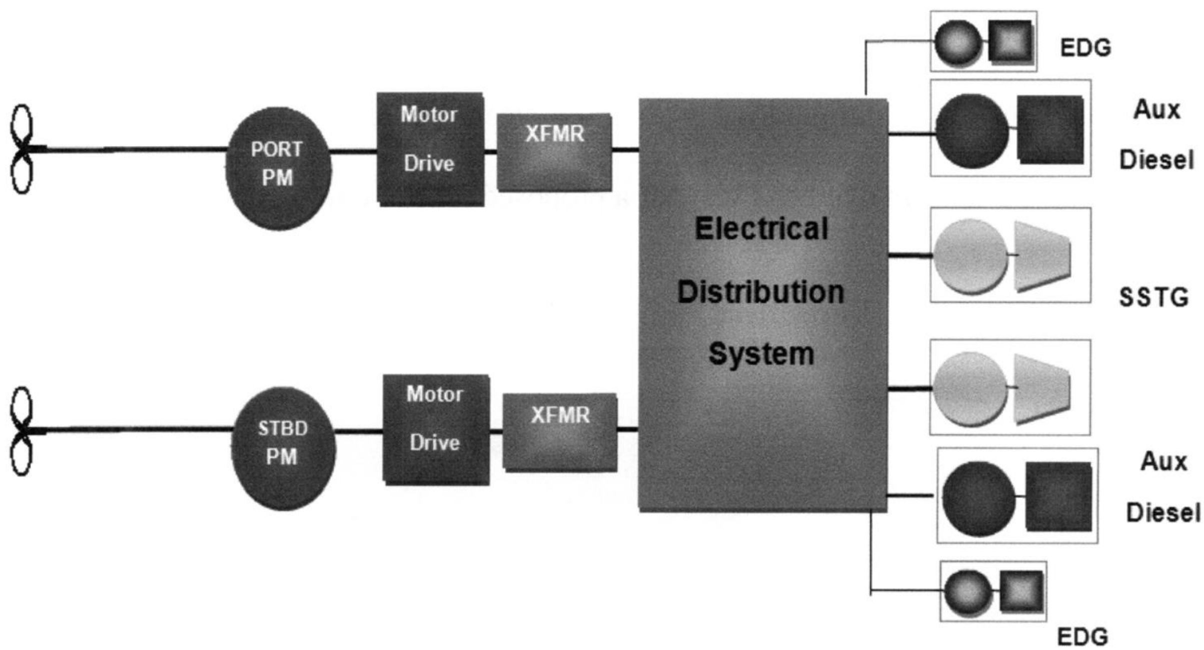


Figure 23: Past Proposed Electrical Distribution System [76]

Specifically recommended systems for the electric plant included:

Past Proposed System Specifics			
Type	Manufacturer	Model	Maximum Rating (MW)
SSTG	Siemens	SST-500	100
ADG	Caterpillar	CAT 16CM43	14.4
EDG	Caterpillar	CAT 3616C	2.5

Table 7: Past Proposed System Specifics [76]

Overall, this proposed system drew insights from existing nuclear-propulsion systems and represented a simple and risk-averse electrical distribution system with enough redundancy to withstand a variety of different casualty situations. Thus, it was anticipated that this project would build upon this past thesis' proposed electrical distribution design.

With respect to overall obstacles that would hinder the real-world feasibility of a NPMS, licensing and regulatory oversight was listed as, "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" [76]. To combat this issue, the author recommended that Naval Reactors (the US Navy's current office which oversees all NNPP operations) establish a civilian branch and de-militarize their reactor designs to advance the regulatory timeline. Additionally, the author assumed that ABS would be involved in the nuclear-powered ship's classification process.

For the economic analysis, two different studies conducted by the US Navy and Manalytics International were used to create an economic model which could estimate the bunker fuel cost where a nuclear-powered vessel would be more cost effective. This approach was chosen because the author found the conventional baseline ship's costs were mainly driven by the cost of fuel, so this fuel cost was a key insight in determining when the nuclear-powered variant was economically preferable. From this analysis, the nuclear-powered ship's breakeven cost corresponded to a crude oil cost of approximately $206/barrel.

As stated previously, the author's final conclusion was that a nuclear-powered cargo ship was "technically feasible" but "economically inferior" compared to a conventional cargo ship [76]. The "technically feasible" aspect aligns with more recent research conducted, and this past project's conclusion also emphasized the importance of government intervention if a nuclear-powered ship were ever to be achieved. With respect to future research recommendations, applying newer reactor designs (such as ones from NuScale) was cited as a potential area for future research.

2.7.2 National Reactor Innovation Center (NRIC) Challenges and Opportunities for the Development of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP)

The NRIC is a national program established by the US Department of Energy (DOE) in 2019 and led by INL [38]. In 2021, the NRIC surveyed 65 experts from various parts of both the maritime shipping industry and nuclear power sector to learn about potential barriers and opportunities that exist in attempting to introduce nuclear power into the commercial shipping industry [38]. The distribution of the participant's backgrounds was as follows:

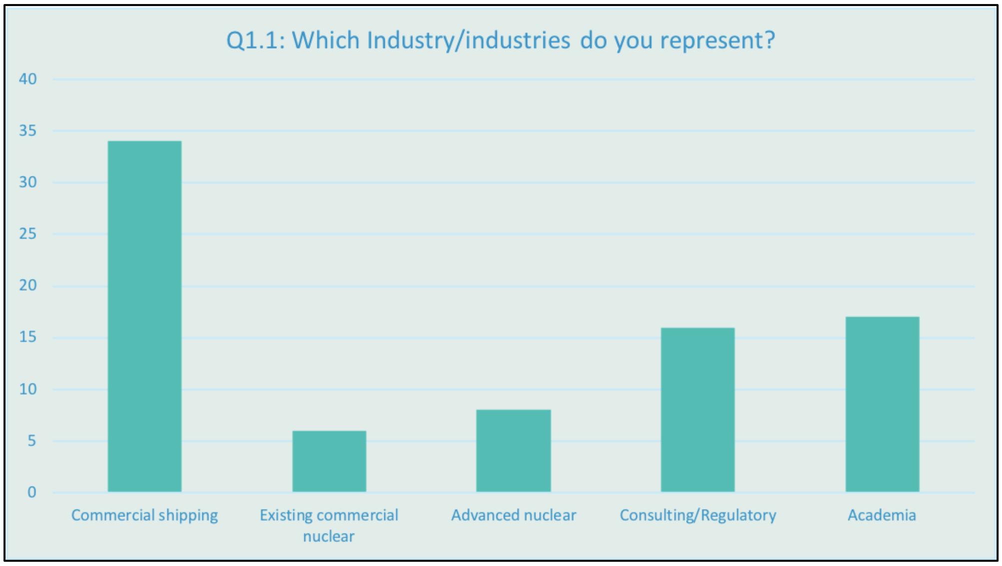


Figure 24: NRIC Survey Industry Representation [38]

From these surveys, the main challenges listed (ranked from most to least influential) were as follows:

1. **Licensing and Regulatory.** Technology Licensing, Limited Trade Routes, Limited Port Access, U. S. Government Approvals/Regulatory, Foreign Government Approvals/Regulatory, Deciding Under Which Flag the Ship will Sail, Jones Act/Cabotage Laws.
2. **Public Opposition.**
3. **Economics.** Economics, Insurance/Liability.
4. **Logistics.** Procuring Sufficient Nuclear Fuel, Need for Refueling, Nuclear Waste Disposal, Security, Adequate Number of Trained Personnel, Public Safety, Vessel Safety.
5. **Technology.** Nuclear Reactor Technology, Nuclear Fuel Technology, Reactor-Ship, Interface Technology [38].

As stated above, licensing and regulatory issues was recognized as the greatest hurdle by subject matter experts (SMEs), and within this hurdle's sub-issues, foreign government regulations and approval was the greatest concern [38]. While the IMO was identified as the most likely candidate to establish an international regulatory system for the commercial shipping industry, foreign government approval was seen as the most impactful challenge that needed to be overcame because it could reduce port access (which would highly impact economic opportunities) regardless of any certifications provided by IMO [38]. This challenge was also difficult to navigate and try to mitigate because it could stem from overall public or administrative opinion within foreign countries [38]. Nevertheless, the report presented multiple technical solutions to try and mitigate these concerns. These solutions included dual fuel designs and/or an articulated tug barge system like the concept presented in the figure below:

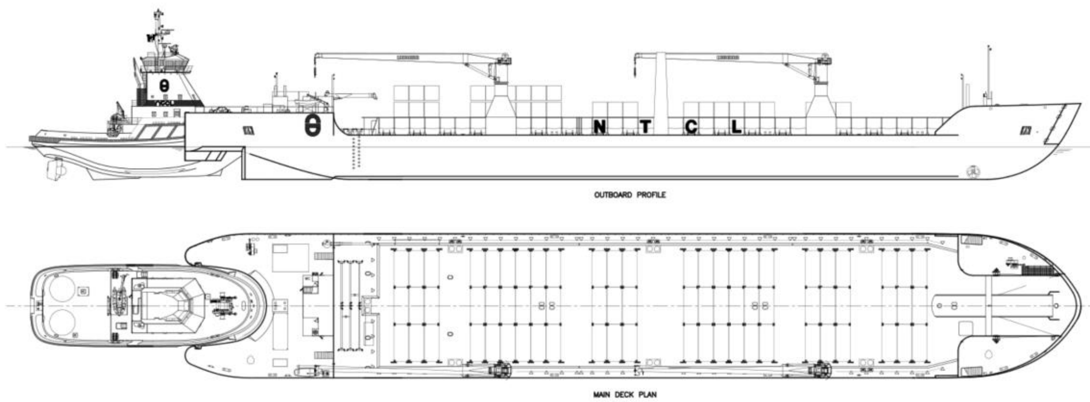


Figure 25: Proposed Articulated Tug Barge System [38]

On the topic of port access, this report also analyzed the 50 largest global ports alongside the associated country's nuclear experience to determine how many would have a higher likelihood of allowing a NPMS [38]. From this analysis, the following information was gathered on the various ports:

- Two are in the US (which has commercial nuclear power and uses naval nuclear power).
- Ten are in China (which also has commercial nuclear power and uses naval nuclear power.
- Thirteen are in countries that either have or are expected to develop nuclear-powered naval vessels.
- Seventeen are in countries with commercial nuclear power plants.

- Of the remaining ports in countries that do not have nuclear power, the US Navy has entered at least two of them (Singapore and Port Klang, Malaysia). This fact leaves only six ports which may not allow the NPMS [38].

This analysis pointed to a general correlation between nuclear experience and the ports most likely to work with the NPMS. Although this correlation did not guarantee each port's willingness to grant nuclear-powered ships access, it did imply that a possibility existed where potential agreements could be established.

Outside of port access and foreign government approval, another concern related to licensing and regulations surrounded the process of receiving regulatory approval within the US [38]. This sub-issue resulted from the current lack of a licensing framework for marine applications [38]. However, the development of such a framework through the NRC has progressed throughout recent years driven by a need to certify ARDs developed by various private companies (like TerraPower and X-Energy) [38].

Within the second-most concerning challenge of public opposition, the most significant sub-issue was general apprehension to nuclear power among people working within the marine shipping industry [38]. In fact, some experts felt this community's opposition could be more impactful than the general public's because the commercial shipping industry mainly operates outside of the public eye [38]. Therefore, members of the marine shipping industry could be more influential in resisting nuclear power than the customers [38]. However, a lack of public approval could still generally influence other factors that affect the NPMS' implementation (such as port access and willingness to purchase shipped goods), so developing public trust was recognized as a major factor in adopting nuclear power [38].

Related to economic challenges, these concerns mainly related to the high capital costs associated with nuclear power [38]. Although it's more well known in current times that nuclear power has much lower operational costs than conventional power sources, SMEs felt the high cost of entry would be difficult for any single company within the commercial shipping industry to support [38]. However, some experts felt this initial investment could be offset if ARDs were used [38]. Specifically, ARDs provide the opportunity to increase available cargo space (due to their smaller size), sell power to ports through reverse cold-ironing, and manufacture modular reactors using a factory production approach which could be paired with shipyard construction timelines [38]. Nevertheless, economics was listed as a high concern since it would largely impact the overall likelihood of the NPMS' adoption.

Within the logistic challenges, the main concerns related to general safety as well as handling nuclear waste. With respect to nuclear waste, the key interest among experts was the uncertainty surrounding which stakeholder would become responsible for handling and processing this waste. Therefore, this issue seemed manageable if the same company that handled all other aspects of nuclear power operations also handled the nuclear waste management [38].

To ensure security, multiple measures were recommended to address a variety of potential concerns. These measures included:

- Deterring pirates through:
    - Onboard security and naval escorts (which is already common within modern commercial shipping operations).
    - Higher ship speeds (which can be more easily achieved using the higher power outputs from nuclear power).
- Adapting safety protocols and lessons learned from liquid natural gas (LNG) tankers, hydrogen tankers and nuclear waste transports.
- Conducting special background checks on crew to avoid nefarious agendas [38].

Using these measures, experts were confident that security concerns could be sufficiently mitigated.

Also related to logistics, experts noted that an opportunity existed with respect to refuels in that fewer refuelings (compared to diesel systems) could improve the operational schedule and reduce the risk of spills in port (which threaten public and environmental safety).

Technological challenges were seen at the most manageable concern since feasibility had already been proven through both naval and space applications [38]. Specifically noted concerns included how the selected reactor technology needed to be capable of performing within typical sea conditions and motion, and this technology's design also needed to withstand a capsizing event [38]. Furthermore, the NPMS's operational profile would need to account for the additional time required to start up a reactor (compared to either a diesel or gas-powered ship) [38]. Lastly, potential technology options listed (in terms of most to least technologically ready to implement) included tri-structural isotropic particle (TRISO) fuel, metal fuels and molten salt reactors [38].

Lastly, this report provided a few overall conclusions in attempting to introduce a NPMS, and in summary, those conclusions were as follows:

- At least initially, shipbuilders and shipowners would be more likely to adopt nuclear power if its design, construction, operation, maintenance, decommissioning and waste management is owned and overseen by an outside company [38]. Therefore, experts believed some sort of leasing structure would be the most viable approach, and ships with an electric drive should be seriously considered since the power source would be more flexibly adapted into the propulsion system [38].
- As discussed within previous sections of this project, experts also agreed the Navy's historic approach to nuclear power does not present the best model for the commercial sector [38].
- Although challenges existed in implementing nuclear power into the maritime shipping industry, opportunities exist as well. The specific opportunities cited by SMEs included the ability to:
    - Eliminate carbon (and other GHG) emissions. Carbon specifically was a main benefit presented by nuclear power since other types of pollutants could be reduced using low-sulfur fuels and LNG [38].
    - Optimize operational profiles by running at much higher average speeds. While operating diesel systems at higher speeds results in increased pollution and higher rates of fuel consumption, these concerns are less significant onboard nuclear platforms [38]. Therefore, raised speeds could be achieved with the NPMS to deliver goods more expeditiously (when an economic benefit exists to do so) [38].
    - Introduce more cargo space. As stated before, ARDs have the potential to be smaller than conventional propulsion systems, so by reducing the size of the engine room, more space onboard ships can be dedicated to cargo space. As a

result, either all ships would be able to carry more cargo capacity, or the current cargo capacity could be carried by fewer ships in the future [38].

- The development timeline for making the NPMS market-ready is crucial to its adaptation [38]. Other conventional fuel options such as hydrogen and ammonia exist, but these energy options also have their own challenges [38]. Therefore, the best way to increase the NPMS' likelihood in comparison to these other fuel options would be to ensure the technology is ship-ready soon (within the next 10-15 years was specifically cited within this report) [38].
- Specific ship platforms that would be best suited for nuclear power were also evaluated within this report.
    - In reviewing the different vessel types, container ships were recognized as the platform that would benefit most from nuclear power due to their, "high fuel consumption, limited number of ports visited, and high percentage of time at sea" [38]. The specific results from this question were as follows:

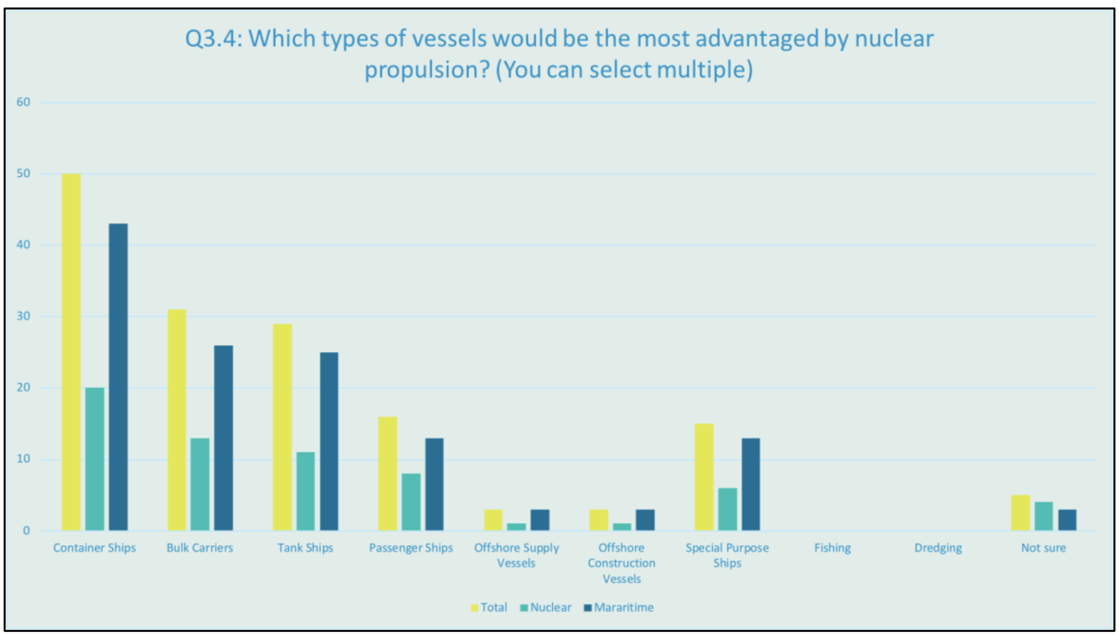


Figure 26: Vessel Types Most Advantaged By Nuclear Power [38]

- While most responses agreed a "bigger is better" approach was best to capture economies of scale, SMEs also noted that a "sweet spot" may exist for container ships with 10,000 – 14,500 twenty-foot equivalent units (TEU) [38]. This observation resulted from how this ship size is commonly used for routes that required refrigerated containers (which require more electrical power), and generally speaking, this size of vessel is very typical [38].

3.0 Licensing and Classification

The NPMS's licensing and classification process has the potential to drastically impact the ship's real-world implementation feasibility. Thus, the specifics surrounding these processes and associated recent developments have been discussed in the subsections below.

3.1 Licensing Process Overview

Receiving a license is a major step in demonstrating a reactor's commercial readiness with respect to safety analysis, design validity and emergency preparedness to a variety of organizations including operators, foreign governments, insurers, investors and the general public [77]. Licenses are typically issued by the respective country's regulatory body where the prospective reactor will be built, and to that end, the International Atomic Energy Agency (IAEA) lists 53 different regulatory organizations globally [78]. Related to timelines, the licensing process (specifically within the US) can take up to five years to complete, and following a license's issuance, reactor construction and/or operation can begin [79] [77].

3.2 The Current Licensing Process

Within the US, the NRC licenses nuclear power plants using the Title 10 Code of Federal Regulations (CFR) Part 50 and 52 [77]. Part 50 is an older, two-step process which required a separate construction permit and operation license, and Part 52 was established in 1989 to offer a combined construction and operation license option. The combined license process (which includes similar steps as required by Part 50) is shown in the figure below:

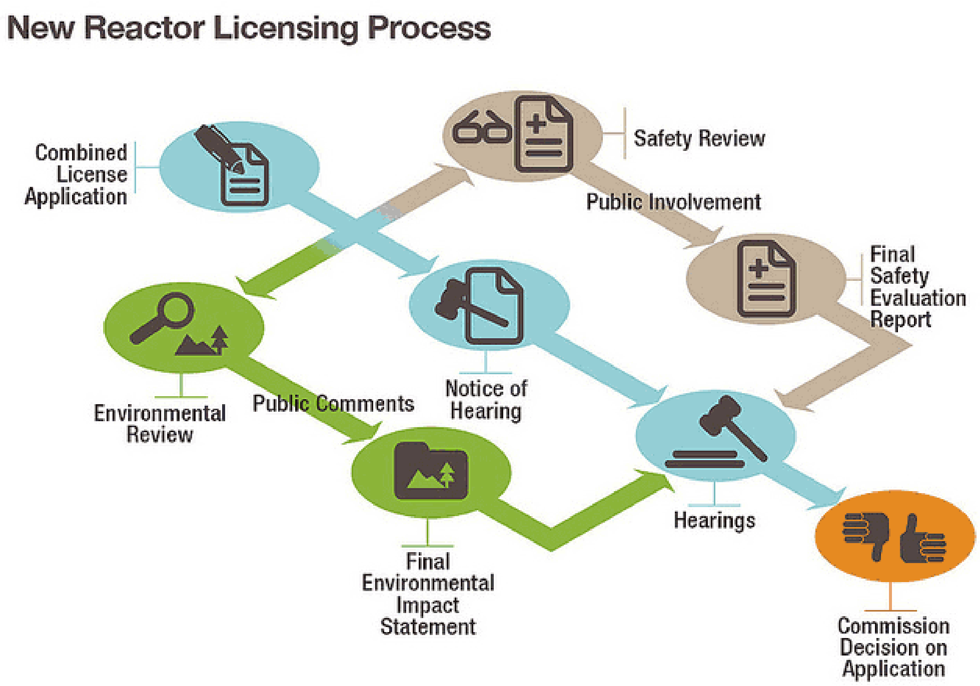


Figure 27: Combined License Process Under 10 CFR Part 52 [77]

Additionally, it is important to note that both Part 50 and 52 were developed during a period within nuclear power's history when the predominantly used design was a large, light-water PWR. As a result, these license processes require explicit design features which specifically apply to PWRs to meet various safety requirements (rather than setting performance-driven safety goals which could be innovatively met in whatever way is best for the specific reactor design being evaluated) [80]. Therefore, it has consistently been difficult to fit ARDs into these licensing paradigms without exceptions, waivers and additional analyses conducted by the NRC (which consumes the organization's time and resources as well as extends the overall licensing process) [80]. While some ARD companies such as NuScale and Oklo have achieved licensing success using Part 52 regardless of these hurdles, a more performance-based approach would allow the NRC to more easily regulate and license newer reactor designs [80].

Alongside the current issues related to licensing ARDs, the NRC also only licenses and regulates civilian reactors which are built on land within the US. Therefore, a new and entirely different process would be needed to license a civilian reactor onboard a ship, and this license would need to be recognized by foreign governments for the ship to be allowed to operate internationally.

3.3 Future Licensing Plans

As previously stated, it is difficult to license ARDs because they do not always mitigate safety concerns through the same design features as PWRs. As a result, the specific design requirements outlined within the NRC's Part 50 and 52 are not always best fit to license these reactors. Therefore, the Nuclear Energy Innovation and Modernization Act (NEIMA) was signed into law in 2019 with bipartisan support to explicitly direct and provide financial support for the NRC to modernize the licensing process [80]. The goal of this initiative was to develop a performance-driven and technology-inclusive framework for ARD licensing (named Part 53) by 2027 so that the US could remain competitive in nuclear technology advancements and combat climate change within a meaningful time frame [80]. If approached carefully, other anticipated benefits of Part 53 include:

- Improving public confidence and reducing unnecessary review period extensions for applications by avoiding issuing exemptions [80].
- Increasing business opportunities with international vendors and investors by introducing an improved and faster US licensing process [80].
- Achieving international licensing harmonization (alongside potential future reactor exportations) by:
    - Developing Part 53 in collaboration with other countries (such as Canada).
    - Including international requirements within Part 53 (such as the IAEA's safety standards) [80].

The benefits listed above reflect legitimate goals the NRC hopes to realize through Part 53's careful formation. To that end, the following road map was established to guide the ongoing development of this document:

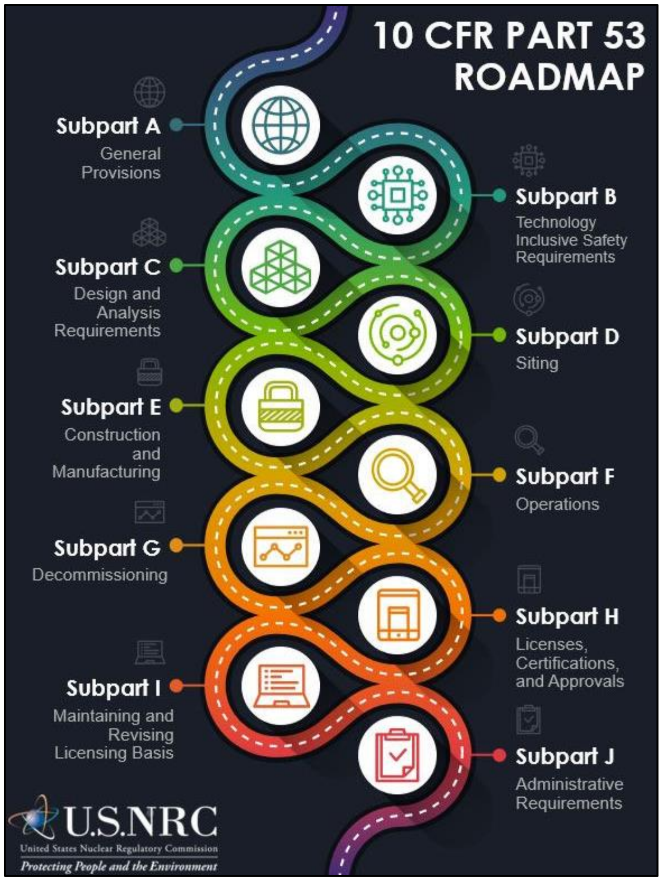


Figure 28: NRC Part 53 Roadmap [81]

3.4 Licensing the NPMS

There currently exists significant concerns surrounding the ability to license a NPMS due to the nature of the licensing process (as discussed above). As stated before, many experts even recognize licensing and regulation to be the biggest hurdle that must be overcome in bringing nuclear power to the commercial maritime industry. On a deeper level, specific concerns surrounding licensing the NPMS include:

- There is no international licensing authority or internationally recognized licensing process which could oversea the NPMS and increase the likelihood that the ship would be accepted into foreign ports.
- Outside of international concerns, there is no licensing process within the US for a civilian reactor that is installed on a ship (versus on land).
- Related to the current licensing process in general:

- It is an expensive, time-consuming process which discourages any potential stakeholders from reducing GHG emissions by implementing nuclear power.
- It does not address licensing ARDs.

Fortunately, the NRC's Part 53 aims to address many of these issues. Therefore, all concerns could be addressed through one (or a combination) of the following solutions:

- The NRC could explicitly include special applications of nuclear power (such as marine propulsion, space exploration and others) within Part 53 to increase the license process' technological inclusivity.
  - In developing these requirements related to marine propulsion into Part 53, the NRC could collaborate with the IMO to better align with the commercial marine industry and increase the likelihood that other countries would recognize the resultant license (and potentially someday adopt the same requirements established by Part 53).
  - As previously stated, the NRC has also licensed nuclear merchant ships in the past (specifically, the NS Savannah under the AEC). As a result, these historic documents could serve as a baseline and potentially assist with integrating requirements for the NPMS within Part 53.
- Outside of the NRC's modernization efforts, the IMO could work with various nuclear regulatory organizations (such as the IAEA and other individual country's regulatory organizations) to develop its own licensing process. There is much support for this solution among experts, and this idea has been previously suggested with such high frequently that the initial steps required to begin this process have already been outlined within past reports to give an idea of this scenario's required scope of work [38].
  - In developing an international license process, the IAEA could be an especially helpful resource after having regulated the safety and security of international radioactive materials transportation over the last 60 years (within a program called Safety Standards Series No. SSR-6) [38] [82].

3.5 Classification Process Overview

Outside of licensing the reactor, ships must also be classed by a classification society. According to the International Association of Classification Societies (IACS), classification societies are, "organizations that establish and apply technical standards in relation to the design, construction and survey of marine related facilities including ships and offshore structures" [83]. There are currently twelve members of the IACS which represent the main classification societies throughout the global community, and those members are as follows:

IACS Members		
Classification Society		Associated Country
	American Bureau of Shipping (ABS)	US
	Bureau Veritas (BV)	France
	China Classification Society (CCS)	PRC
	Croatian Register of Shipping (CRS)	Croatia
	Det Norske Veritas (DNV)	Norway
	Germanischer Lloyd (GL)	Germany
	Indian Register of Shipping	India
	Kean Register (KR)	Korea
	Lloyd's Register (LR)	UK
	Nippon Kaiji Kyokai (Class NK)	Japan
	Polish Register of Shipping (PRS)	Poland
	Registro Italiano Navale (RINA)	Italy
	Russian Maritime Register of Shipping (RS)	Russia

Figure 29: IACS Members [84]

While national authorities (called flag authorities) have the final responsibility of validating the safety of ships that fly their national flag, many countries have delegated this responsibility to classification societies and authorized them to certify on their behalf [85]. Therefore, classifying a NPMS would be another major step towards displaying commercial readiness to the world.

To date, the RS has had the most experience with classifying nuclear ships due to Russia's operation of the Sevmorput and various Arktika-class icebreakers. Historically, ABS was also responsible for classifying the NS Savannah, but this classification process has not been revisited or updated since the Savannah's decommissioning in the 1970s.

3.6 Future Classification Plans

As previously discussed, ship classification is a significant step in constructing and operating a new ship design. Therefore, developing an internationally recognized classification authority and/or classification process for a nuclear-powered ship is an important step in increasing the overall feasibility of a NPMS. While current global experience with classifying a nuclear ship is low (especially with respect to ABS who has a higher likelihood of working with nuclear vessels based on the US' historic position as a global leader in advancing nuclear technology), recent trends display recognition for the need to develop one such classification process for a NPMS if society is to successfully reduce GHG emissions within the maritime shipping industry and combat climate change.

First, ABS displayed support for nuclear power applications through their collaboration in 2020 with a Danish nuclear company named Seaborg technologies to assess and provide a feasibility report on the company's compact molten salt reactor design to be deployed onboard floating power barges [86]. The power barge concept is shown in the figure below:

Figure 30: Seaborg Technology's Floating Power Barge Concept [86]

As a global leader in ship classifications, ABS' recent actions help increase the overall possibility of a commercially viable NPMS.

Next, ABS released a report in 2021 entitled, "Advisory on Decarbonization Applications for Power Generation and Propulsion Systems." Within this report, a variety of alternative fuel and power systems were analyzed to assess their technological maturity and overall compatibility with the maritime industry. Within this report, nuclear power in its entirety (including various ARDs) was recognized as, "an option that merits further research and consideration" [87].

Outside of this report, there have been other developments which indicate ABS' openness to nuclear power. In November 2021, the DOE awarded ABS with approximately $800,000 to help the classification society research and address, "hurdles in the maritime domain so that new reactor technology can be rapidly deployed for commercial applications" [88]. Following this award, ABS outlined that the organization would develop models of different ARDs for maritime applications and write an industry advisory on the commercial use of modern nuclear power [89]. Additionally, ABS confidently expressed implementing nuclear-powered propulsion into the commercial maritime industry presents an opportunity to revitalize and transform the US shipping industry through the introduction of nuclear-based manufacturing and clean-energy job growth [89]. In summary, public releases from ABS related to a NPMS have been very positive and optimistic for the prospects which a NPMS could bring to the US economy while combating GHG emissions.

Outside of ABS, the UK's Maritime and Coastguard Agency launched a consultation in 2021 to develop a regulatory framework that would support nuclear-powered ships for the purpose of reducing air pollution [90]. The goal was that this framework would mirror established international requirements including the IMO's 1981 Resolution A.491(XII) Code of Safety for Nuclear Merchant Ships (or Nuclear Code), and Chapter 8 from the IMO's 1974 International Convention for the Safety of Life at Sea (SOLAS) (which are both discussed more in depth within the next section) [90]. These efforts display the UK's interest in introducing nuclear power to the commercial marine industry.

3.7 Other Current Regulations

As previously discussed, there are two regulations outside of the licensing and classification processes (the IMO's Nuclear Code, and Chapter 8 from the IMO's 1974 International Convention for SOLAS) which currently exist within the maritime industry and could apply to the NPMS. These other regulations have been analyzed and summarized throughout this subsection.

3.7.1 The IMO Nuclear Code

The Nuclear Code is a highly comprehensive document which was developed as a guide for, "Internationally accepted safety standards for the design, construction, operation, maintenance, inspection, salvage and disposal of nuclear merchant ships" [91]. While this code was specifically written to apply to light-water PWRs, it was also intended to be reviewed and updated as reactor technology progressed, and the following reasons were explicitly listed as anticipated motivators for review:

1. Technical progress in ship designs or light-water PWRs.
2. Technical progress in safety analysis.
3. Application to new types of ship.
4. Change in the degree of risk (e.g., increased numbers of nuclear ships using a single port at the same time).
5. Compatibility with future codes and conventions.
6. International agreement on revised safety standards. [91]

Therefore, the Nuclear Code was drafted with the intent that it would be revised to include new technologies in the future, and therefore, it could be revisited and serve as a foundational guide as modern regulations are developed.

The Nuclear Code was also very similar to the NRC's Part 50 and 52 in that it listed highly specific system designs to meet safety requirements that mainly relate to PWRs. While this approach causes issues in attempting to create a NPMS with ARDs, some of the outlined design considerations still have potential to provide guidance for the NPMS' design requirements. There were too many considerations to fully summarize them within this project, but noteworthy ones included:

- The effect of a nuclear ship within ports being used with respect to local meteorological conditions, population density and land usage factors [91]
- The effects of natural phenomena, such as extraordinary seaways, tornadoes, tsunamis, hurricanes, winds, snow and ice (applicable to the ship's service) [91].
- The inertial forces acting on the ship in a seaway including ship motion within six degrees of freedom, utilizing wave spectrum for the intended area of operation [91].
- The effects of shock loads on reactor plant components from accidents such as collision, grounding, or explosion [91].
- The effects of ship motion in a seaway on the stability of reactor controls and the reactor's dynamic behavior (assuming both an average as well as an extreme condition of seaway) [91].
- The ability for reactor safety systems (and their energy supplies) to operate without malfunction within the following ship conditions:
    - A static list of up to 30°.
    - Rolling angles of up to 45°.
    - Incline of up to 10° (either in the fore or aft direction).
    - Any combination of angles within the listed limits [91].

The Nuclear Code also outlined radiological requirements in that exposure should be kept as low as is reasonably achievable, and within the relevant dose-equivalent limit [91]. The specific dose-equivalent limits were as follows:

The Nuclear Code Limiting Dose-Equivalent Rates for Different Areas and Spaces	
Area or Space	Dose-Equivalent Rate* μSv/hr (mrem/hr)
In the navigating bridge	0.75 (0.075)
In accommodation spaces	0.15 (0.015)
On upper deck and in cargo spaces	0.50 (0.05)
On ship's sides above the waterline	0.50 (0.05)
On ship's bottom, where "in water" maintenance or survey is contemplated: with the reactor at 10 per cent power	7.5 (0.75)
*The dose-equivalent rates are from ship sources only and do not include natural background radiation.	

Table 8: The Nuclear Code Limiting Dose-Equivalent Rates for Different Areas and Spaces [91]

Other noteworthy requirements outlined within the Nuclear Code related to damage stability, floodability requirements, fire safety, anticipated reactor casualties (and their corresponding protections), radiation safety, waste management, operating requirements, survey requirements and quality assurance [91]. With respect to the Nuclear Code's real-world implementations, the Sevmorput was the first and main ship to be designed using the Nuclear Code [92].

3.7.2 Chapter 8 from the IMO's 1974 International Convention for SOLAS

While the IMO's 1974 International Convention for SOLAS was released prior to the Nuclear Code, it was updated upon the Nuclear Code's publication to echo the same requirements with respect to radiation hazards and safety [93]. Therefore, those same requirements will not be repeated within this discussion.

4.0 Design Setup

Moving forward in this project, a currently active merchant ship was selected to demonstrate this concept's initial feasibility. Within this project specifically, the ship's power requirement was the main design feature which helped drive the reactor selection process by providing a general size and scale that the reactor technology must align with.

To select a reactor technology, a design philosophy was also established to guide the decision-making process and determine a solution which was most likely to be well-received by the maritime shipping industry. Then, assumptions were developed to further constrain the design efforts. Additionally, this design setup was established before evaluating the different reactor technology options to better inform this selection process and help identify the best reactor design for the ship's operational environment.

4.1 Design Philosophy

It was well known based on historic trends that the civilian commercial maritime shipping industry and its main players (such as shipbuilders and shipowners) generally have a high aversion to risk. As a result, this industry has typically leaned towards continuing to use existing technology with proven economic viability compared to implementing new technology (despite how these newer technologies may also have the potential for increased profitability and/or reduced environmental impact). As previously stated, this risk averse approach should not be viewed as a disadvantage within commercial shipping, and in fact, the industry's longstanding stability and success is most likely the result of this mindset.

With that said, implementing new technology is a necessity if the shipping industry is to successfully reduce GHG emissions. To that end, some evidence exists which indicated the industry would be willing to adopt new systems when the associated risks have been properly mitigated, and this change can be seen in the most recent breakdown of the world fleet:

Table 2.11 World fleet by fuel type as of 1 January 2021

Fuel type	Ships	GT	TEU	dwt	Ships %	GT %	TEU %	Dwt %	Ships % of known fuel type	GT % of known fuel type	TEU % of known fuel type	Dwt % of known fuel type
Very Low-Sulphur (VLS) Intermediate Fuel Oil (IFO)	36 188	993 715 259	18 384 210	1 534 083 046	36.26	69.08	70.97	72.11	47.12	72.26	71.29	74.54
VLS Marine Diesel Oil (MDO)	33 118	29 698 675	149 929	27 886 341	33.18	2.06	0.58	1.31	43.12	2.16	0.58	1.36
IFO 380*	3 635	283 299 533	6 949 482	437 386 040	3.64	19.69	26.83	20.56	4.73	20.60	26.95	21.25
VLS Marine Gasoil (MGO)	2 539	7 441 142	34 467	6 769 951	2.54	0.52	0.13	0.32	3.31	0.54	0.13	0.33
Ultra-Low Sulphur (ULS) MDO	381	697 587	7 000	661 627	0.38	0.05	0.03	0.03	0.50	0.05	0.03	0.03
LNG, VLS IFO	373	36 964 811	144 014	30 159 817	0.37	2.57	0.56	1.42	0.49	2.69	0.56	1.47
LNG, VLS MDO	168	10 814 060	12 703	8 190 743	0.17	0.75	0.05	0.39	0.22	0.79	0.05	0.40
IFO 180	166	7 351 589	75 955	9 536 173	0.17	0.51	0.29	0.45	0.22	0.53	0.29	0.46
ULS IFO	43	352 580	15 617	438 639	0.04	0.02	0.06	0.02	0.06	0.03	0.06	0.02
LNG, VLS MGO	37	424 846	10	430 662	0.04	0.03	0.00	0.02	0.05	0.03	0.00	0.02
LNG	32	459 380	260	139 039	0.03	0.03	0.00	0.01	0.04	0.03	0.00	0.01
MDO	22	652 797	1 629	188 652	0.02	0.05	0.01	0.01	0.03	0.05	0.01	0.01
ULS MGO	22	26 594		16 571	0.02	0.00		0.00	0.03	0.00		0.00
Biofuel	18	360 677	11 684	386 434	0.02	0.03	0.05	0.02	0.02	0.03	0.05	0.02
MGO	12	880 222		122 003	0.01	0.06		0.01	0.02	0.06		0.01
Methanol, VLS IFO	11	336 377		552 044	0.01	0.02		0.03	0.01	0.02		0.03
Ethane, VLS IFO	7	292 595		264 750	0.01	0.02		0.01	0.01	0.02		0.01
Nuclear	6	144 573	1 324	50 079	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00
LPG, VLS IFO	5	236 752		272 690	0.01	0.02		0.01	0.01	0.02		0.01
Biofuel, LNG	4	43 851		3 907	0.00	0.00		0.00	0.01	0.00		0.00
Compressed Natural Gas (CNG), VLS MDO	3	111 058		105 325	0.00	0.01		0.00	0.00	0.01		0.01
IFO 380, LNG	2	251 144		18 400	0.00	0.02		0.00	0.00	0.02		0.00
MDO, MGO	2	183 254		16 030	0.00	0.01		0.00	0.00	0.01		0.00
Biofuel, VLS MGO	2	6 810		9 876	0.00	0.00		0.00	0.00	0.00		0.00
VLS IFO, Well Fuel	1	86 952		166 546	0.00	0.01		0.01	0.00	0.01		0.01
CNG, VLS MGO	1	30 742		31 473	0.00	0.00		0.00	0.00	0.00		0.00
LNG, MDO	1	65 314	600	22 437	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IFO 380*, MGO	1	149 215		19 189	0.00	0.01		0.00	0.00	0.01		0.00
Methanol	1	51 837		10 670	0.00	0.00		0.00	0.00	0.00		0.00
Nuclear, VLS MDO	1	33 500		9 000	0.00	0.00	-	0.00	0.00	0.00	-	0.00
Unknown fuel type	*22 998*	*63 435 988*	*115 238*	*69 356 421*	*23.04*	*4.41*	*0.44*	*3.26*				
Grand Total	**99 800**	**1 438 599 714**	**25 904 122**	**2 127 304 575**	**100.00**	**100.00**	**100.00**	**100.00**				
World total known fuel type	***76 802***	***1 375 163 726***	***25 788 884***	***2 057 948 154***					***100.00***	***100.00***	***100.00***	***100.00***

Source: UNCTAD, based on data provided by Clarksons Research.
Notes: * Intermediate fuel oil with a maximum viscosity of 380 centistokes (<3.5 per cent sulphur).
All variations of MGO, MDO and IFO are traditional fuel types.
Alternative fuels encompass: LNG, LPG, methanol, biofuels, hydrogen, ammonia; synthetic methane and nuclear - highlighted in green.
Fuels that mention a traditional fuel type, along with an alternative fuel (for example: "Ethane, VLS IFO"; "Biofuel, VLS MGO" or "Nuclear, VLS MDO" refer to dual-fuel ships highlighted in light orange.

Figure 31: World Fleet by Fuel Type as of 1 January 2021 [94]

This breakdown of the world fleet demonstrates how the commercial shipping industry has begun trialing alternative fuel systems onboard a small group of ships, so it was possible that the NPMS would be well-received if the industry's concerns were sufficiently addressed.

Therefore, it was important to acknowledge this preference for risk aversion throughout the NPMS' development so that the final design could align with the current shipping industry and represent a highly feasible solution. Thus, the main design philosophy for this project was that implementing risk mitigation should be prioritized where possible to demonstrate a safe and economically viable final design.

4.2 Baseline Ship Selection

For this feasibility study, a container ship was used as the baseline ship for showing how nuclear power could be implemented onboard a merchant ship. A container ship was specifically selected because this cargo type represents a sizeable and growing portion of commercial shipping as seen within the figure below:

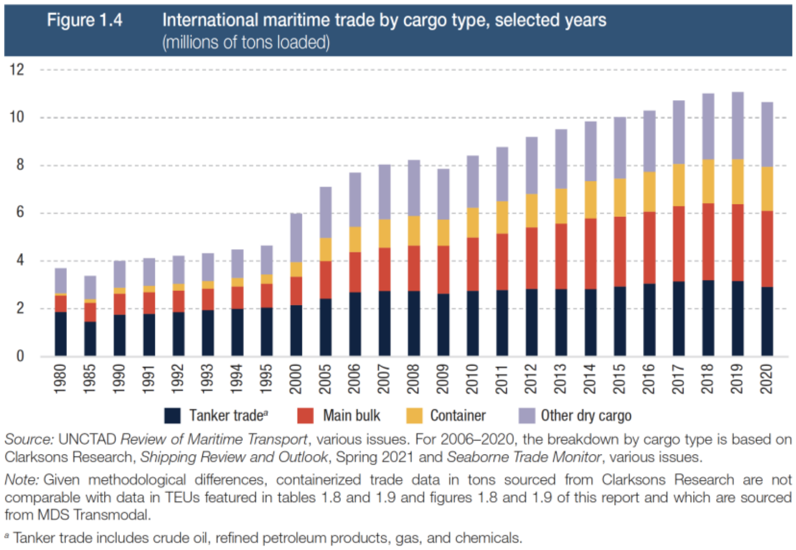


Figure 32: International Maritime Trade by Cargo Type [94]

Furthermore, container ships account for the greatest contribution of carbon emissions as seen in the figure below:

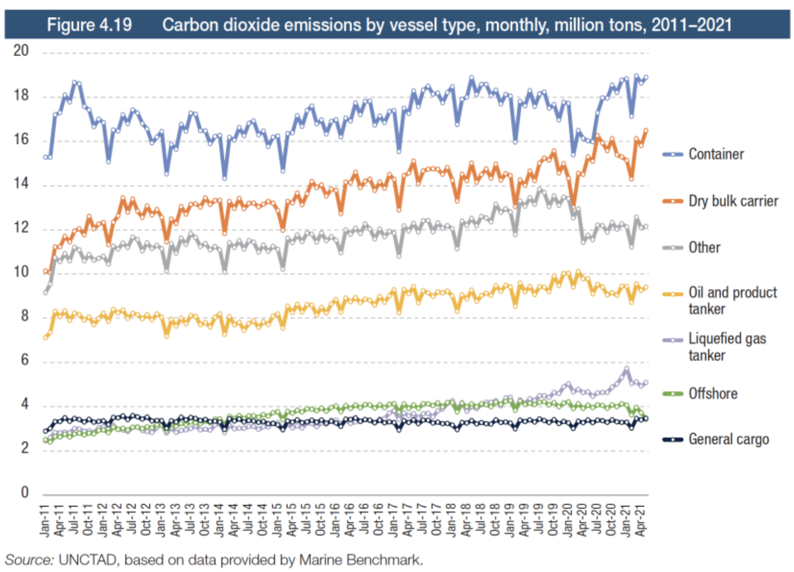


Figure 33: Carbon Dioxide Emissions by Vessel Type [94]

Lastly, surveyed experts agreed, as discussed within Section 2.7.1 An Early Conceptual Design and Feasibility Analysis of a Nuclear-Powered Cargo Vessel, that container ships would be most advantaged by converting to nuclear propulsion since:

- Reduced refuel time could improve profitability by allowing ships to spend more time at sea.
- Nuclear power allows ships to achieve higher speeds without the penalty of correspondingly increased fuel costs. Therefore, implementing nuclear propulsion could allow for goods to be delivered faster, or in the same amount of time using a smaller quantity of faster ships [38].

In addition to the reasons stated thus far, experts also noted how tankers would not benefit from achieving higher speeds the same away container ships would since the profit of their cargo is not as dependent on the delivery time [38]. For all these reasons, a container ship was selected as the baseline ship type for this project.

4.2.1 Primary Baseline Ship

For the specific ship, the largest container ship available was used as the baseline to demonstrate feasibility at the largest scale (i.e., if a solution could be found for the largest ship, this solution could theoretically be scaled down to other platforms). Using the largest ship also increases the opportunity for economies of scale and provides the largest reduction in GHG emissions per ship. Therefore, the baseline ship selected was the Evergreen's A-class which are built by Samsung Heavy Industries in South Korea.

As an additional note, the first ship in this class, the Ever Ace, was built in 2021. Therefore, it is unlikely that this ship would be converted to nuclear power since it was recently purchased, and it has significant carbon emission reduction technology installed onboard. However, the goal of the baseline ship was to prove feasibility (versus develop a solution which was specific to a particular ship), so the Ever Ace was deemed sufficient for that purpose. The ship's technical data is as follows:

Ever Ace Technical Data	
LOA (ft)	1312.24
BOA (ft)	201.87
Depth (molded, ft)	108.92
Draft (ft)	55.83
Displacement (LT)	238,138.61
Cargo Capacity (TEU)	23,992
Maximum Speed (kts)	22.6

Propulsion Power (MW)	117.2
Installed Propulsion Engines	2 WinGD X92-B, 11-cylinder, 58.6 MW
Shipbuilder	Samsung Heavy Industries
Year Built	2021

Figure 34: Ever Ace Technical Data

One of the most important conclusions from this data was that the currently largest ship required 117.2 MWe for propulsion. Since a nuclear power solution would most likely be best implemented as an electric drive (to increase reactor placement flexibility and provide a more streamlined system to supply both propulsive and electrical power), a 20% margin could be added to estimate the ship's electrical power requirement. Therefore, the largest necessary reactor would need to supply approximately 140 MWe (or approximately 470 MWt).

Another helpful data point from this ship information related the installed engine model, and a figure of this engine (the WinGD X92-B, 11 cylinder engine) is shown below:

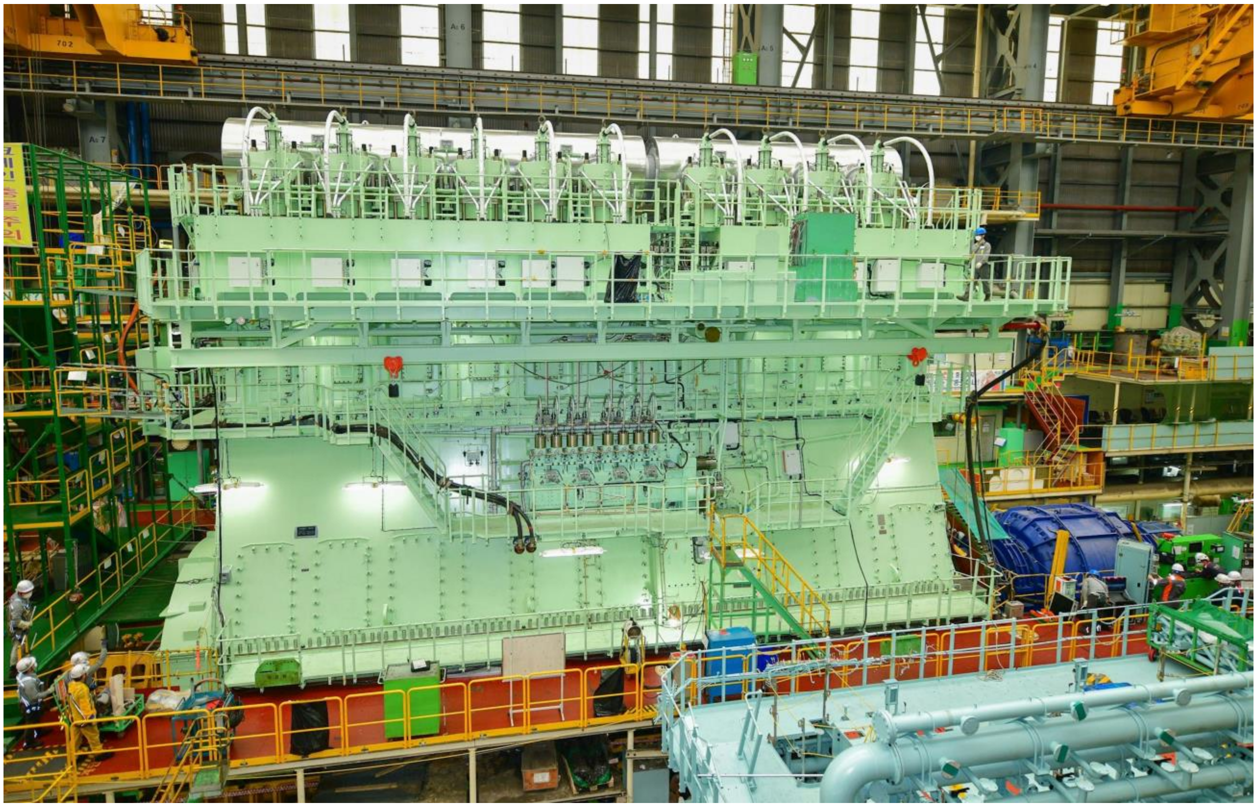


Figure 35: WinGD X92-B, 11 Cylinder Engine [95]

Equipped with information related to the engine installed onboard the Ever Ace (and the knowledge that each ship uses two engines), the approximate space and weight available onboard which could be allocated to the selected reactor technology was determined:

Approximate Reactor Space and Weight Allocations	
Longitudinal Length (ft)	69
Transverse Width (ft)	36.4
Vertical Height (ft)	57
Weight (ton)	3,920

Table 9: Approximate Reactor Space and Weight Allocations [96]

Moving forward, it was important to remember that these values represented an overall estimate of the space and weight available for the selected reactor system. Factors that were not well-reflected within this estimate included:

- Related to the current ship's engine room, more machinery beyond the main engines would likely need to be altered and/or removed from the ship's design (which would impact the space and weight available). However, the main engines were a large space and weight contributor within this system, so evaluating their specifications was a good first-step to better understand the machinery spaces.
- Outside of the reactor system (which generally includes the reactor, primary coolant loop and any additional fluid loops for electrical generation), other systems (such as emergency and auxiliary diesel engines) were anticipated to be installed as well. Therefore, machinery space would also need to be allocated to these supporting systems (and therefore could not be completely budgeted towards the reactor system).

With these considerations in mind, analyzing the currently installed systems still provided helpful data points related to the general size of the engine room available for the selected reactor technology. Additionally, it was anticipated that specific size and weight specifications would not be publicly available for various Gen IV technologies at this time (due to the overall newness and ongoing development of the technologies), so with this in mind as well, the WinGD's size and weight continued to serve as an overall data point within the operational space.

In conclusion, the primary baseline ship helped establish that the preferred reactor technology should have a power output near 140 MWe (or approximately 470 MWt) to prevent the need for redesigns and/or modifications before installation onboard the NPMS.

4.2.2 Secondary Baseline Ship

While the largest container ship demonstrates feasibility at the largest scale, this vessel's size was much larger than more prevalent container ships within the maritime commercial shipping industry. Therefore, a theoretical secondary baseline ship was established with a power output near 50 MWe (or 165 MWt) to provide a solution that could be implemented on a greater quantity of existing container ships (either through a conversion project, or at the onset of a newly constructed ship).

As a result, reactors rated near 50-140 MWe (or 165-470 MWt) in their original design were seen as preferential for the NPMS, and it was recognized that the same design would not likely meet both criteria.

4.3 Trade Route Assumptions

To increase economic viability, it would be best with respect to trade routes and port access if the NPMS was allowed access to as many ports as possible. With that said, a single trade route between two ports was determined and used where necessary within this project for use as the NPMS' typical endurance range. Therefore, the largest worldwide ports were analyzed to determine a single trade route, and two ports were chosen that were:

- A significant distance away from one another (since many of the world's largest ports were in Asia, so this shorter distance would not represent a range on the same scale as a worldwide trade route).
- Located within countries with established histories of nuclear power operation to increase the likelihood that:
    - The NPMS would be allowed into these ports.
    - These ports would be willing and supported by their corresponding government to implement any additional infrastructure needed to support a nuclear-powered vessel.

To help determine the best port options, the following map was also analyzed which shows the main global shipping routes, and the most prominent ports based on their liner shipping connectivity index (which measures a port's access to the existing shipping network and helps quantify competitiveness within the shipping industry):

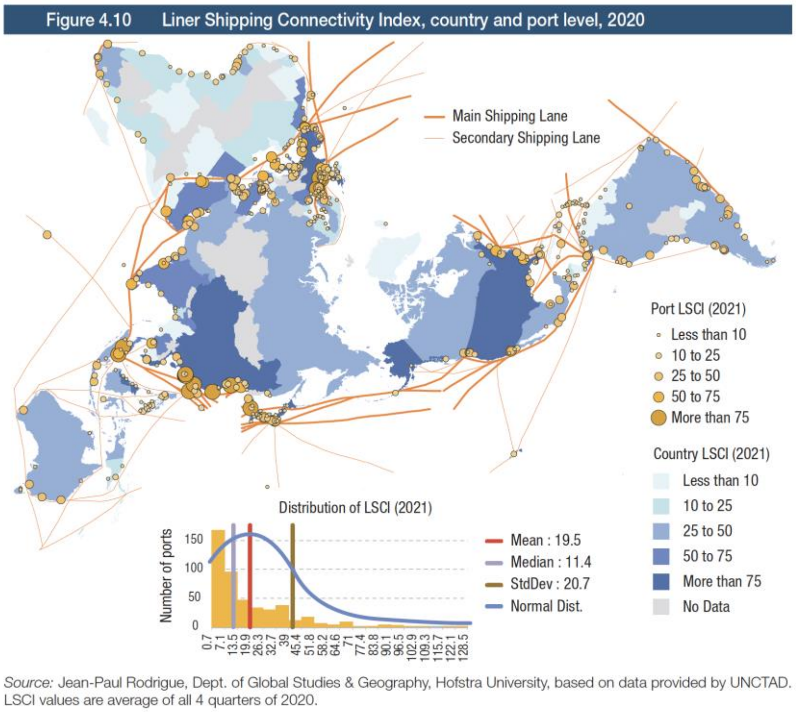


Figure 36: Liner Shipping Connectivity Index [94]

From this map, the best option was a combination of the Port of Shanghai (which is currently the largest container port in the world), and either a port in Europe or along the US' west coast [97]. After factoring in the potential country's nuclear experience, the Port of Los Angeles was selected since it is the US' largest container port (and it is also located near the US' second largest port, the Port of Long Beach) [97]. Additionally, this selection was further validated by how it is one of the busiest international trade routes, and this same route was also analyzed in previous feasibility studies related to nuclear-powered container ships [76] [98].

Lastly, this specific trade route was also a more favorable choice for this project because both the Shanghai and Los Angeles ports announced in January 2022 that they were partnering to create a "first-of-its-kind green shipping corridor" and assist with decarbonization efforts through the support of low, ultra-low and zero carbon fueled ship [98]. One reason for this initiative was to improve air quality for the communities surrounding these ports, so with this new partnership, it seems increasingly likely that these ports would allow access to nuclear-powered ships for the purpose of reducing GHG emissions in the shipping industry. This partnership also suggested these ports would be willing to implement any new facilities that would be needed to service nuclear-powered ships.

The current trade route between these two ports is provided in the figure below:

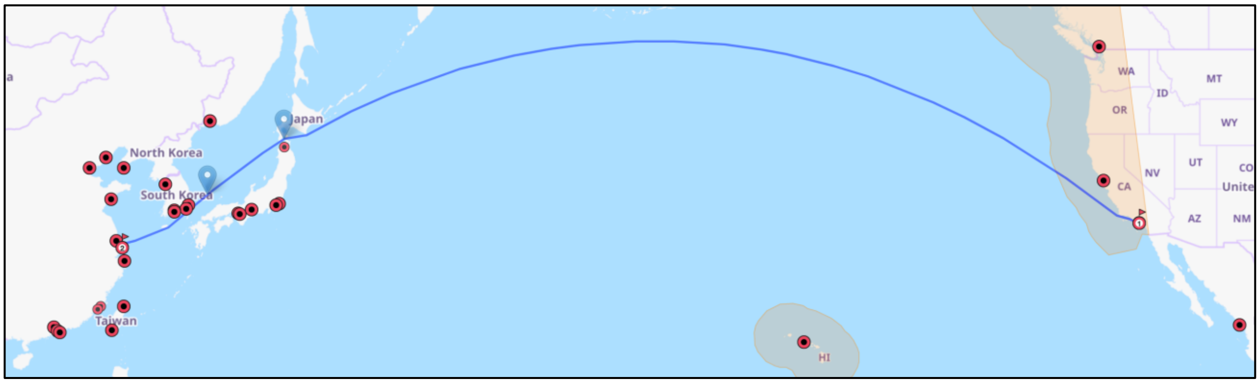


Figure 37: Trade Route Between Shanghi and Los Angeles [99]

For analytic purposes, this trade route is approximately 5,700 nm in length.

4.4 Reactor Selection Criteria

Selection criteria were divided into two main categories, basic requirements and desirable features, to select the optimal reactor technology for this feasibility study. Other criteria were also anticipated at more specific, technical levels which could influence this design decision, and within this selection process, it was recognized as very possible that the selected reactor would meet all the basic requirements but only a subset of the desirable features. Therefore, the criteria listed in this section represent the high-level concerns which helped narrow all the potential reactor technologies down to a smaller subset of options. Those criteria were as follows:

Basic requirements. The reactor design must:

- Supply the necessary power rating to support both the NPMS' propulsive and electrical power requirements.
    - Related to this point, ARDs are typically designed for land-based usage where power ratings are much higher. Therefore, reactor designs which could meet the

NPMS' power requirement in their original configuration would be preferred compared to other concepts that would need to be re-designed as a smaller system before they could reasonably be used onboard the NPMS.

- Fit within the reduced area and volume constraints associated with typical engine rooms onboard ships (compared to land-based applications). To achieve this requirement, it was anticipated that the reactor would be more compact in nature compared to reactors used within commercial nuclear power plants.
- Fit within the ship's weight and arrangement limitations.
- Withstand flooding and corrosion from the presence of seawater.
- Be compatible with watertight bulkhead placement.
- Withstand a ship's degrees of motion.
    - As an additional note, this final requirement was very specific to ship environments and had the potential to highly influence the final selection since most reactor designs were intended for land-based use (where the degrees of motion were significantly more limited). These six degrees of motion are shown in the figure below:

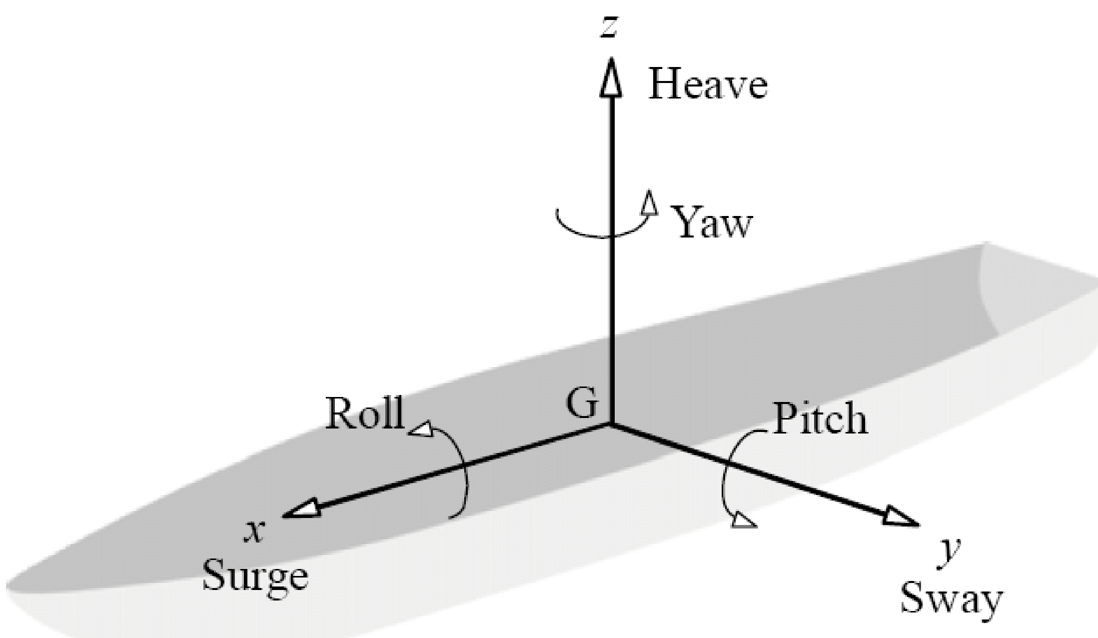


Figure 38: Six Degrees of Ship Motion [100]

Desirable Features. To promote the NPMS' real-world implementation and economic feasibility, the reactor should:

- Have a high technical readiness level (i.e., designs which were closer to commercial use were preferred).
  - Similarly, designs with support from governments and regulators were preferred as well.
- Show economic viability (and preferably, superiority) compared to a conventional ship.
- Have a long total core life.
- Allow for greater time spans between refuels.
- Fit within the existing engine room space (or a smaller space) of the baseline ship.
- Be less susceptible to tampering.
- Utilize a fuel which supports non-proliferation agendas.

While it was recognized that it may not be possible to achieve all the desirable features, these features helped begin to identify the optimal solution.

In addition to all these criteria, the selected reactor design needed to also have sufficient passive safety design features. However, implementing sufficient passive safety features is a significant, longstanding requirement within the nuclear power industry, so it was anticipated that all the evaluated technologies would meet this requirement.

Lastly, an overall goal was set to select a reactor design which would be ready for commercial implementation onboard the NPMS by 2030. Although it was hard to assess this goal's actual feasibility before deeply evaluating the various design options and their technical readiness, this objective was still established because it:

- Aligned with the IMO's 2018 Strategy to reduce CO_2 emissions per transport work (as an average across international shipping) by at least 40% by 2030 (compared to 2008) [2].
- Improves the likelihood that this solution will be adapted by:
  - Delivering the NPMS to market before other alternative energy solutions (such as ammonium or hydrogen) have the chance to enter and dominate the market.

- Developing a solution within a timeline which increases the likelihood that it will be well-received by the commercial shipping industry.

Therefore, each reactor design’s current and projected technical readiness could greatly impact its feasibility onboard the NPMS, and both current and projected technical readiness was considered throughout the design analysis process.

5.0 Reactor Technology Overview

Within this section, various reactor technologies (excluding traditional PWRs) were reviewed to determine their feasibility for implementation onboard the NPMS. The basic requirements and desirable features from Section 4.4 Reactor Selection Criteria were considered throughout this evaluation, and from the onset of this analysis, it was recognized that multiple designs could provide potential solutions onboard the NPMS (i.e., multiple designs could meet sufficient criteria to be considered for use). Thus, this section also highlighted any private sector interest and/or government support various designs had received to give insights into which technologies were most likely to reach the necessary level of technical readiness by 2030.

5.1 Commercial Nuclear Power Industry Background

Before reviewing newer technology, the nuclear industry's past was briefly reviewed to understand historical influences on recent development. Nuclear power has progressed in waves both within the US and throughout the world. After an initial explosion of growth throughout 1950s and 60s, declines rooted in economic concerns began during the mid-1970s. From there, accidents in 1979 (Three Mile Island), 1986 (Chernobyl) and 2011 (Fukushima) further impacted the nuclear industry by degrading public opinion and introducing concerns surrounding the technology's safety. However, many experts argued these events did not cause the resultant periods of stagnation and/or decline, but rather, they acted as the breaking point for an industry which required large upfront capital investments and lengthy, initial periods of interest payment before power plants could become profitable. This history is reflected in the figure below:

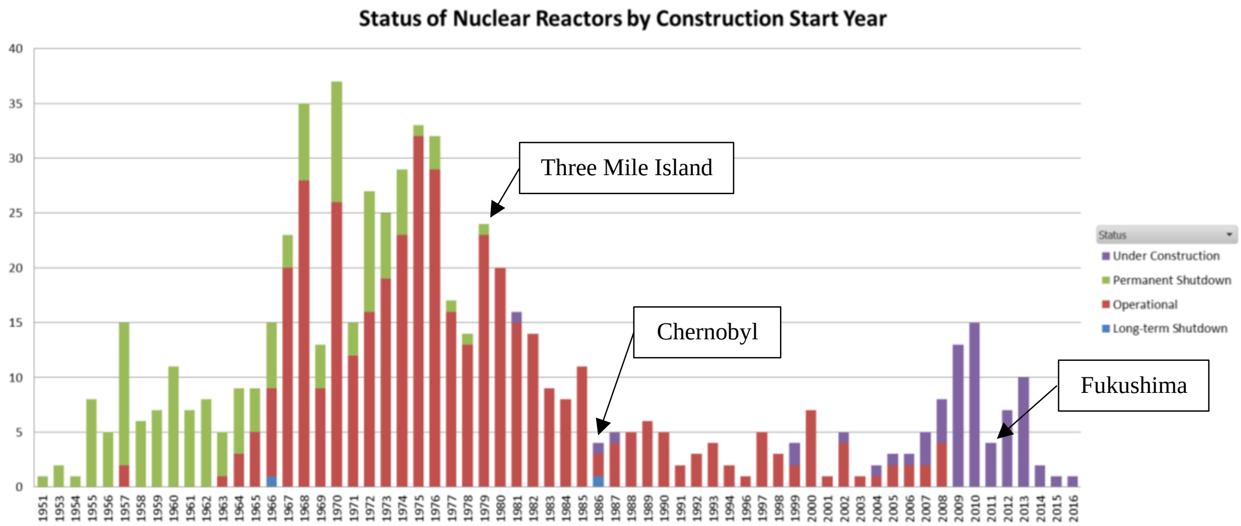


Figure 39: Status of Nuclear Reactor by Construction Start Year [101]

From this data, the following trends were noticed:

- A surge in new construction occurred from approximately 1951 to 1975.
- Prior to the Three Mile Island accident in 1979, new construction declined drastically from 1976-1978. This trend was the result of the previously discussed economic issues surrounding large, high-power PWR plants.
- Following the Three Mile Island accident and subsequent safety concerns, new construction declined consistently until 1985.
- Following the Chernobyl accident in 1986, new construction remained low until it underwent a period of revitalization and renewed interest (often referred to as the "nuclear renaissance") in early 2000s [102]. This renaissance was driven by the need for carbon-free energy solutions in response to climate change [102].
- Although the Fukushima accident in 2011 somewhat impacted growth during the 2010s, this event's influence was not on the same scale as previous accidents due to overarching concerns surrounding GHG emissions and environmental preservation.

In evaluating these trends, it was also important to note that other factors stalled the nuclear renaissance throughout the early 2000 and prevented nuclear power from immediately becoming the carbon-free energy solution. These factors included:

- The 2008 global financial crisis which impacted the entire energy industry [103].
- The increase in widely available and affordable natural gas.
- Unexpectedly competitive/profitable wind and solar power installations.
- Continued issues with the regulatory process and obtaining the requisite licenses within an economically viable timeline.
- Low investor interest due to the first three listed factors combined with large upfront capital requirements [102].

In summary, most of the currently operating power plants throughout the world today were built during the 1970s, 80s and 90s using older technology, and as a result, the rate of plant shutdowns currently outpaces the rate of new plant startups [104]. While the US' electrical generation capacity from nuclear power has consistently increased through modifications made at existing power plants, the overall conclusion was that the nuclear power industry was in a state of regression from 1970s to 2000s, and future nuclear power applications will most likely utilize newer, innovative technology which operates on a smaller power scale [104].

In reviewing past trends within the nuclear power industry, it was also important to note an increase in new construction in the early 2000s as concerns for climate change increased and nuclear power was identified as a carbon-free energy source with sufficient technical maturity to provide a solution within the necessary timeline. In 2006, this upward trend was further propelled by interest from the private sector as major entrepreneurs (such as Bill Gates) began to look at opportunities within ARD development [105]. This high-profile attention was met with support from various government and regulatory bodies (as discussed within Section 3.3 Future Licensing Plans), and this collaboration between the public and private domain further fostered an environment where nuclear power had potential for future growth. Therefore, various private companies which have explored ARDs have been discussed within the upcoming sections of this project, and this chapter also reviewed the history of government funding and policies that have supported the nuclear industry. The goal of this review was to identify reactor technologies with a higher likelihood to achieve the necessary technical maturity needed for the NPMS.

5.2 US Advanced Reactor Policies and Financial Support

5.2.1 Policies

The main policies which have influenced ARD development in recent years are the Gateway for Accelerated Innovation in Nuclear (GAIN) Program of 2015, the Nuclear Energy Innovation Capabilities Act (NEICA) of 2017, and the previously discussed Nuclear Energy Innovation and Modernization Act (NEIMA) of 2019.

In 2015, the GAIN Program's goal was, "to provide the nuclear energy community with access to the technical, regulatory, and financial support necessary to move new or advanced nuclear reactor designs toward commercialization while ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet" [106]. The program met this goal through:

- Better access to information through established databases and official points of contact [106].
- The use of small business vouchers to support new companies in the ARD field [106].
- Increased collaboration and assistance from the DOE while navigating the regulatory process [106].

Following the GAIN Program, the NEICA continued to ensure government support for ARD advancements. With strong bipartisan support, the overall goal of the NEICA was, "To enable civilian research and development of advanced nuclear energy technologies by private and public institutions, (and) to expand theoretical and practical knowledge of nuclear physics, chemistry, and materials science..." [107]. Measures taken within the NEICA included:

- A cost-share grant program that would cover a portion of the NRC's licensing fees and reduce regulatory costs for new reactor technologies [108] [109].
- A directive to construct the country's first fast neutron test reactor to develop fuels and other materials required within ARDs [108] [109].
- The establishment of the Advanced Reactor Demonstration Program (ARDP) which facilitated new partnerships between the DOE and companies within the private sector to fast-track ARD tests [108] [109].

- The expansion of software and computing tools to allow for better ARD modelling and simulation [108] [109].
- Significant funding to support the various efforts listed above [108] [109].

Following the NEICA, the NEIMA further built upon this legislation by directing the NRC to develop a new regulatory framework better suited for ARDs which would allow for an achievable path through the licensing process within a reasonable timeline (as discussed within Section 3.3 Future Licensing Plans).

Established within the NEICA, the ARDP represented a major step towards achieving ARD commercial viability through public-private partnerships that aimed to develop full-scale demonstrations during the 2020s [110]. Following its launch in May 2020, the DOE selected two reactor designs in October 2020 (TerraPower's Natrium SFR and X-Energy's High-Temperature Gas-cooled Reactor (HTGR)) for full-scale demonstration by 2027 [110]. From there, the DOE also selected five other companies in December 2020 (BWX Technologies, Holtec, Kairos Power, Southern Company, and Westinghouse) for a risk reduction program that would, "design and develop safe and affordable reactor technologies that can be licensed and deployed over the next 10 to 14 years, with a focus on resolving technical, operational, and regulatory challenges" [110]. As a result of the progress made within the ARDP, the technologies developed by these companies were all strong candidates for deployment onboard the NPMS, and the specifics of these ARDs have been reviewed in the forthcoming sections.

5.2.2 Financial Support

In addition to support through written policies, the US government has extended significant public backing to nuclear industry's future through financial support. Therefore, the following table was developed to summarize the US' recent backings of ARDs and nuclear power progress:

US Reactor Technology Investments				
Year/Source	**Amount (Million $)**	**Source**	**Recipient**	**Venture and/or Technology**
1998-2015/ [108]	2,000	DOE Office of Nuclear Energy (ONE)	Various	ARD R&D
2015/ [106]	2	GAIN	Various	Small business vouchers for ARD R&D
2016/ [111]	40	DOE	TerraPower	Molten chloride fast reactor (MCFR)
2016/ [108]	53	DOE	X-Energy	Modular pebble bed HTGR design
2018/ [108]	10	DOE	X-Energy	Modular pebble bed HTGR design

2018/ [108]	36	DOE's Advanced Research Project Agency-Energy (ARPA-E)	Various	ARD research
2019/ [108]	433.5	Congress	ONE	Nuclear R&D
2019/ [108]	5	Congress	ONE	Supercritical energy conversions in sodium-cooled fast reactors
2019/ [108]	100	Congress	ONE	SMR R&D
2019/ [108]	111.5	Congress	ONE	ARD R&D
2019/ [108]	65	Congress	ONE	Versatile fast test reactor
2019/ [108]	38	Congress	ONE	Material recovery and waste form development
2019/ [108]	432	Congress	DOE Office of Science	Fusion R&D
2019/ [108]	132	Congress	International Thermonuclear Experimental Reactor (ITER)	Fusion
2020/ [112]	80	DOE	TerraPower	ARDP: Sodium-cooled fast reactor (Natrium Reactor)
2020/ [112]	80	DOE	X-Energy	ARDP: HTGR (Xe-100)
2020-2027/ [113]	303	DOE	Kairos Power	ARDP: TRISO fuel fluoride salt-cooled high temperature reactor
2020-2027/ [113]	7.4	DOE	Westinghouse Electric Company	ARDP: Heat pipe cooled microreactor (eVinci)
2020-2027/ [113]	85.3	DOE	BWXT Advanced Technologies	ARDP: TRISO fuel transportable reactor
2020-2027/ [113]	116	DOE	Holtec Government Service	ARDP: Light-water cooled SMR
2020-2027/ [113]	90.4	DOE	Southern Company Services	ARDP: MCFR construction
2020-2024/ [114]	27.5	DOE	Advanced Reactor Concepts	Advanced Reactor Concepts-20 (ARC-20) Project: seismically isolated advanced sodium-cooled reactor facility
2020-2024/ [114]	24.8	DOE	General Atomics	ARC-20: fast modular reactor conceptual design
2020-2024/ [114]	3.9	DOE	MIT	ARC-20: Modular integrated gas-cooled high temperature reactor
2021/ [115]	48.8	DOE	69 Universities	Nuclear Energy University Program (NEUP): "Increase capacity and explore novel methods for isolating, immobilizing and storing nuclear waste"
2021/ [115]	5.9	DOE	25 Universities	NEUP: Improve nuclear reactor infrastructure and provide crucial safety and performance upgrades to various university research reactors
2021/ [115]	7.1	DOE	Iowa State University, North Carolina State University, GE Research, Oak Ridge National Laboratory (ORNL)	Nuclear Energy Enabling Technologies (NEET), and the Nuclear Science User Facilities (NSUF): advanced materials, manufacturing, and digital instrumentation technologies to support advanced nuclear reactors, and to investigate the application of nuclear fuel and materials
2021/ [116]	8.5	DOE	Various	ARD commercialization
Total	**4.347 Billion**			

Table 10: US Reactor Technology Investments

In addition to the contributions listed above, the DOE also planned to invest $3.2 billion from 2020 to 2027 part of the ARDP into TerraPower and X-Energy's designs, and plans are also in place for these two companies to match the DOE's contribution [110].

In developing this table, it was important to note that the US government's expenditures are part of a vast and complex system, and therefore, this table most likely did not reflect all investments made into reactor technology advancements or the nuclear industry from 1998 to 2021. Regardless, it demonstrated financial investment increases throughout the last decade into ARD progress, and it also reflected the significant plans in place to continue funding future ARD advancement. While governmental plans can always change due to shifts in political interests and/or powers, the overall conclusion was that ARDs have already received substantial government support, and from this support, it was clear that some technologies may be more promising than others.

Having reviewed the US' political and financial support for reactor technology development, specific Gen IV technologies have been evaluated in the forthcoming sections to determine the best options for the NPMS. Additionally, there were approximately 35 different companies in the US alone as of 2018 that were developing ARDs [108]. Thus, it was not possible to deeply evaluate all possible technology options, and priority was given to designs with higher technological readiness.

5.3 Sodium-Cooled Fast Reactor

SFRs are the oldest form of non-PWR reactor technology. In fact, the world's first proof-of-concept reactor that was constructed following the 1942 Chicago Pile experiment was a SFR (which was the Experimental Breeder Reactor-I (EBR-I) located at what is now INL) [117]. Since the EBR-I began generating power in December 1951, over 22 SFR have been constructed throughout the world and operated at the experimental, prototype and commercial scale [117] [118]. An overview of these plants and their corresponding major events dates are shown in the figure below:

Plant	Country	MWt	Dates of major events				
			Start of construction	First criticality	First electricity generation	First full-power operation	Final shutdown
EBR-I	U.S.	1.4		1951			1963
Rapsodie	France	40	1962	January 1967		March 1967	April 1983
KNK-II	Germany	60		October 1972	April 1978	1978	October 1991
FBTR	India	40	1972	October 1985	1994	1996	
PEC	Italy		January 1974	Project canceled			
Joyo	Japan	140	February 1970	July 2003		October 2003	
DFR	U.K.	60	1954	1959	1962	1963	1977
BOR-60	Russia	60	1964	1968	1969	1970	
EBR-II	U.S.	60	June 1958		August 1964	1965	1998
Fermi-1	U.S.	200	August 1956	August 1963	August 1966	October 1970	1975
FFTF	U.S.	400	June 1970	February 1980		December 1980	1996
BR-10	Russia	10	1956	1958		1959	December 2003
CEFR	China	65	May 2000	July 2010	July 2011	December 2014	

Plant	Country	MWt	Dates of major events				
			Start of construction	First criticality	First electricity generation	First full-power operation	Final shutdown
Phenix	France	560	1968	1973	1973	March 1974	
SNR-300	Germany	950	1973	Finished in 1985, project cancelled in 1991			
PFBR	India	1250	2003	2019			
Monju	Japan	715	1985	1994	1995		
PFR	U.K.	650	1966	1974	1975	1977	March 1994
CRBRP	U.S.	2750	Project canceled				
BN-350	Kazakhstan	750	1964	November 1972	1973	Mid-1973	April 1999
BN-600	Russia	1500	1967	February 1980	April 1980	December 1981	
Super-Phenix	France	3000	1976	1985	1986	1986	1998
BN-800	Russia	2000	2002	2014	2016	2018	

Figure 40: Summary of SFR Applications [118]

This figure also showed how multiple countries have developed experience operating SFRs, and as previously discussed, this technology has already been used by the US Navy onboard a submarine in the 1950s. SFRs are also the predominant type of Fast Neutron Reactor (FNR) technology, and to further support FNR research and development, an agreement was formed in the late 2000s between the Japan Atomic Energy Agency (JAEA), the French Alternative Energies and Atomic Energy Commission (CEA) and the DOE to expand FNR collaboration among various countries and private companies [119]. Research efforts conducted within this agreement include:

- Development of a demonstration reactor to follow the prototype SFR and Fast Breeder Reactor (FBR) Monju in Japan [119].
- Collaboration between France and Japan on the Advanced Sodium Technical Reactor for Industrial Demonstration (ASTRID) [119].
- French fuel tests within Japan's Monju reactor [119].
- American research into systems, materials and safety analysis [119].
- Significant American investment into two versions of General Electric (GE) Hitachi's new Power Reactor Innovative Small Modular (PRISM) ARD which is specifically used within the Versatile Test Reactor and TerraPower's Natrium reactor (which is part of the ARDP) [119].
    - For additional consideration, PRISM has already passed the NRC's preapplication review process, and it is also the only SFR to have passed this review process [108].
    - PRISM has also been strongly considered in the UK to burn the country's reactor-grade plutonium stockpile (which would concurrently produce electricity) [119].

5.3.1 SFR Technology Overview

As previously discussed, SFRs operate on the fast neutron spectrum, and the main difference specific to SFRs is that liquid sodium is used as the reactor's coolant. A diagram of a typical SFR reactor design is shown below:

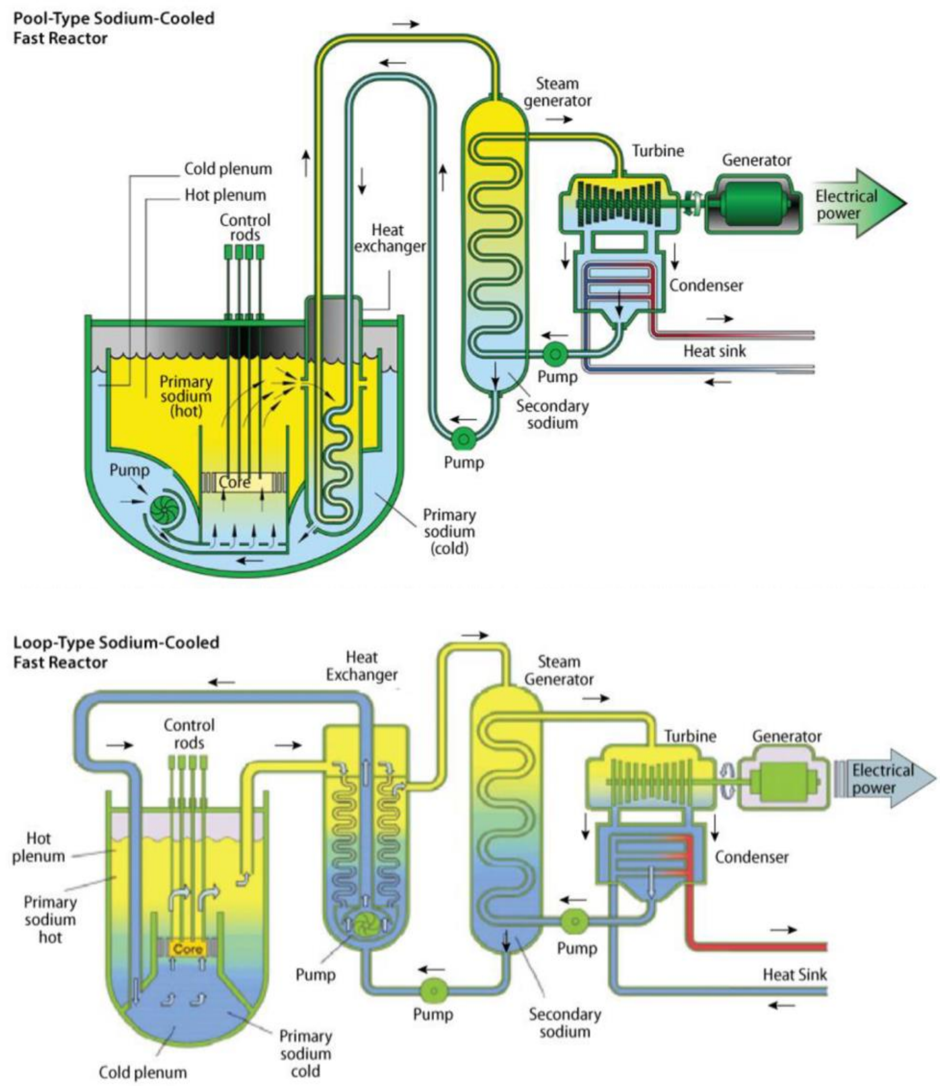


Figure 41-42: SFR Pool-Type (Top) and Loop-Type (Bottom) Design Overview [108]

For the NPMS, a loop-type design would most likely be preferred since they typically weigh less and are more compact compared to the pool-type design. Within both designs, it was important to note an intermediate cooling loop has been used between the reactor coolant and power-generating working fluid to increase the reactor's safety due to sodium's potential for volatile reaction with water and/or air [120].

The main benefits of SFRs include:

- High technological maturity following an established history of operating various prototype and commercial SFR reactors globally (some of which have supplied power to public electric grids) [119].
- SFR are typically smaller in size due to higher power densities and more efficient heat transfer.
- By operating in the fast spectrum, SFRs can operate with either a closed fuel cycle or as a breeder reactor [119].
    - In a closed fuel cycle, heavier fission products (often referred to as actinides based on their periodic group) such as Plutonium-239 (Pu-239) and Pu-241 are "burned" and produce energy through additional neutron-induced fission reactions [119].
        - With a closed fuel cycle, the reactor's waste is less radioactive due to the mitigation of long-lived actinides and transuranics (or elements whose atomic number is greater than uranium's 92) [120]. Therefore, less decay heat management is required throughout the follow-on storage process [120].
        - A second added benefit of a closed fuel cycle addresses proliferation concerns because less plutonium is available for repurposing within the SFR's fuel waste as actinides are burned throughout the reactor's life cycle.
    - In a breeder reactor, fertile material is used to produce fissile material which then fissions to produce power. Examples of these reaction which result in Pu-239 production from U-238 and U-233 production from Thorium-232 (Th-232) are shown in the figures below:

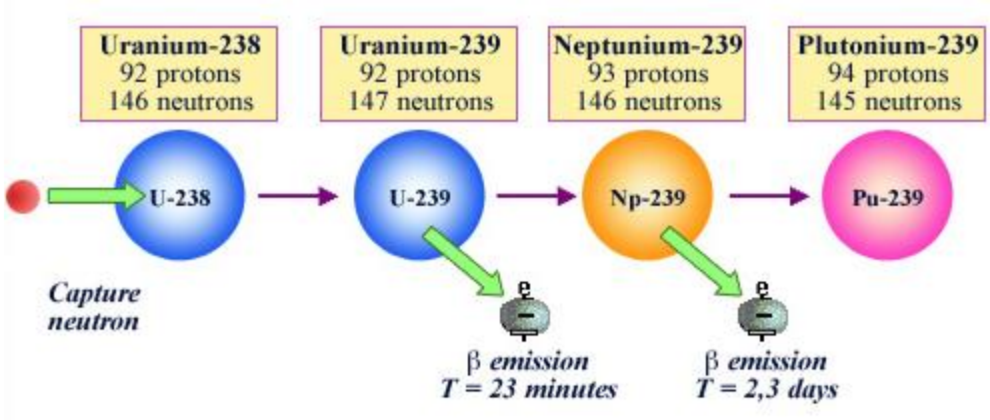


Figure 43: U-238 to Pu-239 Production Process [121]

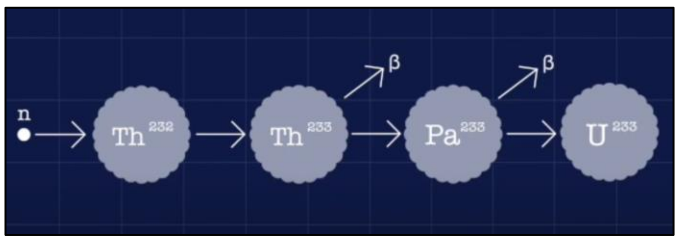


Figure 44:Th-232 to U-233 Production [122]

Often within breeder reactors, more fissile material is produced than consumed by the reactor to generate power, so operating in this configuration can introduce the additional benefit that the resultant fuel waste can be loaded into future reactors as fuel.

- Related to SFR's fuel options specifically, natural or recycled U-238 can be used as fuel material for SFRs (which provides additional benefits related to fuel availability) [120].

- Higher thermal efficiency (compared to PWRs) due to sodium's higher operating temperatures (around 500-550 °C, or 932-1022 °F) [120].
- Increased safety features such as:
  - The ability to operate at atmospheric pressure [120]. This feature eliminates the need for significant over-engineering (which would typically be required for a highly pressurized system) within the primary system's construction [119].

Operating at atmospheric pressure also reduces concerns surrounding the severity of a loss of coolant casualty.

    - Long thermal response times (which promotes stable, controllable operation) [120].
    - A "reasonable" margin between operating temperatures and the coolant's boiling temperature (at which point the coolant's heat transfer properties reduce and core damage can become more likely) [120].
    - As previously stated, an intermediate heat transfer loop is used to ensure reactor safety [120].
        - This benefit also comes with a drawback in that the SFR requires a larger space and weight allocation to include this intermediate loop [108].
- The primary system can be oxygen-free (which prevents corrosion and eliminates a major concern within PWRs) [120].
- The working fluid can be selected from a variety of options (including water, supercritical carbon-dioxide and nitrogen) [120].
- Reactors can be designed to provide inherent safety with a "net negative reactivity feedback during accidents that lead to elevated core/coolant temperatures" [123].
- Passive cooling can be achieved through natural circulation to remove decay heat due to large temperature differences across the core (approximately 150 °C (302 °F) in an SFR vs. 30 °C (86 °F) in an LWR) [123].

The biggest concerns surrounding SFRs involve:

- As discussed, sodium is highly reactive with both air and water, and therefore, the reactor must be designed with sufficient safety features in place to prevent these interactions [123].
- Additional cooling systems are required to maintain the sodium's liquid phase during reactor shutdowns and start-ups.
- Electromagnet pumps are needed to move the liquid sodium through the primary loop. These pumps have a more robust design and higher electrical load compared to conventional pumps.

- For large cores, sodium voids can add positive reactivity [123].
- Operating within the fast neutron spectrum can make shielding more challenging [123].
- The sodium coolant's opaqueness can create challenges related to inspections and maintenance [123].

Overall, SFRs are a technologically mature ARD which represent a significant opportunity to mitigate nuclear waste using recycled fuel material and increased actinide consumption. For these reasons, the DOE selected this Gen IV technology as one of two main demonstrations for the ARDP (where SFRs are used specifically in TerraPower's "Natrium" system). This technology is named Natrium after the Latin name for Sodium, and within this land-based system, a 345 Mega-Watts electric (MWe) SFR has been combined with a 500 MWe molten salt thermal storage technology [124]. A visual overview of the Natrium system is provided below:

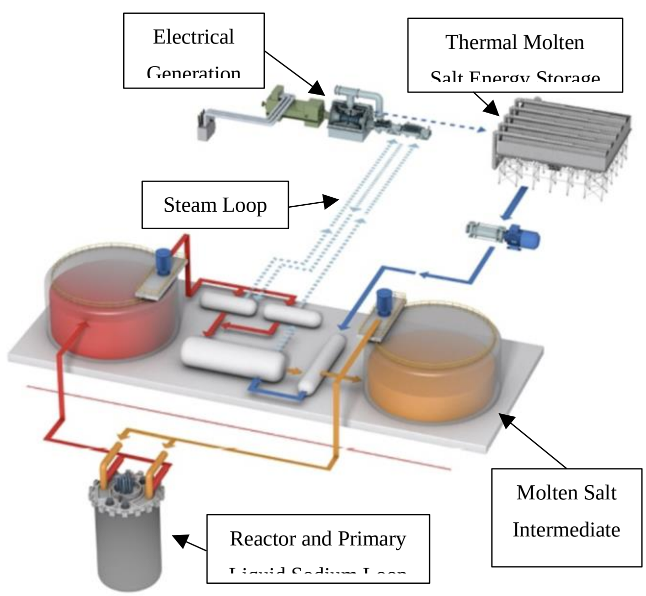


Figure 45: TerraPower Natrium Reactor System [125]

Related to specific configuration options, there are three main variants currently being considered within the SFR space, and those variants include:

1. A small sized (50 to 150 MWe) modular-type reactor with uranium-plutonium-minor-actinide-zirconium metal alloy fuel. This design is supported by a fuel cycle based on

electrometallurgical processing (or pyroprocessing) which occurs in on-site facilities integrated with the reactor [126] [120].

2. An intermediate-to-large sized (300 to 1,500 MWe) pool-type reactor with oxide or metal fuel [126] [120].
3. A large sized (600 to 1,500 MWe) loop-type reactor with conventional mixed uranium-plutonium oxide fuel (or MOX fuel) and potentially minor actinides [126] [120]. This reactor design is supported by a fuel cycle based upon advanced aqueous processing which occurs at a separately located central location which serves multiple reactors [126] [120].

Within these variants, the first option would work well onboard the NPMS based on the primary and secondary baseline ships' power requirements.

Additionally, other companies working to develop SFRs include SFRs Advanced Reactor Concepts, Columbia Basin Consulting Group, General Electric-Hitachi and Oklo [108]. This significant private sector interest combined with government support through the ARDP suggests SFRs are one of the Gen IV ARDs most on track to reach commercialization in the near future. As also previously discussed within Section 2.4 Naval Nuclear Propulsion and Commercial Shipping, a report submitted to Congress in 2020 by the US' national laboratories recommended PWRs, SFRs and Lead-cooled Fast Reactors (LFRs) for further consideration for deployment onboard, "ship-borne systems and transportable systems to fixed locations, e.g., to a remote base or to a seawater desalination service location" [41]. There is also a substantial record of past and present SFR operation, so with all these factors combined, SFRs were a strong candidate for the NPMS.

5.4 Molten Salt Reactors

Molten Salt Reactors (MSR) have been experimented with and developed since the 1950s at Oak Ridge National Laboratory (ORNL) [108]. Following its origin within the Aircraft Reactor Experiment, two demonstration reactors were constructed and operated in the US throughout the 1950s and 1960s [127] [128]. These original MSR reactors were initially approached as an alternative to fast breeder reactors, so they operated as thermal breeder reactors [127] [128] [126]. To achieve this behavior, the reactor's fuel was suspended in fluoride salt coolant which flowed through graphite moderator channels located within the core (which also ensured fission would only occur in the core) [127] [128] [126]. After logging 10,000 operational hours, these projects were discontinued, and MSR interest within the US was greatly reduced from 1975 to 2010 [128].

In more recent years, MSRs regained interest as one of the six identified Gen IV ARDs and has been revisited in China, France, Japan, Russia and the US [128]. After further evaluation, MSRs were regrouped into two separate Gen IV designs (Molten Salt Fast Reactors (MSFR) and Advanced High Temperature Reactors (AHTR)), and both technologies have been reviewed in greater depth throughout the subsequent sections [128].

5.4.1 Molten Salt Fast Reactors Technology Overview

MSFRs were developed to try and combine the benefits of fast reactors with the benefits of MSRs [127]. Like the original MSR design, the MSFR's fuel is mixed with the fluoride salt coolant to create a homogenous composition which circulates through the reactor [127]. A diagram of a general MSFR is shown below:

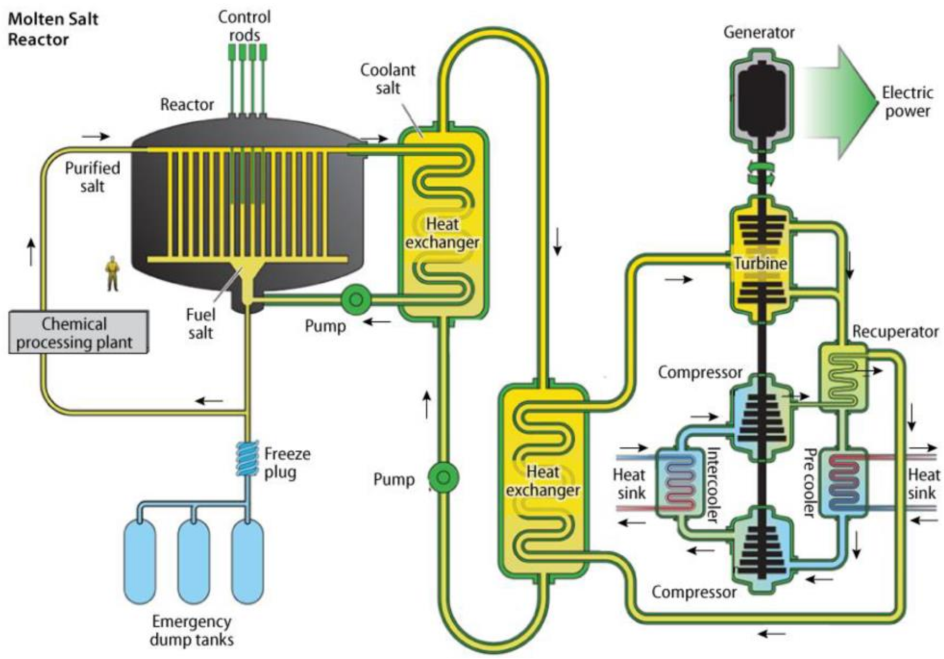


Figure 46: MSR Design Overview [108]

Like SFRs, intermediate coolant loops are employed to protect the reactor and prevent potential reactions between the molten salt and the electricity-generating working fluid. Another feature specific to MSFRs is the addition of the freeze plug and emergency dump tanks. The freeze plug is made of solid fuel salt which melts as an emergency response should the liquid salt coolant reach too high of a temperature [129]. In this scenario, the freeze plug provides passive safety, and the reactor's fuel/coolant mixture drains into the dump tanks where it cools and halts the fission process within the reactor [129]. This safety feature can be utilized during a loss of electrical power casualty since it does not require electrically powered components to occur [129]. Additionally, operator actions exist which allow for controlled draining to the dump tanks to support short duration maintenance (which could last a few days to a few weeks) [130]. While it was not explicitly stated whether this process was easily reversible (i.e. easily enough to achieve that the reversal process could occur in response to an emergency action while the NPMS would be out at sea), reversibility seems possible considering how transferring the coolant to the dump tanks was described as a controllable and routine part of MSFR operation (though this inference would need to be verified further) [130].

Another unique feature within MSFRs is the core construction and operation. A graphic of the MSFR core design developed by TerraPower and Southern Company (specifically named the Molten Chloride Fast Reactor (MCFR)) is shown below:

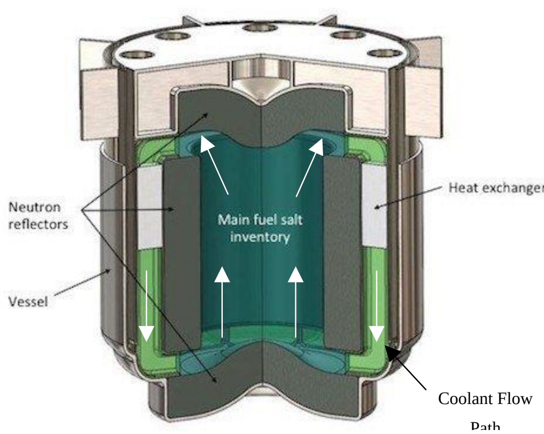


Figure 47: TerraPower MCFR Core Diagram [131]

Within this core, neutron reflectors are used to induce the fission process so that power is generated specifically within the core (versus in the coolant loops). Like SFRs, the MSFR's reactor walls are also not as thick compared to PWRs because MSFRs are operated near atmospheric pressure (and therefore do not need to contain a pressurized system) [128].

The main benefits of MSFRs include:

- The nature of MSFR's operation is very similar to how spent nuclear fuel is processed before storage. Therefore, it is possible to conduct refuels and/or remove fission products while on-site and during normal operations [131].
    - Related to onsite fuel reprocessing, it is also possible to employ gas processing bubbling extraction with MSFRs to remove Xenon (Xe), Krypton (Kr) and other unfavorable gaseous fission products [130].
    - A figure which displays both bubbling extraction and fuel reprocessing within a MSFR is shown below:

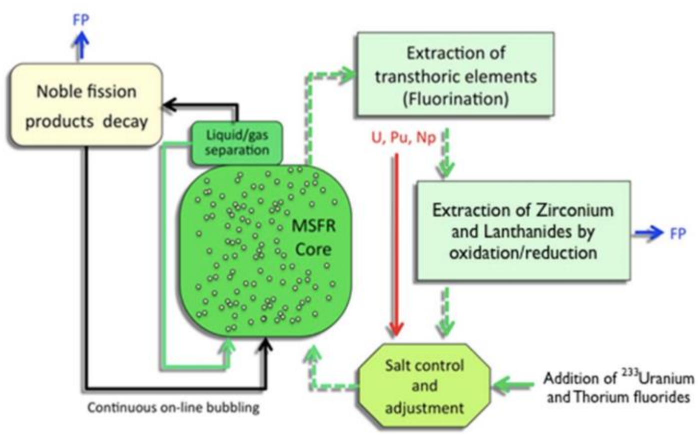


Figure 48: MCFR Fuel Processing [130]

- A variety of advantages are associated with how MSFRs use molten salt as both the coolant and fuel. Those advantages were as follows:
    - No solid fuel assemblies are required for operation which must be designed, fabricated, maintained, replaced or stored [131].
    - The fuel generates heat directly within the coolant (which promotes a simplified and more efficient heat transfer process) [130].

    - MSFRs exhibit strong negative temperature and void coefficient relationships which results from how the fuel and coolant expand at high temperatures [128]. This expansion behavior also allows MSFRs to achieve load-following during normal operations and reactivity control without the use of control rods [128].
- Increased safety features such as:
    - The ability to operate at atmospheric pressure [128].
    - Passive cooling through natural circulation which can be achieved at any size [128].
    - The fluoride salt used for coolant boils at 1430 °C (or 2606 °F) which results in a large margin between operating temperatures and the coolant's boiling temperature [128].
    - An intermediate heat transfer loop is used to ensure reactor safety.
- Higher thermal efficiency (compared to PWRs) due to molten salt's higher operating temperatures (around 700 °C, or 1292 °F) [128].
- Natural uranium as well as depleted uranium and spent fuel are all fuel material options for MSFRs [131].
    - For the MSFR technology specifically related to Gen IV initiatives, a combination of Uranium and Thorium is anticipated to be used for the fuel source due to MCFR's high U-233 yield which results from the fertile Thorium [126].

The biggest concerns surrounding MSFRs involve:

- Like SFRs, cooling systems are required to maintain the molten salt's liquid phase during reactor shutdowns and start-ups.
- Like SFRs, fast reactors typically have greater shielding requirements due to increased neutron leakage.
- With respect to the NPMS, additional space would be required onboard for the emergency dump tanks system. Since this system is typically placed underground within land-based systems to encourage greater heat transfer between the fuel and surroundings, the dump tank's location onboard the ship would also need to be taken into careful

consideration to ensure both high heat transfer from these tanks to their surroundings and overall safety for the ship and crew.

- While MSRs have been previously operated (as mentioned above), a MSFR has never achieved criticality. As a result, there is effectively no prior operational experience with this technology, and the world's first MSFR (the MCFR which was developed by TerraPower and Southern Company at INL and discussed earlier) is not scheduled to achieve criticality until 2025 [132].
- Also due to the overall novelty of this technology, limited information was publicly available related to projected reactor sizes and power ratings. Therefore, only one reference generally listed the MSFR's power rating on the scale of 1,000 MW, and this value would be much higher than necessary for the NPMS [126].
    - Though in contrast, the MCFR is anticipated to generate 0.5 MWt as a demonstration reactor, and through this project, TerraPower has partnered with another company named COREPOWER who seeks to adapt this technology to the marine environment [132]. Therefore, a possibility existed that this technology could be adapted to the appropriate size for the NPMS.

Overall, MSFRs presented multiple benefits which would make them potential candidates for the NPMS. However, the research and development phase alone is not anticipated to be completed until 2025, and MSFRs have been recognized as one of the Gen IV ARDs that are further from commercialization [126] [108]. According to the China Academy of Sciences, MSFR's main research needs are fuel treatment, materials and reliability [126].

With that that said, the DOE recently awarded significant financial support through the Risk Reduction for Future Demonstration Program for the MCFR (shown in Figure 47) developed by TerraPower in partnership with Southern Company [113]. This support from the public sector combined with interest from the private sector and a history of demonstration reactor operation throughout the 1960s indicates MSFRs should be monitored closely for technological progress and potentially considered in the future for NPMS application.

5.4.2 Advanced High Temperature Reactors Technology Overview

Unlike the MSFR, the AHTR (which is also known as the Fluoride salt-cooled High-temperature Reactor (FHR)) uses a solid fuel core combined with molten salt coolant [126]. In developing this ARD, the main goal was to combine collective benefits from four promising technologies at the time:

1. Coated-particle graphite-matrix nuclear fuels (or TRISO fuel) which was traditionally used for helium-cooled reactors [133].
2. Brayton power cycles [133].
3. Passive safety systems and plant designs from liquid metal cooled fast reactors [133].
4. Low pressure molten salt coolants with boiling points far above the maximum coolant temperature [133].

Equipped with these goals, the following AHTR concept was developed and shown in the figure below:

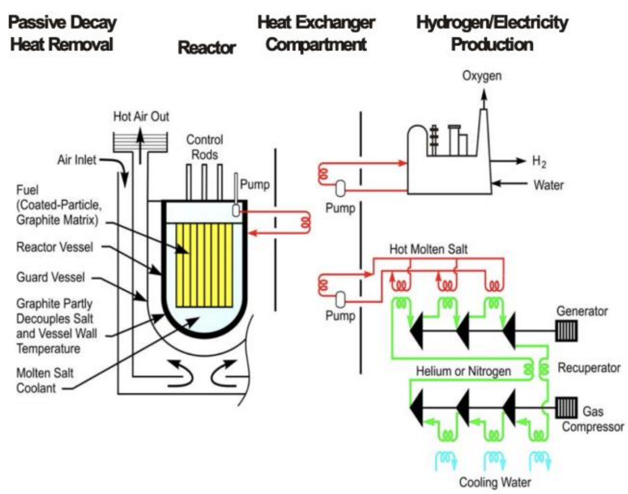


Figure 49: AHTR Diagram [133]

Similar to Very High Temperature Reactors, AHTR's use TRISO coated particle fuel structures, but AHTRs are able to achieve power densities 4 to 6 times greater than HTRs and power levels up to 4,000 MWt (with passive safety systems) due to their use of molten salt (versus helium) as the reactor coolant [126] [127]. AHTRs also operate in the thermal neutron spectrum with graphite moderators and an open fuel cycle [126]. AHTRs are also typically very large and produce 1,000-1,500 MWe. As previously discussed, this power rating would be too large for the NPMS, so design modifications would be required to reduce the system's size.

While researching AHTRs, information surrounding this system seemed generally low, and discussions of technical progress seemed to indicate the technological maturity and advancements were also low. When this low technical maturity is combined with the significantly high-power output, AHTRs were an unlikely selection for the NPMS.

5.5 Very High Temperature Reactors

The Very High Temperature Reactor (VHTR) operates in the thermal neutron spectrum using graphite as the moderator and helium gas as the primary coolant [126]. As the name suggests, the VHTR aims to have outlet coolant temperatures near 1000 °C (1832 °F) for the purpose of hydrogen and electricity cogeneration [126]. In fact, a unique feature of this Gen IV ARD is that it was designed with the specific intent to cogenerate electricity and produce hydrogen [134]. A diagram of the VHTR is shown in the figure below:

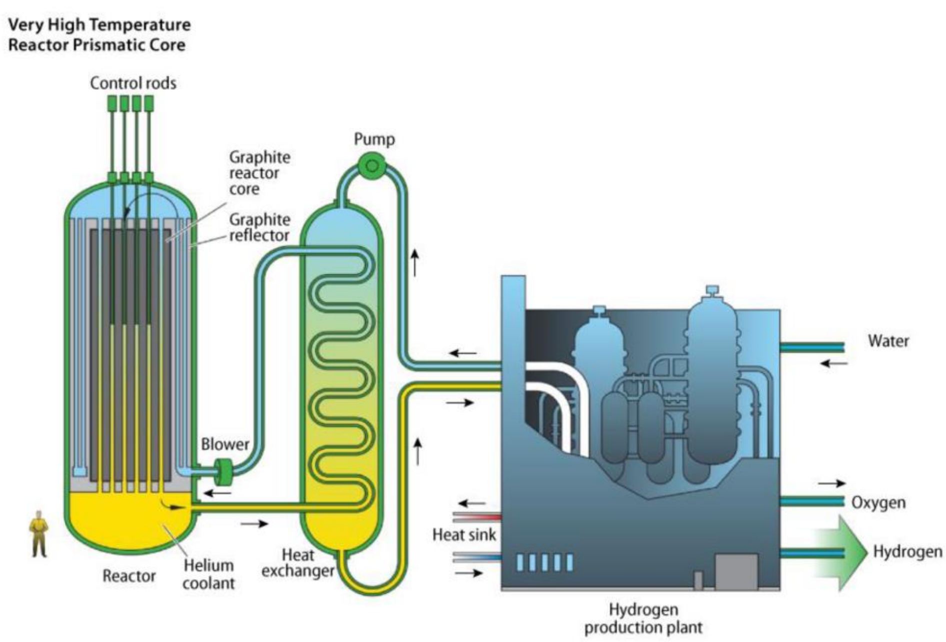


Figure 50: VHTR Design Overview [108]

To achieve these high temperatures, either a TRISO coated fuel particle within a pebble bed or prismatic fuel block configuration can be used [134]. Images of TRISO fuel and these various fuel configurations have been provided in the figures below:

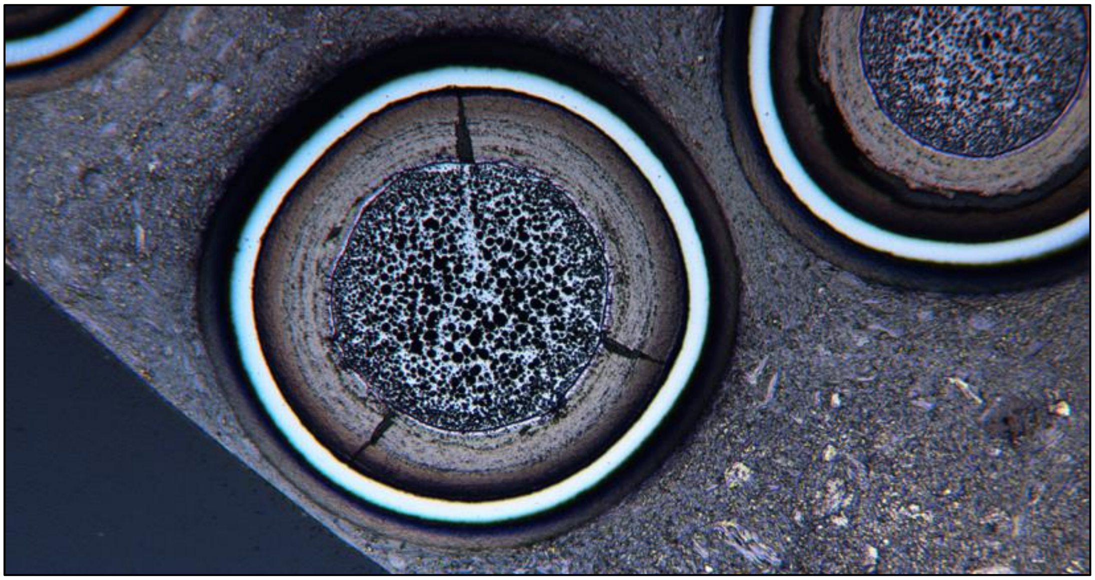


Figure 51: TRISO Fuel Particle [135]

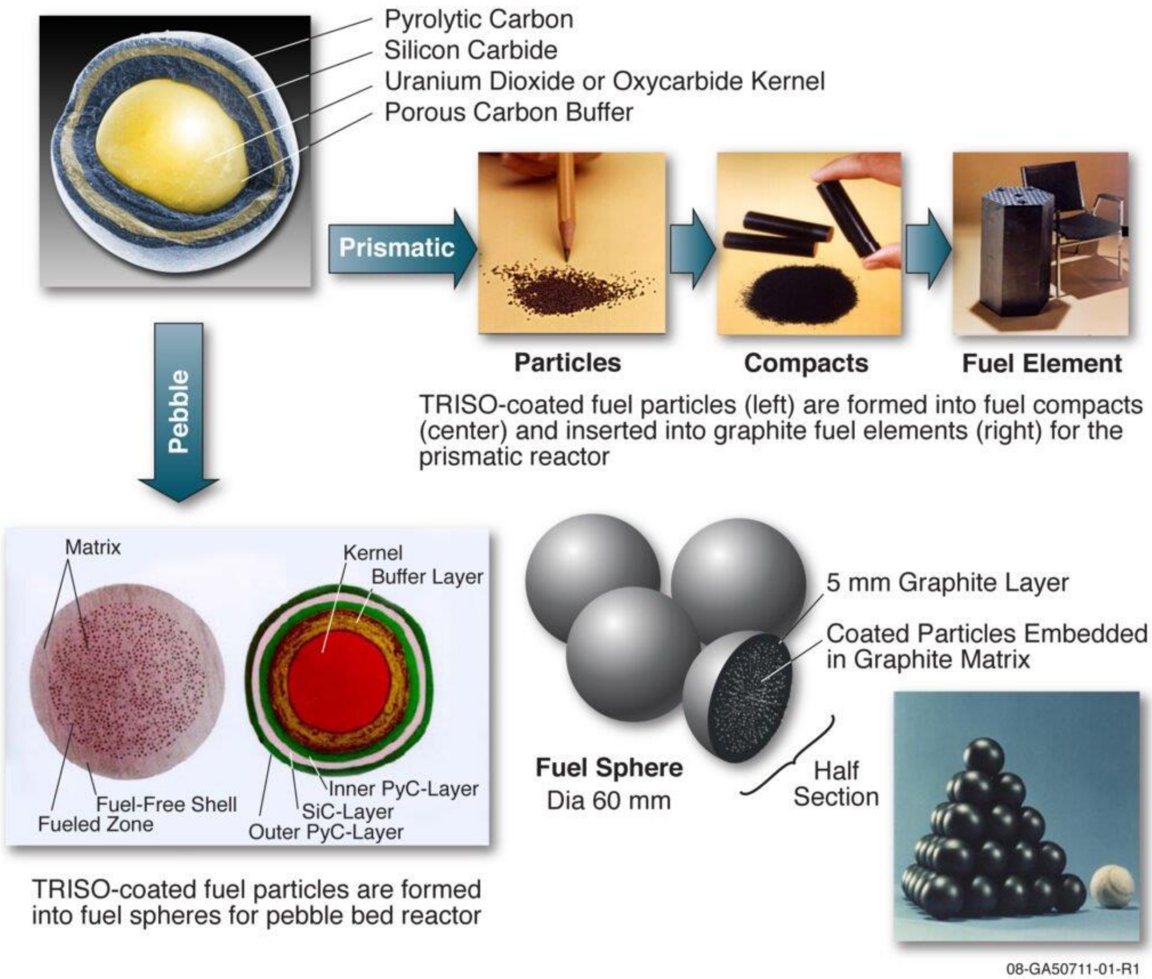


Figure 52: TRISO Fuel Configurations [136]

TRISO fuel was originally developed by the US and the UK in the 1960s, and it was revisited and greatly improved upon in 2002 [135]. TRISO fuel is considered to be very robust in that they are resistant to neutron irradiation, corrosion, oxidation and high temperatures (up to 1800 °C or 3272 °F), and each individual particle is able to retain fission products [135] [136]. Continued research on this fuel is currently underway as TRISO fuel is used in one of the two reactor technologies selected for the ARDP (the specific TRISO technology selected has been developed by X-Energy within their high-temperature gas-cooled reactor) [110].

Additionally, VHTR's are expected to have a power rating near 600 MWt [126]. While this value is higher than desired for the NPMS, this design provides the added benefit of hydrogen generation (which could be used as an additional or auxiliary source of power). Furthermore, the

VHTR's power rating is not as far from the desired range compared to other technologies, so with this fact combined with the high government support (through the ARDP) and robust fuel structure, the VHTR was a moderate contender for the NPMS.

5.6 Gas-Cooled Fast Reactors

Gas-Cooled Fast Reactors (GCFRs) combines the SFR's fuel recycling technology with the VHTR's reactor technology [137]. As a result, the GCFR is a helium-cooled reactor which operates on the fast spectrum with a closed fuel cycle and high thermal efficiency due to the system's high temperatures [137]. A diagram of the GCFR's design is shown below:

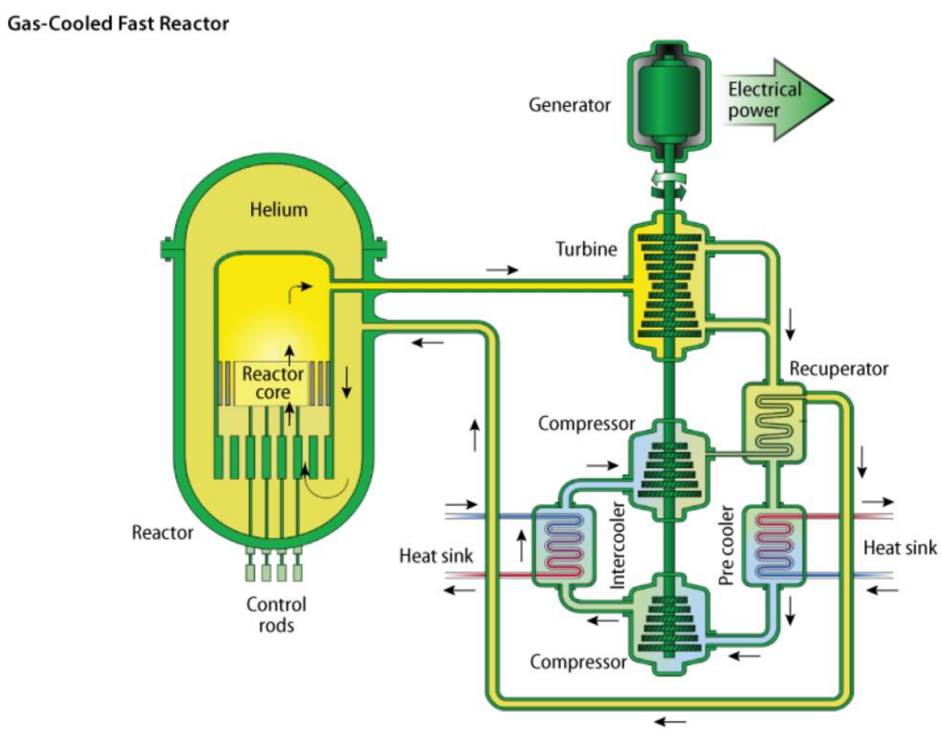


Figure 53: GCFR Design Overview [108]

Like the VHTR, the GCFR would operate at sufficiently high temperatures (approximately 850 °C or 1562 °F at the reactor outlet) to be capable of hydrogen production [119]. One of the key differences between the GCFR and the VHTR is that the GCFR operates on the fast neutron spectrum while the VHTR operates on the thermal neutron spectrum. Therefore, the GCFR does not require graphite moderators within the core, but its operation is more novel compared to traditional PWRs.

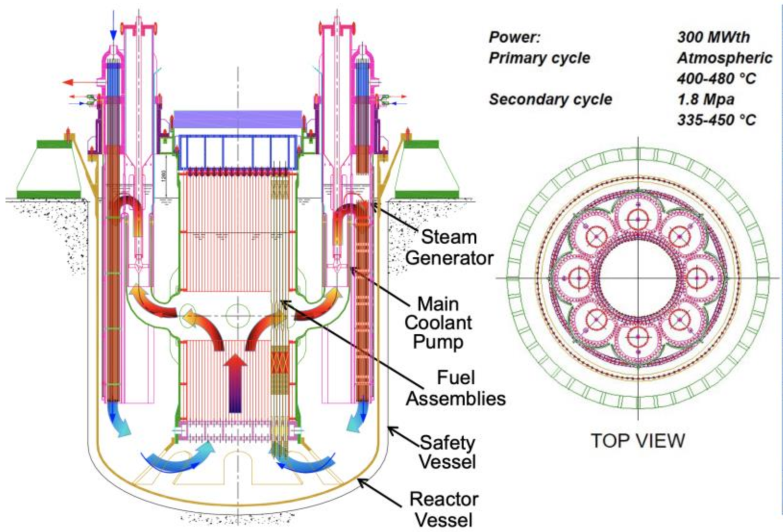
With respect to technological maturity, it was important to note that no GCFR has ever been previously built, and this ARD is the only Gen IV design with no previous operation experience [126]. Of note, the main areas where further research needs are recognized relate to the reactor's fuel, materials and thermal hydraulics [126]. Therefore, the European Atomic Energy Community (Euratom) plans to build a 75 MWt experimental demonstration GCFR named Allegro [126]. According to the World Nuclear Association, "the Allegro project has been taken over by the V4G4 partnership in Eastern Europe, with French CEA support and the prepatory phase now extending to 2026. Euratom, France, Japan and Switzerland have signed onto system arrangements for the GFR under the framework agreement" [126].

Due to the low real-world demonstrations so far, the GCFR is recognized by experts as farther from commercialization compared to other Gen IV ARDs [108]. Therefore, GCFRs were classified as a moderate contender for the NPMS due to their simplified system design (with less components overall, well-sized power range and high international interest.

5.7 Lead-Cooled Fast Reactors

Like SFRs, LFRs have a longstanding history of implementation and operation. While SFRs are the most common form of liquid metal fast reactor, Russia initially experimented throughout the 1960s with powering submarines using lead-bismuth LFRs (as previously discussed within Section 2.5.5) [21]. Although the Russian Navy did eventually switch their fleet to all PWR reactor systems, there have been a few other instances of LFRs demonstrations throughout the world. Three main systems recognized for their leadership in current LFR development include [126]:

- **Europe's Advanced Lead Fast Reactor European Demonstrator (ALFRED).** The ALFRED is a 300 MWt (~125 MWe) demonstration unit which is the resultant product of significant LFR European demonstration concept research which dates to 2002 [138]. Additional information related to the ALFRED is shown in the figure below:



Primary system	Pool-type, compact
Coolant circulation	
Normal operation	Forced (8 pumps)
Accident conditions	Natural (pressure drop 0.15 MPa)
Pressure	< 0.1 Mpa
Temparature	400-480°C
Flowrate	26 000 kg/s
Reactor vessel	Austenitic SS, hung
Safety vessel	Anchored to the pit
Inner vessel (Removable)	Cylindrical, Integral with the core support grid and the hot collectors
Steam generators	8, bayonet type with double walls,
Primary pumps	8, integrated with the SGs, in hot leg
Fuel assembly	Closed (with wrapper), Hexagonal, forced in position by springs
Control/Shutdown Systems	2 diverse and redundant systems concept derived from MYRRHA
Decay Heat Removal	2 separate and redundant systems of 4 Isolation Condensers connected to the Steam Generator (actively actuated, passively operated)
Refuelling System	No refuelling machine stored inside the Reactor Vessel

13

Figure 54: European ALFRED LFR [138]

This project's completion and full-power operations are anticipated by 2040 [138].

- **Russia's BREST-OD-300.** The BREST-OD-300 is a 300 MWe LFR demonstration unit with an on-site fuel fabrication/refabrication module and fuel recycling unit [139]. A rendering of this reactor is shown in the figure below:

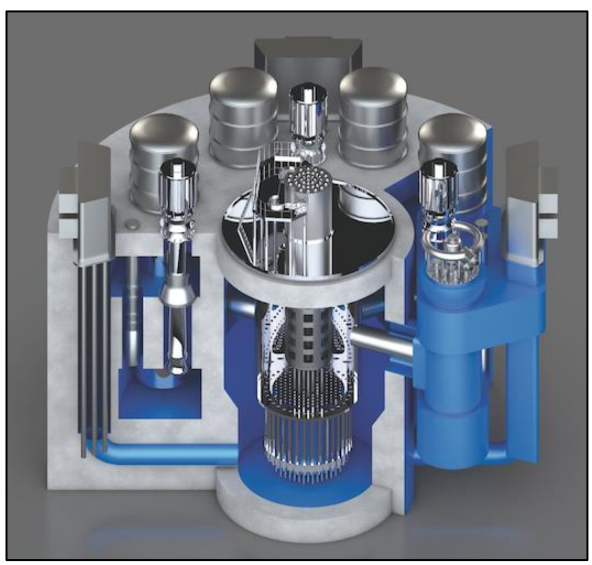


Figure 55: Russian BREST-OD-300 LFR [139]

This reactor was originally planned for start-up in 2020 with the fuel processing plant completed in 2022, but these plans have been delayed [139]. Now, the fuel fabrication module is scheduled for completion in 2021, the reactor in 2026 and the recycling unit in 2028 [139].

- **Belgium's Multi-Purpose Hybrid Research Reactor for High-Tech Applications (MYRRHA).** The MYRRHA reactor is a subcritical LFR rated for 100 MWt with Lead-Bismuth Eutectic (LBE) coolant which will be used to power world's first large scale Accelerator Driven System (ADS) [140]. A diagram of the reactor and overall facility are provided in the figure below:

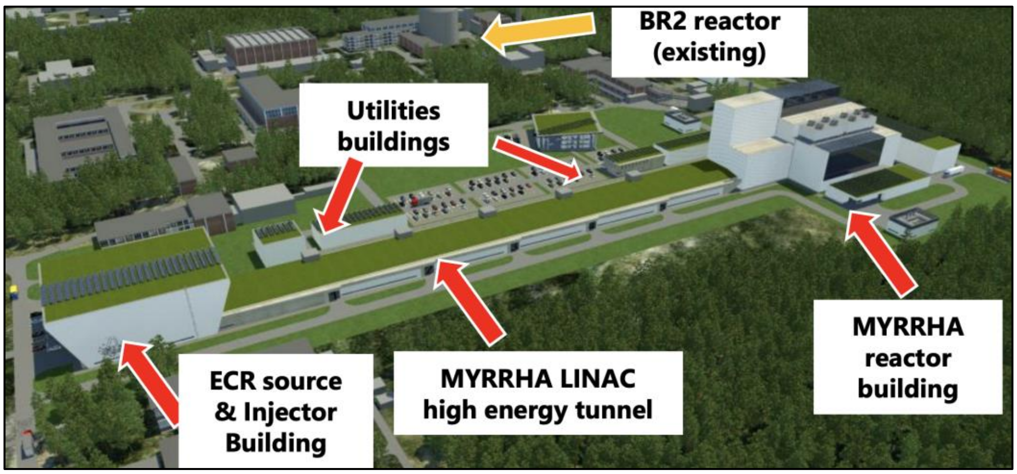


Figure 56: MYRRHA ADS Facility [141]

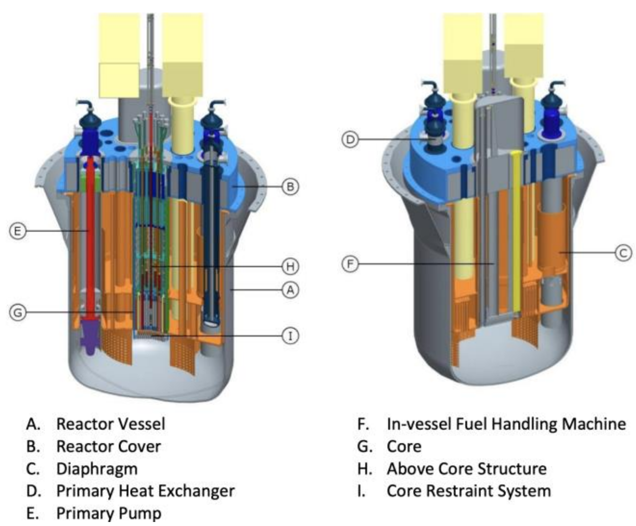


Figure 57: MYRRHA Reactor [142]

Anticipated academic contributions from this facility include:

- Transmutation (Partitioning & Transmutation) of radioactive waste [141].
- Production of nuclear medicine and medical radioisotope [141].
- Demonstration of ADS technology [141].
- Research into new materials [141].
- Contributions to the development of lead fast reactors [141].

This facility's construction is currently underway using a phased approach, and the first research and development facility is anticipated to be available by 2024 [141]. The Belgium government has also secured funding for this facility's design, construction and operation from 2019 to 2038 [141].

In addition to these LFR ventures, other LFR concepts have reached various development stages within China, Russia, Sweden, Korea, Japan and the US (specific domestic companies exploring LFRs include Hydromine and Westinghouse) [143] [108]. This global advancements in LFR technology alongside historic operations and ongoing demonstration projects substantiate LFR's promising future as a prospective nuclear power option.

5.7.1 LFR Technology Overview

The LFR is another liquid metal fast reactor variety with key similarities and differences when compared to SFRs. Like the SFR, the LFR operates with a closed fuel cycle on the fast neutron spectrum at high temperature and low pressure (which provides good heat transfer capabilities and high system safety) [143]. A diagram of the LFR is shown in the figure below:

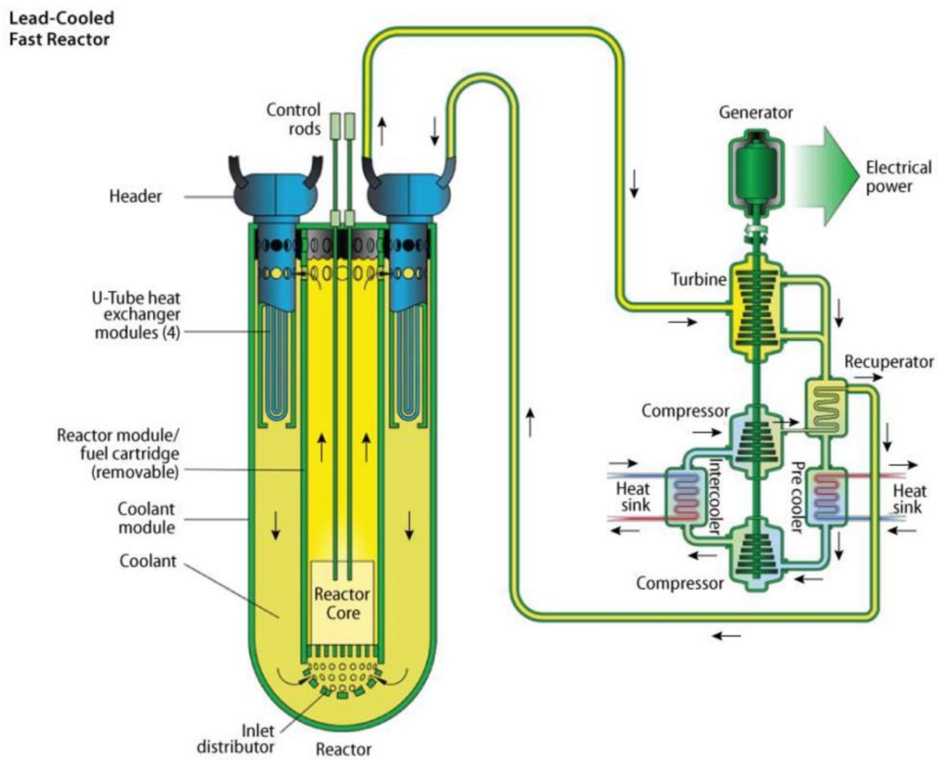


Figure 58: LCFR Design Overview [108]

Within this system, LFRs use either molten lead or LBE as the primary coolant. Benefits of using lead or LBE as a coolant include:

- Compared to liquid sodium, both are “relatively inert” when they interact with air and water [143].
    - This material property combined with operating near atmospheric pressure means concerns surrounding loss of coolant casualties are greatly reduced.
    - This material property also eliminates the need for an intermediate cooling loop.
- Both have a relatively low melting point (125 °C (or 257 °F) for LBE, and 328 °C (or 622 °F) for lead), so less energy is needed during shutdowns to keep these coolants in liquid form [140].
- In addition to the low melting point, these coolants have high boiling points (1670 °C (or 3,038 °F) for LBE, and 1,749 °C (or 3,180 °F) for lead) [140]. With typical operating temperatures around approximately 500-800 °C, concerns surrounding coolant boiling are effectively eliminated [126].

- While various fuel oxides can be used, these coolants have a higher density than all options [144]. Therefore, a core catcher is not required to contain the molten fuel and cladding during a potential meltdown [144].
- Related to the reactor's fast neutron population, these coolants have a low probability for both neutron absorption and moderation [144].
- Related to gamma radiation, the lead-based coolant can provide shielding effects.
- Natural circulation can be used for decay heat removal [126].

With these benefits in mind, disadvantages of this coolant include:

- One of the main hurdles with using lead or LBE as a coolant are their high corrosive properties with typically used structural steel alloys [143]. Therefore, corrosion is often cited as a major concern that must be mitigated within LFRs.
- Like Sodium, these coolants' opaqueness can create challenges related to inspections and maintenance [143].
- The coolants' high density also results in greater mass and weight required within the primary system (which is disadvantageous for the NPMS) [143].
    - Related to the NPMS, an increased core mass combined with the core's placement onboard the ship also has the potential to impact the ship's stability and seakeeping performance.

Overall LFRs continued to validate LMRs as a potential option for the NPMS. With respect to LFRs specifically, the use of lead or LBE as coolant provides noteworthy benefits compared to liquid sodium that would make it a desirable candidate so long as the associated disadvantages could be properly mitigated. On the topic of the noted disadvantages, LFRs have been analyzed for a noteworthy period of time thus far, and multiple solutions have been presented to mitigate this ARD's specific concerns [144].

5.8 Supercritical Water-Cooled Reactor

The Supercritical Water-Cooled Reactor (SCWR) are high-temperature and high-pressure (374 °C (or 705.2 °F), and 22.1 MPa (or 3205 psi)) PWRs which utilize either light or heavy water as the coolant and moderator [145]. The SCWR was developed to combine benefits from existing

PWR technology, BWR technology and supercritical steam system technology which is present within current fossil-fuel based power plants [126]. A diagram of a SCWR is shown in the figure below:

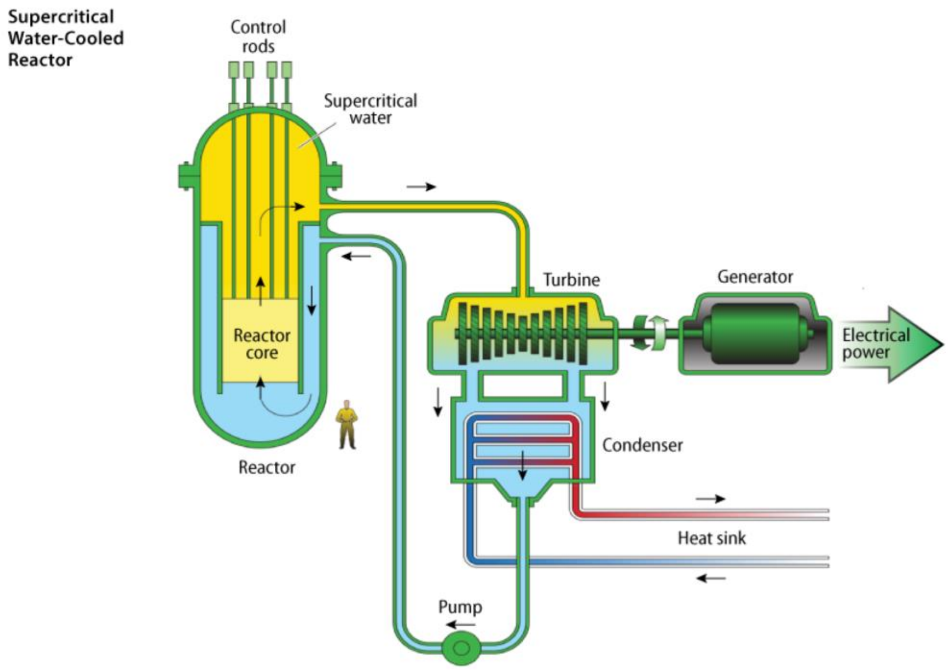


Figure 59: SCWR Design Overview [108]

A key benefit which can be seen within Figure 59 is the overall simplicity of the system's design. Since supercritical steam directly leaves the reactor and flows through the turbine generator, the need for a steam generator and secondary loop is eliminated. By using supercritical steam, SCWRs are also able to achieve higher thermal efficiencies (approximately 44% compared to PWR's current 34-36%) [145].

However, SCWR progress thus far has seemed mainly conceptual, and examples of real-world operations are low [145]. Additionally, passive safety system validation was listed as an ongoing area of research, and the main pre-conceptual plant designs have power ratings from 1,000 MWe to 1,700 MWe [145]. For this reason, SCWRs were the least likely candidate for the NPMS.

5.9 Reactor Technology Selection

In evaluating the possible ARDs for the NPMS, each option had its respective benefits and drawback. Therefore, each technology and its system-specific features were reviewed with the NPMS' design philosophy, basic requirements and desirable features in mind. Current and projected technological readiness also played a large role in the final selection to increase the NPMS' ability to assist with reducing GHG emissions in accordance with the IMO's goals, and also to promote the potential for commercialization and profitability on a sooner timeline (which is advantageous for the commercial shipping industry).

After all technologies were reviewed, they were ranked in terms of most to least recommended for implementation onboard the NPMS, and the results of that ranking was as follows:

Final NPMS Reactor Technology Ranking and Recommendation		
Recommendation Ranking	**Reactor Technology**	**Justification**
1	SFR	High government support. High private sector support. Closed fuel cycle. High previous operation experience. High international interest. Low-pressure operation. Well sized initial power ratings.
1	MSFR	Moderate government support. High private sector support. High research and demonstration. Good fuel cycle control. Low-pressure operation. High safety feature implementation. Simplified design.
1	LCFR	High research and demonstration. Closed fuel cycle. High international interest. Low-pressure operation. High safety feature implementation. Well sized initial power ratings.
2	VHTR	High government support. Moderate private sector support. Moderate international interest. High-pressure operation. Moderately high initial power ratings. Multiple use-cases.

2	GCFR	High international interest. No previous operation experience. High-pressure operation. Well sized initial power rating. Simplified design.
3	AHTR	Low government support. No previous operation experience. Low technological readiness. Very high initial power ratings.
3	SCWR	Low government support. Low previous operation experience. Low technological readiness. High-pressure operation. Very high initial power ratings.

Table 11: Final NPMS Reactor Technology Ranking and Recommendation

As seen in the table above, liquid metal fast reactors were ranked highest followed by gas-cooled reactors. The lowest ranked reactors were not as strongly recommended mainly for their low technological readiness. Power rating also played a significant role throughout the selection process to avoid modifying or redesigning the reactor to fit the NPMS' power requirement. Additionally, the various types of liquid metal fast reactors provided multiple options at the desired power rating for the NPMS, so future selection could be based upon whichever technology progresses most successfully.

6.0 Conclusions and Recommendation

6.1 Conclusions

If the marine shipping industry is to tackle climate change and reduce GHG emissions within an impactful timeline, alternative power sources are a necessity onboard ships. To this end, container ships have proven an effective implementation platform for nuclear power. In evaluating the alternative power options, nuclear power is one of the few sources which provides:

- Complete elimination of carbon emissions.
- Sufficient technological maturity needed to meet the necessary level of carbon elimination within the reduced timeline.
- A vast history of research ventures, demonstrations, commercial operations and marine power and propulsion applications.

In addition to nuclear power's existing technological maturity, the international Gen IV initiative has motivated further progress throughout the last two decades to develop innovate reactor designs which address the issues and concerns which lead to the nuclear power industry's decline in the latter half of the twentieth century. As a result, these newer designs are safer, more economically viable and prioritize fuel cycle management from the onset of the reactor's design phase.

As previously mentioned, there is a proven history of nuclear power utilization for marine propulsion within naval applications and previous commercial ships, and to further encourage future commercial nuclear-powered uses, significant research has been conducted outside of this project into the various details and feasibility associated with nuclear-powered merchant ships. Considering the recent developments into new reactor technologies, this project aimed to contribute to that established body of work by evaluating the specific feasibility of Gen IV ARDs onboard container ships. Through this evaluation, multiple observations related to the overall approaches surrounding nuclear power indicated a NPMS had high potential to be well received by the international community, and these observations included:

- Regulatory bodies are actively evolving to better support the commercialization of new reactor technology.
- Governments have both previously and are projected to further invest heavily into the continued research and development of ARDs to promote their viability as future energy solutions.
- Private sector interest into ARD advancements has been consistently high, and to that end, strong partnerships have been established between private companies and the various national laboratories.
- Similar trends are seen internationally, and these similar trends reflected within other countries indicates the global community has the potential to strongly support the NPMS as an energy solution within the maritime commercial shipping industry.

Therefore, ARDs were evaluated using NMPS-specific requirements and desired features, and in general, liquid metal reactors ranked highest as the best fit for this platform due to:

- An abundance of previous uses and successful applications.
- Generally high government support across the specific designs.
- High interest and substantial research efforts both domestically and internationally.
- Consideration for initial fuel availability and later fuel waste management using recycled fuel materials and a closed fuel cycle.
- High passive safety and overall increased safety through measures such as low-pressure operation.
- Well sized power ratings for application onboard a container ship (i.e., 50-300 MWe).

For all these reasons, liquid metal reactors were ranked highest within this project's recommendations, and SFRs received the highest recommendation.

Moving forward, the biggest hurdles identified which much be overcome to implement the NPME were:

- For these ARDs to be installed onboard the NPMS, they must continue to progress and move through the necessary research, validation and certification stages within a reasonable timeframe. While recent trends indicate these milestones will likely be achieve, the NPMS' successful implementation depends upon current stakeholders within the Gen IV research and development field to remain on track and successfully develop these technologies within a usable timeframe.

- Regardless of the best possible NPMS solution, this concept cannot move forward without support from the maritime commercial shipping industry. Therefore, ship builders, owners and operators must overcome any remaining reluctance surrounding this idea and begin to consider its feasibility if the NPMS is ever to become a real-world solution.
- As previously discussed, port access was frequently recognized as a major logistic concern which could highly impact the NPMS' profitability and utilization capabilities. Therefore, this issue must be sufficiently addressed through design considerations and foreign relations if the NPMS is to achieve its full potential and become commercially viable.

If all these concerns are addressed, NPMS could drastically reduce carbon emissions and revolutionize the commercial maritime shipping industry.

6.2 Recommendations for Future Research

Having established the NPMS' recommended reactor concept, the following areas represent opportunities for future research:

Further validation of the reactor concept. Equipped with the recommended ARDs, deeper analysis could be conducted into the anticipated timeline and remaining specific milestones needed to bring the selected reactor technology to market. Additionally, the technology could be evaluated further to identify any modifications that would be needed to adapt it to the ship environment.

Further technical validation onboard the NPMS. Multiple aspects of technical validation could be applied when combining the recommended ARD with the container ship, and those analyses are as follows:

- Within the NPMS, the space and weight required to accommodate the ARD must be evaluated to compare it to the container ship's current configuration. In doing so, it is also possible that the nuclear system will require less space, so more room onboard can be allotted to the ship's cargo capacity.

- Related to space utilization onboard the NPMS, it was anticipated that the nuclear reactor would be part of an electrical drive system to increase flexibility within the engine room layout and allow the reactor to be placed as close to the center of the ship as possible to reduce the effects of ship motions. Therefore, the engine room layout is not anticipated to be highly constrained, but it is another aspect of technical validation which would increase the NPMS' real-world viability.
- Also related to space allocation and arrangement, changes in the ship's stability and seakeeping properties should be analyzed to understand:
    - How the reactor responds to ship motion.
    - How the ship's motion performance is changed and impacted by the presence of the reactor.
- In better understanding the size and operational profile onboard the NPMS, it would also become possible to more accurately anticipate the specific manning requirements needed to operate and supervise the nuclear system. Understanding these manning requirements would also help project changes in the ship's operational costs.
- With additional onboard analysis, it would be possible to address concerns surrounding port access within the reactor's operational design. For example:
    - The reactor's shielding and safety measures during normal operation could be further validated to ensure that no additional design measures or operational changes are needed while pulling into and departing from port.
    - The reactor's power could be reduced within a certain proximity to shore to allow for slower speeds at a lower power output.
    - Auxiliary diesel systems (separate from emergency diesel systems) could be installed onboard to grant the ship port access at lower speeds without an operating reactor.
    - Completely novel approaches (such as the articulated tug barge system discussed in Section 2.7.2 National Reactor Innovation Center (NRIC) Challenges and Opportunities for the Development of Commercial Maritime Surface Vessel

Nuclear Propulsion (CMNP)) could be explored and potentially implemented to address port call concerns using entirely different methods.

Further economics analysis. As previously stated, the NPMS must provide an economically feasible solution with reasonable capital costs and either comparable or lower operating costs to the currently used conventional ships. With respect to a nuclear system, insurance and interest could also potentially impact the overall ship's cost Therefore, an economic model must be developed and validated to understand the financial space and predict the comparable cost of marine diesel at which point the NPMS achieves a breakeven condition.

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