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Challenges and Opportunities for the Development of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP)

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ACRONYMS

AGR	Advanced Gas Reactor
ARDP	Advanced Reactor Demonstration Program
CCS	Carbon capture and storage
CMNP	Commercial Maritime surface vessel Nuclear Propulsion
COSCO	China Ocean Shipping Company, Limited
DOE	Department of Energy
FPSO	Floating production storage and offloading
HFO	Heavy fuel oil
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
INL	Idaho National Laboratory
ISPS	International Ship and Port Facility Security
ITAR	International Traffic in Arms Regulations
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MSR	Molten Salt Reactor
NR	U.S. Naval Nuclear Propulsion Program
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NS	Nuclear Ship
PWR	Pressurized water reactor
SMR	Small modular reactors
SOLAS	Safety of Life at Sea
TEU	Twenty-foot equivalent units
TRISO	Tristructural isotropic
USCG	U.S. Coast Guard

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1. INTRODUCTION

Maritime transport and trade are currently responsible for nearly 1 billion metric tons of CO2 emissions annually, representing 3% of global greenhouse gas emissions.[a] While maritime shipping is acknowledged as the most efficient carrier of goods in terms of its costs and carbon intensity, the sector relies overwhelmingly on the use of heavy fuel oil (HFO). Currently, this fuel source is unmatched in terms of its global availability, safety, security of supply, price, and energy density. Combined, these characteristics are responsible for the outsized contribution of the sector to the global economy: roughly 90% of all transported goods spend time at sea.[b]

As the world rises to the challenge of addressing climate change, the maritime sector is increasingly concerned with how it will meet looming emissions reduction targets. The International Maritime Organization (IMO)—a United Nations agency responsible for regulating shipping—is expected to adopt a 2050 target of reducing total carbon emissions from international shipping by at least 50% compared to 2008 levels.[c]

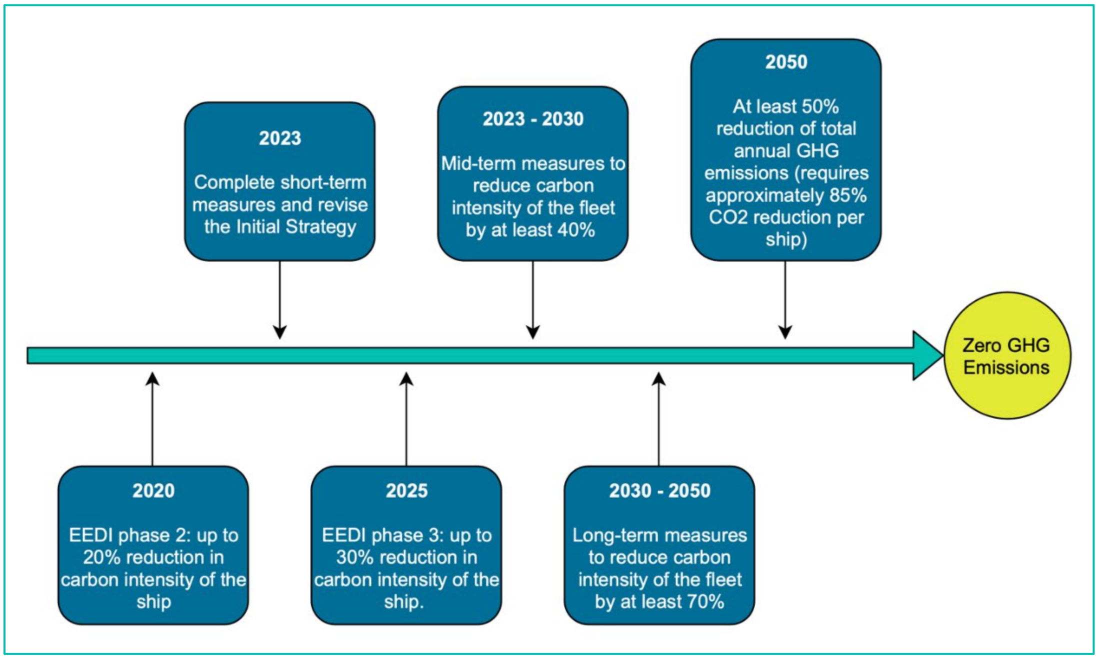

Figure 1. IMO action to reduce greenhouse gas emissions from International Shipping (From: IMO[c]).

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[a] Npr.org. 2021. “Shipping industry is pressured to cut pollution caused by merchant fleet.” Accessed November 8, 2022 https://www.npr.org/2021/12/01/1060382176/shipping-industry-is-pressured-to-cut-pollution-caused-by-merchant-fleet

[b] Npr.org. 2021. “Shipping industry is pressured to cut pollution caused by merchant fleet.” Accessed November 8, 2022 https://www.npr.org/2021/12/01/1060382176/shipping-industry-is-pressured-to-cut-pollution-caused-by-merchant-fleet

[c] IMO.org. 2019. “Initial IMO GHG Strategy.” Hot Topics. Accessed June 25, 2021. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

To put that number in perspective, 20% of the global fleet – roughly 17,000 ships – emits approximately 80% of the emissions from shipping transport. Between 70 and 80% of the sector's emissions come from container ships, bulk carriers, and tankers.[d] While the first steps toward addressing these emissions are already underway in the form of improving operational efficiencies, ship owners and operators are preparing for an industry-wide overhaul in the way that vessels are powered.

This overhaul is approaching rapidly. The lifetime for most commercial vessels is between 20 and 30 years, which means that many constructed in the next 5 to 10 years will need to be compliant with 2050 regulations. This reality is putting pressure on the sector to identify and pursue solutions this decade. The adoption of nuclear propulsion is a proven solution that is being proposed.

In the wake of World War II, the U.S. Navy—led by Admiral Hyman G. Rickover—successfully deployed nuclear power reactors as a propulsion technology for naval vessels. Commercial reactor technologies were developed soon after for use on land for civilian purposes. Today, there is growing interest in using these land-based commercial reactor technologies for commercial shipping purposes.

Several major factors are responsible for this interest. These include IMO regulations, changing attitudes toward commercial nuclear power in the face of climate change, multiple floating commercial nuclear power plant technologies being developed around the world, and the push within the United States to demonstrate and commercialize multiple advanced nuclear technologies by the end of this decade. Increased interest in nuclear power is also being driven by the absence of other clear solutions to support decarbonization goals in the maritime sector.

Over the past 2 years, renewed concerns around energy security and the continued focus on addressing climate change have contributed to increased support of nuclear power and broader interest in its diverse applications, including for maritime uses. Several countries are moving forward with actions that contribute to the evolution and development of maritime reactors. This includes Russia who contracted with the Chinese shipyard Wison in 2021 to build the hulls for two new floating nuclear power plants[e] as well as South Korea, where the Korea Atomic Energy Research Institute (KAERI) and Samsung Heavy Industries are now cooperating to develop a molten salt reactor for marine propulsion and floating nuclear power plants.[f] In the U.S., the Department of Energy has issued a number of awards to support research and demonstration of a range of advanced reactor technologies for maritime uses.[g] [h] Challenges for the development of advanced reactors have also transformed, which include securing a domestic fuel supply in the wake of Russia's invasion of Ukraine and building regulatory confidence in new reactor technologies that will be used in many new markets and configurations for the first time. Overall, advanced nuclear is enjoying growing support but with this comes increased attention: the ball is firmly in the industry's court to deliver revolutionary products for this century.

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[d] Corepower.energy. 2022. "Introduction to Advanced Commercial Nuclear for Maritime." Section 3: The Global Fleet. Accessed November 8, 2022. https://corepower.energy/mnag

[e] Upstreamonline.com. 2021. "Wison to build nuclear power floaters for Russia" Accessed November 8, 2022. https://www.upstreamonline.com/rigs-and-vessels/wison-to-build-nuclear-power-floaters-for-russia/2-1-1068362

[f] World-nuclear-news.org. 2021. "Korean collaboration to research marine SMR" Accessed November 8, 2022. https://www.world-nuclear-news.org/Articles/Korean-collaboration-to-research-marine-SMR

[g] Neup.inl.gov. 2022. "Integrated Thermal-Electric Energy Management of All-Electric Ship with Advanced Nuclear Reactors" Accessed November 8, 2022. https://neup.inl.gov/FY22%20Abstracts/CFA-22-26915_TechnicalAbstract_2022CFATechnicalAbstractCFA-22-26915.pdf

[h] Maritime-executive.com. 2022. "DOE and ABS Launch New Studies on Nuclear Energy for Commercial Ships" Accessed November 8, 2022. https://www.maritime-executive.com/article/doe-and-abs-launch-new-studies-on-nuclear-energy-for-commercial-ships

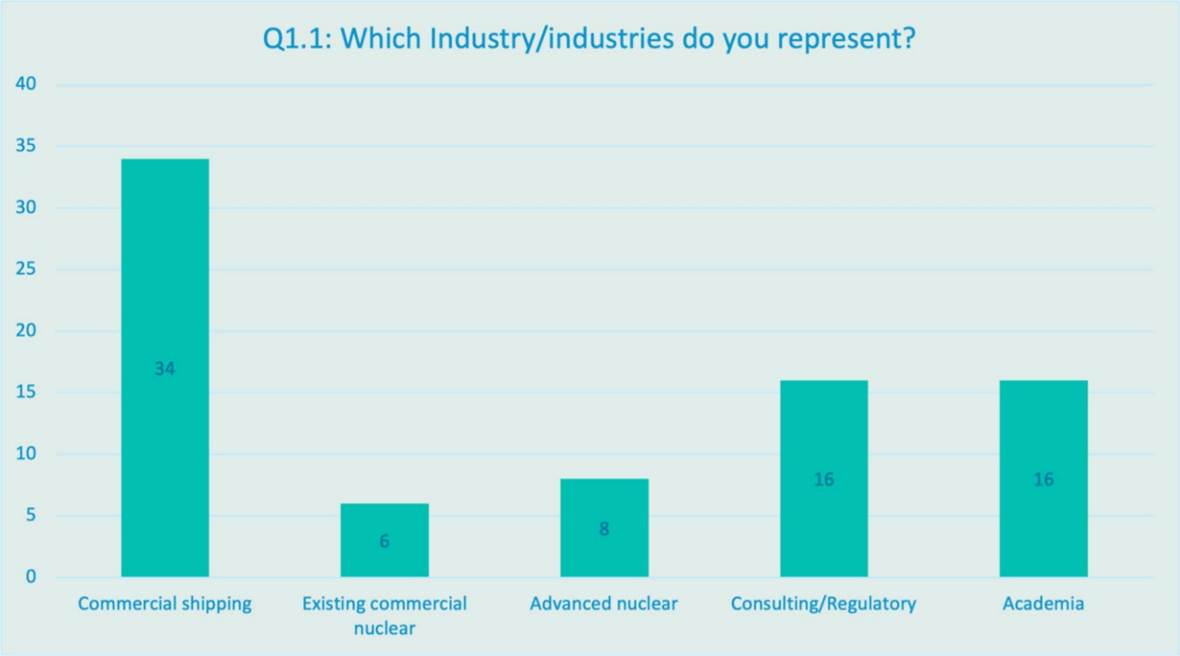
1.1 The National Reactor Innovation Center and the Design of this Research

The National Reactor Innovation Center (NRIC) is leading the push to demonstrate advanced reactors in the United States. Established by the U.S. Department of Energy (DOE) in August 2019, NRIC is designed to accelerate the demonstration and deployment of advanced nuclear reactors. NRIC is a national program led by Idaho National Laboratory (INL) that enables collaborators to harness the world-class capabilities of the U.S. National Laboratory System. NRIC is designed to bridge the gap between research, development, and the energy marketplace to help convert some of the U.S.'s most promising advanced nuclear concepts into commercial applications as soon as 2030. To achieve this bold vision, NRIC is partnering with the U.S. private sector, national labs, government agencies, and regulators to decrease the risks associated with new technology deployment and provide access to capabilities, facilities, and tools essential to demonstration.

NRIC researched and wrote this report to identify and examine barriers to adopting this technology, and gauge perceptions of how those barriers might be addressed. The report also strengthens partnerships NRIC is building to support the continued investigation of use cases for advanced nuclear technology within the maritime arena.

This report incorporates the input of 65 experts and industry representatives from the maritime shipping and nuclear sectors, with 50 and 24% representing upper and middle management roles, respectively. Thirty-five participants identified themselves as representing the maritime industry, 10 represented the nuclear energy industry, and 15 represented both industries. In five cases, groups of two participants answered together on behalf of the company or organization they represented. Their feedback was treated as an individual response.

Thank you to all of those who participated.



Input was recorded during interviews in which participants responded to and commented on a survey that required quantitative and qualitative responses. The survey was divided into two sections that addressed barriers and opportunities for the development of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP). An additional section was included at the end for advanced reactor designers, vendors, or affiliates to discuss their progress toward developing a CMNP technology, as well as the capabilities that a demonstration platform like NRIC could provide to benefit their development pathway. The survey can be found in Appendix I.

The first half of this report is written in a way that groups specific challenges together that in the survey are treated as separate. These groups of issues are listed below. Each section also begins with numbers on a range from 1 to 5 that represent the average scores given by survey participants. For the challenges section, participants were asked to score each specific issue based on how large a barrier it is perceived to be for the development of CMNP (with 5 representing the largest barriers). For the opportunities section, participants were asked to score each specific issue based on how much of a driver each issue is toward the development of CMNP (with 5 representing the largest drivers). “Total” scores represent the average scores of all participants, “nuclear” represents all participants with nuclear experience plus those who designated experience in both sectors, and “maritime” represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both “nuclear” and “maritime” scores.

- **Technology:** Nuclear Reactor Technology, Nuclear Fuel Technology, Reactor-Ship Interface Technology
- **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
- **Logistics:** Procuring Sufficient Nuclear Fuel, Need for Refueling, Nuclear Waste Disposal, Security, Adequate Number of Trained Personnel, Public Safety, Vessel Safety
- **Economics:** Economics, Insurance/Liability
- **Public Opposition**

Throughout the process of interviewing experts for this research, two important themes emerged that will be explored in more detail throughout the report:

1. When participants were familiar with the differences between conventional pressurized water reactor (PWR) technologies and proposed advanced reactor technologies, their responses diverged based on which technology they were speaking to. This observation is closely related to the second theme.
2. It seems highly unlikely that the "Navy model" could be used for commercial shipping. That is, adapting U.S. Navy technology, training, and protocols to a merchant setting would be challenging for reasons related to classified information, costs, and international diplomacy. As one participant formerly associated with the U.S. Naval Nuclear Propulsion Program (NR) summarized: "Technically this is possible, economically it's expensive, and politically it's really tough." Additionally, there are key differences between the operational profiles of merchant and naval vessels that suggest a CMNP technology would need to be drastically different from a naval technology. This includes factors like the percentage of a commercial vessel's lifetime spent in transit and the power demand throughout that transit. The average container vessel, for example, spends far less time at port than the average aircraft carrier.

2. CHALLENGES

2.1 Challenges: Technology

Table 1: Technological Challenges.[i]

Individual Issues Related to CMNP Technology	Total	Nuclear participants	Maritime participants
Nuclear Reactor Technology	3.05	3.06	3.12
Reactor-Ship Interface Technology	2.61	2.58	2.64
Nuclear Fuel Technology	2.79	2.90	2.96

The technology development required to commercialize CMNP was largely seen as manageable. Many respondents pointed out that the experience and track record of the world's nuclear navies demonstrated that the technology is feasible. As one respondent pointed out in reference to NASA's Kilopower project, "If you can develop a lunar reactor then you can definitely develop one for a ship." At the same time, many respondents also recognized that the success records of navies using PWR technologies will not directly translate to success with advanced reactors in a commercial setting. Successful demonstration of new reactor technologies will be a necessary first step.

Respondents identified many issues that would have to be considered during the design stage. Similar to terrestrial NPPs, a viable CMNP technology must consider cradle-to-grave issues including refueling and disposal. The reactor system would also have to be recoverable in the case of an accident while being designed to handle the routine conditions of a vessel at sea, including movements like pitching, swaying, and rolling. Fundamental questions like locating a core-catcher also come into question when considering scenarios in which a vessel capsizes. Reactor startup times would be an important factor as well.

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[i] Participants were asked to score each specific topic associated with the development of maritime nuclear technology based on how large a barrier they perceived it to be for commercializing CMNP, with "5" representing the largest barriers. As explained in section 1.1, "Total" scores represent the average scores provided by all survey participants, the "nuclear" column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and "maritime" represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both "nuclear" and "maritime" scores.

The answers to some of these questions could be fundamentally different when considering advanced reactor designs and some respondents made it clear that the scores they provided in their interviews would likely change for advanced reactors. Many respondents pointed out that the ongoing development of small modular reactors (SMRs) and microreactors had helped them to imagine the development of a CMNP product. This was as compared to conventional commercial nuclear power plants with sizes far too large (greater than 1000 MWe) to use onboard a ship. The abilities for the reactor to be small, segregated from the rest of the vessel, and able to be modularly "locked into" the ship were seen as essential characteristics. Due to lower source term, the small size of a reactor could also help mitigate the consequences of an accident where the reactor system was breached.

Developing a CMNP fuel technology was also seen as manageable. Several participants pointed out that the lifetime core technologies being designed for many terrestrial advanced reactors would be necessary in a maritime setting in order to reduce the frequency of refueling outages. In terms of different fuel types for CMNP, very few participants could speak to the relative advantages of using different advanced reactor fuels such as tristructural isotropic (TRISO) or molten salts. Of those that could speak to the relative advantages, they pointed out that current first-of-a-kind demonstrations of these fuels will provide regulatory predictability for their application.

Of those who could speak to these differences, TRISO was largely perceived as the most technically ready because of existing licensing activities for the technology as well as the experience gained through the DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification Program. Metal fuels were seen as second in line in terms of technical readiness because of the experience of reactors like Experimental Breeder Reactor-II (EBR-II). Liquid-fueled molten salt reactors (MSRs) were perceived as having the least amount of historical operational and demonstration experience.

An important perspective on nuclear fuel technologies came from the shipowners and shipbuilders, who generally felt that management of the fuel cycle should belong to an external entity. These two groups explained that the reactor technology and fuel should be treated as a black box from which they purchase power, similar to the common practice of leasing aircraft engines within the airline industry. Both participant groups largely agreed that the technology should be leased and that details including reactor and fuel technology, technology licensing, fuel supply, waste disposal, and security should all be dealt with by the reactor company within a bundled offering. Representatives from a major Korean shipyard explained that it is normal for shipyards and customers to discuss these types of details regarding fuel technologies when designing a ship; however, the details should already be worked out as part of the product offering.

Several advanced reactor designers, vendors, and affiliates currently developing CMNP who participated in this research are exploring a leasing model for their proposed technology. This would not be new for the industry and one participant highlighted the experience of *Radio Holland*, which in the past would contract out radio operators and equipment to Dutch ships. A more modern example of this arrangement comes from *Value Maritime*, a company producing modular scrubber technologies that can be temporarily installed on vessels.

Figure 2. The radio console of the 'Rotterdam' (radio call sign PHEG). (From: Radio Officers. Used with permission[j].)

In terms of reactor-ship interface technologies that facilitate controls between the ship's helm and power generator, few participants anticipated any large issues coming from CMNP. Especially when considering ships that use electric drives, CMNP was seen as a straightforward technology to "plug in."

One participant from a major container shipping company pointed out the importance of this interface in terms of scrapping the ship at the end of its lifetime. In their case, the interface would represent a vital barrier. They explained that it would be essential for the reactor module and containment to be separate so that radiological contamination did not escape into other parts of the ship and present additional decontamination costs prior to scrapping.

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[i] trafficlist.altervista.org. 2022. "Special MRD station – SS ROTTERDAM c/s PHEG." Accessed November 8, 2022. https://trafficlist.altervista.org/special-mrd-station-ss-rotterdam-cs-pheg/

2.2 Challenges: Licensing and Regulatory

Table 2: Licensing and Regulatory Challenges.[k]

Licensing + Regulatory	Total	Nuclear	Maritime
Technology Licensing	3.02	3.48	3.00
Limited Trade Routes	3.35	3.15	3.34
Limited Port Access	3.83	3.48	3.83
U.S. Government Approvals/Regulatory	4.03	4.10	3.97
Foreign Government Approvals/Regulatory	4.24	4.06	4.20
Deciding Under Which Flag the Ship will Sail	2.26	2.40	2.21
Jones Act/Cabotage Laws	1.94	2.21	1.80

Licensing and regulatory issues were seen as the largest hurdles for the development of CMNP. Foreign Government Approvals/Regulatory received the highest average score among all participants.

Licensing a CMNP technology in the U.S. would incorporate a broad range of complicated parameters because the reactor system would be mobile, moving, and operating simultaneously. It is also not clear what types of scenarios would need to be considered during licensing. While licensing could consider issues like collisions with other ships or structures, it is not clear how a regulator would consider other factors like security or piracy.

Individually, these issues are currently being explored by NRIC and the U.S. Nuclear Regulatory Commission (NRC) with regard to projects like the Department of Defense's proposed deployable microreactor (Project Portable Energy for Lasting Effects [PELE]) and, more specifically, the processes by which reactors with loaded cores could be transported.[l] Licensing experience is also expanding with advanced reactor startups like Oklo, X-Energy, TerraPower, and Kairos submitting or preparing to submit license applications for new fuel and reactor designs.

More research will need to be done to determine whether existing regulatory requirements and licensing pathways are appropriate for CMNP. A current topic of interest among those interested in maritime applications for reactors is the potential application of a "Manufacturing License" under Title 10 Part 52 of the U.S. Code of Federal Regulations (referred to as "10 CFR Part 52"). This type of license was awarded to a joint venture called *Offshore Power Systems* in 1982 to manufacture floating nuclear power plants, however the company was never successful in completing any plants.[m] Today, manufacturing licenses are being explored again for the mass production of land-based SMRs and microreactors.

Beyond licensing the technology, receiving approval within the U.S. to operate a CMNP system is seen as a significant challenge, largely because a regulatory framework does not exist and U.S. commercial maritime expertise is limited to the *NS Savannah* (Nuclear Ship Savannah), which operated between 1959

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[k] Participants were asked to score each specific topic associated with licensing and regulatory requirements based on how large a barrier they perceived it to be for commercializing CMNP, with "5" representing the largest barriers. As explained in section 1.1, "Total" scores represent the average scores provided by all survey participants, the "nuclear" column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and "maritime" represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both "nuclear" and "maritime" scores.

[l] Gain.inl.gov. 2019. "Key Regulatory Issues in Nuclear Microreactor Transport and Siting." Accessed November 8, 2022. https://gain.inl.gov/MicroreactorProgramTechnicalReports/Document-INL-EXT-19-55257.pdf

[m] Adensam, Elinor. 1982. "Notice of issuance of Manufacturing License ML-1." Nuclear Regulatory Federal Register Notices, December 17, 1982. (ML20070J219)

and 1971. Many participants familiar with and working on nuclear power technology licensing in the U.S. were confident[n] that a regulatory framework could be developed, but a larger issue that often came up was how to reconcile the different regulatory philosophies in the nuclear and maritime sectors. Commercializing this technology will depend first on the maritime community becoming comfortable with it.

The NRC is in the early stages of working with stakeholders and the public to develop 10 CFR Part 53, a new licensing framework for advanced nuclear reactors that is expected to be more adaptive to technological differences with designs by being "performance-based and risk-informed." This stands in contrast to the prescriptive licensing practices of the maritime industry, which is largely populated by small ship-owning companies that benefit from explicit rules that regulate the ships they order and operate. This keeps requirements clear and predictable without the need to hire certain competencies. Similarly, the most popular open registries where vessels are flagged (Panama, Liberia, Marshall Islands, etc.) are not perceived to have the competency to properly review a technology as complex as CMNP. Still, the industry is in the process of adopting increasingly complex digital technologies and more automation that, according to one U.S. Coast Guard (USCG) official, will eventually require new forms of credentialing and licensing for mariners. New credentialing practices could impact CMNP training.[o]

With respect to U.S. Federal approvals, delineating between "maritime" and "naval" technologies and assuring to regulators that their technology will be sufficiently proliferation-resistant, is perceived as a significant hurdle. If the technology falls within the scope of the U.S. Department of State's International Traffic in Arms Regulations (ITAR), the State Department essentially will have a veto in approving the export of the technology, hardware, and services.

By far, the largest barrier identified during this research was foreign (non-U.S.) government approvals and regulations. While the U.S. Navy largely relies on bilateral agreements that allow its nuclear-powered vessels to access over 150 ports around the world, most participants acknowledged that international regulatory approval for CMNP would have to come through the IMO. Over time, national maritime regulations have started to become standardized internationally in order to ensure harmonization. International approval was also seen by many participants as a requisite for success. One USCG official pointed out, "Any kind of technological improvement on shipping will have domestic and international implications. There's no chance for success of that technology without an agreement between domestic and international regulators."

Working with IMO to regulate the technology would help with access to ports and various territorial waters along key trade routes, but there is a lot of work to do. Today, there are currently no modern international laws for regulating CMNP, with the exception of Chapter 8 of the *International Convention for the Safety of Life at Sea* (SOLAS), which gives basic requirements for nuclear-powered ships and is particularly concerned with radiation hazards. There are additional international regulations that would impact a nuclear-powered vessel, including the International Ship and Port Facility Security Code (ISPS).[p]

While an international regulatory framework is currently lacking, there may be pieces available to borrow from other international bodies. The International Atomic Energy Agency (IAEA) has overseen a harmonized international regulatory structure for the transport of radioactive materials for roughly 60 years, known as SSR-6. National and local-level stakeholder engagement strategies for working with communities along those transportation routes could similarly be adapted.

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[n] Staff members from the U.S. Nuclear Regulatory Commission participated in this research as interviewees however their views are not official reflections of the NRC's stance on CMNP.

[o] Riotta, Chris. Fcw.com. September 12, 2022. "Maritime cybersecurity is front and center in Coast Guard reauthorization bill". Accessed November 8, 2022. https://fcw.com/security/2022/09/coast-guard-bill-looks-boost-maritime-cybersecurity/377020/

[p] Imo.org. 1974. "International Convention for the Safety of Life at Sea (SOLAS), 1974". Accessed November 8, 2022. https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

Engagement with the IMO would most likely begin with the request for an output from the Maritime Safety Committee. This application would require a justification for the need of a review, which would likely be based on carbon emissions reduction. While the IMO mostly agrees by consensus and is host to very little debate, it is hard to anticipate the politics that would take place surrounding the introduction of CMNP technologies. For example, movements to pass decarbonization targets at IMO have historically been challenged by oil-producing and developing countries.

While the IMO can help establish international standards for the adoption of CMNP, it is important to keep in mind that national governments still hold the final word on what they do and do not allow port access to. National administration changes or events that change public opinion with regard to nuclear power could undermine international protocols at key ports.

Limited port access and trade routes were considered lynchpin issues. Participants' views on these topics were largely organized into two groups: those who felt CMNP would need global access and those who felt it only needed acceptance at the busiest 20 to 30 international ports. The first group argued there would need to be nearly ubiquitous global access for ships using CMNP for the technology to be successful. Without global access, nuclear-powered vessels would be restricted to specific routes, which would affect a vessel's liquidity as well as its potential future value. For issues related to trade routes specifically, the costs of diverting a ship would need to be factored into transport costs, although those would primarily be measured in time as opposed to fuel consumption when considering a nuclear-powered vessel. The most contentious routes are expected to be major canals like the Panama and Suez and high-traffic regions like the Malacca Strait. However, multiple participants pointed out some of these routes are host to routine shipments of nuclear waste, which could provide some precedent for the passage of CMNP vessels.

The second camp related to limited port access and trade routes felt that port access would only need to be guaranteed at the busiest 20–25 ports in order for the technology to be successful. These ports are host to many fixed liner routes in which ships—primarily container ships—only travel between several set locations. This keeps the number of regions visited very low and is in contrast to tramp shipping, which involves visiting a wider range of ports on non-fixed routes and is primarily done by bulk carriers and tank ships. Liner container shipping specifically requires access to fewer ports but also introduces outsized risk if one of those ports becomes inaccessible. While liner container shipping relies on fewer ports, it still depends on a degree of operational flexibility within a ship owner's network and fleet. For example, the ability to swap vessels between different trade routes has been important during the COVID-19 pandemic. This flexibility could be reduced if certain vessels within a company's fleet could only sail on a specific subset of that company's routes.

Within the body of this CMNP research, an analysis was completed to examine the 50 largest global seaports based on the nuclear power experience of the countries where they are located. Of the top 20 ports, findings include:

- Two are located in the United States
- 9 are located in China
- 12 are located in countries that either have or are expected to develop naval propulsion
- 17 are located in countries with commercial nuclear power plants
- The U.S. Navy has called at port in Singapore and Port Klang, Malaysia – two of the three ports not in countries with commercial nuclear power plants. The third of these three ports is Tanjung Pelepas, Malaysia.

Using port call articles and other public information, this analysis also included the creation of a "CMNP Port Access Map" in order to provide a nation-level visualization of the experience that various countries have with commercial nuclear power and naval nuclear propulsion. Real-world acceptance of CMNP would most likely diverge significantly, meaning that this map does not offer an accurate depiction of international CMNP acceptance. However, this exercise provides a hint at the places that could become early adopters of the technology. Figure 3 shows the map followed by the scoring system used to color code it. Appendix II includes a full breakdown of the data and sources.

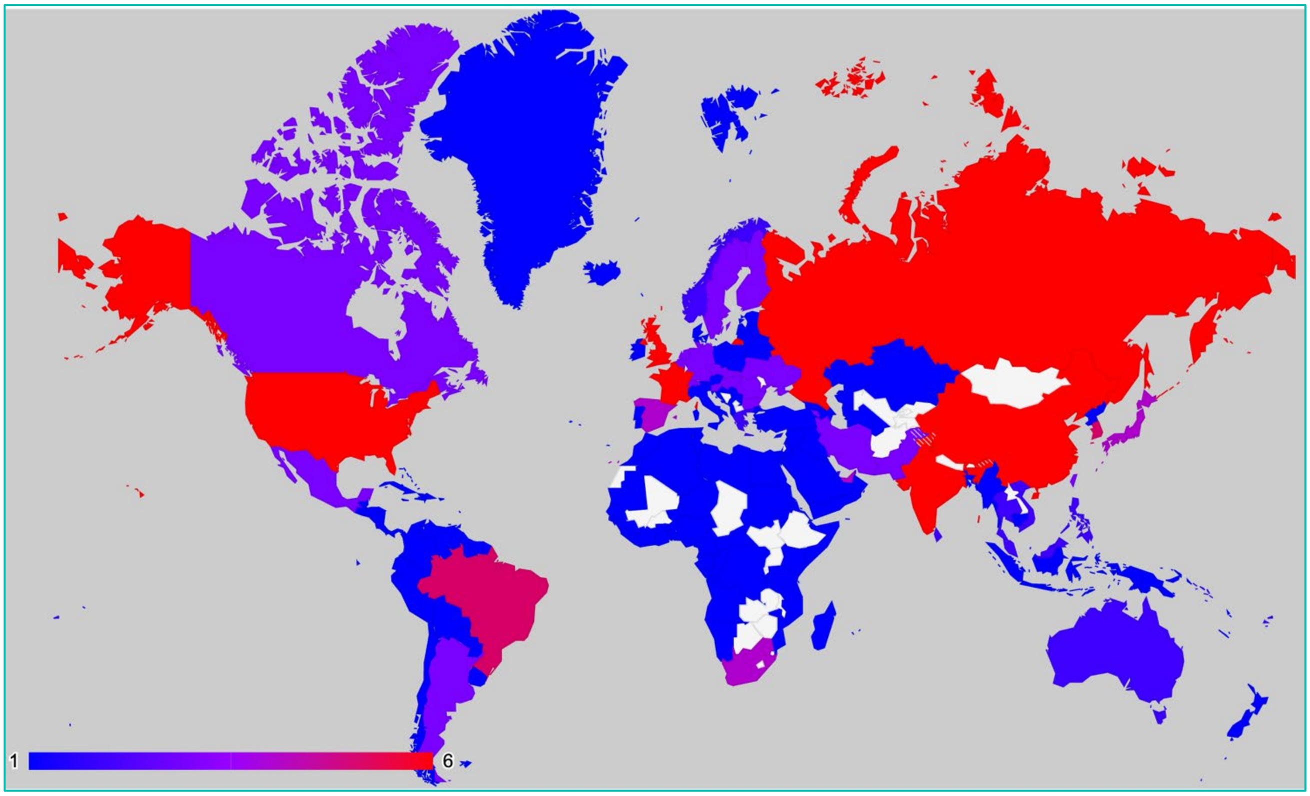

Figure 3. CMNP Port Access Map. Red countries have the most experience associated with commercial nuclear power and naval nuclear propulsion. Color scale examples: U.S. (6), Brazil (5), South Africa (4), Canada (3), Australia (2), Mongolia (1). A larger version of this map can be found at the end of Appendix II.

CMNP Port Access Map scale:

- 6: Country has a nuclear navy and at least one commercial nuclear power plant
- 5: Country plans to develop a nuclear navy and has at least one commercial nuclear power plant
- 4: Country allows access to nuclear-powered vessels and has at least one commercial nuclear power plant
- 3: Country has at least one commercial nuclear power plant but port access for nuclear-powered vessels has not been publicly documented
- 2: Country allows access to nuclear-powered vessels
- 1: Country does not allow port access or no public information exists regarding port access

The issue of port access was demonstrated most recently in November 2020 when the Russian nuclear-powered container ship *Sevmorput* lost a propeller blade off the coast of Angola. Because of its propulsion system it could not enter any ports in the region and had to be repaired offshore before returning to St. Petersburg.[q]

Port access issues were also highlighted by survey participants who represent the cruise industry. Depending on where it operates, the average cruise ship can visit between 100 and 200 ports during its lifetime. It is not uncommon for a 7-day cruise to include five different stops.

A number of participants suggested that port access specifically would not be an issue because of the exemplary track record of the U.S. Navy. Participants with naval experience largely disagreed and felt that access for naval vessels would not guarantee access for CMNP vessels. Simply maintaining existing bilateral agreements is precarious and one former Navy participant commented that “we have limits on how often we visit different ports so as not to wear out our welcome.”

Some participants suggested that this issue could be addressed through technological fixes. Using a dual-fuel system, for example, in which the nuclear propulsion component was turned off at port was one such proposal. Others suggested the use of articulated tug barge systems in which the entire cargo of a ship could be detached from the part of the ship that houses the controls and propulsion system.

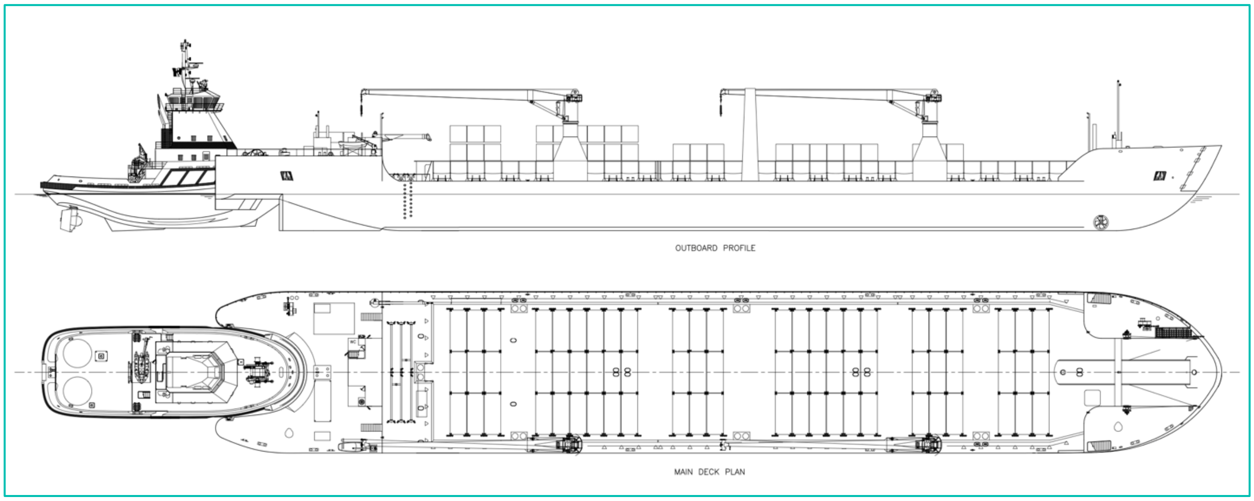

Figure 4. Articulated tug and barge systems. From: Robert Allan Ltd. Naval Architects & Marine Engineers. Used with permission.

Issues associated with flagging and cabotage were ranked low in importance. Most participants assumed that at least one registry would be available if CMNP was commercialized. The most common question, however, was whether the vessel would have to be flagged in the same country as the CMNP system was licensed.

While a ship’s flag is a primary cost-driver because of its impact on construction, fees, and staffing, section 27 of the Merchant Marine Act of 1920 (known as the “Jones Act”) was ranked lowest among all issues. The Jones Act is a cabotage law requiring that all goods transported by water between U.S. ports be carried on U.S.-flagged ships, constructed in the United States, owned by U.S. citizens, and crewed by U.S. citizens and U.S. permanent residents. Most participants found it unlikely that any vessels subject to the

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[q] thebarentsobserver.com. November 26, 2020. “Nuclear-powered carrier returns from South-Atlantic after propeller blade fell off”. Accessed November 8, 2022. https://thebarentsobserver.com/en/nuclear-safety/2020/11/nuclear-powered-carrier-returns-south-atlantic-after-breakage-newly-shifted-0

Jones Act would make economic sense to have CMNP installed onboard. Those who did see a potential application for CMNP on Jones Act vessels argued that the high costs of producing a Jones Act vessel could help to insulate the high capex associated with the CMNP system.

2.3 Challenges: Logistics

Table 3: Logistical Challenges.[r]

Logistics	Total	Nuclear	Maritime
Procuring Sufficient Nuclear Fuel	2.63	2.71	2.78
Need for Refueling	2.43	2.76	2.42
Nuclear Waste Disposal	3.65	3.37	3.84
Security	3.53	3.48	3.54
Adequate Number of Trained Personnel	2.96	2.60	3.12
Public Safety	3.07	2.78	3.16
Vessel Safety	3.09	2.88	3.19

Few participants felt that procuring sufficient supplies of nuclear fuel would present a challenge for the development of CMNP. Those who were more familiar with advanced reactor designs pointed out that supply chains for advanced reactor fuels are currently being built out. One example of this is the first round of awards within the DOE's Advanced Reactor Demonstration Program (ARDP) to TerraPower and X-Energy, whose applications included proposals for fuel fabrication.[s] Additionally, the Energy Act of 2020 included a section focused on high-assay low-enriched uranium (HALEU)—an important fuel source for many advanced reactor designs. Participants who were not familiar with the fuel demands of advanced reactors still felt confident that supply could match demand as it grew.[t]

It is important to point out that the interviews for this research were conducted before Russia's invasion of Ukraine in early 2022. This is a key issue for the nuclear power industry in western countries because Russia is currently one of the largest suppliers of enriched uranium on the global market. It is also one of the only countries with the capacity to produce HALEU, the specific fuel type that nearly all advanced reactor companies plan to use for their designs.[u] The US Nuclear Industry Council's 2021 *Advanced Nuclear Survey* found that the top-ranked issues for advanced reactor vendors included fuel qualification and fuel availability.[v] The issue is being addressed and the recently passed Inflation Reduction Act included

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[r] Participants were asked to score each specific topic associated with the anticipated logistics involved with maritime nuclear technology based on how large a barrier they perceived it to be for commercializing CMNP, with "5" representing the largest barriers. As explained in section 1.1, "Total" scores represent the average scores provided by all survey participants, the "nuclear" column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and "maritime" represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both "nuclear" and "maritime" scores.

[s] Clearpath.org. October 14th, 2020. "It's Happening… US to Build Two New Advanced Nuclear Reactors". Accessed November 8th, 2022. https://clearpath.org/our-take/its-happening-us-to-build-two-new-advanced-nuclear-reactors/

[t] Energy.senate.gov. 2020. "Energy Act of 2020 Section-by-Section". Accessed November 8, 2022. https://www.energy.senate.gov/services/files/32B4E9F4-F13A-44F6-A0CA-E10B3392D47A

[u] Reuters.com. October 20, 2022. "America's new nuclear power industry has a Russian problem" Accessed November 8, 2022. https://www.reuters.com/business/energy/americas-new-nuclear-power-industry-has-russian-problem-2022-10-20/

[v] Usnic.org. September 2, 2021 "USNIC Announces Results of 2021 Advanced Nuclear Survey." Accessed November 8, 2022. https://www.usnic.org/news/usnic-announces-results-of-2021-advanced-nuclear-survey

$700 million to develop the domestic infrastructure needed to produce HALEU at scale.[w] While it is difficult to say what the impact of this will be on future maritime reactors, it has quickly become a primary issue during 2022.

The need for refueling was scored low and most participants saw this not as a challenge but as a potential opportunity: in theory, fewer refuelings could enhance the operational and business models of a commercial vessel. Additionally, less refueling would reduce the risk of spills at port that can threaten public and environmental safety. However, many participants pointed out that for this topic to not create issues, refueling would need to be spaced out sufficiently so as not to significantly reduce the amount of time that a vessel could operate. One former Navy contractor said that the cost of refueling naval vessels is comprised not only of the time (measured in months) and money it takes to refuel the vessel, but also the cost of an interim replacement. Many participants suggested that refueling could take place during routine vessel safety surveys, some of which take place over roughly 5-year periods. Most participants familiar with refueling processes for land-based and naval reactors argued that any economical, proliferation-resistant CMNP technology would need to be developed such that it could be fueled for the life of the ship.

The issue of nuclear waste disposal represented one of the largest gaps between participants representing the two industries. When excluding participants who had experience in both sectors, the average score among maritime sector participants was 3.88, while nuclear sector participant scores averaged 2.9. Nuclear sector participants largely felt that nuclear waste disposal can be done safely and that this would be no more of an operational issue than it currently is for land-based plants. Maritime sector participants had more concerns that were mostly related to public perception. Many agreed that this would have to be a consideration within reactor lifecycle management that was taken care of by the reactor owner. Several participants suggested that the global nature of the maritime sector would increase the likelihood that at least one country would be willing to take responsibility for waste. However, a significant barrier would emerge if no countries were willing to take it.

An additional issue came up related to end-of-life scrapping. As mentioned earlier in this report, it would be essential that no radiological contamination escaped the CMNP system. Today, ship owners can receive up to $650/ton for scrapped material when recycling their vessels at the end of useful life.[x] According to one participant, “Green recycling” can bring that price down by around $100 per ton. Any radiologically contaminated materials would likely end up costing the ship owner instead.

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[w] Nuclearinnovationalliance.org. September 2022. “HALEU Provisions in the Inflation Reduction Act of 2022”. Accessed November 8, 2022. https://nuclearinnovationalliance.org/haleu-provisions-inflation-reduction-act-2022

[x] Go-shipping.net. 2022. “Demolition Market”. Accessed November 8, 2022. https://www.go-shipping.net/demolition-market

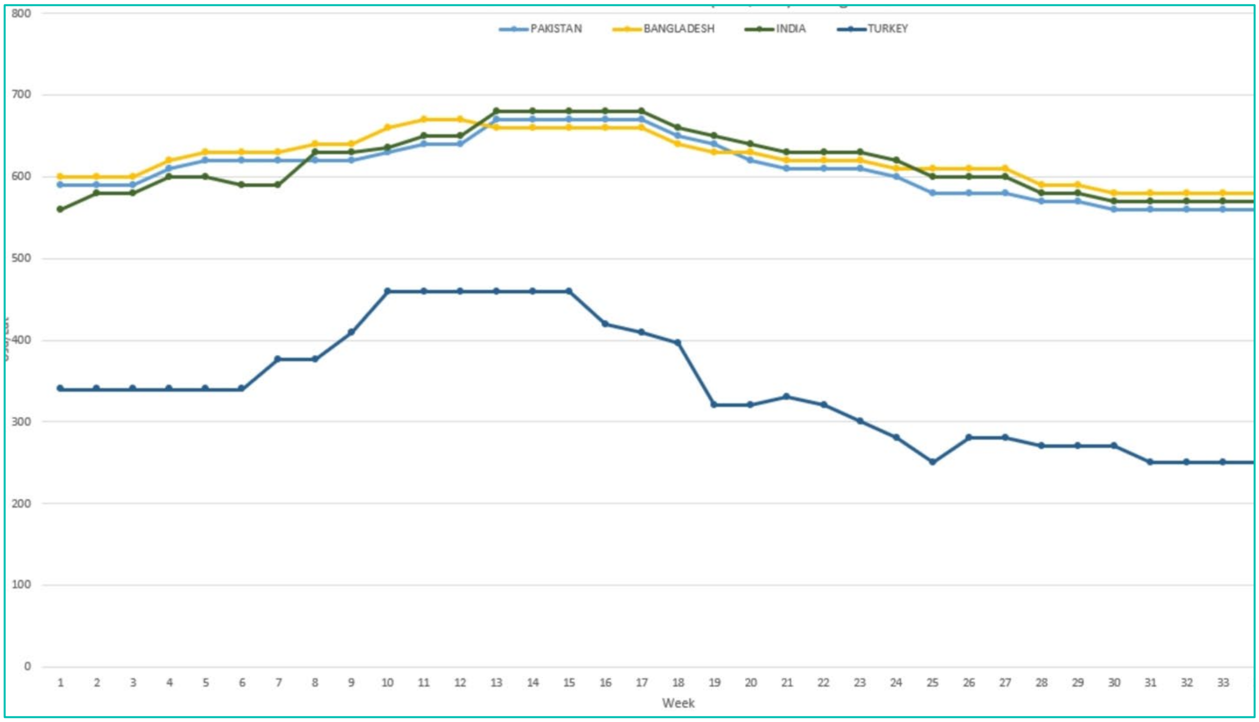

Figure 5. Average 2022 ship demolition prices (U.S. Dollars / Lightship Displacement Tonnage) From: Go-Shipping.[y]

When discussing personnel training for the operation of CMNP, nearly all participants agreed that the immersive instructional model and large crew sizes used by the U.S. Navy would be too expensive for a commercial setting. The goal for a CMNP system would be to have as few technicians on board as necessary and, ideally, for the technology to operate in a way that requires limited management. Some participants suggested the use of nuclear "batteries," which are reactors designed to regulate their own outputs and would only require personnel to provide routine maintenance as opposed to around-the-clock operation.

Although training programs do not currently exist for CMNP, most participants were confident that one which was sufficiently rigorous could be established during the time leading up to piloting the technology. Many assumed that a training program could be built out of existing training programs for terrestrial plant operators. Several participants pointed out that there are also synergies to capture from nearby industries, with one example being the training of mariners to run liquefied natural gas (LNG) or ammonia-powered engines by building on previous experience working on LNG or ammonia tankers. CMNP operators could similarly come from those who have experience transporting nuclear waste.

There was also a common belief that former Navy nuclear operators could be recruited for these roles. However, some participants acknowledged that crewing vessels or hiring support staff with former Navy nuclear experience may not be financially feasible in light of existing crewing trends. Overall, recruiting new talent did not appear to be a major barrier. One representative from a U.S. maritime college explained that environmental concerns related to climate, pollution, and marine stewardship are increasingly important to young cadets. A CMNP training program that led with those values would not have difficulty with recruiting.

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[y] Go Shipping S&P. 2022. "Demolition Market: Weekly Indicative Scrap Price Levels Worldwide, Week 41." Accessed November 8, 2022. https://www.go-shipping.net/demolition-market

Security concerns were ranked high among all participants as the threat of nuclear materials being accessed and used nefariously would exist for as long as a CMNP system was installed on a ship. Most participants agreed however that any potential threats seemed more perceived than actual: pirates that had boarded a CMNP vessel would make for a much more compelling news story than those on a conventionally fueled vessel, regardless of their capacity to actually inflict harm on the propulsion system. Many participants pointed out that there would be security on board and naval escorts in some regions, but that neither of these are new to the industry. Additionally, there are protocols from LNG tankers, hydrogen tankers, and nuclear waste transports that could be adopted. In the case of container vessels, the most effective proven way to deter pirate attacks has been to increase vessel speed, something that a CMNP system could easily provide. Still, most participants assumed a CMNP vessel would still require an above-average level of security by way of safeguards like special background checks for crews.

The largest issue associated with security came back to licensing and regulation. Although many potential threats could be minimized, government defense and security agencies would continue to hold a "massive veto" (as one former IMO participant put it) over the use of this technology. For example, a pirate attack could prove largely uneventful to the ship and crew while at the same time seriously damaging a bilateral agreement between the U.S. Navy and a foreign port.

Public safety and vessel safety associated with the use of CMNP were also seen as more perception than reality. Many pointed both to the decades of successful operation of nuclear propulsion by the U.S. Navy as well as the NRC's rigorous licensing process as proof that the technology is safe. It was also mentioned frequently that the potential for an event at the scale of Chernobyl or Fukushima would not be possible based simply on the fact that the CMNP system would incorporate a small modular reactor or microreactor and therefore be a fraction of the size of the Japanese plants. One participant suggested that in the case of a potential accident, a vessel could be designed to evacuate itself from a port (as opposed to the port evacuating from the vessel). Several participants from both the nuclear and maritime sectors believed that a CMNP system would actually *improve* public and vessel safety when compared to the use of HFO.

The unique challenge presented for a CMNP system was how to recover systems from sunken vessels. While this would represent a serious design and licensing consideration, several participants highlighted recovery of the Russian nuclear submarine *Kursk* as precedent for this type of an operation. It is important to note however that the *Kursk* was much lighter than many of the commercial ships used today, weighing roughly a tenth of a Maersk E-class container ship.

2.4 Challenges: Economics

Table 4: Economic Challenges.[z]

Economics	Total	Nuclear	Maritime
Economics	4.11	3.90	4.20
Insurance/Liability	3.55	3.65	3.49

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[z] Participants were asked to score each specific topic associated with the economics of maritime nuclear technology based on how large a barrier they perceived it to be for commercializing CMNP, with "5" representing the largest barriers. As explained in section 1.1, "Total" scores represent the average scores provided by all survey participants, the "nuclear" column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and "maritime" represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both "nuclear" and "maritime" scores.

Economics was scored the third highest barrier after *Foreign Government Approvals/Regulatory* and *Public Opposition*. Nearly all participants felt that the economics of a CMNP system could make sense because of small lifetime operational expenses, but that feasibility would depend largely on how the system was financed. Most participants expect the technology would come with high upfront capital expenses that prove too risky for the average shipowner. Several participants also suggested that additional costs would come from nuclear-specific compliance and required "premium" services like mariners, port engineers, and security that all had additional qualifications. One former Navy submarine squadron commander explained that half of the operations associated with these vessels was dedicated to maintenance.

Participants who were more optimistic about the economics of a CMNP system spoke to the innovations that could only be introduced by using advanced reactor technologies. Smaller sizes that increased available cargo space, the potential to sell power to ports through reverse cold-ironing, and factory production of modules paired with shipyard construction timelines were all mentioned. It is important to note that research into cost and budget overruns for terrestrial plants in the U.S. and Europe have identified the construction phase as the largest cost-driver, largely because construction is done on-site with the incorporation of some modular elements.[aa] A CMNP system installation would need to avoid this phase altogether by being standardized, factory manufactured, and installed "plug-and-play" style into an established vessel design. Substituting the construction phase with a shipyard installation phase has the potential to bring down capex, which would be important for the technology to achieve necessary economies of scale through volume. One executive from a leading financial advisory firm explained, "the economics [for CMNP] make sense, but the challenge is getting it to scale."

Still, services would need to be offered as a package. As one shipowner at a major tanker company noted: "There would need to be some bundling involved. For example, if a Korean shipyard made the ships with a 10-year fuel supply already loaded and a team of operators that came with the purchase, then we might be able to consider it."

Finally, many participants pointed out that the development timeline for getting a CMNP product to market is key. It is impossible to know if the technology would still be attractive in 10 to 15 years if other energy sources like hydrogen or ammonia solve fundamental challenges like fuel storage.

Access to insurance was not perceived to be a major barrier and most participants were certain that a CMNP vessel that could receive the necessary certifications from a class society would be able to find insurance. In fact, one representative of a major class society expressed that they were confident a pathway already exists. Examples of the type of complicated vessels the maritime industry already deals with include floating production storage and offloading (FPSO) units in the oil and gas sector. Multiple participants believed that insurance would be made more accessible if CMNP could be proven to have a superior risk profile to hydrogen or ammonia. It could also become a potential topic for discussion within the scope of the reauthorization of the Price-Anderson act, which is currently in place until the end of 2025.

Plenty of questions were still presented, however. Since the late 1950s, nuclear power plant operators in the U.S. have needed federal legislation (the Price-Anderson Act) to ensure that third-party nuclear liability insurance is available, and to channel claims into federal court.[bb] How this would impact a vessel at sea is not certain. Smaller advanced nuclear plants with smaller liabilities have the potential to be entirely privately insured. The risk of accidents at foreign ports would also be complicated—a liability that terrestrial nuclear plants built outside of the vendors' home countries already have to contend with. The

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[aa] lucidcatalyst.com. 2020. "The ETI Nuclear Cost Drivers Project: Summary Report." Accessed November 8, 2022. https://www.lucidcatalyst.com/the-eti-nuclear-cost-drivers

[bb] Nrc.gov. 2021. "The Price-Anderson Act: 2021 Report to Congress". Accessed November 8, 2022. https://www.nrc.gov/docs/ML2133/ML21335A064.pdf

first private insurance package for a CMNP vessel would also be difficult to quantify considering the unprecedented arrangement.

2.5 Challenges: Public Opposition

Table 5: Public Opposition Challenges.[cc]

Public Opposition	Total	Nuclear	Maritime
Public Opposition	4.23	3.94	4.33

Public opposition received the second-highest average score among all participants after *Foreign Government Approvals/Regulatory*. As a subgroup, maritime sector participants scored public opposition at 4.33—the highest average score given for any issue by either of the two subgroups (nuclear and maritime). Simply characterizing public opposition is challenging, but some examples from the past decade help to illustrate the impact public opposition has had on the development of CMNP.

In the years leading up to the 2011 Fukushima Daiichi nuclear disaster, multiple class societies and private companies undertook internal feasibility studies to explore the potential use of CMNP. The two most public of these studies were conducted by the Chinese shipping company China Ocean Shipping Company, Limited (COSCO)[dd] and classification society Lloyd's Register.[ee] [ff] Both were seemingly abandoned in the wake of Fukushima. In 2017, Russia was required to change the fueling location for its floating nuclear power plant *Akademik Lomonosov* after protests from the Norwegian government, which was concerned about the vessel sailing through Norway's waters.[gg]

For many participants, the "public" also included the maritime industry at large. As one shipbroker explained, "A lot of people need to get on board with this technology for it to outweigh public and industry perception issues." Many participants felt that resistance within the maritime industry was based on concerns about financing and cost amortization as well as perceptions of nuclear energy that are based on outdated technology. Among participants who were aware of advanced nuclear technologies, most agreed that the technology would have to be proven on land before it could be seriously considered at sea. This sentiment was also reflected in a recent report by Shell and Deloitte, titled *Decarbonising Shipping: All Hands on Deck*. "Interviewees indicated that many onshore sectors are also undergoing transitions in energy source and that decisions made on land will have major consequences for which fuel will be viable in shipping."[hh]

[cc] Participants were asked to score the impact of public opposition based on how large a barrier they perceived it to be for commercializing CMNP, with "5" representing the largest barriers. As explained in section 1.1, "Total" scores represent the average scores provided by all survey participants, the "nuclear" column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and "maritime" represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both "nuclear" and "maritime" scores.

[dd] Nextbigfuture.com. July 14, 2011. "Energy: China COSCO Suspended nuclear powered shipping study." Accessed November 8, 2022. https://www.nextbigfuture.com/2011/07/china-cosco-suspended-nuclear-powered.html

[ee] Seatrade Maritime News, March 27, 2014. "Just how viable is nuclear-powered shipping?". Accessed November 8, 2022. https://www.seatrade-maritime.com/asia/just-how-viable-nuclear-powered-shipping

[ff] Lr.org. January 19, 2021. "How can nuclear support shipping's route to zero-carbon?". Accessed November 8, 2022. https://www.lr.org/en/insights/articles/how-can-nuclear-support-shippings-route-to-zero-carbon/

[gg] thebarentsobserver.com. July 22, 2017. "After pressure from Norway, Rosatom says floating nuclear plant will be fueled in Murmansk." Accessed November 8, 2022. https://thebarentsobserver.com/en/industry-and-energy/2017/07/after-pressure-norway-rosatom-says-floating-nuclear-plant-will-be-fueled

[hh] Shell. 2020. "Decarbonising Shipping: All Hands on Deck, Industry Perspectives." Accessed November 8, 2022. https://www.shell.com/DecarbonisingShipping

Most participants fell into one camp that argued the public would need to be convinced of CMNP's safety for it to be successful. Two additional, but smaller, camps also emerged—one suggesting that the Navy's safety record with nuclear propulsion would demonstrate the success of this technology to the public. The third camp felt that public opposition would be manageable because the shipping industry and ports are largely out of sight for most people. This third camp received some pushback as other participants pointed out that many ports are still near population centers. One participant could also envision problems where consumers would not want to purchase items that had been transported on a vessel using CMNP.

Nearly all participants agreed that the increased importance being placed on addressing climate change is changing public attitudes about nuclear power. However, the general sentiment that advanced nuclear technology should be piloted on land first is supported by recent research. A recent master's thesis from the Technical University of Denmark, *A pre-feasibility Study of Molten Salt Reactor Technology in Ship Propulsion*, polled 195 people from the United States and European Union regarding their feelings about using MSR technology for commercial ship propulsion. This polling—in which 75% of participants were under the age of 30—found "a slightly negative change in the attitude toward nuclear power for marine applications compared to the general perception of nuclear power." Another interesting finding was that compared to survey respondents who had no experience in the shipping industry, "people connected to the industry [were] more resistant to the potential implantation of nuclear power as a ship propulsion system."[ii]

An important sector to watch with respect to public perception issues is the transport of LNG, as well as its use as a bunker fuel. Places where LNG terminals are built often encounter public opposition, both related to climate impacts and the immediate dangers of LNG tanker traffic. Despite these issues in ports, LNG has been well received as a fuel for cruise ships. Three executives from the cruise industry participated in this research and each expressed their surprise at the level of acceptance among their customers. They explained however that the switch from HFO to LNG is consistent with their product offering: cleaner burning fuels reduce the impact these vessels have on the destinations that they visit.

[ii] Knudesen, Rikke Louise Kjær. 2020. "*A pre-feasibility Study of Molten Salt Reactor Technology in Ship Propulsion*." Master's Thesis, Technical University of Denmark.

Figure 6. Cruise ships at the Port of Miami. From: flickr[ii].

2.6 Challenges: Other

During the interviews for this research, participants brought up several specific issues that did not fit into the above categories. These included political opposition at ports, identifying shipyards to construct CMNP vessels, additional complexities presented by passenger vessels, and industry engagement for technology piloting.

Multiple participants felt that political opposition to CMNP could become a barrier because of the proposed business model of a vessel that does not require routine bunkering. Ports that can no longer sell fuel to visiting ships could see a threat to a significant portion of their own business as well as the jobs associated with bunkering.

Many participants were unsure of where a CMNP vessel would be constructed. As most noted, ship building today is dominated by China, and although countries like South Korea and Japan are heavily involved in the ship building industry, popular opinion in those two countries toward nuclear is not favorable. There is also a long list of questions about how and where nuclear materials would be managed and installed.

Passenger ships, and cruise ships more specifically, provide an interesting application for CMNP because of these vessels' massive power demand and associated pollution streams. Today's *Oasis*-class cruise ships each have an installed power capacity of over 90 MW and the sector as a whole is moving toward using LNG as a fuel. However, many of the issues listed above are amplified by the number of

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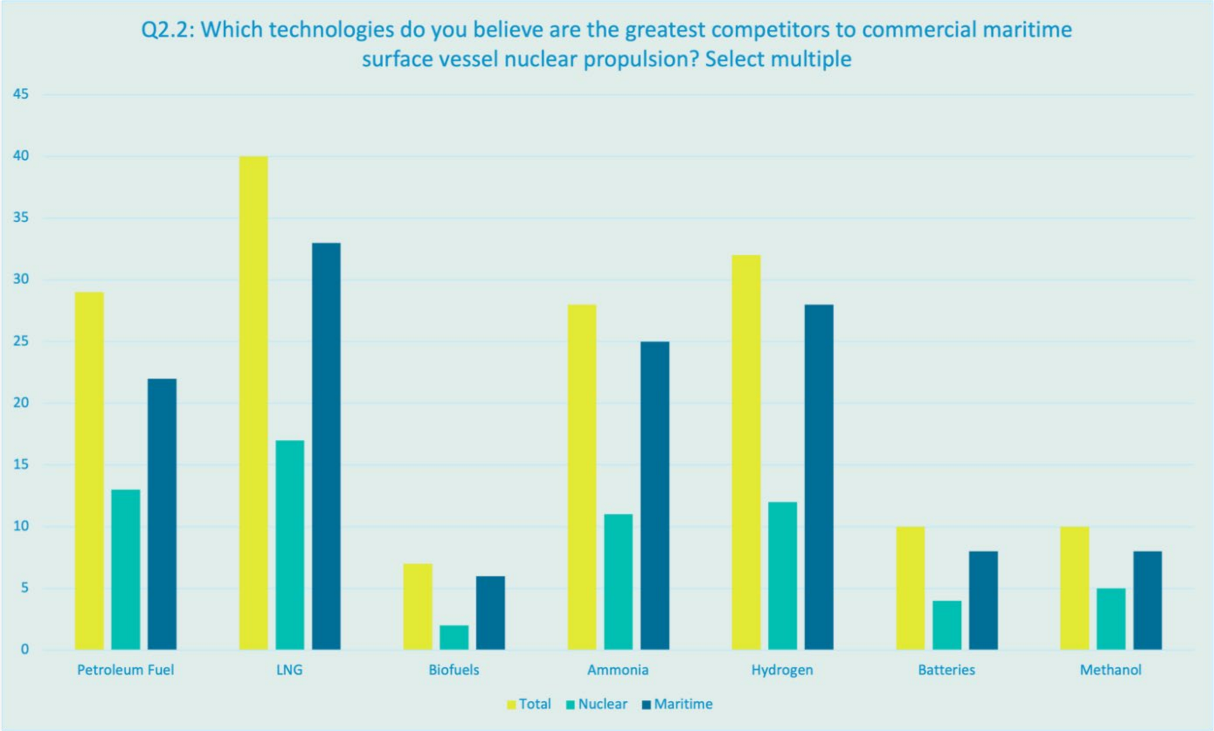
[ii] Photo by Corey Seeman. Attribution: NonCommercial-ShareAlike 2.0 Generic (CC BY-NC-SA 2.0). Link to license: https://creativecommons.org/licenses/by-nc-sa/2.0/legalcode.

passengers that travel on these ships—the same *Oasis*-class cruise ship can house over 6,000 people.[kk] In addition to safety concerns, many international voyages are governed by the national laws of countries different from the vessel's flag. The U.S. for example has protections for passengers that extend to certain voyages outside of the U.S., which could add further complexities to how a CMNP system is regulated on board a passenger vessel.

A lingering issue for any type of technology development is the necessary funding and resources for piloting that technology. The maritime industry is populated by small and midsize companies with minuscule R&D budgets. Maersk is the largest container shipping company in the world but with just more than 700 vessels, it still represents less than 1% of the global fleet. It is unlikely that the bulk of the money needed to develop and pilot a CMNP technology could come from industry.

2.7 Challenges: Competition

Participants were asked to comment on a list of fuels by sharing their thoughts on what they believe will be the largest competitors for CMNP. Considering the scale of industry-wide changes anticipated in the coming decades, answers included the participants' views on short-term and long-term trends in fuel use.



[kk] Web.archive.org. November 2008. "Creating the Incredible: Oasis of the seas & Allure of the seas". Accessed November 8, 2022. https://web.archive.org/web/20091229111539/http://www.cruiseweb.nl/images/oasisoftheseas/Brochure2.pdf

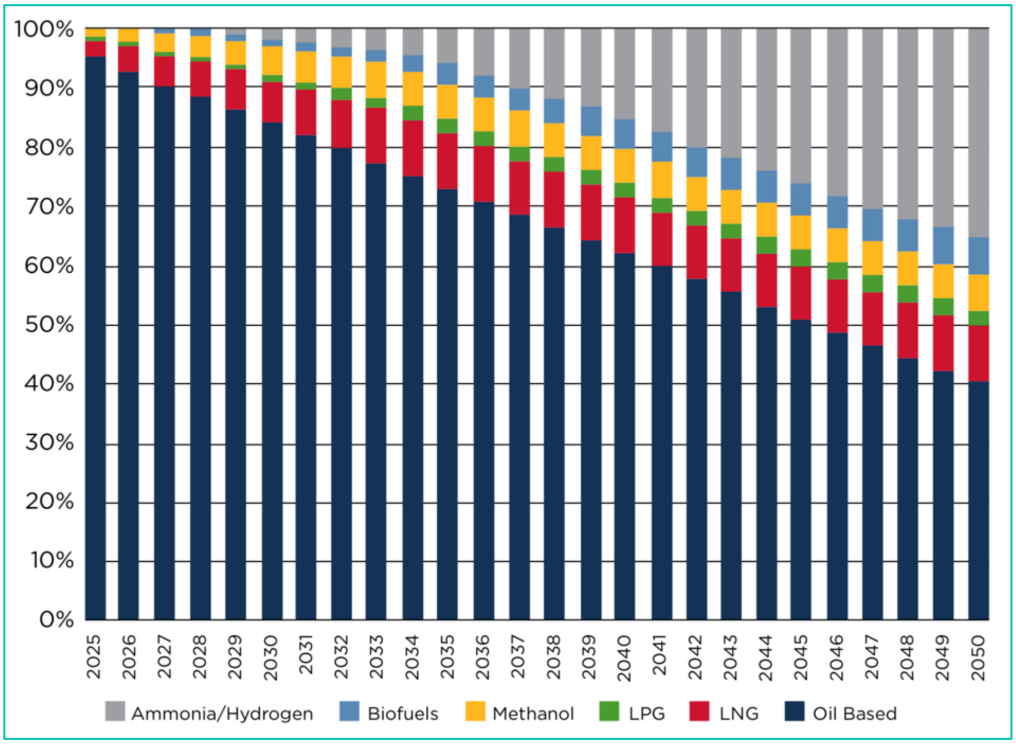


Figure 7. Projected marine fuel use to 2050. From: Pathways to Sustainable Shipping, American Bureau of Shipping, pg. 79.[ll]

In the short term, participants expected that petroleum fuels will continue to dominate the sector for at least the next decade. This was largely based on the industry's recent transition to low-sulfur fuels, which guarantees some short-term emissions compliance. In relation to most clean fuels including CMNP, participants largely felt that any progress toward developing new technology would be based on oil prices and a carbon tax. Some participants argued that HFO could become a long-term fuel if economic carbon capture and storage (CCS) technologies were developed that could pair well with it.

LNG was the most selected option among all participants who believe that it will be the primary transition fuel from HFO to a low- or zero-carbon fuel by midcentury. According to several participants representing classification societies, this is supported by a number of analyses that show a considerable increase in the number of orders for LNG-powered ships. So far, cleaner burning LNG has been successful in reducing local air pollution that comes with HFO. Some of the most significant challenges for LNG include lower energy density, associated system costs like the need for double-walled piping, and the availability of bunkering capacity worldwide. While some participants saw a potential for LNG to be synthetically produced and therefore made into a long-term solution, the costs of such an approach are unknown. This sentiment was the same for biofuels, which are prohibitively expensive to adopt at scale. While most participants could see these fuels being useful in the near term, few saw them as economic in the face of the IMO's proposed emissions targets.

Ammonia and hydrogen were seen as the most significant long-term competitors. Similar to LNG, the use of these fuels depends largely on bunkering capacity and production trends on land. Challenges for ammonia included the fuel's toxicity, difficulty of handling, and storage requirements. Storage challenges,

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[ll] Absinfo.eagle.org American Bureau of Shipping. 2020. "Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping." Accessed November 8, 2022. https://absinfo.eagle.org/acton/media/16130/setting-the-course-to-low-carbon-shipping-pathways-to-sustainable-shipping-outlook-ii-low

security of supply, and energy density were listed as fundamental issues for hydrogen to overcome before becoming competitive.

Batteries were not seen as a competitor in the near term or long term for deep sea shipping. Short sea applications were seen as the only viable use case for this technology based on limitations related to energy density and weight.

Methanol also scored low as a solution because of availability, price, and associated emissions. Benefits include a high boiling point and high water solubility if spilled, but most participants did not believe that the fuel would see increased use unless it was produced in an economical and carbon-free way. In the past year however, the fuel has received increase attention. Most notably, Maersk has submitted orders for methanol dual fueled vessels.[mm]

Participants also suggested some additional technologies that could see increased use within the sector. One of these is the class of wind power technologies that can be used to augment installed propulsion systems by reducing fuel consumption, some of which have been modeled to provide up to 80% reductions.[nn] Another suggestion was liquefied petroleum gas (LPG) for tankers that are dual fueled and can use their own boil-off, similar to how LNG tankers currently burn the boil-off of their cryogenic liquid methane cargo. Finally, many participants suggested the use of nuclear power not as a propulsion technology but as an energy source for producing synthetic fuels at port.

Two important trends that were brought up are the increased use of dual-fuel engines and electric drive motors. The former was introduced as a potential work-around for CMNP ships that had port access issues: a CMNP ship that had multiple fuel types on board could in theory use an alternative fuel when entering a harbor. The move toward electric drive propulsion was also seen as a potential benefit for nuclear, as a self-contained CMNP system that was built with modularity in mind could be “dropped into” a propulsion system that just requires an electricity source. Shell and Deloitte’s *Decarbonising Shipping* report also identified “flexible and modular designs” for ship propulsion as a priority for reducing emissions in the sector.

Finally, many participants pointed out that a lot will change this decade as CMNP technologies are developed. For example, 10 years might be enough time to produce solutions for handling ammonia, or to sufficiently lower the price of hydrogen. Nuclear power will have to become increasingly competitive in order to contend with advances in other technologies.

3. OPPORTUNITIES

3.1 Opportunities: Largest Drivers

The second half of the survey focused on the potential benefits for the maritime sector by adopting CMNP. The responses made it clear that addressing carbon emissions within this sector will lead to transformational changes in the industry. Using nuclear propulsion at scale would help to meet those goals while also introducing new practices that could fundamentally change the nature of maritime trade.

The first of these questions asked participants to score several drivers toward the adoption of CMNP in order to examine what would most motivate the sector to begin using this technology. CO2 emissions reductions were clearly ranked the highest among all participants and each of the two subgroups. While this driver scored highest, many respondents pointed out each of the topics listed are interconnected as they underpin the economics of managing a commercial vessel. However, this was built on the assumption

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[mm] maersk.com. March 10, 2022. “A.P. Moller - Maersk engages in strategic partnerships across the globe to scale green methanol production by 2025.” Accessed November 8, 2022. https://www.maersk.com/news/articles/2022/03/10/maersk-engages-in-strategic-partnerships-to-scale-green-methanol-production

[nn] Lr.org. November 18, 2020. “Wind power strengthens as decarbonisation drive becomes more urgent.” Accessed November 8, 2022. https://www.lr.org/en/insights/articles/wind-power-strengthens-as-decarbonisation-becomes-urgent/

shared by nearly all participants that emissions targets will be enforced through penalties like a potential carbon tax. Several participants suggested a future scenario in which IMO regulations were weak and CO2 emissions did *not* drive decisions related to fuel technologies. The majority of participants did not see this as likely, however.

Table 6: Opportunities.[oo]

Largest Drivers	Total	Nuclear	Maritime
CMNP has a strong business case	3.73	3.69	3.71
CO2 emissions restrictions	4.46	4.15	4.53
Non-carbon environmental benefits	3.67	3.54	3.71
Reduced refueling	3.08	3.19	3.18
Improved performance	3.13	3.33	3.05
Enhanced speed	2.82	2.85	2.83

3.1.1 Business Case

Most participants felt that while a business case does not yet exist for CMNP, one could be made. Many were familiar with the high capital expenses and low operational expenses associated with nuclear power technologies on land and felt confident that a CMNP technology could be designed so that the net costs of using one were compelling. Multiple feasibility studies done to date have come to similar conclusions. However, without any operational history for this technology they will require demonstration and piloting to prove.

These assumptions are primarily based on the fuel costs for uranium, which are low and inherently fixed during periods between reactor refuelings. As one shipowner for a major tanker company pointed out, “The potential to cut fuel costs in half because we only have to do one refuel every 10 years would provide a tremendous benefit.”

Many participants scored CMNP’s business case low because it has yet to be proven and the experience with navies has proven the technology to be very expensive. On top of this, the maritime industry’s general conservatism toward adopting new practices and technologies was seen as an inhibitor. As one representative of the U.S. Coast Guard pointed out, “Even if it makes economic sense but deviates from a shipowner’s comfort zone, they will not pursue it. This technology would represent a major overhaul for the industry.”

3.1.2 CO2 Emissions Reductions

The potential for emissions reductions was seen as the primary driver for adopting CMNP and many participants saw the rest of the benefits of CMNP as byproducts of adoption. One ship broker pointed out that their customers are already willing to make larger capital expenditures based on this. Many participants also pointed out that nuclear’s potential as a carbon-reduction tool could be well-proven in this environment and potentially improve public perception issues.

[oo] Participants were asked to score each potential driver for adopting CMNP based on how strong they felt it would drive the commercialization of CMNP, with “5” representing the largest drivers. As explained in section 1.1, “Total” scores represent the average scores provided by all survey participants, the “nuclear” column represents all participants with self-identified nuclear experience plus those who designated experience in both sectors, and “maritime” represents all participants with maritime experience plus those who designated experience in both sectors. Therefore, the scores from those who designated experience in both sectors were included in both “nuclear” and “maritime” scores.

Most participants from the maritime sector highlighted container vessels as especially poised to benefit from reduced emissions. Many container customers are applying pressure to these companies to improve their energy efficiency, which is difficult to reconcile with comparatively high fuel consumption for this class of vessels. For example, oil tankers are not exposed to the same demands from their customers, oil companies.

Much of the maritime industry's anxiety today related to carbon emissions goals is based on uncertainties around the profile of future emissions penalties. The size and scale of a carbon tax would be irrelevant for a vessel that produces no CO2. One vendor developing a CMNP technology suggested a potential added benefit for ports could be the opportunity to earn carbon credits by receiving non-emitting vessels.

A small group of participants ranked this item low mostly because of their skepticism around the actual strength of future emissions restrictions. As one participant made clear, "Restrictions are currently very weak, and they will have to be much stronger to become a driver."

3.1.3 Non-carbon Environmental Benefit

Non-carbon environmental benefits include the reduction of other pollutants like nitrogen oxides (NOx) and sulfur oxides (SOx). This was ranked high among participants but not seen as a primary driver considering the industry's switch to low-sulfur fuels and expected adoption of LNG in the near term.

Where these benefits were expected to be most pronounced was in the cruise sector. Representatives from this space expressed the challenge of providing a pristine travel experience to customers while balancing the operations of some of the largest vessels in the world. The impact of these vessels is regulated in terms of pollution and sewage outputs and some emissions restrictions are already being implemented this decade. In 2019 the Norwegian parliament declared that the country's UNESCO-protected fjords shall be free from cruise and ferry emissions no later than 2026. [pp]

Many participants pointed out that while protocols in place for dealing with nuclear waste are effective, management of this material detracts from nuclear's non-carbon environmental benefits.

One participant from the nuclear sector suggested the potential to use a CMNP system for ballast water decontamination, which could be an additional benefit of the technology.

[pp] Dnv.com. February 25, 2019. "Norway challenges the cruise industry to operate emission free." Accessed November 8, 2022. https://www.dnv.com/expert-story/maritime-impact/Norway-challenges-the-cruise-industry-to-operate-emission-free.html

Figure 8. Geiranger Fjord in Norway. From: Pixabay (Free for commercial use).

3.1.4 Reduced Refueling

Participant responses to this topic fell into two groups. One group did not see any potential benefit from this because the practice of bunkering is already routine for ships. The other group saw the potential to reduce refueling as "transformational."

Many participants pointed out that while routine, bunkering in its current form takes time and always comes with the risk of spills and penalties. As an executive from a major container shipping company noted, "Our business would be transformed if we did not have to think about refueling anymore." The benefits of fixed costs and no bunkering would be accentuated for charter ships on fixed contracts or liner ships on fixed routes. One consultant with more than 30 years of experience for the maritime and offshore sectors pointed out that this could de-risk the business model for vessels in a way that would represent a "new paradigm for ship owners and operators."

While potentially exciting, many participants pointed out that these benefits would be hard to capture if a nuclear ship needed to refuel relatively frequently. Nuclear reactors can be designed to operate without refueling for the life of a ship or for periods in between safety surveys. In order to prevent costly refueling outages, a commercial ship would need to operate on a timeframe that integrates with these vessel lifetime events. If that timeframe cannot be guaranteed, then this potential benefit of CMNP could end up costing the shipowner in the long run.

3.1.5 Improved Performance

The concept of improved performance was open-ended and encouraged participants to think about how the operational profile of a vessel could be improved by using CMNP. A frequent topic that came up was space considerations: a CMNP system that took up less space than its competitors and provided more space for cargo would be attractive for all shipowners.

These cargo space improvements could also have fleet-wide impacts: the potential to move the same amount of goods with fewer ships would be beneficial. Similarly, a smaller fleet of ships going faster with CMNP could potentially cover the same routes in the same amount of time as a larger fleet going slower. Speed was addressed as its own potential benefit.

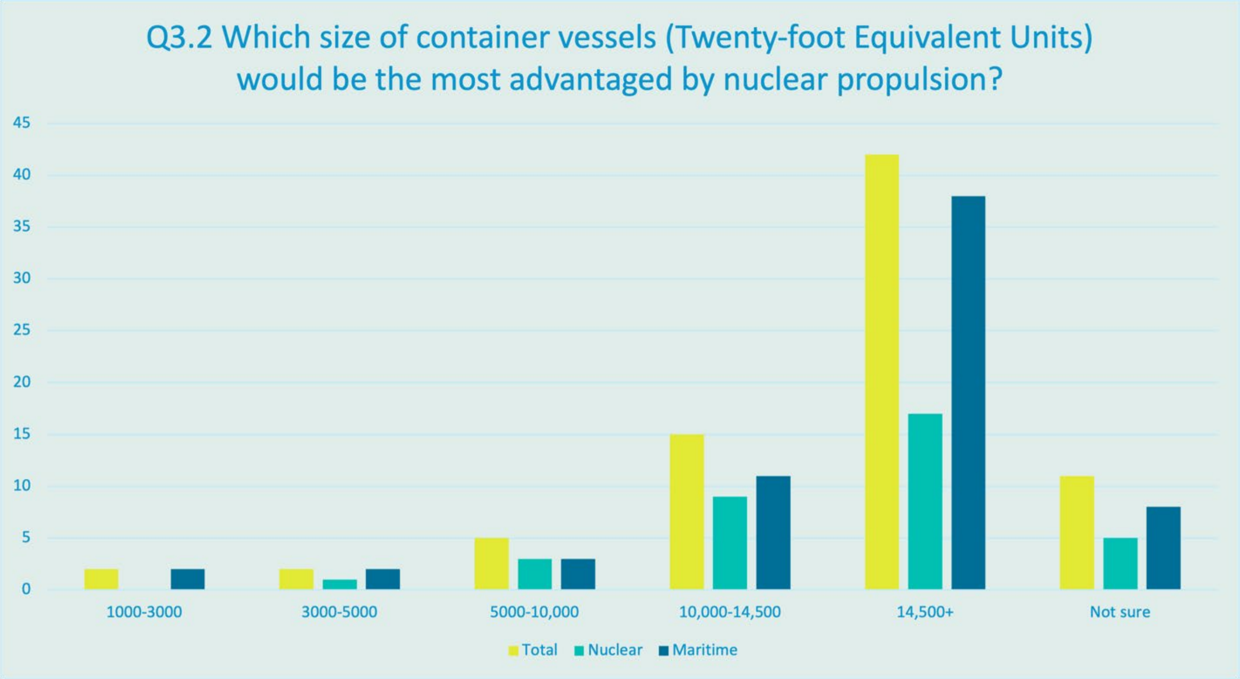
3.1.6 Enhanced Speed

Most participants felt that enhanced speed would be “nice to have” but largely inconsequential. Many ships like oil tankers do not benefit from moving faster because the value of their goods onboard is traded elsewhere in commodity markets. Additionally, participants based their answers on the assumption that with the introduction of slow-steaming across shipping to reduce fuel costs and emissions, there is limited marginal benefit to capture by going faster. However, this stance is largely predicated on the use of fuels like HFO that are polluting and whose rate of consumption increases with increased speeds. Neither of these would be significant for a CMNP system. It is for this reason that many participants noted container shipping as a potentially game-changing application for CMNP.

As one representative of a major container shipping company pointed out, “We provide a fast and cheap lane between continents.” It is for this reason that the speed of container shipping can have impacts on the speed of the global economy. The potential for container ships to access new speeds—limited only by the design of their hulls—could limit the overall capex of a shipowner’s fleet by allowing them to run fewer ships faster and make up the same distance as with a larger fleet. All of this could be accomplished in the face of increased slow-steaming that is anticipated to occur industry-wide over the coming years. Many participants wondered if faster ships could encroach on certain parts of the airfreight and rail markets, which currently provide a premium for speed but not for weight. Opex could also be reduced if a vessel is capable of shaving off days from its schedule.

3.2 Opportunities: Container Vessels

The survey included specific questions about container vessels and the ideal size for implementing CMNP. The majority of participants’ answers boiled down to “the bigger the better,” both in terms of vessel size and route length. This also reduces the number of ports at which a large container vessel can dock, which many participants thought would reduce port access issues.



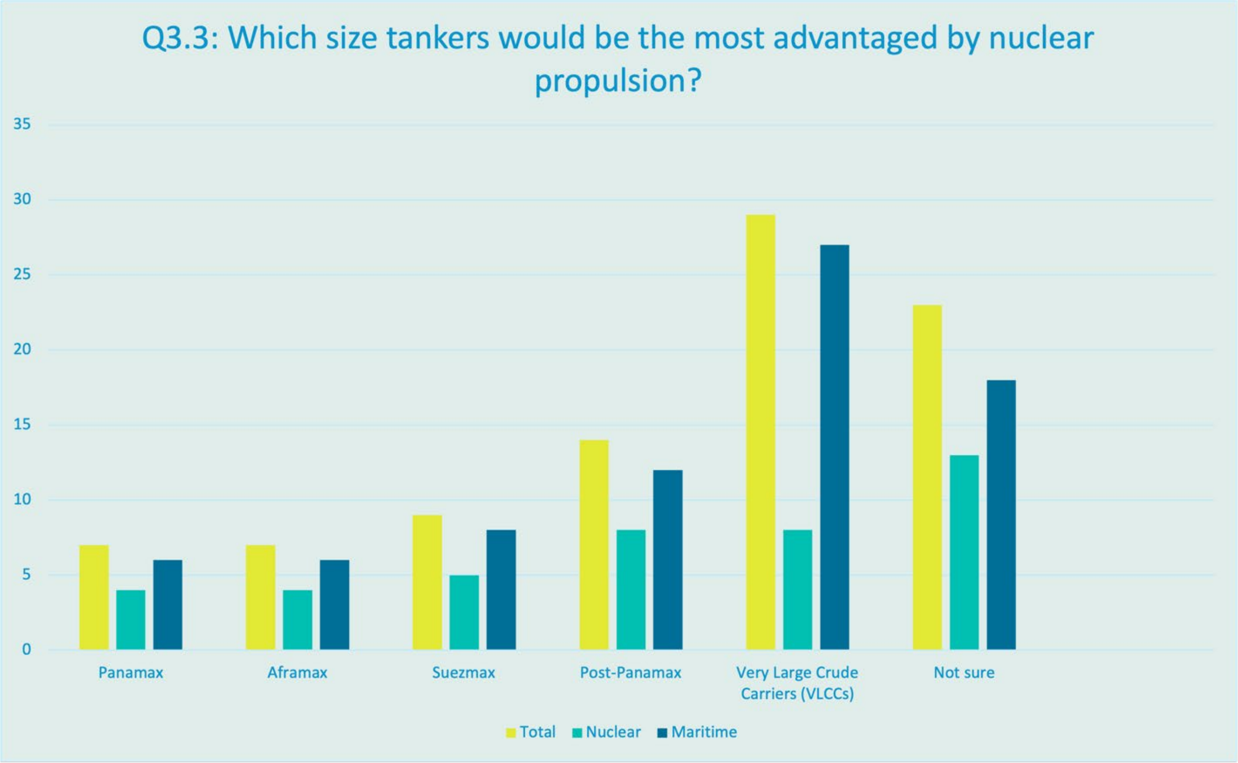
Answers were mostly based on capturing economies of scale but also spoke to some of the restrictions that smaller container vessels might have. For example, some in the 1,000–3,000 twenty-foot equivalent units (TEU) range make intracontinental voyages that could result in additional public opposition. However, these vessels spend less time at port and have less cargo space, so the benefits of a CMNP system on these ships could be outsized. Most participants still agreed that CMNP would need to first be installed on large vessels in order to start the process of bringing down marginal costs.

One interesting observation was the 10,000–14,500 TEU "sweet spot." Multiple feasibility studies have identified this size as optimal for the use of CMNP.[qq] A shipbroker who was interviewed pointed out that 12,000 TEU is the current "trendy" size for north–south routes with large volumes of refrigerated containers, also known as "reefers." This is notable because of the additional electric load that comes with using large volumes of reefers. One representative of a major container shipping company also noted that container vessels of this size range make up the largest percentage within their fleet and will soon represent half of all ships they own.

3.3 Opportunities: Tankers

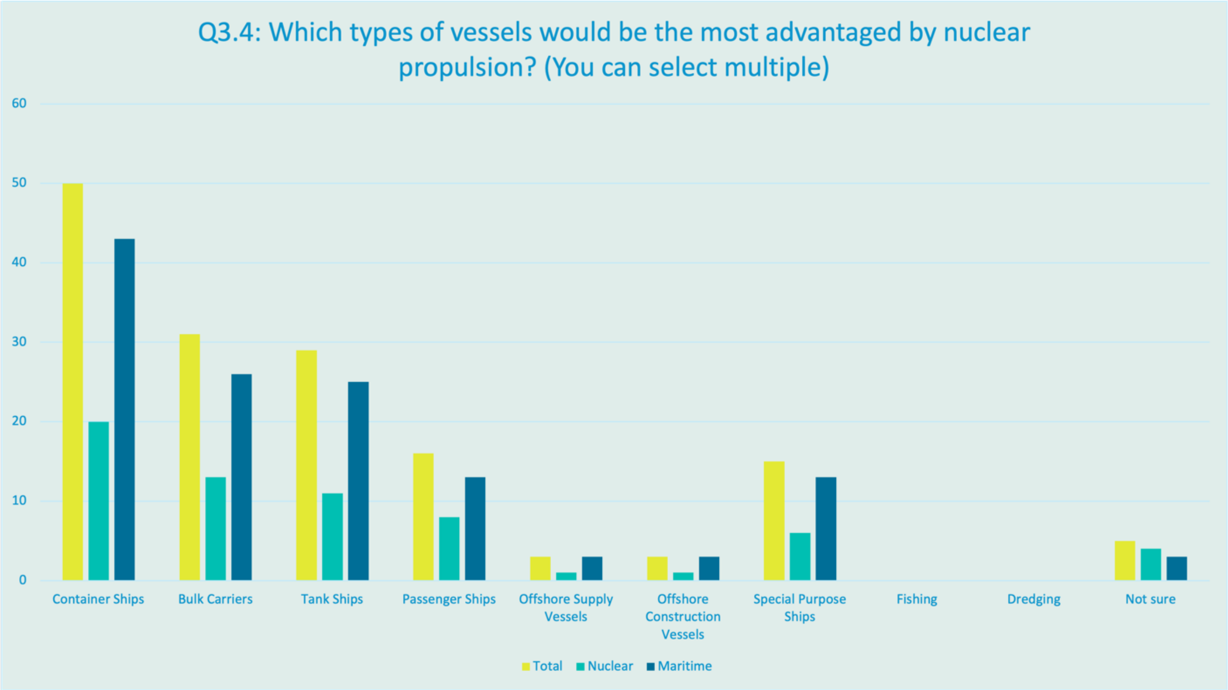
Participants were also asked to comment on the optimal tanker size to use CMNP. Although answers were similar to those of the container question ("the bigger the better") many participants felt that tankers might not be the optimal place for CMNP to be first introduced. Most of these ships "tramp" to multiple ports and do not benefit from speed, which means that the potential added benefits of CMNP might be lost on them. Considering oil tankers currently make up one-third of maritime trade, many participants also questioned how large the tanker industry would still be at a future time when CMNP is commercially available.

[qq] Youngmi Gil et al. 2013. "Feasibility Study on Nuclear Propulsion Ship according to Economic Evaluation". Accessed November 8, 2022. https://www.academia.edu/7918824/Feasibility_Study_on_Nuclear_Propulsion_Ship_according_to_Economic_Evaluation



3.4 Opportunities: Vessel Types

Finally, participants were asked to comment on the specific classes of vessels that would most benefit from CMNP.



Container ships scored highest and participants felt that these vessels would be the first to adopt this technology because of their high fuel consumption, limited number of ports visited, and high percentage of time at sea.

Bulk carriers also received high scores, but many participants were doubtful that their economic model made sense. More than one person referred to them as "cookie-cutter bathtubs with motors." Because most of them tramp and cost little to build, it seemed unlikely that they could absorb the cost of a CMNP system. Where these vessels seemed to make sense however were long trips to remote regions with limited bunkering infrastructure along the way. Responses to this specific class of vessel made it apparent that while the entire class might not be suitable, there could be specific routes that make sense.

Tank ships scored the third highest and many saw this class as a good starting point for CMNP because the bulk of their operations take place in remote locations or offshore discharging hubs that are largely "out of sight, out of mind." This could help with public perception issues as well as the bottom line for these vessels, of which fuel can be the number-one cost.

Many participants saw passenger ships—cruise ships specifically—as potentially having the most to gain operationally from adopting CMNP. Cruise ships are expensive to build and consume massive amounts of power, which currently has the industry thinking hard about what type of future fuels could meet their needs while complying with emissions restrictions. Still, public perception and safety issues for adopting CMNP could prove insurmountable.

While few participants saw offshore supply vessels as potentially benefiting from CMNP, an interesting case was made for offshore construction vessels. Some of those used by the oil and gas sector have enormous energy demand for the tools they use onboard, which includes dynamic positioning systems and machines for underwater construction. The cost to construct and power some of these vessels throughout their lifetimes could also make the price of CMNP comparatively easy to incorporate.

Many participants agreed that special purpose ships, including icebreakers and research vessels, could also benefit from this technology, especially considering the modern experience of Russia's nuclear icebreakers. Other suggestions included FPSO vessels that have large machinery power demands, as well as freshwater lake freighters that can operate for twice as long as their saltwater counterparts because of the lower rates of corrosion they experience.

Figure 9. SSCV (Semi-submersible crane vessel) Sleipnir: weighing over 300,000 short tons with 96 MW of installed power on board. From: Wikimedia Commons.

4. FEEDBACK

4.1 Feedback from Advanced Reactor Designers and Vendors or Affiliates

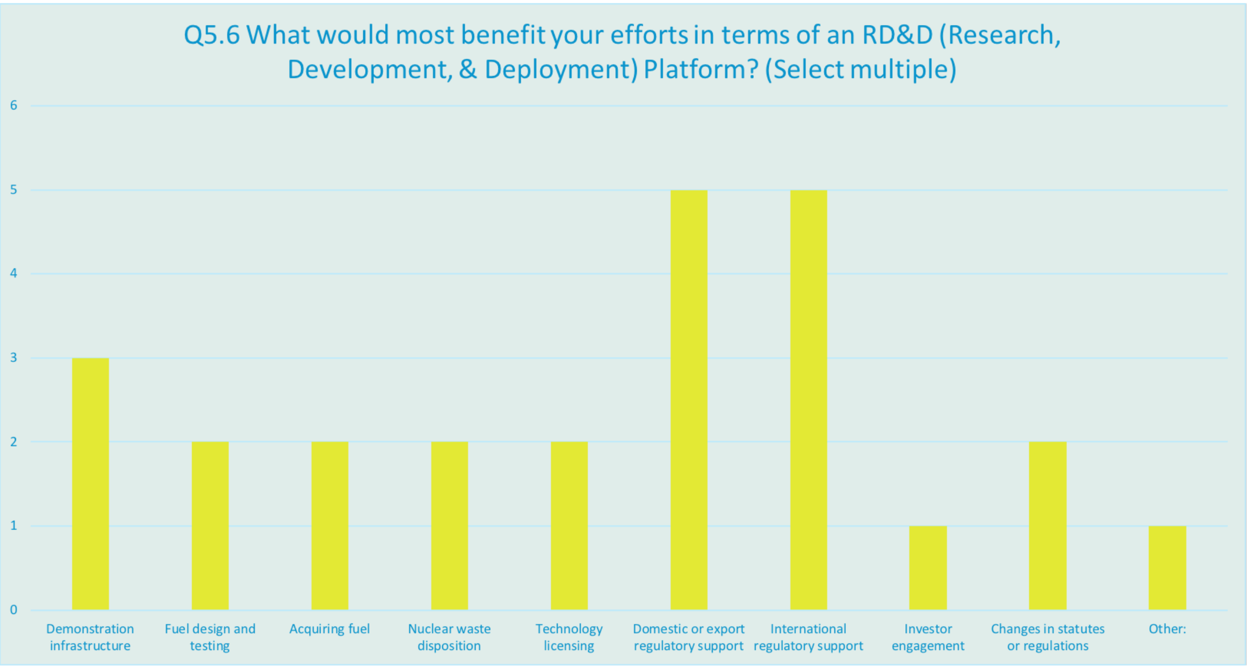
The final section of the survey was reserved for groups that are currently developing CMNP technologies. Five participants representing four different ventures and university projects provided high-level information on their plans as well as feedback on the resources that they would find useful if provided by NRIC.

Two of the groups specified they are developing technologies considered “life of ship,” meaning their fueling would be designed so that it would not need to be changed before the end of the ship’s life. In terms of flagging, countries that are being considered include France, the Republic of Korea, Singapore, the U.S., and U.K. One group has not yet publicly announced where they would like to develop the technology; however, they did outline what they are looking for in a host country. This included an existing regulatory regime for nuclear power, visible political support for advanced nuclear and its export potential, a focus on reducing CO2 emissions, and an influential role within global shipping and at the IMO.

Two of the groups specified the ownership models for the ships where their CMNP technology would be installed: for one group, ownership would remain with the ship owner. The other group proposes an international consortium of ship and reactor owners.

Reactor ownership models were more consistent: three of the groups specified that their reactors would be owned by a manufacturing consortium and leased out, similar to the common practice of leasing aircraft engines to airlines. The primary reason for this was so that shipowners would not be responsible for the large capex associated with the CMNP system and could instead be charged simply for the power that they consume.

Each of the groups is focused on demonstrating their technologies on land within the next 6 years with a first-of-a-kind reactor licensed and operational by the end of the decade.



5. Appendix I: Survey Questions

Idaho National Laboratory

NRIC National Reactor Innovation Center

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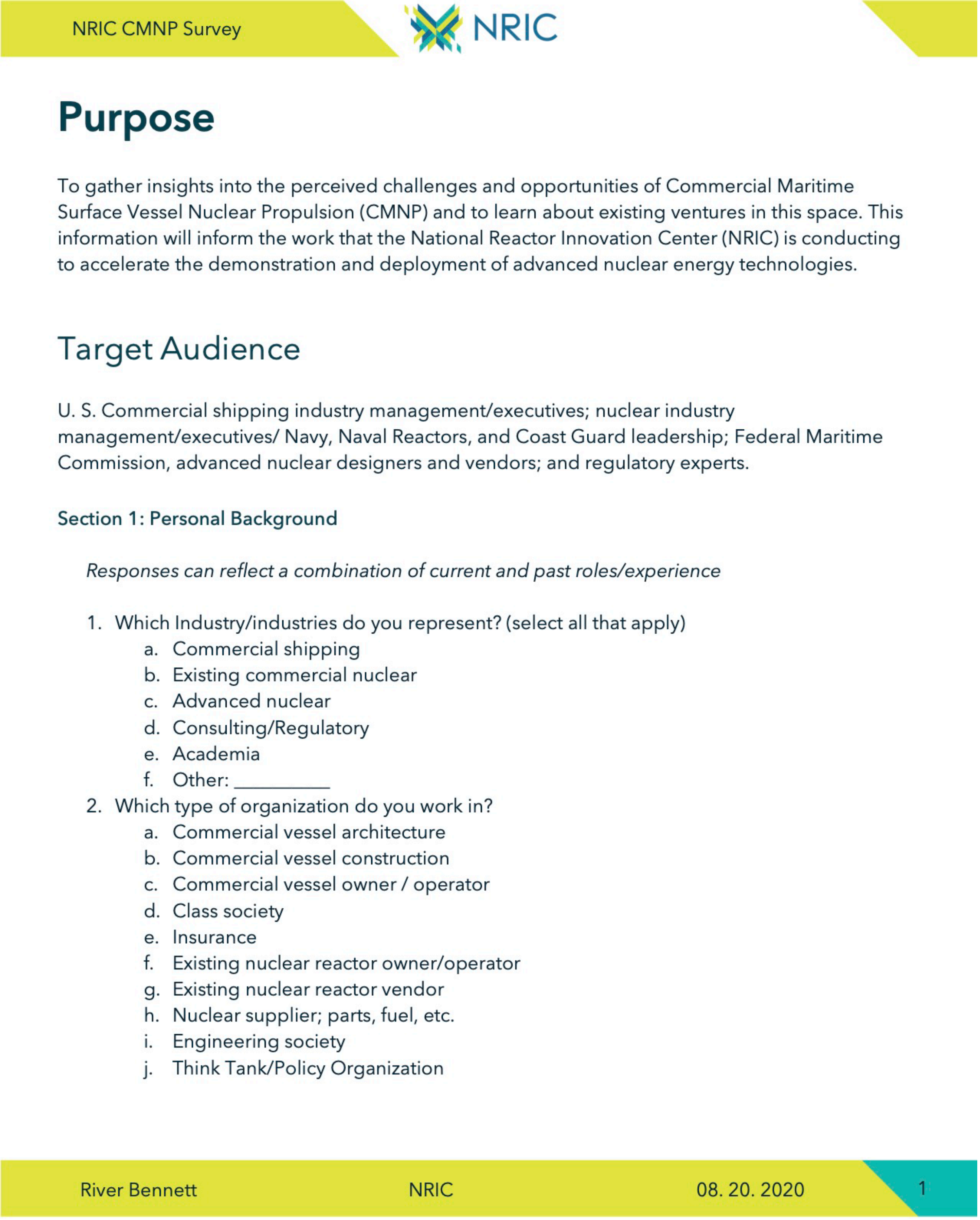
NRIC Survey on Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP)

River Bennett

NRIC | 08. 20. 2020



Purpose

To gather insights into the perceived challenges and opportunities of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP) and to learn about existing ventures in this space. This information will inform the work that the National Reactor Innovation Center (NRIC) is conducting to accelerate the demonstration and deployment of advanced nuclear energy technologies.

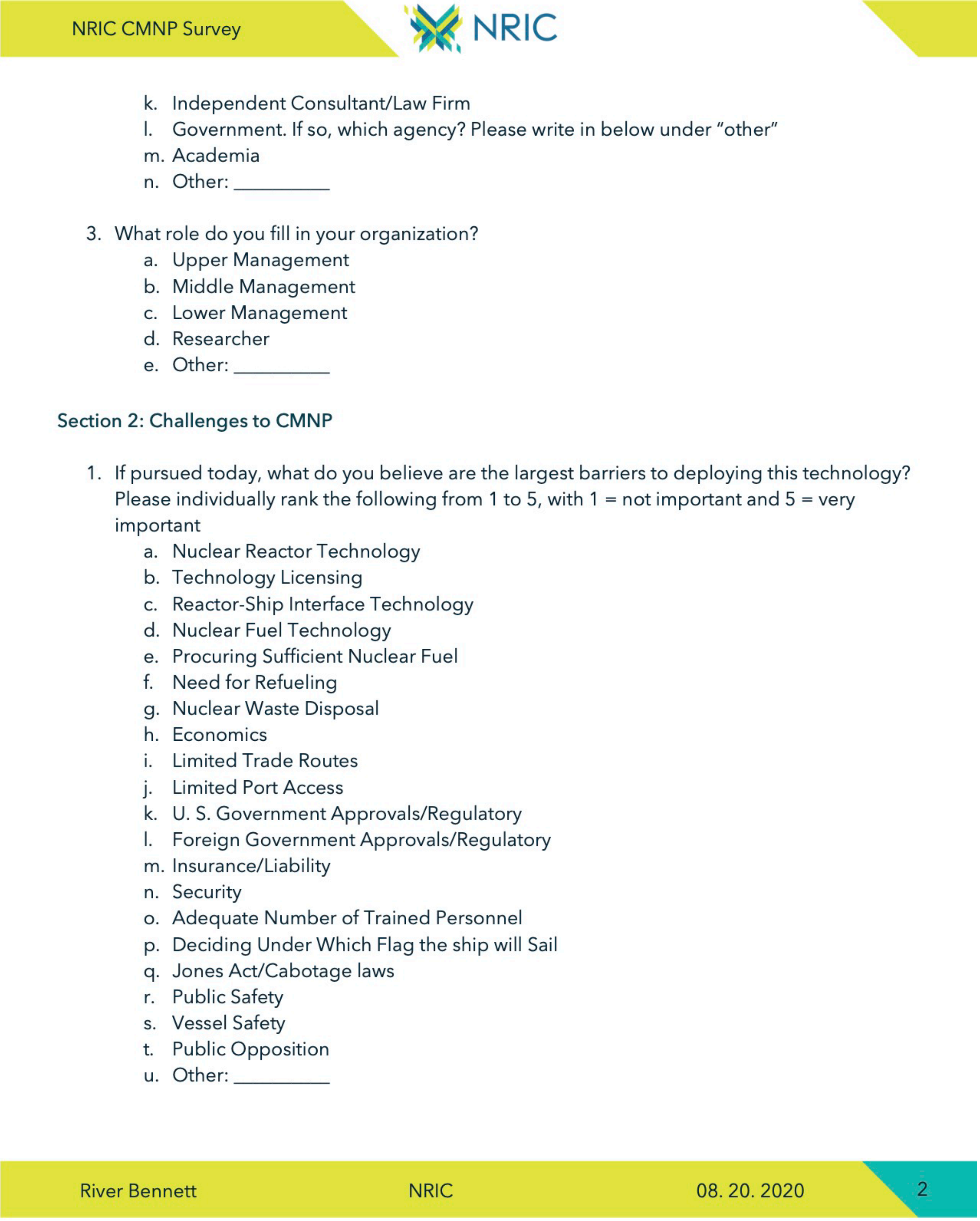
Target Audience

U. S. Commercial shipping industry management/executives; nuclear industry management/executives/ Navy, Naval Reactors, and Coast Guard leadership; Federal Maritime Commission, advanced nuclear designers and vendors; and regulatory experts.

Section 1: Personal Background

Responses can reflect a combination of current and past roles/experience

1. Which Industry/industries do you represent? (select all that apply)
   a. Commercial shipping
   b. Existing commercial nuclear
   c. Advanced nuclear
   d. Consulting/Regulatory
   e. Academia
   f. Other: __________
2. Which type of organization do you work in?
   a. Commercial vessel architecture
   b. Commercial vessel construction
   c. Commercial vessel owner / operator
   d. Class society
   e. Insurance
   f. Existing nuclear reactor owner/operator
   g. Existing nuclear reactor vendor
   h. Nuclear supplier; parts, fuel, etc.
   i. Engineering society
   j. Think Tank/Policy Organization



NRIC CMNP Survey

   k. Independent Consultant/Law Firm
   l. Government. If so, which agency? Please write in below under "other"
   m. Academia
   n. Other: __________

3. What role do you fill in your organization?
   a. Upper Management
   b. Middle Management
   c. Lower Management
   d. Researcher
   e. Other: __________

Section 2: Challenges to CMNP

1. If pursued today, what do you believe are the largest barriers to deploying this technology? Please individually rank the following from 1 to 5, with 1 = not important and 5 = very important
   a. Nuclear Reactor Technology
   b. Technology Licensing
   c. Reactor-Ship Interface Technology
   d. Nuclear Fuel Technology
   e. Procuring Sufficient Nuclear Fuel
   f. Need for Refueling
   g. Nuclear Waste Disposal
   h. Economics
   i. Limited Trade Routes
   j. Limited Port Access
   k. U. S. Government Approvals/Regulatory
   l. Foreign Government Approvals/Regulatory
   m. Insurance/Liability
   n. Security
   o. Adequate Number of Trained Personnel
   p. Deciding Under Which Flag the ship will Sail
   q. Jones Act/Cabotage laws
   r. Public Safety
   s. Vessel Safety
   t. Public Opposition
   u. Other: __________

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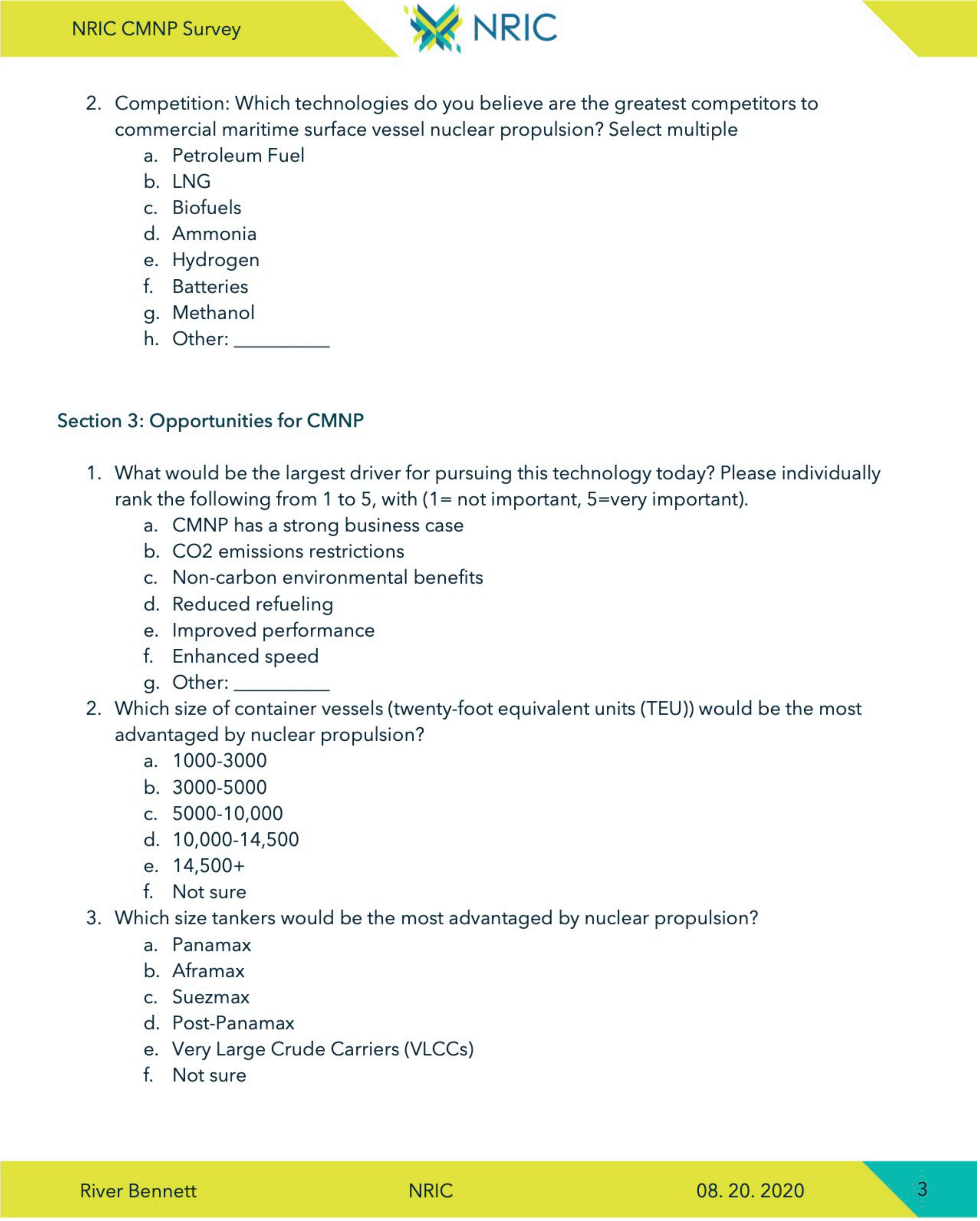
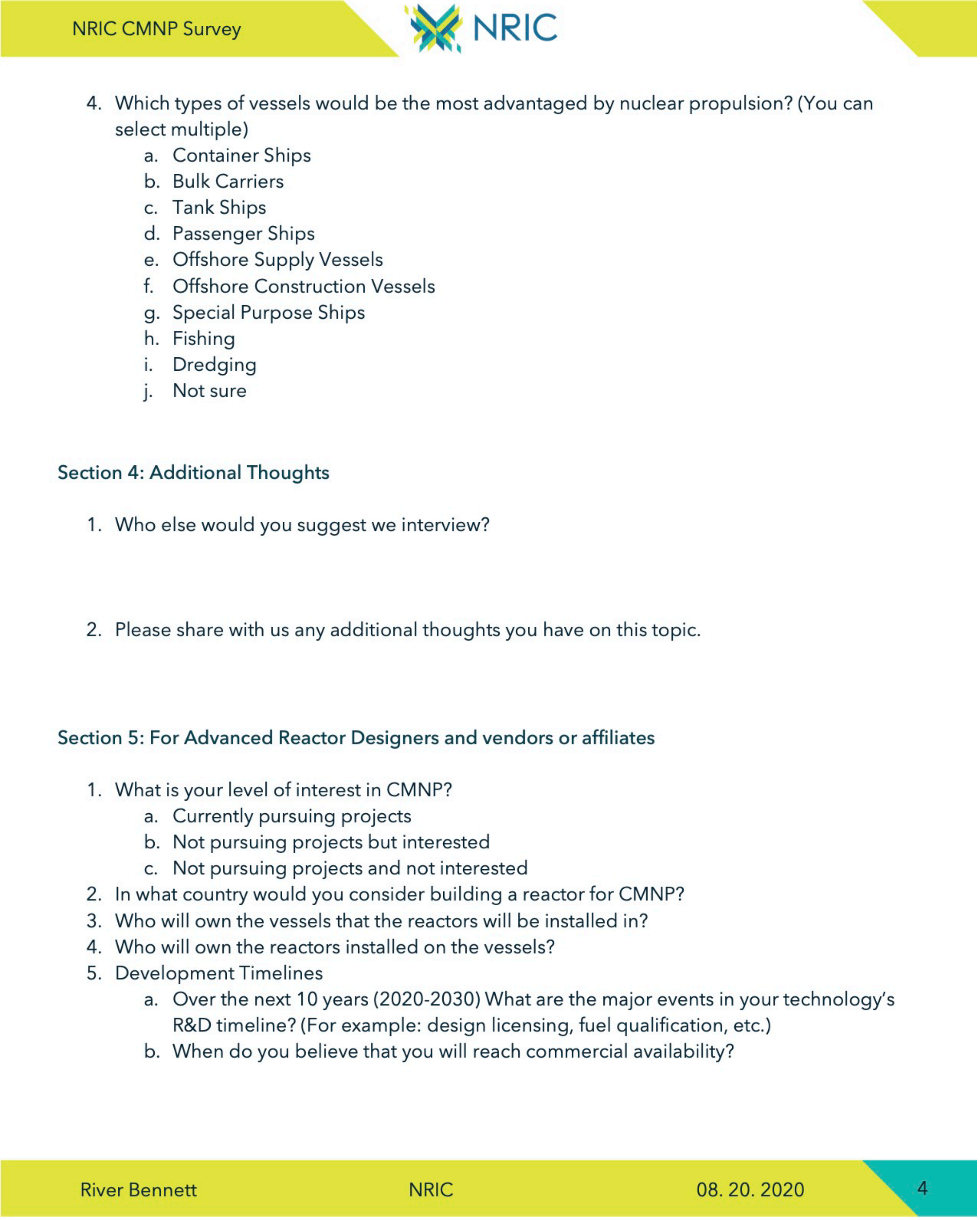


2. Competition: Which technologies do you believe are the greatest competitors to commercial maritime surface vessel nuclear propulsion? Select multiple
    a. Petroleum Fuel
    b. LNG
    c. Biofuels
    d. Ammonia
    e. Hydrogen
    f. Batteries
    g. Methanol
    h. Other: __________

Section 3: Opportunities for CMNP

1. What would be the largest driver for pursuing this technology today? Please individually rank the following from 1 to 5, with (1= not important, 5=very important).
    a. CMNP has a strong business case
    b. CO2 emissions restrictions
    c. Non-carbon environmental benefits
    d. Reduced refueling
    e. Improved performance
    f. Enhanced speed
    g. Other: __________
2. Which size of container vessels (twenty-foot equivalent units (TEU)) would be the most advantaged by nuclear propulsion?
    a. 1000-3000
    b. 3000-5000
    c. 5000-10,000
    d. 10,000-14,500
    e. 14,500+
    f. Not sure
3. Which size tankers would be the most advantaged by nuclear propulsion?
    a. Panamax
    b. Aframax
    c. Suezmax
    d. Post-Panamax
    e. Very Large Crude Carriers (VLCCs)
    f. Not sure



4. Which types of vessels would be the most advantaged by nuclear propulsion? (You can select multiple)
    a. Container Ships
    b. Bulk Carriers
    c. Tank Ships
    d. Passenger Ships
    e. Offshore Supply Vessels
    f. Offshore Construction Vessels
    g. Special Purpose Ships
    h. Fishing
    i. Dredging
    j. Not sure

Section 4: Additional Thoughts

1. Who else would you suggest we interview?

2. Please share with us any additional thoughts you have on this topic.

Section 5: For Advanced Reactor Designers and vendors or affiliates

1. What is your level of interest in CMNP?
    a. Currently pursuing projects
    b. Not pursuing projects but interested
    c. Not pursuing projects and not interested
2. In what country would you consider building a reactor for CMNP?
3. Who will own the vessels that the reactors will be installed in?
4. Who will own the reactors installed on the vessels?
5. Development Timelines
    a. Over the next 10 years (2020-2030) What are the major events in your technology's R&D timeline? (For example: design licensing, fuel qualification, etc.)
    b. When do you believe that you will reach commercial availability?

NRIC CMNP Survey

6. What would most benefit your efforts in terms of an RD&D (Research, Development, & Deployment) Platform?
    a. Demonstration infrastructure
    b. Fuel design and testing
    c. Acquiring fuel
    d. Nuclear waste disposition
    e. Technology licensing
    f. Domestic or export regulatory support
    g. International regulatory support
    h. Investor engagement
    i. Changes in statutes or regulations
    j. Other: __________

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6. Appendix II: CMNP Port Access Map data and sources

6.1 CMNP Port Access Map: Top 20 Ports

Sources:

- Seaport Size Rank: worldshipping.org
- Nuclear Navies: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx
- Countries with commercial Nuclear Power Plants: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx
- Official U.S. Navy access and Port Call information linked below

Seaport Size Rank (2020)	Seaport	Country / District	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
1	Shanghai	China	Yes	Yes			
2	Singapore	Singapore	No	No	Yes + 1 U.S. Installation	Nimitz Class	4/2/18
3	Shenzhen	China	Yes	Yes			
4	Ningbo-Zhoushan	China	Yes	Yes			
5	Guangzhou Harbor	China	Yes	Yes			
6	Busan	South Korea	Expected	Yes	1 U.S. Installation	Nimitz Class	10/20/17
7	Hong Kong, S.A.R, China	China	Yes	Yes			
8	Qingdao	China	Yes	Yes			
9	Tianjin	China	Yes	Yes			
10	Jebel Ali, Dubai	United Arab Emirates	No	Yes	2 U.S. Installations	Nimitz Class	10/18/2017
11	Rotterdam	Netherlands	No	Yes			
12	Port Klang	Malaysia	No	No		Nimitz Class	10/6/12
13	Antwerp	Belgium	No	Yes			
14	Kaohsiung, Taiwan	Taiwan	No	Yes			
15	Xiamen	China	Yes	Yes			
16	Dalian	China	Yes	Yes			
17	Los Angeles	United States	Yes	Yes			
18	Tanjung Pelepas	Malaysia	No	No		Nimitz Class	10/6/12
19	Hamburg	Germany	No	Yes			
20	Long Beach	U.S.	Yes	Yes			

6.2 CMNP Port Access Map

Sources:

- Number of Ports: http://www.worldportsource.com/countries.php
- Nuclear Navies: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx
- Countries with commercial Nuclear Power Plants: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx
- Official U.S. Navy access and Port Call information linked below

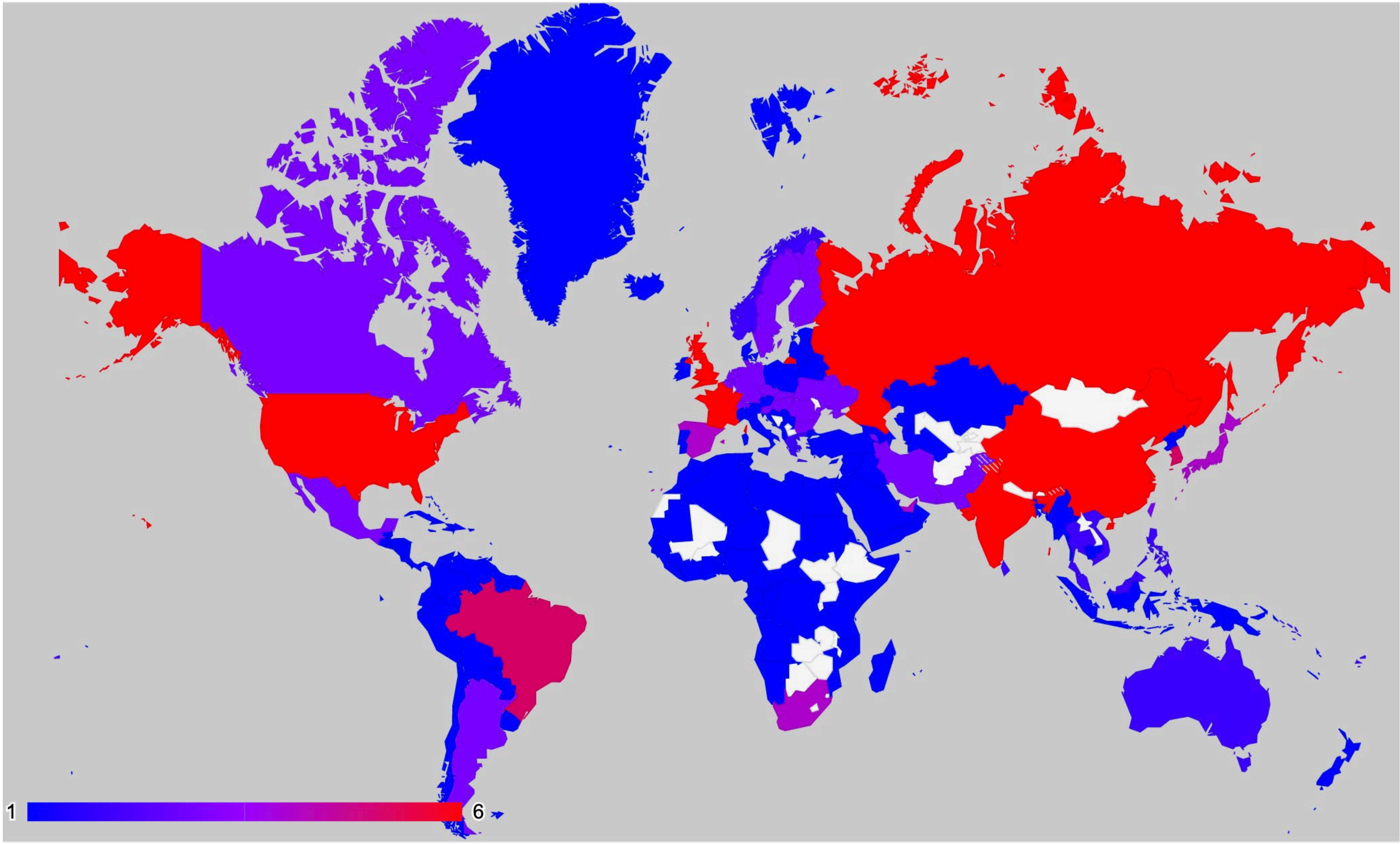
Country	Number of Ports	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
Albania	4	No	No			
Algeria	18	No	No			
American Samoa	1	No	No			
Angola	16	No	No			
Anguilla	1	No	No			
Antigua and Barbuda	1	No	No			
Argentina	55	No	Yes			
Armenia	0	No	Yes			
Aruba	3	No	No			
Australia	106	No	No		Nimitz Class	6/4/19
Austria	4	No	No			
Azerbaijan	1	No	No			
Bahamas, The	8	No	No	1 U.S. Installation		
Bahrain	2	No	No	2 U.S. Installations	Nimitz Class	2017
Bangladesh	4	No	Expected			
Barbados	1	No	No			
Belarus	1	No	Expected			
Belgium	8	No	Yes			
Belize	1	No	No			
Benin	1	No	No			
Bermuda	3	No	No			
Bolivia	1	No	No			
Brazil	81	Expected	Yes			
British Virgin Islands	2	No	No			
Brunei	1	No	No			
Bulgaria	2	No	Yes			
Burma	5	No	No			
Cambodia	2	No	No			
Cameroon	1	No	No			
Canada	239	No	Yes			
Cape Verde	7	No	No			
Cayman Islands	2	No	No			

Country	Number of Ports	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
Central African Republic	1	No	No			
Chile	46	No	No			
China	172	Yes	Yes			
Christmas Island	1	No	No			
Colombia	15	No	No			
Comoros	3	No	No			
Congo, Democratic Republic of the	3	No	No			
Congo, Republic of the	4	No	No			
Cook Islands	1	No	No			
Costa Rica	6	No	No			
Côte d'Ivoire	4	No	No			
Croatia	34	No	No			
Cuba	37	No	No	1 U.S. Installation		
Cyprus	4	No	No			
Czech Republic	2	No	Yes			
Denmark	159	No	No			
Djibouti	1	No	No	1 U.S. Installation		
Dominica	3	No	No			
Dominican Republic	14	No	No			
Ecuador	9	No	No			
Egypt	28	No	No	1 U.S. Installation		
El Salvador	3	No	No			
Equatorial Guinea	9	No	No			
Eritrea	2	No	No			
Estonia	26	No	No			
Falkland Islands	7	No	No			
Faroe Islands	4	No	No			
Fiji	5	No	No		Nimitz Class	2017
Finland	60	No	Yes			
French Guiana	5	No	No			
French Polynesia	7	No	No			
Gabon	6	No	No			
Gambia	1	No	No			
Georgia	4	No	No			
Germany	98	No	Yes			
Ghana	4	No	No			
Gibraltar	3	No	No			
Greece	103	No	No	1 U.S. Installation	L.A. Class	2019
Greenland (Denmark)	22	No	No			
Grenada	1	No	No			
Guadeloupe	3	No	No			
Guam	1	No	No		Nimitz Class	6/3/20

Country	Number of Ports	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
Guatemala	5	No	No			
Guinea	2	No	No			
Guinea-Bissau	2	No	No			
Guyana	6	No	No			
Haiti	11	No	No			
Honduras	6	No	No			
Hong Kong	2	No	No	No, as of Dec. 2019		
Hungary	1	No	Yes			
Iceland	67	No	No			
India	76	Yes	Yes		Nimitz Class	4/7/12
Indonesia	154	No	No			
Iran	9	No	Yes			
Iraq	4	No	No			
Israel	5	No	No			
Italy	311	No	No	3 U.S. Installations		
Jamaica	15	No	No			
Japan	292	No	Yes	6 U.S. Installations	L.A. Class	12/22/16
Jordan	3	No	No			
Kazakhstan	9	No	No			
Kenya	3	No	No			
Kiribati	3	No	No			
Korea, North	8	No	No			
Korea, South	17	Expected	Yes	1 U.S. Installation	Nimitz Class	10/20/17
Kuwait	3	No	No	1 U.S. Installation		
Latvia	6	No	No			
Lebanon	2	No	No			
Liberia	4	No	No			
Libya	15	No	No			
Lithuania	1	No	No			
Macau	1	No	No			
Madagascar	11	No	No			
Malaysia	25	No	No		Nimitz Class	10/6/12
Maldives	1	No	No		Nimitz Class	2011
Malta	2	No	No			
Marshall Islands	2	No	No		L.A. Class	2017
Martinique	3	No	No			
Mauritania	2	No	No			
Mauritius	1	No	No			
Metropolitan France	268	Yes	Yes			
Mexico	42	No	Yes			
Micronesia, Federated States of	2	No	No			

Country	Number of Ports	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
Monaco	2	No	No			
Montenegro	1	No	No			
Montserrat	2	No	No			
Morocco	15	No	No			
Mozambique	5	No	No			
Namibia	2	No	No			
Nauru	1	No	No			
Netherlands	24	No	Yes			
New Caledonia	7	No	No			
New Zealand	25	No	No			
Nicaragua	7	No	No			
Niger	1	No	No			
Nigeria	12	No	No			
Northern Mariana Islands	3	No	No		L.A. Class	2012
Norway	83	No	No	Yes	Seawolf	2020
Oman	7	No	No	Yes + 1 U.S. Installation		
Pakistan	3	No	Yes			
Panama	13	No	No			
Papua New Guinea	19	No	No			
Paraguay	4	No	No			
Peru	33	No	No	1 U.S. Installation		
Philippines	68	No	No		Nimitz Class	4/10/18
Poland	12	No	No			
Portugal	62	No	No			
Puerto Rico	22	No	No			
Qatar	6	No	No	1 U.S. Installation	Nimitz Class	2017
Republic of China (Taiwan)	6	No	Yes			
Republic of Ireland	49	No	No			
Réunion	2	No	No			
Romania	18	No	Yes			
Russia	105	Yes	Yes			
Saint Helena, Ascension and Tristan da Cunha	1	No	No			
Saint Kitts and Nevis	2	No	No			
Saint Lucia	4	No	No			
Saint Pierre and Miquelon	2	No	No			
Saint Vincent and the Grenadines	5	No	No			
Samoa	1	No	No			
São Tomé and Príncipe	2	No	No			
Saudi Arabia	18	No	No	2 U.S. Installations		
Senegal	4	No	No			
Serbia	1	No	No			

Country	Number of Ports	Nuclear Navy?	Commercial NPPs?	Official U.S. Navy Access?	Port Call Article	Port Call Date
Seychelles	1	No	No			
Sierra Leone	3	No	No			
Singapore	2	No	No	Yes + 1 U.S. Installation	Nimitz Class	4/2/18
Slovakia	1	No	Yes			
Slovenia	3	No	Yes			
Solomon Islands	14	No	No		Nimitz Class	2017
Somalia	4	No	No			
South Africa	10	No	Yes		Nimitz Class	2008
South Georgia and the South Sandwich Islands	1	No	No			
Spain (Including Canary Islands)	382	No	Yes	1 U.S. Installation	Virginia Class	6/23/20
Sri Lanka	4	No	No		Nimitz Class	10/27/17
Sudan	3	No	No			
Suriname	2	No	No			
Svalbard	3	No	No			
Sweden	82	No	Yes			
Switzerland	5	No	Yes			
Syria	5	No	No			
Tanzania	6	No	No			
Thailand	21	No	No		Nimitz Class	2/10/19
Timor-Leste	1	No	No			
Togo	2	No	No			
Tokelau	3	No	No			
Tonga	3	No	No			
Trinidad and Tobago	11	No	No			
Tunisia	8	No	No			
Turkey	50	No	Expected			
Turkmenistan	1	No	No			
Turks and Caicos Islands	3	No	No			
Tuvalu	1	No	No			
U.S. Virgin Islands	6	Yes	Yes			
Ukraine	18	No	Yes			
United Arab Emirates	9	No	Yes	2 U.S. Installations	Nimitz Class	10/18/2017
United Kingdom	391	Yes	Yes			
United States	554	Yes	Yes			
Uruguay	10	No	No			
Vanuatu	2	No	No			
Venezuela	41	No	No			
Vietnam	15	No	No		Nimitz Class	3/4/20
Yemen	8	No	No			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