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REDUCING RISKS FROM NAVAL NUCLEAR FUEL

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REDUCING RISKS FROM NAVAL NUCLEAR FUEL

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Frank von Hippel

Frank von Hippel is the co-founder of Princeton University's Program on Science and Global Security as well as the International Panel on Fissile Materials. Prior to Princeton, he spent a decade working in the field of elementary-particle theoretical physics. He has written extensively on the technical basis for nonproliferation and disarmament, the future of nuclear energy, and policy-making for science and technology. During 1993-1994, he served as the Assistant Director for National Security in the White House Office of Science and Technology Policy. Frank holds a DPhil in Theoretical Physics from Oxford and a BS from MIT.

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Introduction

SHARON SQUASSONI

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The use of nuclear fuel to power naval vessels has provided distinct advantages to countries able to master the technology, especially when it comes to enhancing the stealth and range of submarines. Those countries with the resources and impetus to proceed down this path have leveraged their nuclear-weapon programs. Japan and Germany were exceptions to this rule, and they limited their experimentation to nuclear-powered ships for civilian purposes. Canada contemplated nuclear submarines in the 1980s but ultimately abandoned its plan.[1]

Financial and technical hurdles make the naval nuclear club exclusive, but no legal barriers exist. In fact, parties to the Nuclear Nonproliferation Treaty (NPT) with or without nuclear weapons are free to develop nuclear fuel for nonproscribed military applications.[2] This "naval nuclear loophole" poses several dilemmas. The first is a well-known monitoring problem that arises because nuclear material for military reactors arguably passes in and out of the civilian and military sectors throughout its life cycle. The only inherently military segment of the naval nuclear fuel cycle involves the use of the fuel aboard the military vessel, although some information associated with the composition of the fuel and its irradiation along the way might be sensitive.

[1] Both domestic (e.g., cost) and foreign (particularly US) pressure helped cancel the program. A more recent proposal to resurrect nuclear submarines for Canada can be found in Dunlop (2017).

[2] For states without nuclear weapons, Article III of the treaty requires monitoring of nuclear material in all peaceful nuclear activities, while Article II specifically prohibits the diversion from peaceful activities to nuclear weapons or other nuclear explosive devices. For a more detailed analysis of NPT obligations and safeguards, see the discussion in the contributions to this volume by Frank von Hippel and Laura Rockwood.

The monitoring dilemma has lain dormant for several reasons. Nuclear-weapon states party to the NPT have thus far solved this problem by cordoning off their military programs from monitoring, as they are able to do under the terms of the treaty and their voluntary safeguards agreements. Non-nuclear-weapon states have never reached the point of needing to address the issue. According to the monitoring requirements of the standard comprehensive safeguards agreement (INFCIRC/153) that non-nuclear-weapon states sign with the International Atomic Energy Agency (IAEA), states would inform the agency when they intended to use material in a nonproscribed military activity and make arrangements for the nonapplication of safeguards for that period or set of circumstances (Paragraph 14 of INFCIRC/153).

No non-nuclear weapon state has yet challenged the naval nuclear loophole, but this may change. Brazil, a state that had a nuclear-weapon program but abandoned it more than 20 years ago, has been inching forward with a nuclear-powered-submarine program. South Korea, another state with a past nuclear-weapon program, declared a desire to counter future North Korean nuclear capabilities by developing its own nuclear-powered submarine. Those plans undoubtedly will be greatly influenced by what happens with North Korea's nuclear program and by US preferences. Iran in the last decade has also expressed interest in building nuclear-powered submarines and maritime transport, but the timing and scope of any activities are difficult to predict, particularly with the Joint Comprehensive Plan of Action for Iran in considerable jeopardy.

Plans for new nuclear-submarine programs are not the end of the challenges posed by naval nuclear fuel, however. A treaty to limit fissile material production for use in nuclear weapons—a so-called Fissile Material Treaty, or Fissile Material Cutoff Treaty—would likely require more stringent monitoring in nuclear-weapon states and would be unlikely to perpetuate the existing loophole for naval fuel.[3] There is little impetus at the moment to pursue a fissile-material treaty, but this also could change in the aftermath of what will likely be a contentious review conference for the NPT in 2020, the 50th anniversary of the treaty's entry into force.

Another dilemma arises from the fact that some nuclear naval programs—those of the United States, the United Kingdom, Russia, and India—use highly enriched uranium (HEU) in their fuel. Proponents of HEU naval fuel see few reasons to abandon HEU, citing operational requirements, especially for submarines. For non-nuclear-weapon-state parties to the NPT, a naval nuclear program provides a credible rationale for indigenous uranium enrichment with no limits on the level of enrichment. As such, a naval nuclear fuel program could provide an opportunity for potential proliferators to hide activities or hide materials that could be diverted to a nuclear-weapon program. Moving away from HEU in all naval nuclear reactors would substantially reduce proliferation and nuclear-security risks. Doing so would parallel the growing norm in the civilian sector to minimize and, where possible, eliminate HEU for civilian applications, as well as simplify some elements of future negotiations on a fissile material treaty.

The essays in this volume address some of the problems that nuclear naval fuel poses for the nonproliferation regime and for nuclear security. Frank von Hippel's analysis, "Mitigating the Threat of Nuclear Proliferation from Nuclear-Submarine Programs," describes the risks broadly and suggests that some navies could achieve the same effectiveness with conventionally powered submarines that feature new technology, and at a lower cost. Von Hippel also discusses the significant barriers to acquiring the requisite enriched uranium from foreign suppliers. Matias Spektor's contribution, "Brazil's Nuclear Naval Fuel: Choices and a Road Map for Productive Engagement," lays out the current status of Brazil's program and recommends steps for building confidence in Brazil's intentions. Laura Rockwood's essay, "Naval Nuclear Propulsion: Seeking Verification Processes," suggests potential pathways for developing an international project to devise monitoring schemes. As a former lawyer for the IAEA, Rockwood expertly lays out historic precedents for developing new norms and approaches for safeguards. George Moore's essay, "The 6 Percent Solution: LEU-Fueled Reactors and Life-of-Ship Reactors for the US and UK Navies," lays out the rationale for the United States and United Kingdom switching to low-enriched uranium fuel. Peter Lobner describes the US naval nuclear program in detail in his essay, "Assessing Challenges to Completely Eliminating Use of

[3] An agreement to end production of fissile material for nuclear weapons has been on the nuclear-disarmament agenda for decades and is considered, along with a Comprehensive Test Ban Treaty, to be a critical step on the path toward disarmament. Debate has raged over whether the treaty should ban just future production or also include existing stocks. The only negotiating mandate ever (briefly) agreed upon, the Shannon mandate of 1995, left the question of scope open for negotiators to determine. Besides meetings of governmental experts, no negotiating progress has occurred at the Conference on Disarmament in Geneva on this topic.

Highly Enriched Uranium in US Naval Reactors." A former nuclear submariner, Lobner lays out mission and procurement considerations of the US Navy.

For bureaucratic, political, and economic reasons, steps that could mitigate the risks that naval nuclear fuel pose for proliferation and nuclear security have been unpopular. The four nuclear-security summits held between 2010 and 2016 successfully challenged the status quo regarding HEU in the civilian nuclear sector but left HEU in the military sector untouched. Legal routes to further restrictions, such as amending the NPT, completing a fissile-material treaty, or bringing the nuclear-weapons ban into effect, are long, arduous, and possibly not worth the effort. In the interim, therefore, it makes sense to explore whether countries with naval nuclear programs can take actions individually or together that would support norms to reduce the proliferation and security risks associated with existing and future programs. This compilation of essays explores whether norms such as greater transparency in the form of new monitoring approaches, restraint in the use of HEU stocks, and a global cap on uranium enrichment levels might be feasible or achievable.

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Mitigating the Threat of Nuclear Proliferation from Nuclear-Submarine Programs

FRANK VON HIPPEL

Frank von Hippel is Professor Emeritus at Princeton University. He co-founded the Science and Global Security Program at Princeton and the International Fissile Materials Panel.

The "submarine loophole"[1] in the nonproliferation regime is as old as the Nuclear Nonproliferation Treaty (NPT), which entered into force in 1970. Under that treaty, non-nuclear-weapon-state parties forgo nuclear explosive devices, and all nuclear materials in "peaceful nuclear activities" must be placed under International Atomic Energy Agency (IAEA) safeguards. But these states are allowed to use nuclear materials for nonexplosive military purposes outside safeguards. The loophole was inserted into INFCIRC/153 (IAEA 1972), the basic safeguards agreement between the IAEA and non-nuclear-weapon states in 1972 at the behest of Italy and the Netherlands. At the time, Italy was interested in building a nuclear-powered naval transport and the Netherlands was interested in nuclear attack submarines (Fischer 1997, 272).[2]

The result was INFCIRC/153, paragraph 14, "Non-Application of Safeguards to Nuclear Material to

[1] In addition to nuclear submarines, the United States and France have used nuclear reactors to power aircraft carriers, and Russia has used them to power guided-missile cruisers. To date, however, non-nuclear-weapon states have only expressed an interest in acquiring nuclear-powered attack submarines.

[2] Jeffrey M. Kaplow cites sources to the effect that the United Kingdom was also concerned that, if the treaty banned the transfer of naval propulsion technology, that might become a barrier to such transfers from the United States to the United Kingdom (Kaplow 2017).

Be Used in Non-Peaceful Activities,"[3] which allows a non-nuclear-weapon state to remove nuclear materials from IAEA monitoring ("safeguards") for any military purpose other than the "production of nuclear weapons or other nuclear explosive devices." No non-nuclear-weapon state has yet invoked paragraph 14, but a number have expressed an interest in acquiring submarines powered by nuclear reactors.

The official US interpretation of paragraph 14 when it was negotiated states that

> "it provides for the narrowest possible circumstances under which safeguards would not be applied with respect to activities and materials employed in 'non-proscribed military uses.' While the [International Atomic Energy] Agency has no right to approve such uses, or to request classified information concerning them, states may exercise this discretion only after entering into arrangements with the Agency which delimit the exemption insofar as possible. Of particular significance, activities, such as enrichment or reprocessing, which simply produce or process nuclear materials employed in non-proscribed military uses are not themselves military non-proscribed uses, and must be safeguarded" (International Energy Associates Limited 1984, 134).

For the case of Brazil,[4] which is building its first nuclear submarine in collaboration with France, academics have put forward proposals for how to verify that the enriched uranium Brazil removes from safeguards is not diverted to make a nuclear explosive. The basic idea is as follows:

1. The enriched uranium would remain under IAEA safeguards until it is introduced into the fuel fabrication process.

2. Thereafter, if the design of the fuel is considered sensitive, IAEA inspectors would use containment-and-surveillance techniques to verify that no material leaves the fuel fabrication facility or associated storage facilities without the IAEA's knowledge. The inspectors would check the interiors of these facilities after production campaigns to verify that no undeclared enriched uranium remains.

3. Until the fuel was loaded into a submarine's reactor, inspectors would monitor the fuel from outside a container that would conceal its design details.

4. After the submarine fueling was complete, the inspectors would seal the pressure vessel containing the reactor core and the submarine's refueling hatch in a manner that would reveal if they had been opened before the next inspection.

5. When spent fuel is discharged from the reactor, inspectors would be present and place it under safeguards, with the fuel again inside a sealed container if necessary.

6. Ultimately, the spent fuel would be deposited into an IAEA-safeguarded geological repository or would be reprocessed. If it were reprocessed, some sort of containment and surveillance of the process would be required until after the fuel was dissolved and the additional elements of regular IAEA safeguards (that is,

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[3] "The Agreement [between the state and the IAEA] should provide that if the State intends to exercise its discretion to use nuclear material which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement, the following procedures will apply
(a) The State shall inform the Agency of the activity, making it clear:
(i) That the use of the nuclear material in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and
(ii) That during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices;
(b) The Agency and the State shall make an arrangement so that, only while the nuclear material is in such an activity, the safeguards provided for in the Agreement will not be applied. The arrangement shall identify, to the extent possible, the period or circumstances during which safeguards will not be applied. In any event, the safeguards provided for in the Agreement shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity. The Agency shall be kept informed of the total quantity and composition of such unsafeguarded nuclear material in the State and of any exports of such material; and
(c) Each arrangement shall be made in agreement with the Agency. The Agency's agreement shall be given as promptly as possible; it shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of the nuclear material therein" (IAEA 1972).

[4] It has been pointed out to me by Leonam dos Santos Guimarães, formerly a senior official in Brazil's nuclear-submarine program (Leonam dos Santos Guimarães, email to author, January 6, 2018) that the IAEA's safeguards agreement with Argentina and Brazil, INFCIRC/435, is unique, because it is a quadripartite agreement between the IAEA and the two countries plus their joint safeguards agency, the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials, or "ABACC." Furthermore, Article 13 of INFCIRC/435 contains a sentence that does not appear in paragraph 14 of INFCIRC/153: "[T]he State Party and the Agency shall make an arrangement so that, these special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity as agreed between the State Party and the [International Atomic Energy] Agency." This language suggests that the IAEA and Brazil could agree on nonintrusive verification arrangements ("special procedures") while the fissile material is not subject to standard IAEA safeguards. If this language does indeed give the IAEA additional leverage in the negotiation of verification arrangements with Brazil, an agreement with Brazil on such procedures could be a valuable precedent in negotiating verification arrangements on submarine nuclear fuel cycles with other countries.

in addition to containment and surveillance) could be reimposed on the recovered uranium and plutonium. (Philippe 2014; Diniz Costa 2017)

Even assuming perfect seals, the interval between the refuelings of nuclear submarines is typically on the order of a decade or more,[5] which is much longer than the weeks or months (depending on the enrichment level) within which the IAEA would consider detection of diversion to be timely (IAEA 2002, 22). Confidence in the verification system would therefore depend on a diversion analysis that concluded that, after the reactor compartment is closed up and its reactor is powered up, clandestine diversion and recovery of the enriched uranium in the fuel would be either detectable or implausible. It could, for example, be argued that fuel could not be extracted from a submarine except at a known facility with the necessary capabilities and that activities at the small number of possible sites could be monitored by satellites. It also could be argued that, after a submarine reactor has been powered up for a significant length of time, its fuel will be radioactive and recovery of its enriched uranium would require a reprocessing plant. Clandestine arrangements could be improvised, however, and these issues can be debated.

Nuclear-Submarine Programs as Justifications for National Enrichment Programs

A second proliferation issue associated with nuclear-submarine programs is that they provide excuses for acquiring national enrichment plants—or, for a country that already has an enrichment plant, an excuse to produce highly enriched uranium (HEU). Brazil's enrichment program, which was launched while the country was ruled by a military junta (1964-85), is still controlled by Brazil's navy. Brazil has two enrichment plants: one that produces uranium enriched up to 20 percent uranium-235 for a prototype naval reactor and for research reactors, and a "commercial" plant that enriches uranium up to about 4 percent for Brazil's power reactors. As of the end of 2016, although it had been three decades since Brazil mastered centrifuge technology, Brazil's civilian enrichment plant had only enough capacity to produce about 40 percent of the annual enrichment requirements for its first power reactor, the 34-year-old, 600-megawatt electric (MWe) Angra-1 (INB 2016, 11).[6] This is not a significant amount of civilian capacity, but it is a proliferation concern because, if reconfigured to produce weapon-grade (90 percent enriched) uranium, it could produce enough material for a nuclear bomb in about a month.[7] Recall that the Obama administration's requirement for the Iran nuclear deal was that Iran's enrichment capacity and stock of potential low-enriched uranium (LEU) feed be reduced to the point where it would take Iran at least a year to produce enough HEU for a bomb.

To prevent use of the submarine loophole to acquire HEU for a nuclear weapon, the IAEA would have to determine whether a country was truly pursuing a naval nuclear program or not. In 1978, in response to a question from Australia, IAEA Director General Sigvard Eklund stated that, if any member state invoked paragraph 14 of INFCIRC/153, the IAEA's agreement with that state on the arrangements for removal of enriched uranium from safeguards would have to be submitted to the IAEA Board of Governors (Hibbs 2017). This would give concerned countries represented on the board an opportunity to ask pointed questions about the proposed program even if the IAEA Secretariat had not.

This paper discusses the following subjects:

1. Historical and current interest among non-nuclear-weapon states in acquiring nuclear-powered attack submarines;

2. That the missions for submarines sought by countries such as Brazil and South Korea could be accomplished more cost-effectively with advanced conventional attack submarines; and

3. The options for obtaining the necessary enriched uranium fuel if countries insist on nuclear submarines.

Interest Among Non-Nuclear-Armed States in Acquiring Nuclear Submarines

Since INFCIRC/153 was introduced in 1972, five countries without nuclear weapons have considered with various degrees of seriousness acquiring nuclear-powered attack submarines. In approximate historical order, they are Brazil, Canada, Iran, Australia, and South Korea.

[5] A decade for France, Russia and probably China. The United States and the United Kingdom are moving to lifetime cores—that is, 30-40 years—for their submarines. Recently, Russia's lead design bureau for submarine propulsion reactors has announced that it is working on a lifetime core (RT News, 2018).

[6] Assuming an annual consumption of 20 tons of 4 percent enriched uranium per gigawatt electric of capacity.

[7] For 90 percent enriched uranium containing 25 kilograms (kg) of U-235 assuming 4.3 percent enriched feed and 0.4 percent U-235 depleted uranium.

Brazil[8]

Brazil's navy has been interested in nuclear submarines since the end of the World War II and made its first attempt to acquire gas centrifuges for uranium enrichment from Germany in 1954. In 1975, after the United States indicated that it did not have enough enrichment capacity to provide fuel for Brazil's first nuclear reactor, which the United States had supplied, Brazil signed a contract with Germany for power reactors, an enrichment plant, and a reprocessing plant.

The Netherlands, which is a partner with German utilities and the United Kingdom in Urenco, a uranium enrichment combine, vetoed the transfer of centrifuge technology to Brazil, which the United States also opposed. Germany therefore delivered instead jet nozzle enrichment technology that was not subject to the Urenco agreement. That technology proved impractical, however. Starting around 1978, therefore, Brazil's navy launched an indigenous centrifuge enrichment program based in part on detailed design information on the first Soviet gas centrifuges that had been published by the US Atomic Energy Commission in 1960 (Kemp 2017). This program succeeded in 1985—possibly with the clandestine assistance of German engineers—and, by 1988, Brazil was producing uranium enriched up to the internationally agreed threshold for weapon usability, 20 percent (Glaser 2006).

In 2008, Brazil signed a contract with France to build five submarines of French design in Brazil, with the fifth submarine to be powered by a Brazilian-designed reactor (Groizeleau 2017). A land-based prototype reactor, LABGENE, with a design power of 48 megawatts thermal, is currently under construction at Brazil's Naval Technological Center in Iperó, Sao Paolo (Piovezan and Abe 2014; de Carvalho and de Oliveira Neto 2011).

Canada

Canada explored buying nuclear attack submarines in 1987. Both France and the United Kingdom offered to sell versions of their nuclear attack submarines. The project was abandoned, however, because of cost, opposition from the United States, and opposition from Canadian citizens concerned about nuclear accidents in the wake of the 1986 Chernobyl accident (Burns 1987; Weston 2011; Wikipedia 2018b).

Iran

It is not clear that Iran's interest in nuclear submarines is serious. Its government has publicly expressed interest in developing propulsion reactors on only two occasions—both after the United States escalated sanctions on Iran. It is therefore possible that these statements were simply signals that Iran too could escalate by producing HEU—nominally for a future propulsion reactor. Although China and France are believed to use LEU to fuel their nuclear submarines, the United States, the United Kingdom, Russia, and India have all set the unfortunate precedents of using HEU—weapon-grade HEU in the US and UK cases (von Hippel 2016).[9]

In 2013, during the period of confrontation before productive negotiations over Iran's nuclear program began, the head of the Atomic Energy Organization of Iran (AEOI) suggested that Iran might require uranium enriched to 45-56 percent for a nuclear-submarine program (Reuters 2013). More recently, after the US Congress extended the Iran Sanctions Act in 2016, Iran's president, Hassan Rouhani, ordered the head of the AEOI to come up with a plan for producing nuclear-powered ships and the fuel to propel them (AP 2016). Since Iran committed in the July 2015 nuclear deal—formally known as the Joint Comprehensive Plan of Action (JCPOA)—that its nuclear program would be "exclusively peaceful," it must be assumed that the plan that President Rouhani called for would be implemented only if the deal collapsed or that it would be for a civilian ship, in which case the fuel would be under safeguards (Hibbs 2017).

Australia

In December 2016, Australia signed a $38 billion (AUD 50 billion) contract with France for 12 submarines that will be diesel-driven derivatives of France's latest class of nuclear attack submarines, the Barracuda class (Ohff 2016). With the cost comparable to that of nuclear submarines, the obvious question was raised: Why not buy the nuclear version? This idea was rejected, however, in part because of the country's lack of the personnel and infrastructure to operate nuclear submarines (Scimia 2017).

South Korea

South Korea's president, Moon Jae-in, has declared his interest in building or buying nuclear attack submarines. During US President Donald Trump's November 2017 visit to Seoul, the two leaders reportedly discussed the possibility of South Korea purchasing a US nuclear attack submarine (Yeo 2017). Recently, Russia's premier designer of naval propulsion

[8] Unless otherwise indicated, the history summarized here is from de Sá (2015).

[9] Russia and India are believed to use 21-45 percent enriched uranium.

reactors, OKBM Afrikantov, made public the fact that, in 2017, it had discussions with the Korea Atomic Energy Research Institute on the possibility of providing the design of a new Russian icebreaker reactor as a "reference design" for a South Korean "maritime propulsion" reactor (Sputnik International 2018).[10] The Russian icebreaker reactor, the RITM-200, was designed to use LEU fuel (IAEA 2016a, 180) but apparently will use HEU fuel (IPFM 2017).

Nuclear versus Nonnuclear Submarines

Forty countries have attack submarines today, but only the five original nuclear-weapon states—China, France, Russia, the United Kingdom, and the United States—have nuclear-powered attack submarines.[11]

There are two primary reasons: cost and mission.

Cost

Nuclear submarines usually cost several times more per unit than conventional submarines. For example, in production at a rate of two per year, US *Virginia*-class attack submarines cost about $2.7 billion each (O'Rourke 2018, 3). For comparison, Germany's Type 212 conventional submarines reportedly each cost about $0.4 billion (Roblin 2017) and France's *Scorpène* about $0.6 billion in deals agreed to in 2005 and 2008, respectively (Defense Industry Daily 2014; Rahmat 2017). Nuclear submarines also can be quite costly to repair and decommission.

In part, the disparity in capital cost reflects the larger size of the *Virginia*—about 8,000 tons displacement submerged (US Navy 2017) vs. 1,800 tons for the Type 212. Nuclear submarines generally have much larger displacements than conventional submarines, although France's first nuclear attack submarine, *Rubis*, displaced only 2,600 tons (Wikipedia 2018c).

Two of the five countries with nuclear submarines also operate nonnuclear submarines, perhaps to save money. Only five of China's 59 attack submarines (Office of the Secretary of Defense 2017, 24) and about half of Russia's 41 attack submarines (D-Mitch 2018) are nuclear-powered.

Mission

As the name suggests, the principal mission of attack submarines is to attack other countries' ships and submarines. For most countries, the mission is local—to defend a country's home waters against foreign navies. For this purpose, a modern conventional submarine is adequate. Unlike the World War II diesel submarines, which were powered by batteries with very limited range when completely submerged without access to air,[12] modern conventional submarines operating at depth are powered by fuel cells that consume liquid hydrogen and oxygen stored outside the pressure hull (Biert et al. 2016). This makes it possible for modern conventional submarines to spend weeks on a patrol of thousands of kilometers without putting up a snorkel tube to take in air.[13]

Under license from Germany, South Korea built nine Type 214 (KSS-2) attack submarines similar to the Type 212. South Korea's interest in nuclear submarines reportedly stems from a desire to track future North Korean ballistic-missile submarines at all times (Gady 2017). But the larger number of modern conventional submarines that South Korea already has in its fleet could do as well or better.

One article, by a retired captain of a South Korean destroyer, Sukjoon Yoon, cites a study by the Korea Institute for Maritime Strategy that recommended that South Korea's next attack submarines be nuclear powered and capable of "long-endurance underwater operations (preferably 50 percent longer than [North Korea's] Sinp'o/Gorae-class [ballistic-missile submarines]), high speed, and improved maneuverability at various depths in the complex underwater spaces around the Korea Peninsula (Yoon 2017)." However, the Type 214's fuel cells already give it the desired superiority over the North Korean battery-powered submarines for long-endurance, air-independent underwater operations. Also, smaller nonnuclear submarines can be more maneuverable than large nuclear submarines. On the other hand, nuclear submarines have higher speed than conventional submarines and, as Yoon states, "can both chase enemy submarines and elude torpedo attacks on themselves." But he also acknowledges that "only an ASW [anti-submarine-warfare]-oriented naval task force will be able to conduct effective ASW operations in the complicated underwater environment around the Korea Peninsula, in which sound distortion is commonplace." An

[10] An email communication to the author from a South Korean government official on August 9, 2018, stated that the Moon administration was no longer actively pursuing the idea of a nuclear-powered attack submarine.

[11] At the end of 2017, India announced that it was building six nuclear-powered attack submarines (Business Standard 2017).

[12] The Barbel-class submarines, the last conventional submarines built for the US Navy (1956-59) could spend 102 hours (about four days) submerged while traveling at 5.6 kilometers (km) per hour for a total distance of about 600 km (Wikipedia 2018a).

[13] A German 212-type submarine has traveled 2800 km in two weeks without either surfacing or snorkeling, an average speed of about 8 km/hr (Thomas 2008).

ASW task force would include surface ships, fixed-wing aircraft able to drop sonar sensors and to detect snorkel tubes with radar, and helicopters, as well as attack submarines.

The primary missions of US nuclear-powered attack submarines are to protect US carrier strike forces from hostile submarines and to trail Russian and Chinese ballistic-missile submarines. These tasks require traveling long distances at sustained high speeds submerged, either accompanying an aircraft carrier task force or moving to distant areas where Russian or Chinese ballistic-missile submarines are deployed, missions for which nuclear submarines are uniquely suited. France and the United Kingdom, unlike the United States, no longer have far-flung military commitments. Each does have a single aircraft carrier, however, and he United Kingdom is planning for a second one. An additional task for the French and UK nuclear attack submarines is to assure that hostile attack submarines do not trail the sometimes single ballistic-missile submarine that each has at sea as its nuclear deterrent. A mission for Russian and Chinese nuclear attack submarines would be to attack US carrier battle groups and keep foreign nuclear attack submarines from loitering in the "bastion" areas at sea where they deploy their ballistic-missile submarines.

In short, nuclear attack submarines are superior for travel to distant deployment areas, not for tracking a neighbor's diesel submarine in nearby waters.

Fueling a Nuclear Submarine

A key question a country interested in acquiring a nuclear-powered submarine must consider is where can it obtain the enriched uranium for the reactor fuel? Four of the six nuclear-armed states that currently have nuclear submarines have domestic uranium mines and national uranium enrichment capabilities. Each of the other two (the United Kingdom and the United States), lacks a national enrichment facility but has access to so much excess weapon-grade uranium from the downsizing of the US Cold War nuclear weapon stockpile that it will not need to make more HEU for about another 40 years.[14] Among the non-nuclear-weapon states currently interested in acquiring nuclear submarines, Brazil and Iran both have uranium mines and enrichment programs. This leaves South Korea, which has neither.

Uranium Suppliers

The need to acquire natural uranium is not a major barrier to a country interested in fueling a few nuclear-powered attack submarines. Fueling a single nuclear submarine would require mining less than 10 metric tons of natural uranium per year.[15] A 10-year core would require less than 100 tons. Figure 1 shows that there are 11 countries that each accounted for more than 1 percent of global production of natural uranium in 2014. One percent was about 560 tons per year. Virtually any country has sufficient low-grade uranium ores to produce much more than 10 tons per year (Deffeyes and MacGregor 1980).

IAEA Reporting Requirements

Paragraph 34 of INFCIRC/153, which virtually all non-nuclear-weapon states have signed, requires the following:

> (a) When any material containing uranium or thorium which has not reached the stage of the nuclear fuel cycle described in subparagraph (c) below is directly or indirectly exported to a non-nuclear-weapon State, the State shall inform the Agency of its quantity, composition and destination, unless the material is exported for specifically non-nuclear purposes;
>
> (b) When any material containing uranium or thorium which has not reached the stage of the nuclear fuel cycle described in sub-paragraph (c) below is imported, the State shall inform the Agency of its quantity and composition, unless the material is imported for specifically non-nuclear purposes; and
>
> (c) When any nuclear material of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced, or when such nuclear material, or any other nuclear material produced at a later stage in the nuclear fuel cycle, is imported into the State, the nuclear material shall become subject to the other safeguards procedures specified in [this] Agreement.

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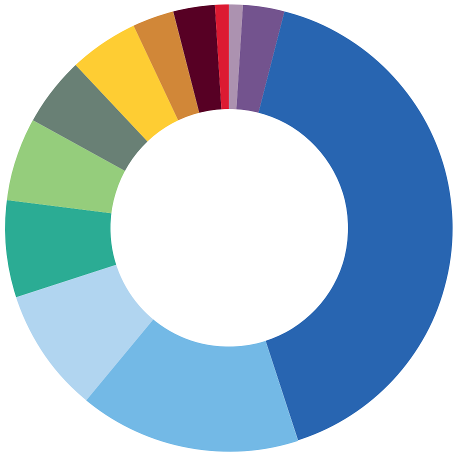
[14] The United Kingdom receives both naval reactor technology and highly enriched uranium for fueling its naval reactors under the Agreement between the Government of the United Kingdom of Great Britain and Northern Ireland and the Government of the United States of America for Co-operation on the Uses of Atomic Energy for Mutual Defence Purposes of 1958. The text of the agreement, as amended through 1994, may be found at http://www.reformation.org/text-of-1958-us-uk-mutual-defense-agreement.html. The most recent amendment and 10-year renewal, which was in 2014, can be found at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/396347/TS_2.2015_Cm_8996_Web.pdf.

[15] A reactor with a capacity of 150 MW thermal (MWt) operating at an average of 25 percent power would fission about 14 kg of U-235. If one assumes 50 percent of the U-235 in the fuel is fissioned, that would increase the annual U-235 requirements to about 30 kg. On the assumption that 60 percent of the 0.7 percent of U-235 in natural uranium ends up in the naval reactor fuel, about 7.5 metric tons of natural uranium would be required annually.

Figure 1: Uranium Production in 2014



- Ukraine 1%
- Others 3%
- Kazakhstan 41%
- Canada 16%
- Australia 9%
- Niger 7%
- Namibia 6%
- Russia 5%
- Uzbekistan 5%
- United States 3%
- China 3%
- Malawi 1%

Source: NEA and IAEA, 2016, 62

As illustrated by Iran's imports prior to the JCPOA, however, some suppliers in Africa have ignored these requirements (Hibbs 2013; Barnes 2013). Israel reportedly simply hijacked a shipment of 200 tons of natural uranium to meet its early needs for fueling its plutonium production reactor (Davenport, Eddy, and Gillman 1978).

Bilateral Obligations

In addition to the IAEA's notification requirement, many uranium exporters have bilateral peaceful-use agreements with importers that prohibit the use of their uranium for any military purpose. Australia, Canada (Canadian Nuclear Safety Commission 2017) and the United States, which together accounted for 28 percent of the uranium mined in 2014, require countries importing their uranium to track it and report its location to the supplier until it is placed under IAEA safeguards.[16]

Enrichment Suppliers

In contrast to the many potential suppliers of natural uranium, only three countries (China, France, Russia) plus the multinational Urenco dominate the enrichment market (Figure 2[17]). In addition, there are three countries—Brazil, Iran, and Japan—with enrichment capacities too small to produce enough enriched uranium to fuel a single 1000-MWe-class nuclear power reactor (about 0.1 million separative work units [SWUs] per year) but big enough to produce enough fuel for a submarine reactor or to be a significant nuclear-weapon proliferation concern (World Nuclear News 2015; Japan Nuclear Fuel Limited 2018).[18]

Brazil's 2016 enrichment capacity of 0.02 million SWU (MSWU) could produce about 500 kilograms of 20 percent enriched uranium per year, enough to fuel a few nuclear submarines.[19] Iran's capacity of 0.005 MSWU is four to five times lower than its capacity prior to the JCPOA but is expected to increase to more than 0.1 MSWU by around 2030 as that deal expires (AEOI 2014).[20]

Thus, South Korea is the only non-nuclear-weapon state currently interested in naval reactors that does not have an enrichment plant.

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[16] Australia describes its bilateral administrative agreements (AAs) with 36 countries as follows: "The AAs are drafted in accordance with IAEA safeguards and to avoid duplication, the AAs use the IAEA's accounting system, but include set procedures by which material included under the corresponding agreement can be identified (country of origin may be traced)… Once [Australian obligated nuclear material] has been converted into a usable form, it becomes subject to IAEA safeguards and [IAEA] inspection activities become responsible for ensuring that nuclear material is used for peaceful purposes" (Joint Standing Committee on Treaties 2006, 51-53).

[17] The figure includes Brazil, India, Iran, and Japan in "other" with a total capacity of 0.045 million SWU/yr. That calculation assumed the following capacities: Argentina (although its plant is not currently operating) 0.02; Brazil, 0.02; Iran, 0.005; and Japan 0.075 million SWU.

[18] Argentina operated its Pilcaniyeu gaseous-diffusion enrichment plant, which has a reported capacity of 0.02 million SWU/yr, from 1983 to 1989. In 2015, it announced implausible plans with no timetable to upgrade it to a capacity of 3 million SWU/yr. In 2017, based on its production of 4.3 percent enriched uranium, Brazil produced about 0.025 million SWU at its commercial enrichment plant (INB 2018, 27). Iran is limited by the Joint Comprehensive Plan of Action till 2025 to operating 5060 IR-1 centrifuges (about 0.005 million SWU capacity); Japan's capacity is about 0.075 million SWU/yr.

[19] Assuming 50 percent fission of the U-235, this much fuel per year could produce an average of 140 MWt. This is approximately the peak output of an attack submarine reactor, but the average output may only be 20 percent as large.

[20] The primary justification for Iran's enrichment program has been to supply the Bushehr power reactor. Assuming 27 metric tons per year of 3.5 percent enriched uranium to fuel the reactor, the enrichment work required to fuel the Bushehr I reactor is approximately100,000 SWU/yr.

Figure 2: Global Enrichment Capacity, 2015

Source: World Nuclear Association, 2017

It therefore would have to either build its own enrichment plant or buy enrichment services.

Building an enrichment plant

The NPT does not explicitly prohibit a country from acquiring an enrichment plant. That is, in fact, one of the most important weaknesses of the nonproliferation regime. South Korea is technically advanced and could build enrichment capacity sufficient to support at least a few submarines in a few years, if it were not concerned about the plant's economic competitiveness. The United States is South Korea's main security and nuclear energy partner, however, and South Korea therefore is sensitive to US views on the matter.

For decades, since the 1992 Joint Declaration of the Denuclearization of the Korean Peninsula, the United States has opposed South Korea building either an enrichment or reprocessing plant because that would undermine the objective of eliminating such facilities in North Korea. The renewal of the US agreement for peaceful nuclear cooperation with South Korea, which was scheduled to expire in 2014, was delayed by more than a year because of the need to resolve disagreements over South Korea's interest in enrichment and reprocessing (Choe 2011). Ultimately, the United States did not agree to South Korea acquiring either type of facility but the left open the possibility for the future. The agreement therefore says:

> Any facility designed or used primarily for uranium enrichment, reprocessing of nuclear fuel, heavy water production, or fabrication of nuclear fuel containing plutonium, and any part or group of parts essential to the operation of such a facility may be transferred under this Agreement if provided for by an amendment to this Agreement, or may be transferred under a separate agreement between the Parties. (South Korean-US Nuclear Agreement 2015)

A provision later in the agreement specifies that, if South Korea enriches uranium under the agreement, it must keep the enrichment level below 20 percent. Elsewhere, the United States has acknowledged that it cannot control what South Korea might do with uranium and technology provided by other countries but, once again, South Korea would be attentive to the views of its principal military ally.

The Trump administration's views may be different from its predecessors' on the desirability of South Korea acquiring an enrichment plant, and South Korea has a new president whose views also may be different from those of his predecessor. A revised agreement for nuclear cooperation would, however, take some time to negotiate and also would have to be submitted to Congress, which could disapprove all or part of it within 90 days of continuous session (Nuclear Nonproliferation Act of 1978).

The Nuclear Suppliers Group (NSG) guidelines discourage the spread of national enrichment plants – especially if they could be used to produce highly enriched uranium:

> If enrichment or reprocessing facilities, equipment or technology are to be transferred, suppliers should encourage recipients to accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities. Suppliers should also promote international

> (including IAEA) activities concerned with multinational regional fuel cycle centres…
>
> For a transfer of an enrichment facility, or equipment or technology therefor, suppliers should seek a legally-binding undertaking from the recipient State that neither the transferred facility, nor any facility incorporating such equipment or based on such technology, will be modified or operated for the production of greater than 20% enriched uranium. Suppliers should seek to design and construct such an enrichment facility or equipment therefor so as to preclude, to the greatest extent practicable, the possibility of production of greater than 20% enriched uranium. (IAEA 2016b, 3, 4)

The guidelines also highlight the NSG requirement that exports not be used for military purposes, advising that suppliers

> should consult with potential recipients to ensure that enrichment and reprocessing facilities, equipment and technology are intended for peaceful purposes only… (IAEA 2016, 3).

Argentina, Brazil, China, France, Germany, Japan, Netherlands, Russia, the United Kingdom and the United States are all members of the NSG.

Provision of enriched uranium

With regard to the provision of enriched uranium, the Chinese, French, Russian, and US agreements for cooperation with South Korea on the peaceful uses of nuclear energy require that materials and technology transferred to South Korea be exclusively for peaceful use (South Korea-Chinese Nuclear Agreement 1995; French-South Korean Nuclear Agreement 1982; South Korean-Russian Nuclear Agreement 1999; South Korean-US Nuclear Agreement 2015). The same situation reportedly applies with regard to the European countries with Urenco enrichment plants (Carlson 2017).

Conclusions

The current nonproliferation regime allows countries to acquire or construct nuclear-powered submarines or ships for military purposes. However, it discourages other countries from providing enriched uranium for nonpeaceful activities. This leaves a country interested in adding nuclear-powered vessels to its navy with the option of mining its own uranium and building its own enrichment plant. This is, in fact, what Brazil, the first non-nuclear-weapon state to embark on building a nuclear submarine, is doing. Iran, which has expressed an interest in building nuclear-powered vessels, already has uranium mines and an enrichment plant and could do the same.

South Korea, if its plans solidify, would be the first country interested in acquiring a nuclear submarine that does not already have an enrichment capacity. It has expressed an interest in acquiring such a capacity in the past but the United States has discouraged South Korea from doing so out of concern that it would make it more difficult to persuade North Korea to give up its enrichment program. US opposition to South Korea building an enrichment plant is also consistent with the policy of the Nuclear Suppliers Group, which is to discourage the proliferation of national enrichment plants. Fortunately, from a nonproliferation perspective, the military case for South Korea acquiring nuclear-powered instead of advanced conventional submarines appears weak.

The acquisition of national enrichment plants by non-nuclear-weapon states to fuel naval reactors remains a challenge to the nonproliferation regime, however. If it becomes possible to end the production of enriched uranium for nuclear weapons in a Fissile Material Cutoff Treaty, the retention of national enrichment plants by the nuclear-weapon states to provide naval reactor fuel will become a major weakness to the nuclear-disarmament program as well.

In the case of the provision of enriched uranium for civilian purposes, the alternative to the proliferation of national enrichment plants has been for a few countries to become the suppliers of enrichment services to the rest of the 30 countries with nuclear power plants. This has worked because the economies of scale have made it less costly for all but the countries with the largest reactor fleets. This arrangement could be made less discriminatory by turning the big suppliers of enrichment into multinationals, building on the model that Urenco has provided.

Could there be multinational arrangements for supplying enriched uranium for naval reactors? The United States already supplies the United Kingdom with enriched uranium for its nuclear submarines. France's enrichment plant uses centrifuges made by a joint subsidiary with Urenco but produces fuel for France's submarines as well as for its power reactors. If South Korea could not be persuaded to abandon its nuclear-submarine project, would it be better for the nonproliferation regime if its principal security partner, the United States, supplied the enriched uranium than for South Korea to acquire its own enrichment plant? Would it make sense for Brazil to form a multinational enrichment partnership with Argentina that would supply enriched uranium both for their power plants and for Brazil's nuclear submarines? The multinational approach for supplying enriched uranium is not obvious for all naval propulsion programs but perhaps it is worth considering as an option.

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Brazil's Nuclear Naval Fuel: Choices and a Road Map for Productive Engagement

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Brazil is likely to be the first non-nuclear-weapon state to commission a nuclear-propelled submarine. This will pose a stress test to the nonproliferation regime, raising a number of issues pertaining to the application of safeguards and the verification of the nondiversion of nuclear materials from a military activity. The existing literature has variously identified key legal issues that are likely to arise and put forward alternative models for the application of safeguards on the naval nuclear fuel cycle in a military environment (Philippe 2014; Diniz Costa 2017; Rockwood 2017). This paper begins by laying out the preferences of the Brazilian nuclear establishment with regard to nuclear fuel for naval reactors. It then assesses the strategic environment within which such preferences play out in practice, highlighting the core dynamics within Brazil that currently affect (and that are likely to shape) the evolution of the nuclear-submarine program in the immediate future. The third and final section identifies avenues for productive engagement by the international community with Brazilian authorities moving forward in three interrelated areas: the nonapplication of safeguards, the future of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), and the future of nuclear latency.

Preferences

Construction work for the nuclear-propelled submarine is under way at the Prosub shipyard in Itaguaí (Rio de Janeiro), where naval infrastructure for the fabrication and assembling of components is already in place. Actual fabrication and assembling of the nuclear-propelled submarine is expected to start in 2020. A facility for specialized maintenance and waste management of nuclear materials and a naval base for the operation of submarines are also being built at the same complex in Itaguaí.

Related developments have also taken place in the Navy's technological center in Iperó, São Paulo, where Brazil is currently developing a land-based reactor prototype for the submarine (estimated to start operations in 2021) at the LABGENE facility, alongside existing infrastructure for conversion and enrichment of nuclear materials and fabrication of the fuel assemblies that make up the reactor core. Safeguards inspections (announced and unannounced) at Iperó have been underway since 1991 even though it is a military installation. Furthermore, Brazil has provided the International Atomic Energy Agency (IAEA) with design information for the reactor, and facilities for the operation of the prototype at Iperó were built under the principle of "safeguards by design," which consists of a "voluntary process to facilitate the improved implementation of existing safeguards requirements, providing an opportunity for stakeholders to work together to reduce the potential of unforeseen impacts on nuclear facility operators during the construction, startup, operation and decommissioning of new facilities" (IAEA 2017).

Judging from publicly available budgetary information, funds from the federal government keep flowing to the nuclear program in spite of Brazil's current fiscal crisis and economic stagnation. The total cost of the submarine program (which also includes four Scorpène-class submarines) is worth BRL 31.8 billion ($8.1 billion) as of this writing (Ministério da Defesa, 2017, 59-67). Although there are no firm dates for commissioning the submarine—and significant delays have plagued the program from the outset—current official estimates for completion point to 2029, with operations starting in 2030.

With a view to minimizing proliferation risks and curbing fears that naval nuclear fuel could be used as a smokescreen for the unmonitored accumulation of fissile material in the future, the Brazilian Navy has committed to using a once-through fuel cycle using low-enriched uranium (LEU) for its submarines and to placing its naval reactor fuel under safeguards. Critics note that the commitment to an LEU submarine is unilateral and could in theory be abandoned or reversed, but it is worth pointing out that Brazilian officials, both in the submarine program and in the government more generally, are very sensitive to criticism that Brazil might become an "irresponsible stakeholder" as the nuclear-submarine program evolves. At least thus far, they have signaled a commitment to LEU each step of the way. The key factor determining the precise level of enrichment for the fuel elements going into the reactor core will be a technical one. Experts such as Odair Gonçalves, the former president of Brazil's National Nuclear Energy Commission, predict an enrichment level of 18 to 19.9 percent uranium-235, a figure that keeps popping up in public presentations by Navy officials (Pomper and Huntington 2005; Freebairn 2014; Kassenova 2014). Others have suggested that Brazil will follow the French model by using fuel that is less than 10 percent uranium-235 (Ata da 2a Reunião Ordinária). In contrast, the land-based prototype for the first reactor core of the submarine was based on uranium dioxide rods with uranium enriched to 5.48 percent. Such a model, however, is too fragile to be used in a submarine, which requires fuel that can withstand battle shocks and other extreme conditions deep underwater. In off-the-record conversations, Brazilian officials have reported that there has been exploration of alternative models with fuel plates, but developing this kind of fuel element remains a major technological hurdle. In an event in December 2017 under the Chatham House rule, a high-ranking official within the Navy stated, however, that the first submarine would work with 4.3 percent enriched uranium and that there was "no need" to surpass 19.9 percent—the threshold between LEU and highly enriched uranium (HEU)—in a second or further core.

The basic infrastructure to support the naval fuel cycle is in place already. In 2012, the Navy launched a pilot unit for the conversion of uranium concentrate into uranium hexafluoride at its Iperó facility, which also houses laboratory-scale units for enrichment (LEI) and fuel fabrication (Labmat, Ladicon). The Navy purchases yellowcake (uranium concentrate) from Indústrias Nucleares do Brasil (INB), a public company dedicated to uranium mining and milling. The Navy then is responsible for uranium conversion, enrichment, and fuel fabrication at Iperó.

One concern observers have raised is a scenario under which Brazil builds new uranium enrichment and fuel fabrication plants for the production of nuclear submarine fuel only to claim that such plants need not be subject to IAEA safeguards since they would be dedicated to a nonproscribed military use. Yet, in order to make such claims Brazil would have to violate its existing commitments to ABACC, which require it to accept safeguards on all nuclear material in all nuclear activities. It is worth pointing out that the nuclear fuel cycle-related facilities at Iperó are safeguarded under the Argentina-Brazil-ABACC-IAEA agreement, and that any decision to enrich uranium at levels higher than 5 percent there would have to be approved by all parties under a special safeguards arrangement. Additionally, the Iperó nuclear complex is home to the Brazilian Multipurpose Reactor (RMB) currently under construction with a view to producing radioisotopes for the domestic market. Once the research reactor is ready, the Navy will provide enrichment services for the reactor. In December 2016, the Navy inaugurated the enrichment cascades dedicated to the RMB, which are expected to enrich uranium up to 19.95 percent. The Navy also leases its uranium enrichment technology to INB for use at the Nuclear Fuel Factory at Resende, which is also under safeguards. (Uranium enrichment for the nuclear submarine cannot in principle be done at Resende, given existing safeguards on German-origin equipment. Resende's license allows for enrichment up to only 5 percent, and changing the regulations would require applying for relicensing.)

With regard to safeguards, Brazil is party to a comprehensive safeguards agreement (CSA) with Argentina, ABACC, and the IAEA (IAEA 1994), known as the Quadripartite Agreement. Officials have stated in public—and repeated in private—that they will place the submarine's fuel under inspections, the terms of which will be negotiated within the CSA framework of the Quadripartite Agreement. At a recent event, a top-ranking official within the nuclear program explicitly said intragovernmental discussions about safeguards are currently taking place in a task force within the Brazilian presidential office. It is unclear who sits on the task force and what the time frame for results will be.

Environment

The first constraint on the submarine program today is its governance structure. The program is coordinated by the Brazilian Navy but run under a public-private partnership with technical assistance from France. Private companies operate throughout the project, either as individual commercial actors or as members of sole-purpose public entities. On the French side, assistance is provided by Naval Group (formerly DCNS), a private shipbuilding company in which the French state holds a 62.49 percent stake. Naval Group is responsible for the transfer of technologies pertaining to the nonnuclear components of the submarine (the nuclear sub, four conventional submarines, and the construction of the shipyard and naval base at Itaguaí). On the Brazilian side, infrastructure giant Odebrecht is the main private player. Nuclep, a state company controlled by the National Nuclear Energy Commission, operates as the major national supplier of heavy equipment. Additionally, Naval Group and Odebrecht created Itaguaí Naval Constructions (holding stakes of 41 percent and 59 percent, respectively), with the Navy retaining veto power under a golden-share agreement. Naval Group and Odebrecht also set up a third company, CBS, to provide the Navy with support in the management, coordination, and integration of the submarine program.

In 2017 a major corruption scandal broke, involving allegations that Navy officials involved in the program had colluded with Naval Group and Odebrecht to generate kickbacks worth some 70 million euros. It is too early to assess the long-term damage because investigations are still unfolding in Brazil and France. But it is not inconceivable that legal challenges against core parts of the program will emerge in coming years, further delaying progress and tarnishing the entire submarine enterprise in the court of public opinion.[1] The scandal may also generate new demands for project transparency, financial accountability, and nuclear safety and security that may retard progress further. As of this writing, there is no indication that the corruption investigations underway threaten the survival of the project.

The second constraint on the future evolution of the Brazilian nuclear-submarine project is the issue of safeguards. In the safeguards agreement between Brazil and the IAEA, there is a legal possibility for Brazil, with the approval of the agency's Board of Governors, to remove from safeguards nuclear materials to be used in nonproscribed military activities such as naval nuclear propulsion. Because this possibility limits the power of the agency to verify that nuclear materials are not diverted to pursue the development of nuclear weapons or other nuclear explosive devices, the terms of the withdrawal from safeguards are likely to generate a period of hard-nosed negotiations between Brazil and the IAEA, and possibly between Brazil and Argentina. It is not at all clear at this stage that Brazil will agree to conduct such negotiations under a quadripartite framework involving Argentina, Brazil, the IAEA, and ABACC.

Details here matter. There is potential legal tension between INFCIRC/153, which regulates the structure and content of comprehensive safeguards agreements applied to parties to the

1 For a search mechanism covering all official documents and plea bargains in the hands of the Office of the Prosecutor (in Portuguese), see https://jota.info/justica/jota-lanca-buscador-para-todos-os-processos-da-lava-jato-12042017.

Nuclear Nonproliferation Treaty (NPT) that are non-nuclear-weapon states, and INFCIRC/435, the Quadrapartite Agreement. Paragraph 14 of INFCIRC/153 contemplates the possibility of the "non-application of safeguards to nuclear material to be used in non-peaceful activities." But that paragraph conditions the withdrawal of safeguards on an "arrangement" made by the IAEA and the state party, which must "identify, to the extent possible, the period or circumstances during which safeguards will not be applied." The state party must also commit itself to keeping the IAEA informed about the quantity and content of the unsafeguarded materials and is required to provide assurances, according to INFCIRC/153, paragraph 14, "that the nuclear material will be used only in a peaceful nuclear activity" (IAEA 1972). Yet, INFCIRC/435 commits Brazil "to accept safeguards on all nuclear material in all nuclear activities," differing from the general commitment expressed in INFCIRC/153 ("to accept safeguards…on all source or special fissionable material in all peaceful nuclear activities"). Article 13 of INFCIRC/435 does not refer to "non-application of safeguards to nuclear material to be used in non-peaceful activities" (as in INFCIRC/153), but to "special procedures," which must be applied if the state intends to use "nuclear material which is required to be safeguarded under this Agreement for nuclear propulsion or operation of any vehicle" (INFCIRC/435, Art. 13). Under the Quadripartite Agreement, "these special procedures shall apply only while the nuclear material is used for nuclear propulsion or in the operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity." (INFCIRC/435, Art. 13, (b)).

Tension between paragraph 14 of INFCIRC/153 and paragraph 13 of INFCIRC/435 could greatly increase frictions around Brazil's nuclear-submarine program. Nongovernmental observers, IAEA officials, and foreign governments will warn that unless the differences between the two norms are properly ironed out, there is the potential for the undetected diversion of nuclear material to proscribed nuclear activities and the misuse of nuclear facilities for such purposes. As of this writing, whether or how fuel will be withdrawn from safeguards by the Brazilian Navy remains unclear. In a December 2017 event under the Chatham House rule, a high-ranking official within the Navy stated that "special procedures may be applicable," but would not elaborate further. Signals that Brazil will indeed place the submarine's fuel under some kind of safeguards agreement abound, however. The Iperó facilities are under safeguards, and the new buildings in the Iperó complex that serve the submarine program were built or are being built within the umbrella of safeguards by design. All conversion facilities are subject to verification, too. What remains unclear at the moment—and is likely to dominate eventual bilateral or multilateral negotiations between Brazil and Argentina, ABACC, and the IAEA in the future—is what procedures will apply at the Itaguaí nuclear-sub shipyard.

But several disputes are likely to arise. Differences in these provisions are significant enough to ensure arduous negotiations over issues such as access to military facilities, the point of withdrawal of nuclear materials from safeguards, the provision of information about quantities and composition of nuclear materials, the reapplication of safeguards to previously withdrawn nuclear material, the verification procedures during fueling and defueling, the procedures concerning seal hatches, and the scope of the Board of Governors' involvement in the safeguards arrangement between Brazil and the IAEA. Whatever the technical details of such a negotiation might be, this is likely to be a politically charged process.

The IAEA is likely to demand that nuclear fuel for the submarine be checked before it is loaded into the reactor, ensure the reactor is sealed, and secure authorization to verify such seals each time the submarine enters port or is refueled. Brazil is likely to negotiate the terms of the agreement informed by a sense of political-diplomatic bargaining rather than a merely technical approach to greater transparency and accountability. This is likely to make for a difficult (and possibly protracted) negotiation. Brazil will probably seek to politicize the terms of the negotiation, given its grudges about the state of the global nonproliferation and disarmament regime. It is likely to condition concessions on some progress by the nuclear-weapon states on their disarmament commitments (Ministério da Defesa 2012). In doing so, Brazil will express the disappointment of non-nuclear-weapon states with the pace of disarmament. It will denounce the disproportionality of verification obligations vis-à-vis those of the nuclear-armed states, expressing the idea common among non-nuclear-weapon states that they have to agree to burdensome measures to show that they are not seeking to acquire nuclear weapons, while the nuclear-armed states are not doing anything comparable.

Road Map for Engagement

Most of the writing on Brazil's nuclear-submarine program is bound up with broader concerns in the global nonproliferation community that an increase in the number of states that possess nuclear-powered submarines may have negative implications for proliferation worldwide (Thielmann and Kelleher-Vergantini 2013; Philippe 2014; Egel, Goldblum, and Suzuki 2015; Ritchie 2015). On the Brazilian side, in recent years, officials have refused to sign an Additional Protocol to the country's IAEA safeguards agreement, have gone as far as preemptively rejecting negotiations over such an agreement in its national defense strategy, and have tied possible accession to the Additional Protocol to significant progress by the nuclear-weapon states on their disarmament pledges under the NPT. Moreover, top-echelon politicians and officials in Brazil have questioned the legitimacy of the NPT, and some have made statements to the effect that Brazil should have never become a treaty member. Some have even argued that Brazil should master the technology to develop a nuclear explosive. For all these reasons, many nonproliferation experts have questioned Brazil's identity as a "responsible stakeholder" in the global nuclear order. Even if Brazilian authorities in the past 30 years have made a constitutional commitment to using nuclear energy exclusively for peaceful purposes and have tied themselves to multilateral nonproliferation commitments such as the NPT, the Quadripartite Agreement, ABACC, the Treaty of Tlatelolco, the Nuclear Suppliers Group, and the Comprehensive Test Ban Treaty, suspicions remain. This suggests that any negotiations over nuclear-submarine safeguards will be bound up with issues that go well beyond the actual submarine and its nuclear fuel. Also, a chief concern for Brazil will be to develop a safeguards agreement that will not reveal sensitive military or proprietary information concerning the design and operation of submarine reactors or allow international inspectors on board the vessel to verify such information. It is uncertain how much information Brazil will withhold about the submarine fuel cycle, or whether inspectors will be able to use material balance accounting to give ex post facto assurance of nondiversion.

As work on the submarine evolves, there are three areas, described below, in which greater policy and scholarly dialogue about the Brazilian submarine project could lead to real progress and advance the cause of nonproliferation.

Non-application of Safeguards

A Track 2 meeting on what nonapplication of safeguards might look like in a Brazilian context would get all major players in the field thinking about alternative models. As long as this is kept strictly Track 2—that is, involving only nongovernmental participants and demanding no formal commitments from the administration—Brazilian officials are likely to pay close attention and informally debate alternative scenarios moving forward. (Given the current sensibilities surrounding the issue of nuclear naval-fuel safeguards, officials probably would be reluctant to engage in a Track 1.5 exercise—that is, one that involves governmental as well as nongovernmental participants.) The reason why Brazilian officials are likely to welcome such a Track 2 initiative is that there are no off-the-shelf models for the nonapplication of safeguards in naval propulsion projects they can borrow from and, as they privately acknowledge, expert input would be useful in building and contrasting alternative models for managing safeguards in the context of the Brazilian submarine.

The Future of ABACC

For a long time, there have been fears in Vienna that ABACC might operate as a spokesperson for Argentina and Brazil rather than an independent agency. At ABACC, on the contrary, the view is that three decades of mutual inspections have produced more detailed knowledge of the two countries' nuclear programs than anything before. What is the role for ABACC in the context of the Brazilian submarine program, if any? And how best to improve cooperation between ABACC and the IAEA? This is a much-needed debate, in part because of the divergent paths that Argentina and Brazil have been taking on a range of global nonproliferation issues, which could jeopardize the institutional bonds on nonproliferation between the two countries under ABACC. Discussing what roles might be assigned to ABACC in the application of "special procedures" for naval nuclear fuel—and how they might relate to IAEA's verification procedures—would be an ideal place to start the conversation. The main lines of engagement should concentrate, for instance, on the desirability and feasibility of mutual peer reviews, integration of safeguards in design of installations, and an auditing system based on international benchmarks.

The Future of Nuclear Latency

Common usage of the expression "nuclear latency" today focuses on the technically complicated tasks of mastering the expertise, technology, raw materials, and political support that is necessary to set up enrichment and reprocessing facilities. These facilities matter because there are two paths to fissile material for nuclear weapons: HEU and separated plutonium. How will the debate about nuclear latency evolve in the face of naval nuclear propulsion? There is no precedent in the literature on latency referring to nuclear-propelled submarine capabilities. But should the building of one such vessel by a non-nuclear-weapon state—and, crucially, of the nuclear fuel on which the vessel will run—be treated as the type of capability that effectively moves a state up the ladder of nuclear latency? And will the possession of a nuclear submarine by one state spur international security competition among its neighbors, thereby affecting the foreign-policy calculations of that state and its commitment to further developing nuclear technology?

Brazil's naval nuclear program—and the fact that it is being conducted in a relatively open fashion with authorities providing significant degrees of information and context to the wider public—opens up an opportunity for scholars and practitioners alike to assess the connections between naval nuclear propulsion and the phenomenon of nuclear latency more broadly.

Should nuclear submarines be considered an index of heightened nuclear latency or should they not? One obvious answer refers to the level of uranium enrichment. If the nuclear sub runs on HEU fuel, then the state commissioning the sub will be in the business of producing HEU fuel at an industrial level. If the sub runs on LEU, however, the state need not reengineer its enrichment facilities to produce HEU. Brazilian officials have committed to running their sub on LEU: the first sub is expected to run a 11 megawatt electric (48 megawatt thermal) nuclear reactor with uranium enriched to 4.3 percent, the same level of enrichment used for fuel at Brazilian nuclear power plants. And officials seem to be sensitive to criticism that in commissioning the sub they might be creating a proliferation risk. But assessing whether nuclear-propelled submarines should be taken as a serious proxy for nuclear latency would probably demand in-depth studies of how indigenous elites conceive of the nuclear submarine and how third countries react to the acquisition of nuclear naval know-how. This is an area that would benefit from a dedicated research program in the future.

Conclusion

Brazil's momentous decision to build a nuclear-propelled submarine is likely to rekindle global debates about nuclear safeguards, international verification, and the future of nuclear latency among non-nuclear-weapon states. A great deal of how that debate evolves will depend on the credibility of Brazil's public statements, its approach to the provision or restriction of information on the submarine project, and the efficacy of its diplomatic communications with the wider world (particularly with Argentina and the United States). But engaging Brazil in productive dialogue will also be dependent on the ability of scholars, practitioners, and observers abroad to correctly interpret policy decisions and signals coming from Brazilian authorities in the next few years. Whatever the outcome of the engagement, states around the globe will form expectations about the international politics of nuclear naval propulsion that will in turn inform how those states approach nuclear latency in the future. The effects of Brazil's interactions with the global nuclear regime are thus likely to be felt past the resolution of particular diplomatic hurdles or tensions and to influence the construction of the international order to come.

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Naval Nuclear Propulsion: Seeking Verification Processes

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This paper explores the practical aspects of organizing an international project on safeguards for naval nuclear reactor fuel, drawing on relevant past experience with other verification projects. It is limited to consideration of the mechanisms for developing a verification approach or approaches, rather than offering verification solutions, and does not address the larger issues of disarmament and security associated with naval reactor fuel.

The Legal Context: The Nuclear Nonproliferation Treaty and Comprehensive Safeguards Agreements

The 1968 Nuclear Nonproliferation Treaty (NPT) prohibits nonnuclearweapon states[1] from acquiring nuclear weapons or other nuclear explosive devices and obliges each of those states to conclude with the International Atomic Energy Agency (IAEA) an agreement for the application of safeguards to all source or special fissionable material "with a view to preventing diversion of nuclear energy from peaceful uses to *nuclear weapons or other nuclear explosive devices*" (emphasis added) (NPT, Article III, para. 1). Such safeguards agreements are required to be applied "on all source or special fissionable material in all peaceful nuclear activities within the territory of such State, under its jurisdiction, or carried out under its control anywhere" (NPT, Article 3, para. 1) and are thus referred to as full-scope or comprehensive safeguards agreements (CSAs).

[1] Under Article IX.3 of the treaty, the only countries that are considered nuclear-weapon states are those that had "manufactured and exploded a nuclear weapon or nuclear explosive device prior to 1 January 1967."

The language of the NPT was specifically negotiated to prohibit the explosive uses of nuclear material by non-nuclear-weapon states, whether for nonpeaceful purposes or for peaceful purposes.[2] To put it another way, not all military uses of nuclear material are prohibited to these states. In fact, the language of the NPT was crafted in such a way as to contemplate the permitted use of nuclear material as fuel for naval ships, specifically nuclear-powered submarines.

The NPT was the first global nonproliferation treaty. With its entry into force in 1970, the IAEA had to develop a system of safeguards to support the objectives of the treaty.

Prior to the entry into force of the NPT, the safeguards agreements concluded by the IAEA served the limited purpose of verifying that the material, facilities, or other items specified in the agreement were not used for military purposes. These agreements were not comprehensive, and they were not designed to verify the nonacquisition of nuclear weapons. In other words, they were designed simply to ensure that the specified items were not used for purposes prohibited by the supplier(s) of the item(s).

With the advent of the NPT, the IAEA needed to define the terms of the safeguards agreements on which the implementation of the verification provisions of the NPT would be based. The IAEA Secretariat initiated an internal analysis in light of which it formulated a draft model safeguards agreement that was used as the basis for negotiations in an openended committee of the Board of Governors—its 22nd such committee—which came to be known as "the Safeguards Committee" or simply "Committee 22." The result of those negotiations was a document entitled "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," reproduced in IAEA document INFCIRC/153 (Corrected) (hereafter referred to as "INFCIRC/153") (IAEA 1974). All CSAs concluded pursuant to the NPT are based on INFCIRC/153.

In the negotiation of INFCIRC/153, the participants in Committee 22 included in paragraph 14 the procedures for the "NonApplication of Safeguards to Nuclear Material to Be Used in NonPeaceful Activities."

This provision addresses the situation in which a state "intends to exercise its discretion to use nuclear material which is required to be safeguarded thereunder in a nuclear activity which does not require the application of safeguards under the Agreement,"[3] specifically, the use of nuclear material for naval propulsion, a military nuclear activity not prohibited under the NPT.

The procedures identified in paragraph 14 specify a number of steps that must be taken to that end. The first of those steps includes the following:

> (a) The State shall inform the Agency of the activity, making it clear:
>
>> (i) That the use of the nuclear material in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the nuclear material will be used only in a peaceful nuclear activity; and
>>
>> (ii) That during the period of non-application of safeguards the nuclear material will not be used for the production of nuclear weapons or other nuclear explosive devices.

The effect of paragraph 14(a) is to preclude a state from using nuclear material that is subject to a "no military use" undertaking in a project-and-supply agreement (or in an item-specific safeguards agreement) concluded with the IAEA, even if the application of safeguards under that agreement has been suspended.[4] What is *unclear* is the process or format through which the state is obliged to "make clear" that the conditions set out in paragraph 14(a) are satisfied.

Paragraph 14(b) requires the state and the IAEA to "make an arrangement so that, only while the nuclear material is in such an activity, the safeguards provided for in the Agreement will not be applied." It goes on to require that the arrangement "identify, to the extent possible, the period or circumstances during which safeguards will not be applied," but that in any event, safeguards "shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity." It also requires that the IAEA be "kept informed of the total quantity and

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[2] Article II of the NPT prohibits a non-nuclear-weapon state from acquiring only "nuclear weapons or other nuclear explosive devices."

[3] Thus, paragraph 14 does not apply to nonnuclear military uses of nuclear material, such as the use of depleted uranium for armor-piercing projectiles or tank shielding.

[4] Paragraph 24 of INFCIRC/153 provides that the application of safeguards in the state concerned under other safeguards agreements with the IAEA "shall be suspended while the [CSA] is in force," but that, if the state has received assistance from the IAEA under a project, "the State's undertaking in the Project Agreement not to use items subject thereto in such a way as to further any military purpose shall continue to apply."

composition of such material in the State and of any exports of such material."

Finally, paragraph 14(c) requires that each arrangement be made in agreement with the IAEA, and that such agreement is to be given "as promptly as possible" and "shall only relate to the temporal and procedural provisions, reporting arrangements, etc., but shall not involve any approval or classified knowledge of the military activity or relate to the use of nuclear material therein."

Thus, although the drafters of INFCIRC/153 attempted to provide some indication of what should be done in the event a state wished to withdraw nuclear material for military (naval) propulsion, the procedures lack details as to how safeguards should be applied to ensure that such programs are not used as cover for a nuclear-weapon program—that is, as a justification for the production of highly enriched uranium (HEU)—and that the nuclear material in question is not diverted for prohibited purposes. They, in effect, "kicked the can down the road."

There has been only a single effort by member states since then to clarify the procedures contemplated by this provision. In 1978, Australia wrote to IAEA Director General Sigvard Eklund seeking confirmation that paragraph 14 would operate to ensure that the use of nuclear material in a nonexplosive military activity would be brought to the Board of Governors for its consideration. In his response to Australia, Eklund stated that it was the Secretariat's view that "any exercise by a state of the discretion referred to in paragraph 14 which comes to the knowledge of the Secretariat, and any notification received by the Secretariat under that paragraph, as well as any arrangement made pursuant to that paragraph, or any breach of the procedures referred to in that paragraph, must be reported to the Board of Governors, and it would be for the Board in each case to take the appropriate action" (IAEA 1978).

And so things remained until 1987, when Canada announced its intention to acquire nuclearpowered submarines and approached the IAEA with a view to concluding an arrangement pursuant to Article 14 of its CSA (the article corresponding to paragraph 14 of INFCIRC/153) (IAEA 1972b, 5). Although Canada and the IAEA held extensive discussions, Canada finally decided in 1989 not to pursue the initiative, and no arrangement of the type foreseen under paragraph 14 of INFCIRC/153 was ever concluded between the IAEA and Canada (Desjardins and Rauf 1988; Rockwood 2017).

While no other state has as yet invoked the provisions of paragraph 14, there appear to be prospects for its use in the future. Specifically, Brazil has been developing a landbased prototype propulsion reactor for its planned nuclear-powered submarines. Brazil has provided the IAEA with design information for the prototype reactor; it has not yet invoked Article 13 of its CSA (IAEA 1994a), which corresponds to paragraph 14 of INFCIRC/153, calling for agreement on "special procedures" in the event the state wishes to use nuclear material for "nuclear propulsion or operation of any vehicle, including submarines and prototypes, or in such other non-proscribed nuclear activity" (IAEA 1994a). The project has been much delayed, however, with the first vessel likely not to be commissioned for another 10 years (Spektor 2017).

While some may see this as indicating a lack of urgency in the matter of devising an appropriate arrangement or "special procedures" with respect to nuclear-fueled submarines, it bears noting that Brazil may not be alone in its pursuit of a naval nuclear program. In 2012, Iran announced its intention to pursue a nuclear-propulsion program. In December 2016, Iran's president, Hassan Rouhani, is reported to have ordered the Atomic Energy Organization of Iran to "come up with a plan for nuclear-powered ships and producing fuel for them" within three months (Burgess 2012; AP 2016; Paton 2017).

Rather than waiting for a state to invoke the provisions in its CSA dealing with the withdrawal of nuclear material from safeguards, the IAEA could start preparing now to address the question of how to prevent the diversion of nuclear material used for naval propulsion. This properly leads to the question of what mechanisms might be available for achieving that goal.

Historical Examples of Verification Projects

The IAEA has in the past employed a variety of mechanisms in developing procedures and guidance on safeguards-related matters. The first inspector general of the IAEA, Allan McKnight, commented in 1971 on how safeguards research can arise:

> The IAEA may discern a need, and define a research requirement with some precision. The required research may then be undertaken by the Agency itself, or by member states, invited to carry out the research under a contract with the IAEA. Alternatively a State may either itself or through one of its institutions perform a

> piece of research specifically for international safeguards and make the results available to [the] IAEA for possible use in its safeguards system. There is another field of research relevant to safeguards which is difficult to identify; that is, research which is done and often developed for some productive or management control purpose without any thought of use in safeguards, but which can, with or without adaptation, contribute to the effectiveness or efficiency of safeguards. (McKnight 1971, 143)

Collective initiatives have included committees created by the Board of Governors, advisory groups appointed by the director general, and technical working groups convened in collaboration with representatives of relevant technology holder states. Other collaborations have included external initiatives of IAEA member states and bilateral negotiations between the agency and individual states.

Committees of the IAEA's Board of Governors

Article VI.I. of the IAEA Statute authorizes the Board of Governors to establish such committees as it deems advisable. The board has formally established 25 committees, with various mandates and increasingly expanded participation by member states of the IAEA (IAEA 1996a). For purposes of this analysis, the experience of the safeguards committees is most relevant. The following discussion highlights the composition and mandates of the three board committees established to create and further develop the IAEA's system of comprehensive safeguards.

Committee 22

Shortly after the adoption of the NPT in 1968, Eklund tasked a group of experts with "studying the impact of the NPT on the Agency's safeguards work and the manner in which the Agency should apply safeguards in relation to a country's entire range of peaceful uses of nuclear energy, with a view to ensuring that such safeguards were effective, economical and widely acceptable." The group was composed of external consultants described as "highly qualified experts in various aspects of safeguards or closely related disciplines" who had been made available by their governments. As noted in Eklund's report to the board in October 1969 on the results of their deliberations, the reports and recommendations made by those experts assisted the Secretariat in preparing a detailed program for its further work on NPT safeguards (IAEA 1969).

One month after the entry into force of the NPT in March 1970, the Board of Governors adopted a resolution in which it decided to establish a committee to "advise the Board as a matter of urgency on the Agency's responsibilities in relation to safeguards in connection with the [NPT], and in particular, on the content of the agreements which will be required." Participation in the negotiations was open to all member states, regardless of whether they were party to the NPT (IAEA 1970a).

In advance of the first meeting of the committee, the member states were invited to communicate their views to the director general, who was in turn requested to circulate to all member states reports on his views, in particular on the content of the future agreements. In his report to the committee, Eklund proposed an annotated draft text with a two-part structure, which served as the basis for negotiation of the document that was, in less than a year, adopted by the committee, approved by the board, and published as INFCIRC/153 (IAEA 1970b).[5]

The success of this effort lies in the common goal of achieving agreement as quickly as possible on a standardized approach to NPT safeguards given the deadlines in the NPT for non-nuclear-weapon states with regard to their safeguards agreements. (They had to initiate negotiations on the agreements with the IAEA within 180 days of the entry into force of the NPT, and the agreements had to enter into force not later than 18 months from the initiation of negotiations.) Among the lessons to be derived from this effort is the importance of preparation by the IAEA Secretariat and the value of securing preliminary technical advice from a limited number of experts before opening up the debate in a more politically oriented environment.

Committee 24

Following the discovery of an undeclared nuclear program in Iraq, the IAEA Secretariat embarked on an ambitious project—Programme 93+2—to develop a comprehensive set of measures to strengthen the effectiveness and improve the efficiency of IAEA safeguards (IAEA 1994b). Between 1993 and 1995, the work was carried out by the Secretariat through the formation of internal task groups, each responsible for a different area of the project. The Secretariat actively sought the participation of member states in the development of the proposals

[5] Among the important issues that Eklund highlighted in that document was the need to specify procedures for withdrawing nuclear material from peaceful uses to military activities not prohibited under the NPT.

and in carrying out field trials. By mid-1995, the Secretariat had identified two categories of measures for strengthening safeguards: those that could be accomplished within the existing legal authority under CSAs—the so-called Part 1 measures—and those that would benefit from additional standardized (rather than ad hoc) legal authority—the Part 2 measures. Director General Hans Blix indicated his intention to implement the Part 1 measures immediately, in consultation with member states, and to further develop the Part 2 measures and provide the board with a draft legal instrument for its consideration by December 1995.

Over the next year, the Secretariat worked closely with member states in frequent and intensive bilateral and multilateral consultations to develop a draft text of a model protocol to supplement CSAs. In June 1996, the Secretariat tabled the draft protocol (IAEA 1996b). At that meeting, the board agreed to establish an open-ended committee—Committee 24—with the task of drafting a model protocol based on the text offered by the Secretariat. The board invited all member states legally obliged to conclude a CSA to participate in the committee's deliberations, and welcomed any related intergovernmental organization to take part as an observer. In nine months, the Committee was able to agree on a text of a "Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards," which became INFCIRC/540 (Corr.) (IAEA 1997). The Board of Governors approved the document in a special session convened on May 17, 1997.

Two factors in particular contributed to the success of Programme 93+2 and Committee 24. The first was the near unanimity on the part of the IAEA's member states that action needed to be taken to strengthen IAEA safeguards under the NPT in light of the events of the early 1990s, particularly the discovery of Iraq's undeclared nuclear-weapon program. The second factor was the Secretariat's engagement in countless consultations with member states on the concepts and documents as they were being developed, an effort that resulted in a sense of shared ownership of and commitment to the process.

Committee 25

The Advisory Committee on Safeguards and Verification within the Framework of the IAEA Statute (Committee 25) was established by the Board of Governors in June 2005, at the initiative of the United States, with an initial two year mandate to consider ways and means to strengthen the safeguards system and to make relevant recommendations to the board.

The committee was open to all member states of the IAEA. The Secretariat prepared a very modest paper on possible strengthening measures, sensitive to the divisive atmosphere within the board over the issue of strengthening safeguards and among the member states more broadly. From the very outset, it was clear that even those modest efforts would be challenged. Given the circumstances, the best outcome that could be hoped for was that the committee would "do no harm"—that is, that the collective committee would resist efforts by some states to roll back the achievements made in the previous decade in strengthening IAEA safeguards. Indeed, the committee was not able to reach agreement on any recommendations to submit to the board and the board did not extend its mandate. The ability of the committee to achieve its task was confounded by the considerable resistance to the actual goal of the committee—to make recommendations for further strengthening safeguards—in particular on the part of Iran, which had just been found to be non-compliant with its CSA. This resistance was exacerbated by some states' distrust of the proponents of the exercise, a result of the United States' misuse of intelligence information that had led to the invasion of Iraq in 2003.

Advisory and Technical Working Groups

SAGSI

Since May 1975, the IAEA's Standing Advisory Group on Safeguards Implementation (SAGSI) has advised the director general on safeguards matters. SAGSI's mandate includes assessing the technical objectives of safeguards, assessing the effectiveness and efficiency of specific safeguards methods, and advising on safeguards techniques (IAEA 1993, 392). The group, which has 20 members, meets twice a year in plenary session and occasionally in working groups. SAGSI played an important role in the evolution of safeguards in the early 1990s, when its recommendations served as the basis for the strengthening measures developed under Programme 93+2. The members of SAGSI serve in their personal capacity, although the director general consults with their respective governments before appointing them.

The value of SAGSI derives from its range of expertise and geographic diversity, without involving an unwieldy number of participants. In addition, while its members are fully apprised of their respective governments' political positions, their deliberations are conducted outside of the political spotlight.

LASCAR

In 1987, the Government of Japan provided funding to the IAEA to develop and test new techniques for safeguarding large-scale reprocessing plants, which became known as the LASCAR project. More than 50 experts from France, Germany, Japan, the United Kingdom, the United States, Euratom, and the IAEA, representing governments, industry, and independent experts, participated (IAEA 1992). LASCAR served as a technical forum and not as a forum for the negotiation of safeguards approaches or the resolution of safeguards policy issues. It concentrated on examining the applicability of safeguards techniques for possible use in such facilities, rather than defining specific safeguards approaches. The participants ultimately identified a wide range of techniques that could be used to safeguard large reprocessing plants, as well as procedures for meeting timeliness requirements, verifying plant design information, authenticating equipment made available to inspectors by the operator, and acquiring and transmitting safeguards-related data (IAEA 1992).

The main factor in the success of the initiative was a shared concern that conventional material accountancy methods alone were unable to provide assurances of the nondiversion of material from large reprocessing plants and a mutual understanding that these new safeguards techniques would benefit all parties.

Trilateral Initiative

In 1996, at the suggestion of Russia, the IAEA launched a joint project with the United States and Russia. Known as the Trilateral Initiative, it sought to examine the feasibility of IAEA verification of classified forms of weapon-origin fissile material declared by the states as excess to their respective defense requirements. The parties established a joint working group to consider the technical, financial, and legal aspects of such verification. Three efforts proceeded in parallel: a technical subgroup focused on developing an approach to the verification of plutonium with classified characteristics; the legal subgroup developed a draft model verification agreement; and the Secretariat drafted and submitted to the Board of Governors in May 1999 a paper on the financing of disarmament verification (IAEA 1999a). The Secretariat also submitted to the board a separate paper describing progress on the Trilateral Initiative (IAEA 1999b). The board indicated its support for the initiative as a valuable contribution to arms control and disarmament and to the fulfilment of the nuclear-weapon states' disarmament obligations under the NPT (UNODA 2000). However, no decisions were requested of, or taken by, the board on either document.

The Trilateral Initiative is a clear case of progress being possible when the political winds are positive, as they were in the mid-1990s when Russia and the United States were simultaneously seeking ways to reinforce their relationship while engaging in mutually beneficial efforts to verifiably demonstrate their commitment to disarmament. Although the joint working group achieved considerable progress on all aspects of the initiative, its implementation required Russia and the United States to take steps that subsequent governments in those countries chose not to pursue.

External Initiatives

An excellent example of an external initiative to develop safeguards was the 1970s Hexapartite Safeguards Project (HSP), which aimed to address the emergence of commercialized gas centrifuge technology to enrich uranium. The purpose of the project was to develop effective and efficient implementation of safeguards at commercial centrifuge enrichment plants without compromising sensitive information related to centrifuge technology. The initiative involved the six technology holder states (Australia, Germany, Japan, the Netherlands, the United Kingdom and the United States), and the two international inspectorates (the IAEA and Euratom). In 1983, the participants produced a final report with an agreed strategy of limited-frequency unannounced access (LFUA) to cascade halls. Ultimately, the HSP concluded with exchanges of letters in which commitments were made by the technology holders to agree to the safeguarding of all existing or planned commercial gas centrifuge plants on the basis of the LFUA approach. For their part, the inspectorates agreed to implement safeguards at all such plants on that basis. According to one of the participants in the HSP (Kessler 2013), among the significant factors that contributed to the success of the HSP were a shared sense of political necessity (the need to maintain effective international safeguards and protect proprietary information); shared pain (the willingness of the two nuclear-weapon states—the United States and the United Kingdom—to subject themselves to the same risks and costs with regard to a highly classified and commercially important technology that they were asking the non-nuclear-weapon states to accept); and the lack of preexisting authoritative determinations about what the answers to key questions, including the safeguards approach, should be.

Bilateral Negotiations between the IAEA and Individual States

The IAEA frequently negotiates safeguards approaches bilaterally with individual states. These are generally derived from and negotiated on the basis of standardized approaches developed internally by the IAEA. Canada's initiation of the process specified in paragraph 14 of INFCIRC/153 for withdrawing nuclear material from safeguards for naval nuclear fuel is a germane, if uncompleted, example of such bilateral negotiations between the IAEA and a single state.

Problems can arise with separate bilateral negotiations on matters of broader safeguards application. These types of problems became manifest in the late 1980s during the negotiation of subsidiary arrangements' facility attachments[6] when issues related to the responsibility for expenses associated with the implementation of safeguards started to emerge. Over the years, the IAEA had found itself in the position of having to negotiate with individual states what constituted reimbursable expenses, with the result that it was becoming difficult to maintain a uniform policy. To resolve this issue, and to ensure consistency in application, the Secretariat presented a document to the board in January 1990 that outlined a list of expenses and indicated whether each of those expenses was reimbursable. The Secretariat simply informed the board that it intended to continue its practice of following a uniform policy and to include, along the lines indicated in the board document, a clause in the relevant section of all future subsidiary arrangements, which it indeed has done since then (IAEA 1990).

Practical Aspects of Organizing an International Safeguards Project

Discussed below are a number of practical aspects of the initiation of an international safeguards project for the development of an effective and credible approach to verification of nuclear material used for naval reactor fuel.

Laying the Groundwork

Key steps should include the collection of background data on existing and planned nuclear-submarine programs, an assessment of the political factors in each country that might contribute to or hinder pursuit of the project, and an assessment of the security sensitivities associated with such programs.

Preparation should also include an assessment of the likelihood of achieving the desired results and of the potential barriers to success. Identifying possible participants or partners, and in particular, a champion for the project (whether a member state or a group of member states or the IAEA itself) will be important. Identifying possible fora and formats for the project will also be necessary.

Building consensus about the need for such a project is crucial. This could require, as it did for the HSP, "extensive informal diplomacy and personal 'off-the-record' conversations" (Kessler 2013) carried out in a timely fashion with political acuity by those interested in launching and successfully concluding the project.

The objective of the project presumably would be to develop an effective and credible verification approach for the use of nuclear material in naval reactor fuel in the context of paragraph 14 of INFCIRC/153. The approach would have to be acceptable to the IAEA and to non-nuclear-weapon states that are party to CSAs and are interested in pursuing nuclear naval propulsion.

An important factor to consider is feasibility:

- Are non-nuclear-weapon states (for example, Brazil) interested in engaging in a multilateral process about the verification approach? Would they prefer bilateral negotiations with the IAEA? While the Brazilian government has been increasingly willing to share with the public some details about its plan for nuclear propulsion, there is considerable domestic resistance in Brazil to oversight by the IAEA in connection with military-related activities.

- Are the nuclear-armed states willing to engage in the project? They must balance their interest in preventing proliferation against the national-security and proliferation challenges posed by their participation. Are there issues related to the classified nature of their nuclear-submarine programs either from the military point of view or from the proliferation sensitivity of technologies associated with the production of fuel for the

[6] In accordance with paragraph 39 of INFCIRC/153, the IAEA and the state are to conclude "subsidiary arrangements" to specify in detail how the procedures laid down in the agreement are to be applied. As a matter of practice, this has evolved so that the subsidiary arrangements consist of a "general part" applicable to the state as a whole and individual "attachments" for each nuclear facility and for other locations where nuclear material is customarily used in amounts of one effective kilogram or less.

programs? They might see more risk than reward in such a project.

- Is the timing optimal for or at least conducive to the implementation of the initiative? A turbulent security environment could offer challenges but also opportunities, for it is usually in the times of greatest change that progress can be achieved. Such was the case in the context of the Trilateral Initiative; the historic upheaval in the US-Russian relationship offered an unparalleled opportunity to make progress on a matter of mutual interest and benefit. On the other hand, states may be less amenable to cooperation on a security-related activity in the face of turbulence, as manifested by the lack of progress in efforts to further strengthen safeguards in the mid-2000s.
- Are there events external to this effort that could adversely impact the likelihood of success of the project? As noted above, the US invasion of Iraq in 2003 poisoned the atmosphere in the IAEA Board of Governors and undercut its subsequent championing of efforts to further strengthen safeguards. Another example may well be that, if the Joint Comprehensive Plan of Action on Iran's nuclear program does not survive, this could call into question the value of multilateral negotiations, which could in turn decrease the willingness of states to engage in international efforts that are intimately associated with verification.

If the larger objective is not considered feasible, or at least practically achievable within a given period of time, there is the option of redefining the objective to a more limited one of identifying useful verification technologies or agreeing on norms for the use of nuclear material for naval propulsion. For example, the focus of the initiative could be redirected to achieving agreement on using low-enriched uranium rather than HEU or on prohibiting transfers of either related materials or technology unless they were subject to conditions that prohibited retransfer or reprocessing unless the original supplier agreed and arrangements were in place to resume the application of safeguards.

Forum

There are multiple fora that could serve as the "seat" of the project. The project could be located, perhaps on an initial basis, in an academic institution that has expertise relevant to the task—for example, a university where technical work could be carried out in support of the project. Another option is a think tank. Alternatively, or subsequently, it could be situated within or under the auspices of one of the principal international organizations, such as the UN General Assembly or Conference on Disarmament, or the IAEA.

The option of a nongovernmental forum, whether an academic institution or a think tank, would likely offer better opportunities for focusing on the technical aspects of the issue, less encumbered by the need for participants to support national political positions. However, placing the project within a multilateral institution could yield political buy-in and legitimacy.

While there may be some value in placing such a project under the UN General Assembly or within the Conference on Disarmament for purposes of debating overarching policy issues, and there is certainly a role for civil society in contributing to the debate, the IAEA itself, as the body that will eventually be responsible for such verification in non-nuclear-weapon states, is perhaps the optimal choice. Ultimately, any arrangement for the nonapplication of safeguards (or, in the case of Brazil, the application of special procedures) would have to be acceptable to the IAEA Secretariat and approved by the Board of Governors. Thus, regardless of the principal forum, involvement of the IAEA at the technical level will be crucial.

Participants

Who are the relevant parties and what interest would they have in such an outcome? Clearly, any non-nuclear-weapon state that is considering nuclear naval propulsion (whether immediately or in the future) would be a relevant party. Currently, the likeliest candidates appear to be Brazil and Iran. Canada might also be relevant, given its historical interest in the exercise. The nuclear-armed states with nuclear-powered submarines would also be relevant, from the perspectives of both verification and nonproliferation. Verification is an issue because if a Fissile Material Cutoff Treaty were ever concluded, it would have to address the issue of nuclear fuel for submarines and its verification. With regard to nonproliferation, a key consideration would be ensuring that nuclear submarine programs do not serve as mechanisms for facilitating or concealing diversion by a non-nuclear-weapon state.

Should the initiative be open to any state or only to a limited number of states with a stake in the outcome? One could imagine a scenario whereby a group of "like-minded" states or nonstate entities or both produces an approach to verification that would be sound and acceptable to them. However, the risk in engaging only like-minded states is that those perceived as not being likeminded might reject the approach, either on technical grounds (for example, that it does not suit the facts on the ground in their states) or in response to not having been part of the process (the sense that the approach has been "precooked" without their concerns having been adequately taken into account).

However, as illustrated in the discussion above, there are positive examples of projects that have engaged a limited number of states. Participation in LASCAR was limited to technology holders; participation in the HSP was similarly limited except that it also included Australia, a state that was on the verge of becoming a technology holder. Of the possible technology holders with respect to nuclear-powered submarines, there are three categories of states: the non-nuclear-weapon states that have expressed a current interest in nuclear naval propulsion (Brazil and Iran); the five NPT nuclear weapon states (China, France, Russia, the United Kingdom, and the United States); and India (Shea 2017).7

While Brazil's submarine program has been in the works for decades, Brazil has yet to invoke the relevant provision in its CSA with respect to the application of "special procedures" in connection with that program. Iran, on the other hand, has only made public pronouncements of its intention to pursue nuclear propulsion; there have been no reports of activities undertaken in that regard. The nuclear-weapon states, on the other hand, are not obliged to accept any verification under their respective voluntary-offer agreements for the application of IAEA safeguards; nor is India, a nonparty to the NPT. As noted above, however, they may share other common interests in engaging in such a project.

Clearly a critical question associated with identifying participants would be motivation: are any or all of the states identified as technology holders interested in engaging in a collective exercise to develop a verification approach? What incentives are there for either Brazil or Iran to come to the table, rather than going it alone with the IAEA in bilateral negotiations? What motivations could bring the NPT nuclear-weapon states or India to the table? A recently published study by Thomas Shea touches on that issue, offering an innovative proposal for a "quid pro quo" initiative that addresses naval reactor programs, coupling proliferation concerns with a corresponding disarmament concern (Shea 2017).[7]

Another consideration in the issue of participants is the role of regional inspectorates, specifically Euratom and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC). Under Article 14(b) of the CSA concluded by the IAEA with Euratom and the European non-nuclear-weapon states (IAEA 1973), Euratom is responsible for concluding the relevant arrangement with the IAEA. No such a role is contemplated for ABACC under the quadripartite CSA concluded by Brazil, Argentina, ABACC, and the IAEA (IAEA 1994a). Under that agreement, the arrangement for "special procedures" is to be concluded between the state concerned and the IAEA. Although there is a stronger legal case to be made for engaging Euratom in the project than for engaging ABACC, as a practical matter, there are currently no European countries that have announced any plans for or interest in naval propulsion. One factor to consider is whether the sometimes-contentious relationships between the IAEA and the other inspectorates would be tempered by a shared interest in effective verification.

The decision about participation would come down to a balance between the value of participation by the nuclear-weapon states, India, Brazil, and Iran and the challenges that such a constellation would pose to reaching agreement. The same may be said with respect to the possible participation of Euratom or ABACC or both. On balance, inclusivity might be more likely to produce a more widely accepted result and greater support once the relevant draft arrangement is presented to the Board of Governors for its consideration.

Process

By whom and how should the process for the verification project be initiated? There are several options:

- the IAEA Board of Governors, through the establishment of a committee of the board;
- the director general of the IAEA, either through the appointment of an expert advisory group or the convening of a technical working group in collaboration with representatives of technology holder states; and
- initiatives external to the IAEA.

[7] Other factors to consider in assessing the composition of the project could include the status of the respective programs and whether they involve HEU or low-enriched uranium (LEU). According to a recently published study, the United States and the United Kingdom use 93 percent enriched HEU; Russia and India use enrichments of around 40 to 60 percent; France and China reportedly use LEU; and Brazil has announced that it will use LEU (Shea 2017).

Given current circumstances, it is unlikely that either the Board of Governors or the director general would initiate a process that could be seen as encouraging states to invoke the provisions corresponding to paragraph 14 of INFCIRC/153 whereby nuclear material could potentially be lost to safeguards. Either scenario would be even less likely if there is no member state willing to champion either the creation of a committee of the board or the convening of a group by the director general.

Given the political sensitivities such a process could entail, it might be politically more tenable for the IAEA if one or more member states of the agency, or a civil-society organization, initiated such a study and invited the IAEA to participate. In that regard, there is an excellent example in the HSP, a process that began domestically by building trust and identifying a common purpose, then moved to bilateral consultations with other states with shared concerns, and finally developed into multilateral negotiations. The HSP had challenges similar to those related to verifying nuclear naval propulsion:

- It involved highly technical issues whose resolution would likely have profound policy implications for international security.
- It posed new challenges in implementing international safeguards on a complex nuclear technology.
- Most importantly, the technology at issue was (and remains) very sensitive for both commercial and nuclear-weapon proliferation reasons, so safeguards had to avoid jeopardizing technical and proprietary information. (One can simply substitute the words "national security" for "commercial" in the case of naval propulsion, keeping in mind the classified nature of such military activities.)

Summary

This paper has explored the practical aspects of organizing an international project on safeguards for naval nuclear-reactor fuel, drawing on relevant past experience. It is hoped that the selected examples offer, for consideration by the champion(s) of such a project, a sense of the range of available options, indications of what has worked in the past and what has been less successful, and a preview of some of the practical aspects involved.

When dealing with novel and complex technical issues, there is merit to leaving their resolution to the technical experts. However, regardless of the option chosen, the necessary groundwork, whether technical, political, or diplomatic, must be laid in advance; the ill-timed launching of even well-intentioned projects can poison the atmosphere and make future efforts even more challenging. Ultimately, the success or failure of any such a project will depend on the unity of political will based on common interests (and in some instances, shared pain). It will also depend on trust: perceptions of preconceived outcomes driven by ulterior motives could lead to the defeat of such efforts even before they get beyond the conceptual stage.

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The 6 Percent Solution: LEU Fueled Reactors and Life-of-Ship Reactors for the US and UK Navies

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Introduction

On January 17,1955, Commander Eugene P. Wilkinson, commanding officer of the USS *Nautilus*, sent the historic message "UNDERWAY ON NUCLEAR POWER" announcing the beginning of the nuclear era at sea (Submarine Forces Museum 2014). The Nautilus was the first true submersible, with its ability to remain submerged limited only by the consumables necessary for the crew's endurance.

This paper will argue that now, almost 65 years later, the US Navy should begin to make fundamental changes in the reactors that power the *Nautilus*'s successors. After a brief review of the Navy's development of reactor fuels and its current plans for future programs, the impact of the Navy's program on future nonproliferation and counterterrorism programs will be considered. The paper will argue that the Navy should phase out its use of highly enriched uranium (HEU) reactor fuel and replace it with low-enriched uranium (LEU) fuel having an enrichment level of about 6 percent uranium-235. In addition, the paper will raise questions about the current use of life-of-ship reactors.

A Brief History

A fact not generally known is that the *Nautilus* was launched with a reactor that was initially fueled with LEU. The LEU fuel was soon replaced with HEU, and since that time, military naval propulsion reactors of the United States and United Kingdom have all used HEU-fueled reactor cores (Moore, Banuelos, and Gray 2016). The navies of the Soviet Union (now Russia) and India, a new operator of naval nuclear propulsion reactors, also use HEU. But their levels of enrichment reported to be in the range of 40 to 50 percent, in contrast to the 90-plus percent used by the United States and United Kingdom. France initially used HEU but converted its aircraft carrier and submarines to use LEU. China is believed to have started with, and remained with, the use of LEU for its submarines (du Close 2016; Moore 2017).

The United States, United Kingdom, Russia, France, China, and now India all have developed military naval nuclear propulsion programs. Prior to its indigenous program, India engaged in a unique agreement to lease two nuclear-powered submarines, one from the Soviet Union, which was returned, and a later one from Russia, which it still operates. In addition, Japan and Germany at one time developed commercial nuclear-propelled vessels, as did the United States. These commercial vessels were powered by LEU reactors. Russia is the only current operator of commercial nuclear-powered vessels (icebreakers). Although the Russian icebreakers were originally LEU powered, they currently use HEU fuel (Moore, Banuelos, and Gray 2016).

Currently Brazil is the only state that has declared that it is developing a new nuclear naval construction program. However, the program, despite French assistance to the nonreactor portions, has developed slowly and has been mired in domestic conflicts. Pakistan is reportedly looking to China for a lease opportunity following India's example of leasing from Russia. Canada and other countries have in the past or currently expressed interest in either construction of nuclear-powered vessels or in leasing them from other countries.

Naval Propulsion Reactors

Until relatively recently all nuclear-propelled vessels routinely refueled their reactors, typically several times during the operational life of the vessel, regardless of whether the reactor was LEU- or HEU-fueled. As will be discussed further below, various navies developed different procedures for the refueling, based on factors such as the original design of the vessel, its operating characteristics, the country's ship construction infrastructure, and procedures for military-civilian contracts.

First, however, it is important to consider how naval propulsion reactors differ from the typical land-based nuclear power plants and research reactors, with which the public is somewhat more familiar. There are significant differences in size, power output, and operational methods that distinguish naval propulsion reactors. Because of these differences, many of the experiences with nuclear power plants and research reactors (such as conversion from HEU to LEU) have little or no applicability to naval reactors. Although the majority of nuclear power plants are pressurized water reactors (PWRs) and naval propulsion reactors are also PWRs with similar components (reactor core, control rods, a pressurized primary loop, one or more heat exchangers, and a secondary steam generation and utilization side, plus assorted coolant pumps, feed pumps, and other components), the naval reactors are far smaller. In addition, they are rated on their thermal power output while nuclear power plants are typically rated on their electrical output. A typical naval propulsion reactor will have a thermal output of somewhere between 80 megawatts (MWt) and 400 MWt, whereas a current-generation nuclear power plant will have an output on the order of 3,000 MWt in order to produce the 1,000 MW of electrical output (MWe) that is typical of such plants.

Ideally, a commercial nuclear power plant goes critical; comes up to maximum power and remain at that level around the clock for as long as possible; and then conducts a protracted shutdown program, decreasing power levels step by step. Military naval propulsion plants may operate at full power for only a small fraction of the time, and the power levels may change rapidly and cover a wide range.[1] The plants are often shut down while the vessel is in port, or they can provide minimal power for the ship's non-propulsion service load. The amount of time a military vessel is underway will depend on the operational commitments it must meet, and this can vary widely from year to year. In addition, the military propulsion reactors must be rugged, adaptable, and able to achieve criticality and operate successfully at all times.[2]

While naval propulsion reactors are closer in power level to larger research and test reactors, their design is not similar. These differences largely eliminate any lessons that may have been learned in what has been a widespread and largely successful effort to convert research and test reactors from HEU to LEU use.

[1] It should be noted that even among naval propulsion reactors there may be wide variation in operation among individual units and vessel types depending on their tasking, operations, and other factors. For example, an attack submarine (SSN) may go through significant power changes in comparison to a ballistic-missile submarine (SSBN), where the reactor power demand may be relative stable during its deployment.

[2] This means, among other things, that military naval propulsion reactors must have sufficient excess reactivity at all times to override post-shutdown xenon poisoning.

Why Use LEU-Fueled Reactors?

The US and UK navies have maintained perfect safety records using HEU-fueled reactors. Why consider changing to LEU? There are at least three reasons—and there is debate over the importance of each of them.

Perhaps the most important reason for concern is that the HEU fuel used by the United States and United Kingdom presents a proliferation and nuclear-terrorism risk. The two countries used to enrich the fuel to a higher level than the typical HEU used in nuclear weapons. Currently, the US and UK navies are burning HEU that has been recovered from nuclear weapons eliminated under arms reduction agreements with the Soviet Union and Russia. Therefore, the fuel itself is a direct terrorism and proliferation risk. A terrorist or subnational group stealing a sufficient amount of US or UK unirradiated naval reactor fuel could quickly convert it to be used in a crude gun-type nuclear weapon. Concern about the weapons usability of HEU fuel exists at all stages of the fuel cycle once the uranium has been enriched. Whether it is as uranium hexafluoride at the fuel fabricator's facility, as fresh fuel in transit or storage, or even spent fuel, HEU must be continuously protected at the highest level of security. The only times that the fuel requires little protection against theft are when it is actually being consumed in a reactor aboard ship or in a land-based training reactor and during the time that, as spent fuel, it is too radioactive to be stolen and used in a nuclear weapon.[3]

In addition to the risk of HEU fuel being used in a nuclear weapon, burned HEU fuel, like LEU fuel, could be sabotaged while in storage or cool down to cause a release of radioactivity or used in a radioactive dispersal device such as a "dirty bomb." Both HEU and LEU spent fuel would contain dangerous highly radioactive fission products, However, HEU fuel arguably presents a lower risk for this type of scenario since an equivalent reactor fuel load of LEU would be significantly larger in volume and contain much more long-lived plutonium, which results from irradiation of the higher uranium-238 content of LEU fuel.

The second reason to convert to LEU is that continued use of HEU fuel in naval propulsion reactors can influence proliferation. As noted above, the HEU fuel might be used directly by a proliferant nation, which might acquire the fuel through theft or by any illegal or legal transfer from a state possessing HEU fuel. Of perhaps more concern is an indirect effect on proliferation. Since the Nuclear Nonproliferation Treaty (NPT) does not prohibit enrichment or the use of enriched material for military uses other than weapons, a proliferant state might first develop and use HEU fuel for naval propulsion reactors and then clandestinely transfer the fuel directly to a nuclear-weapon program or withdraw from the NPT and shift the HEU to use in weapons. Iran raised the specter of needing to enrich uranium for a submarine program prior to the conclusion of the Joint Comprehensive Plan of Action (JCPOA) and has reportedly made the International Atomic Energy Agency aware of post-JCPOA plans for naval nuclear propulsion.[4]

The long-proposed Fissile Material Cutoff Treaty (FMCT), for which negotiation are now essentially dormant, has as one of its principal goals the ending of production of fissile material (both uranium and plutonium) that would be useful for nuclear weapons. The FMCT would arguably never be agreed to by many of the non-nuclear-weapon states under the NPT unless it were to be a complete and enforceable ban on production of weapons-usable material It is hard to believe that many of the non-nuclear-weapon states would ever agree to a treaty that would allow for the production of weapon-grade HEU fuel for naval propulsion reactors in some states while banning it in other states. US presidential statements about a potential FMCT have always been careful to address it in the context of a cutoff of HEU for weapons, leaving HEU production for naval propulsion out of the discussion. It is highly unlikely that production of HEU fuel for naval reactors could coexist with an FMCT. Thus, those navies using HEU fuel would probably need to shift to LEU fuel in the event of an FMCT.

A final reason to shift to HEU fuel is economic. The United States no longer produces HEU and new facilities will have to be built in order to resume production of it. The US Navy currently has a supply of HEU that has been estimated to be sufficient to supply naval needs for the next 50 years at current operational tempos. Decision-making, funding, and construction lead times of about 30 years would probably be necessary

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[3] Note that the radiation hazard from spent fuel is a safety concern and various terrorist or subnational groups may view the radiation risk differently. Fuel that was once considered too radioactive to handle may not be safe from suicidal terrorists.

[4] See, for example, "Iran signals plan to build nuclear-powered ships," DW, February 22, 2018, http://www.dw.com/en/iran-signals-plan-to-build-nuclear-powered-ships/a-42704705.

in order to resume HEU production (US DOE 2015, 40).[5] This would be a significant financial investment that could be avoided by the use of LEU fuel for which production facilities of the current nuclear power industry could be either directly used for or slightly adapted to produce LEU naval reactor fuel.

Advantages of HEU Fuel

The principal advantage of HEU fuel is that it provides a compact reactor core. The smaller core requires fewer control rods and control rod drives, a smaller pressure vessel, and reductions in piping, shielding, and coolant volumes.[6] All of this is extremely desirable in the small space of an attack submarine, whereas larger spaces available in a ballistic-missile submarine (SSBN) and an aircraft carrier or surface combatant arguably make compactness less of a priority.

Therefore, were it not for concerns about nuclear-weapon proliferation and terrorism, as well as economics, HEU would be the clear choice for military naval propulsion reactors. During the Cold War, there was always a premium on military utility, and the choice of HEU fuel was unquestioned. However, since at least the 1990s and the end of the Cold War, Congress has asked the Navy whether it could use LEU fuel for its naval propulsion needs,[7] reflecting perhaps the rise of concerns in Congress about proliferation and terrorism as opposed to the Cold War mind-set that focused on the potential for direct large-scale military confrontation.[8]

Disadvantages of LEU Fuel

It must be clearly understood that the use of HEU fuel does not provide a power advantage. LEU-fueled reactors are capable of producing the same power levels as HEU-fueled reactors. The major disadvantage of LEU fuel is that to a first approximation, the uranium-235 content of the LEU fuel must be approximately the same as the uranium-235 content of the HEU fuel. If the fuel material density of the LEU and HEU fuel are the same, simple approximations of the increased size of the core for an LEU reactor to replace an HEU reactor that would last for the same length of time can be made. For example, if current HEU fuel is approximately 93 percent uranium-235 and the HEU replacement LEU core were to use fuel in the range of 6 to 8 percent, then the fuel volume would be increased by a factor of about 16 ($93 \div 6 = 15.5$). Since the reactor cores are essentially right circular cylinders whose volume is given by the formula: V= h, where r is the radius of the cylinder and h is its height, the radius and therefore the diameter of an LEU core would be approximately $\sqrt{16}$ or about four times the diameter of HEU fuel for the same fuel loading if the height of the cylinder remained unchanged. If the height were increased by a factor of two, the diameter would then increase by a factor of $\sqrt{8}$, or about 3 times the diameter of an HEU core. According to the Navy, the volumetric increase is size prohibitive, at least in the majority of submarines, which are smaller-diameter attack submarines (SSNs). The engineering spaces in SSBNs are somewhat larger but still small in comparison to surface ships.

Thus, the argument goes, the use of LEU cores is a disadvantage because of the need for a larger reactor. If the reactor size is kept at or near the size of the HEU reactor, the LEU cores must be replaced with relatively high frequency in comparison to an HEU core of equivalent size.

In addition, the US Navy contends that the relatively higher buildup of actinides such as plutonium and curium due to the larger presence of uranium-238 would lead to disposal problems and increased security problems.[9] Disposal problems would be of at least two types. First, the LEU fuel assemblies probably would be larger, compelling the Navy to develop new spent-fuel shipping containers. Second, changing to LEU fuel might create political problems with the state of Idaho. Under an agreement with the state, the Navy stores its spent fuel there, and the agreement might not be easily modified.

The Navy has also at times maintained that the variation in thermal response during power transitions could cause control problems

[5] Note, however, that the estimates for the need for HEU may be more critical when other factors are considered. The 2015 report by the Department of Energy estimates that new sources of HEU may be needed by 2060 or perhaps 10 years sooner than the Navy's use might indicate.

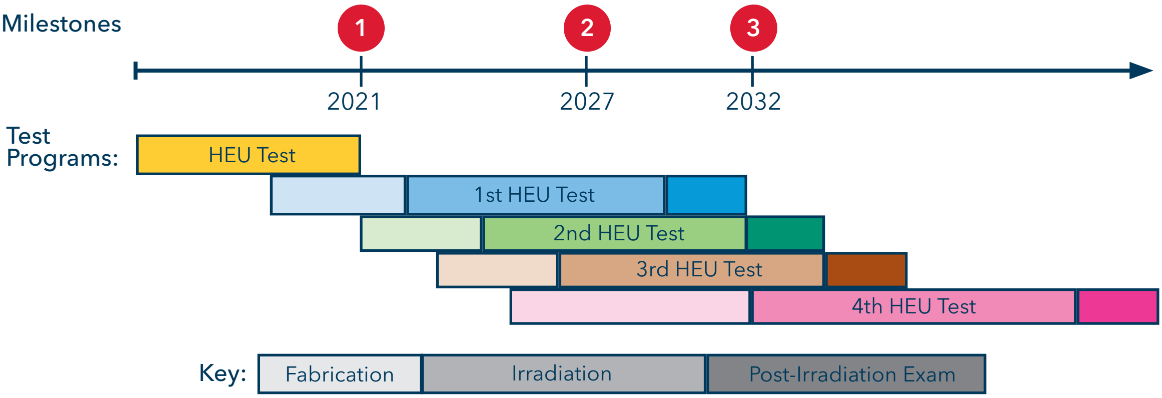
[6] Any increase in component size generally brings with it an attendant increase in weight, and weight will have an effect on maneuverability, buoyancy requirements, and the overall design of the submarine or surface ship.

[7] The congressional requests have resulted in the Navy's reports of 1995, 2014, and 2016 discussed above.

[8] Given the close relationship between the programs, one assumes that the United Kingdom would quickly follow whatever decision the United States makes with regard to conversion from HEU to LEU. The UK program generally tracks the US program, particularly in submarine-launched ballistic missiles. It is highly doubtful that the United Kingdom would have sufficient independent HEU fuel stocks or enrichment capacity to continue to use HEU if the United States stopped using it and refused to supply it to the United Kingdom.

[9] The Navy tends to downplay the security problems associated with spent HEU fuel (which remains HEU even as spent fuel) and tends to exaggerate the problems with spent LEU fuel, which would be no greater than those from the spent fuel of a current nuclear power plant. Assuming equivalent core burnup and about the same enrichment level of LEU for the power plant and a naval reactor, the waste from one nuclear power plant would be approximately equal to about 10 submarines (assuming that a nuclear power plant has an output of 3000 MW thermal and a submarine reactor's is 300 MW thermal).

Figure 1: US Navy 2016 Proposal for Development Program for LEU Fuel.



Source: NNSA 2016

when using LEU fuel. This argument is based on Doppler broadening of resonance capture of neutrons in uranium-238 as a function of temperature changes as power changes. However, as discussed below, the experience of France in converting from HEU to LEU indicated no problems with control due to Doppler broadening. French reactor operators found no significant differences in responses.

Finally, a larger LEU core would presumably require more control rods, more coolant flow, more coolant pumps, a larger primary pressure vessel, a general scaling up of the reactor. All of these factors could contribute to added undesirable increases in weight, increased noise, and other factors that could reduce military effectiveness if not dealt with properly.

Thus, LEU fuel is not without problems. However, these problems are ones of engineering and economics, which must be weighed against the risks—primarily of proliferation and terrorism concerns—associated with HEU fuel and its supporting infrastructure. Reactor safety in the classic sense of avoiding a nuclear reactor accident should not be substantially different for HEU- and LEU-fueled reactors and therefore should not be an issue in comparing the two fuels. The Navy has run a safe and secure HEU fuel program and would certainly run a program as safely and securely using LEU fuel.

Reports to Congress

Since the 1990s, the US Navy has responded publicly to three congressional requests about the use of LEU for naval propulsion reactors. In 1995, 2014, and 2016, the Navy, acting through the director of naval nuclear propulsion in the Department of Energy's National Nuclear Security Administration (NNSA), reported to Congress on the issue (Director, Naval Nuclear Propulsion 1995; Office of Naval Reactors 2014; NNSA 2016).

These reports clearly demonstrate that the Navy consistently asserted that LEU use was not advisable. For example, in its 1995 report, the Navy stated:

> The use of LEU for cores in U.S. nuclear-powered warships offers no technical advantage to the Navy, provides no significant non-proliferation advantage, and is detrimental from environmental and cost perspectives. (Director, Naval Nuclear Propulsion 1995, 1)

Almost 20 years later, in its 2014 report, the Navy admitted that LEU could be used, but still maintained that HEU was highly preferable:

> Substituting LEU for HEU would fundamentally decrease reactor energy density, increase lifecycle and operating costs, increase occupational radiation exposure, and increase the volume of radioactive wastes. Thus, while it may be feasible to replace HEU fuel with LEU fuel in current U.S. Naval reactor plants, it is not economical or practical to do so. (Office of Naval Reactors 2014, 5-6)

The 2014 report contained a tantalizing reference to a new higher-density uranium fuel:

> Recent work has shown that the potential exists to develop an advanced fuel system that could increase uranium loading beyond what is practical today while meeting the rigorous performance requirements for naval reactors. Success is not assured, but an advanced fuel system might enable either a higher energy

> naval core using HEU fuel, or allow using LEU fuel with less impact on reactor lifetime, size, and ship costs. (Office of Naval Reactors 2014, 5-6)

Current Status (2016 to the Present)

The year 2016 was notable for a relative flurry of activity by the Navy on the potential for LEU use (Philippe and von Hippel 2016). By that year, the Navy had recognized the congressional impetus to convert to LEU use and had developed an initial research plan for LEU use in a future aircraft carrier design. Nevertheless, the Navy still said:

> The operational needs of U.S. Navy submarines and aircraft carriers place a high importance on the reactor core energy density. *The replacement of HEU with LEU will result in a reactor design that is inherently less capable and more expensive…* (NNSA 2016, iv; emphasis added)

The report further stated:

> A pressurized water reactor with HEU fuel in high integrity fuel elements has proven to be the optimum design to meet these essential functional requirements for nuclear propulsion for warships. The use of HEU maximizes the amount of fissile material in the small volume of the reactor core, enabling long lifetimes while allowing for a compact reactor plant. (NNSA 2016, iv)

The 2016 report is the Navy's most recent public pronouncement on the use of LEU fuel in its vessels. It rules out the use of LEU for submarines but does set out a program for development of an LEU fuel system that would be used in an aircraft carrier. It estimates that the development program would cost almost $1 billion, which does not include any actual construction costs for reactors that would be potentially put in vessels. The program timeline and milestones are shown in Figure 1 below, which is taken from the 2016 Report (NNSA 2016, 6-7).

The 2021 milestone indicates the point at which the Navy has developed the advanced fuel concept for HEU fuel and is prepared to make a determination as to whether the program should be continued to study LEU fuel (NNSA 2016, 7). The program illustrated in Figure 1 would not determine whether LEU naval fuel is technically feasible until 2032 and then would require construction and testing, with the first actual LEU fuel for an aircraft carrier available approximately 10-15 years later. The Navy estimates that a significant refurbishment of the fuel testing infrastructure would be needed to implement the program, and those costs are included as part of the $1 billion program estimate (NNSA 2016, 7-8).

The additional costs beyond the $1 billion development program for the advanced fuel system—the costs of actually building a reactor to install in a Ford-class carrier around the middle of the century—are estimated in the report based on fiscal year (FY) 2016 dollars. These include $1.5-2.4 billion for actual core procurement for a carrier (development of the core design), the undefined costs of a necessary land-based prototype reactor, increased costs in new spent-fuel transportation and disposal (estimated at $1 billion), and additional manufacturing costs such as those for more complex fuel fabrication. There would be an additional cost to blend down HEU to provide an initial LEU fuel, which the Navy estimates at approximately $265 million per Ford-class reactor core. The Navy states that further, unspecified costs may result from its fuel and reactor vendors being required to maintain two separate work streams, one for HEU-fueled submarines and another for LEU-fueled aircraft carriers (NNSA 2016, 9-11).

In summary, the Navy's 2016 report says that LEU is a bad idea, but if Congress wants to pay for it, the Navy will give it a try for aircraft carriers, but not for submarines. Even for carriers, there is no guarantee that LEU use would be successful. The 2016 report can cynically be viewed as a rehashing of the arguments against LEU set out in the Navy's 1995 and 2014 reports to Congress, but with a promise to look into development of a better LEU fuel for aircraft carriers (the advanced fuel concept floated in the 2014 report) once Congress funds development of advanced HEU that the Navy wants for its submarines and aircraft carriers.

The 2016 report triggered a request by a group led by Representative James Langevin, a Democrat from Rhode Island, that the Navy explain a number of issues in the report (Langevin, 2016). The Langevin letter posed a number of serious questions about the timelines and whether they could be restructured to resolve the issue of LEU use more quickly. To date, no response to this letter seems to have been received. In addition, until early 2018 there was little to no indication of the Trump administration's view on LEU use. Although there were some indications of small amounts of funding to pursue the LEU issue, a congressional funding response to the $1 billion proposal has not emerged. However, the Department of Defense and Department of Energy sent a joint letter to Congress on March 25, 2018, stating that they had "jointly determined that the United States should not pursue research and development of an advanced naval nuclear fuel system using low-enriched uranium (LEU) instead of highly enriched uranium (HEU)" (Reif 2018). It is unclear at this point how willing Congress will be to push the issue or how congressional funds for LEU fuel research will be used.

Use of LOS Reactors

Commencing with the Virginia class of attack submarines, the US Navy has eliminated the need for refueling. The Virginia class employs a reactor that has been designed to be used for the life of the ship without refueling. Conceived in the mid-1990s when the Virginia class was developed, the life-of-ship (LOS) reactors are, from the Navy's point of view, the successful culmination of its efforts to extend the life of naval reactors and decrease the impact of reactor refueling.[10]

The LOS reactors are clearly the Navy's choice for the replacement of the Ohio-class fleet SSBN. The planned new replacement is now known as the Columbia class. Although some questions have been raised about its reactor,[11] it appears that there is insufficient lead time to make it anything other than a HEU-fueled LOS reactor (USNI News 2017).

The LOS reactor concept appears to have been accepted without serious question. It is clearly a step into an unknown area of performance. The Navy has never operated reactors without replacement for the 33- to 40-year lifetimes that the LOS submarine reactors may see. The beauty of the LOS concept is twofold. First, it eliminates refueling and thus saves money because only one reactor core is used for the life of the ship. Second, it minimizes the lengthy US refueling outages, thereby potentially allowing vessels to spend more of their time at sea.

Specific details of the design of LOS cores are not known. It appears, however, that these cores could be removed from the vessels only with relative difficulty. If this is true, then problems that might appear later and not have been detected—either by the testing done to certify the design or the quality assurance for the items manufactured according to the design—could result in serious economic and other problems for the Navy. For example, if fuel elements leak significantly, the Navy might be required to replace them. It might also have to open reactors for inspection should there be a suspicion that problems of any sort are occurring. Should a problem occur in one vessel, it would probably cause at least inspection of all vessels having the same type of reactor.

Under these circumstances, why take whatever risks are involved in the use of LOS cores, whether they are HEU or LEU? Although this question might have been considered within the Navy, it does not appear to have risen to the level of a congressional debate. It appears that for economic reasons, the Navy has been willing to take a risk on a somewhat unknown reactor design. Why take the risk when refueled HEU or even refueled LEU reactors have been a tried-and-true concept? Although the Navy has great expertise in propulsion reactors and has run an extremely safe program to date, there is a strong argument that the LOS concept, either for HEU or LEU, should be reviewed by technical experts who have no vested interests in the outcome of such a review.[12]

The French Experience

France has a modern nuclear-powered navy that currently operates an aircraft carrier, SSNs, and SSBNs. France also relies more heavily on nuclear power plants for its electrical supply than any other nation. Although France originally started its naval propulsion program using HEU fuel, it made a determination to shift to LEU fuel for several reasons. It also has developed a program for refueling its ships that minimizes refueling outages and radiation exposures to workers by using a more automated process than appears to be used by other navies. Current French vessels are designed for easy and rapid refueling.

Several factors contributed to France's decision to convert to LEU. First, in the mid-1990s, France stopped needing to produce HEU for nuclear weapons. In addition, French nuclear-safety regulations require that all reactors in France, including naval reactors, be open for inspection of all components at least every 10 years. The combination of these factors, coupled with the realization that LEU reactors could meet the French Navy's needs, caused the Navy to shift to LEU, thereby allowing it to purchase "LEU fuel

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[10] Refueling impacts the Navy in several ways. First, the vessel is not operationally available during the time it is being refueled. Although naval vessels routinely require overhauls during the service life of the ship for reasons besides reactor refueling (such as installation of weapons-system upgrades, routine hull maintenance, and inspections), reactor refueling has been a controlling factor in the non-availability of US vessels due to overhauls despite attempts to integrate all aspects of needed repairs. In addition to the cost of the refueling itself, the Navy has needed to purchase more vessels than it would otherwise have needed in order to keep a specified number of vessels in operation at sea.

[11] A report by the Government Accountability Office raised issues about the maturity of the nuclear reactor, noting that the use of the Virginia-class LOS reactors would have to increase its service life by about 10 years to match the projected 40-plus years anticipated for the Columbia class (GAO 2017).

[12] Sealing a reactor for 40 years without inspection is unique in nuclear-engineering applications. Forgoing advances in inspection technologies over the operating life is highly questionable.

with enrichments much less than 20 percent" and avoiding the cost of producing expensive HEU fuel (du Clos 2016, iii).

The French Navy has achieved its ability to rapidly refuel through the use of large hatches, known as *brèches*, which allow quick access to the reactor compartment. In fact, the French have been able to replace a reactor core in one of their SSBNs during its normal in-port period between patrols (du Clos 2016, 4-5).

Could the French experience be applied to the potential US Navy shift from HEU to LEU? It is an obvious question to raise, but one that the Navy has failed to even begin to address. In its reports from 1995 to the present, the Navy has not once mentioned the French, or for that matter the Chinese, experience with LEU cores.

Although the French Navy does not disclose the exact enrichment level of its LEU fuel, indications that it is much less than 20 percent and can be produced by commercial suppliers would suggest that it is probably in the range of 5 to 10 percent.

The 6 Percent Solution

When the US Navy has discussed LEU in its various public reports, the clear implication has been that it is looking at using LEU at the upper reaches of the definitional value, something close to but slightly below the 20 percent level that constitutes the border between LEU and HEU. For the sake of simplicity, one can refer to this as "high LEU." Although this would meet the definitional value of LEU and would potentially save some space when compared with the use of fuel with an enrichment level of about 6 percent (a value that is probably close to the level used by the French and perhaps the Chinese), the use of high LEU would be bad for several reasons.

First, there is no physical magic in the 20 percent definitional line for HEU. It is merely a convenient dividing line indicating the ability to use enriched uranium material in a nuclear weapon. While it is not a bright line, as enrichment decreases from high LEU to lower levels, the usability for a weapon becomes far less as the size of a critical mass increases exponentially.

Second, the effort required for enrichment to get to the high LEU region is not much less than that required to produce weapon-grade HEU. Thus, the French approach, which presumably keeps the uranium in the 5-10 percent region of enrichment, is a much more proliferation-resistant option than high LEU.

Finally, there is a possible perceptual benefit for the United States in using naval propulsion fuel enrichment at about the 6 percent level. Using fuel at that level signals to other states that the United States is serious in its commitment to reducing the risks of nuclear proliferation and terrorism.

Conclusion

Naval nuclear propulsion is the largest user of HEU material other than nuclear weapons (von Hippel 2016). Conversion of naval propulsion reactors fueled by HEU should be a high priority for the US Navy. Conversion to LEU fuel with an enrichment level of 6 percent uranium-235 would be a significant advancement in promoting nonproliferation and preventing nuclear terrorism.

Regardless of whether the Navy converts to LEU, Congress needs to understand whether the economic savings from the current shift to LOS reactors are worth any potential downstream economic and safety risks. Given the importance of nuclear-powered vessels to US national defense, Congress should act quickly to implement a study to address the LOS issue.

The US Navy should analyze and, to the extent possible, follow the example of the French Navy and its conversion to LEU use and rapid refueling. Following the French example by building naval propulsion reactors with 6 percent enriched fuel and developing fast refueling procedures would provide immediate benefits in reducing the risks of nuclear proliferation and terrorism. Use of 6 percent fuel would also remove a major potential obstacle to the implementation of an FMCT since the Navy could forgo future production of HEU. A verifiable and enforceable FMCT is an essential step if the world is ever going to be able to minimize or eliminate the risk of nuclear proliferation and establish a pathway to more significant reductions in nuclear arsenals and minimization of the risk of nuclear war.

If the US Navy converted to the use of 6 percent LEU fuel with rapid refueling, would it place itself at a disadvantage in relation to potential enemies that use submarines and surface vessels fueled with HEU? This is an issue that needs to be well understood. It involves not only the nuclear reactor but also consideration of the entire vessel as a weapons system, including issues such as loss of space, noise reduction, and maneuverability.[13] Of course, any analysis should not be considered only from a US perspective.

Although the United States is capable of making a conversion unilaterally, it would probably be ill-advised to make a conversion if doing so would significantly disadvantage the US Navy in comparison to other navies. There is an argument to be made that a unilateral conversion by the United States might convince other navies to follow its lead, but such an argument is political and lacking in military merit. However, the concept of a worldwide ban on using HEU for naval propulsion could potentially lead to a verifiable treaty that would remove concerns about relative disadvantages. It should be noted that a series of naval treaties enacted among the major powers in the period between World War I and World War II were reasonably effective in limiting what otherwise would have been a far more significant naval arms race. These treaties were arguably successful despite the fact that verification was far more limited than that which could be achieved by modern technical means.

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[13] For surface ships, the comparison is probably not too extreme. As mentioned above, LEU use that requires more space would probably have little impact on the warfighting capabilities of surface ships such as aircraft carriers.

Assessing Challenges to Completely Eliminating Use of Highly Enriched Uranium in US Naval Reactors

PETER LOBNER

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The United States pioneered the use of nuclear-fueled ships and today has the only navy that operates an all-nuclear fleet of submarines and aircraft carriers. All currently are operating with highly enriched uranium (HEU)-fueled reactors, with an enrichment level between 93 and 97 percent uranium-235. HEU-fueled reactors enable the desired level of vessel performance while reducing or eliminating need for refueling during the service life of the vessel. Yet for most of the nuclear navy's history, refueling was the norm. A significant question is whether today, in an era of budgetary constraints and a dwindling stockpile of HEU, the US Navy should move more seriously toward reducing the enrichment of its naval reactor fuel and accepting the operational constraint of shorter intervals between refuelings. This analysis discusses some practical obstacles and practical solutions for a future effort.

In 2014 and 2016, Naval Reactors, which is part of the Department of Energy's National Nuclear Security Administration (NNSA), reported on the challenges of implementing a policy of fueling the US nuclear fleet with low-enriched uranium (LEU), which is defined as having an enrichment level below 20 percent (Naval Reactors 2014; NNSA 2016). The Navy concluded that LEU fuel "would not directly produce a more militarily desirable reactor design." In the view of Naval Reactors, substituting LEU for HEU in the fuel systems in current-generation naval reactors would result in a significantly reduced core lifetime, require a larger reactor size, or both. The Navy estimated that additional refuelings of LEU reactors would raise the cost of operating the fleet because of the need to service reactors. Other disadvantages lie in reduced ship availability, increased costs for the disposal of spent fuel and nuclear waste, increased occupational radiation exposure, and increased manufacturing and procurement costs to build refueling cores.

Naval Reactors' 2016 report (NNSA 2016) outlined a two-phase, conceptual research-and-development plan starting in fiscal year (FY) 2018 for an advanced fuel system technology using LEU fuel in reactors that power aircraft carriers. A development phase, costing about $1 billion per year, could lead to a feasibility demonstration in 2032. If successful, it would take another 10 years to design and procure two LEU-fueled reactors for a Ford-class aircraft carrier. That 10-year phase would cost between $1.5 billion and $2.4 billion in FY 2016 dollars. Part of the development process would include building a land-based LEU prototype reactor and improving nuclear infrastructure (primarily fuel manufacturing). The advanced fuel system technology also should be usable with HEU fuel in a more compact core.

Unfortunately, the Navy and other branches of the military are in a budget crisis, as all services are competing for limited funds to recapitalize aging weapons systems. The Navy has aging fleets of nuclear-powered aircraft carriers and submarines, submarine-launched ballistic missiles, conventionally powered surface ships, and most types of naval aircraft. This military budget crisis diminishes the prospects for funding an LEU naval reactor program.

The Mission of the Naval Nuclear Propulsion Program

The Naval Nuclear Propulsion Program, also known simply as Naval Reactors, is tasked with providing militarily effective nuclear propulsion plants as well as ensuring their safe, reliable, and long-lived operation. Ships are expected to "excel in endurance, stealth, speed, and independence from supply chains." Although the program's top priority is ensuring the safety and reliability of all operating naval reactor plants, the preference for HEU-fueled reactors over LEU-fueled reactors is based on longevity, ability to deliver a lot of power in a smaller package, and independence from supply chains, especially those associated with refueling. Safety and reliability, as well as stealth, do not depend on fuel enrichment.

The US nuclear navy has steamed over 157 million miles safely using nuclear power (US DOE and Department of the Navy 2015). According to Naval Reactors, the program in 2015 operated "96 reactors and has accumulated over 6,700 reactor-years of operation. A leader in environmental protection, the Program has published annual environmental reports since the 1960s, showing that the Program has not had an adverse effect on human health or on the quality of the environment."

Two Million Miles, 2.5 Tons of HEU

More than 45 percent of the Navy's major combatant vessels are nuclear-powered. In early 2018, the US nuclear fleet, as listed in Table 1, consisted of 79 combatant vessels powered by 90 reactors fueled with HEU. This fleet steams about 2,000,000 miles per year (US DOE and Department of the Navy 2015) and consumes about 2.5 tons of HEU per year (Philippe and von Hippel 2016). Of the vessels that need mid-life refueling, the Ohio-class SSBNs refuelings will be completed by 2022 and four of the Nimitz-class carriers are scheduled to complete their refueling by 2034. Given the long lead-time for developing LEU cores, only the first Ford-class aircraft carrier, USS Gerald R. Ford (CVN-78), might be eligible for an LEU core when it is refueled in 2042.

Service Life and Engineered Operating Cycle Programs

The Navy has an established policy (OPNAV 2010) that ships will be maintained at the highest practical level of material readiness to meet requirements for operational availability while minimizing total life cycle costs over the design life of the ship. The ships also are to be maintained in a safe material condition and meet environmental and shipboard habitability standards.

To implement this policy, each class of ship operates within an approved engineered operating cycle (EOC) with a defined schedule for the major maintenance activities required to obtain the desired service life. A maintenance strategy and plan are developed based on the design service life of the systems and components in each class of ship (OPNAV. 2014). [1,2]

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1 For submarines, more specific guidance is provided in OPNAV (2013). Two maintenance strategies differentiate between the EOC for most SSNs and the phased planned maintenance cycle for SSBNs/SSGNs and the three Seawolf-class SSNs. Major maintenance cycles for each submarine class are defined in terms of operating intervals (OPINTERVAL) and operating cycles (OPCYCL).

2 Operational planning for the entire US Navy fleet is built around the respective EOC and service life of each ship. In the case of submarines, ship-submerged operation is not allowed with an expired OPINTERVAL, OPCYCLE, or service life. Naval Sea Systems Command can approve a request to extend a submarine's OPINTERVAL or OPCYCLE beyond the normal limits. The director of undersea warfare is required to approve a submarine's service life extension (SLE). An SLE typically is done for a whole class of vessels because extensive inspections and supporting analyses are required to ensure that safety and reliability are maintained during the life extension period. An SLE improves near-term force levels while offering some economic and schedule flexibility in procuring replacement vessels.

Table 1: The US Nuclear-Powered Fleet, April 2018

Ship Type	Ship Class	Number in Class	Ship Service Life (yr.)	Reactor	Reactor Life
CVN	Nimitz	10	50	A4W (2)	Midlife refueling required. Five CVNs refueled; one in process; last will be completed by about 2034.
CVN	Ford	1	50	A1B (2)	Midlife refueling required. First CVN refueling will be in about 2042.
SSBN	Ohio	14	42	S8G	Midlife refueling required. 10 SSBNs have been refueled; last will be completed in about 2022.
SSGN	Ohio (cruise missile conversion)	4	42	S8G	Midlife refueling required. All have been refueled.
SSN	688 "Flight I"	2	33	S6G with a D2W core	Midlife refueling required. All have been refueled with a D2W core (not the original core).
SSN	688 "Flight II"	8	33	S6G with a D2W core	Life-of-the-boat.
SSN	688i (improved)	22	33	S6G with a D2W core	Life-of-the-boat.
SSN	Seawolf	3	30	S6W	Life-of-the-boat.
SSN	Virginia	15	33	S9G	Life-of-the-boat.

Legend: Ship designations: CVN = aircraft carrier, nuclear; SSBN = strategic ballistic-missile submarine, nuclear; SSGN = guided-missile submarine, nuclear; SSN = attack submarine, nuclear. Reactor designations: The US Navy uses a three-character scheme to designate types of naval reactors: Naval platform (S = submarine; A = aircraft carrier; C = cruiser; D = destroyer-leader class ship); reactor design number (e.g., S1W was the prototype and S2W was the similar reactor used on a submarine); and reactor manufacturer (W = Westinghouse; G = General Electric; C = Combustion Engineering; B = Bechtel Marine Propulsion Corp.) .

Sources: Peter Lobner; NavalAnalyses.com; OPNAV 2013; Wikipedia.

Service life is the established number of years that a ship is permitted to operate. It starts the day the ship is delivered to the Navy and ends on the anniversary date after the prescribed number of calendar years. The remaining service life of existing ships is an important input to the Navy's operational and shipbuilding plans.

In the US nuclear fleet, aircraft carriers, Ohio-class ballistic-missile submarines (SSBNs), and cruise-missile submarines (SSGNs) are refueled only once during their service life. Other vessels have "life-of-the-boat" reactors, so called because they are not refueled during their service life. This category includes Virginia-, Seawolf-, and most Los Angeles-class attack submarines (SSNs) and the future Columbia-class SSBNs. The resulting EOCs are simplified by the reduction or elimination of refueling activities, which otherwise would add significant time to a midlife overhaul.

The operational benefits to the fleet can be seen in the procurement plans for the Columbia-class SSBNs, which have a life-of-the-boat, HEU-fueled, S1B reactor. By eliminating the need for refueling, the midlife overhaul is significantly shortened. This will enable better scheduling of midlife overhauls for the SSBN fleet with fewer SSBNs being out of service for maintenance at one time. This also will enable a fleet of 12 Columbia-class SSBNs to perform the deterrent patrol missions previously assigned to 14 Ohio-class SSBNs. The use of HEU fuel will save about $13 billion in procurement for two SSBNs plus 42 years of operating and maintenance costs.

Retrofitting an LEU core into an existing submarine design with a long service life likely will require one or more refuelings where none had been required before. This could decrease the ship's availability, possibly requiring procurement of additional ships to meet the Navy's mission requirements. This is a significant issue in a budget-constrained environment, particularly when the procurement cost for replacement ships is very high.

A new-design LEU-fueled ship can incorporate features that simplify and shorten the refueling processes. Even with such features, the EOC for that new class of ship will require longer maintenance periods than those of its HEU-fueled counterpart. This translates into higher maintenance costs and lower operational availability. Again, the Navy may require additional ships to fulfill its missions if it is required to convert its reactors to LEU fuel.

Retirements and Replacements

In the next decade, the Navy will retire 34 submarines and two aircraft carriers (see Table 2). In anticipation, Naval Reactors has been developing three new HEU-fueled reactors for three classes of ships—CVN, SSN, and SSBN. The latter two will have life-of-the-boat reactor cores (see Table 3).

A1B

The A1B is the reactor for the new Ford-class CVN (previously known as CVNX and CVN-21), which has two A1B propulsion trains. A midlife refueling is required in the 50-year service life of the CVN. The lead ship of the class, USS *Gerald R. Ford*, was commissioned in July 2017. Its first deployment is planned for 2020 to allow time to complete operational testing.

According to the Office of Naval Reactors (2002), the "CVNX reactor will provide 25 percent more energy than the reactors in Nimitz-class ships and will have more than triple the electric power available but will require just half the number of sailors to operate and will be easier to maintain." The Navy was comparing the new reactor to one designed in the 1960s—the A4W reactors used in the current Nimitz class. The higher power of the new reactor reportedly would support a more intense deployment schedule or longer reactor life for the CVN-21 class (Office of Naval Reactors 2004, 522). The two A1B reactors in the USS *Gerald R. Ford* likely use 97 percent enriched HEU fuel, while additional ships in that class will likely use 93 percent enriched fuel with a slightly different core design as indicated by Naval Reactors in its FY 2004 congressional budget request (Naval Reactors 2003)

Table 2: Planned Retirements and Replacements in the US Nuclear-Powered Fleet

Ship Type	Ship Class	Retirement Window	Replacement Plans
CVN	Nimitz	10 CVNs will reach their 50-year service life at a rate of about 1 every 4 years from 2025 to 2059.	Will be replaced on a one-for-one basis by Ford-class CVNs.
SSBN	Ohio	14 SSBNs will reach their 42-year service life at a rate of about 1 per year from 2029 to 2040.	The first 2 Ohio-class SSBNs will be retired without replacement. Thereafter, the remaining 12 boats will be replaced on a one-for-one basis by 12 Columbia-class SSBNs starting in about 2031.
SSGN	Ohio conversion	4 SSGNs will reach their 42-year service life a rate of about 1 per year from 2023 to 2026.	Will not be replaced. The SSGN function will be assumed by Virginia Block V–VII multi-mission SSNs starting in the mid-2020s. There are preliminary plans for a future SSGN that could enter the fleet in the mid-2030s.
SSN	688 Flight I	2 SSNs, already operating beyond their 33-year service life, will be retired in 2018.	Los-Angeles-class SSNs are being replaced on a less than one-for-one basis by Virginia-class SSNs, which currently are being built at a maximum rate of 2 per year. The Navy is considering extending the service life of 688 Flight II and 688i SSNs to 36-37 years to help mitigate the impending fleet shortfall in SSNs.
SSN	688 Flight II	8 SSNs will reach their 33-year service at a rate of about 2 per year between 2019 - 2022.	
SSN	688i (improved)	22 SSNs will reach their 33-year service at a rate of about 2.5 per year between 2021 and 2029.	

Legend: Ship designations: CVN = aircraft carrier, nuclear; SSBN = strategic ballistic-missile submarine, nuclear; SSGN = guided-missile submarine, nuclear; SSN = attack submarine, nuclear.

Sources: Peter Lobner; NavalAnalyses.com; OPNAV 2013; Wikipedia.

Table 3: US Navy's Development of New HEU-Fueled Reactors

New Reactor	Reactor Life	Class of Ship	Ship Service Life (yr.)
A1B	About 25 years	Ford-class CVN	50
TTC and NGR forward-fit cores for S9G	Life-of-the-boat	Virginia-class SSN	33
S1B	Life-of-the-boat	Columbia-class SSBN	42.5

Legend: Ship designations: CVN = aircraft carrier, nuclear; SSBN = strategic ballistic-missile submarine, nuclear; SSN = attack submarine, nuclear. Reactor designations: The US Navy uses a three-character scheme to designate types of naval reactors: Naval platform (S = submarine; A = aircraft carrier; C = cruiser; D = destroyer-leader class ship); Reactor design number (e.g. S1W was the prototype and S2W was the similar reactor used on a submarine); Reactor Manufacturer (W = Westinghouse; G = General Electric; C = Combustion Engineering; B = Bechtel Marine Propulsion Corp.). TTC = Transformational Technology Core; NGR = Next Generation Reactor.

Sources: OPNAV 2013, O'Rourke 2017a, O'Rourke, 2017b, and supporting text in Naval Reactors congressional budget requests for fiscal years 2003-2012.

The Transformational Technology Core (TTC) and Next Generation Reactor (NGR)

The TTC appeared in Naval Reactor's FY 2004 Congressional budget request as a forward-fit, higher-performance core for Virginia-class SSNs. TTC was being developed in response to higher operating tempos of submarines (30 percent higher) since September 11, 2001. Continuing to operate at this pace would decrease core life below 30 years unless adjustments were made. Naval Reactors sought to mitigate this effect by using 97 percent enriched fuel and advanced reactor core materials to "achieve a significant increase to the core energy density—more energy without increasing size, weight or space while still at a reasonable cost." Accordingly, the Navy designed the TTC to do one or more of the following: extend ship life by as much as 30 percent; increase operating hours per operating year; or allow operation at a higher average power during ship operations."

Largely dictated by the Navy's goal to reduce the cost of Virginia-class submarines to $2 billion per unit, Naval Reactors ended TTC development in FY 2007 with the completion of TTC fuel system design and reactor development was re-directed to a lower-cost, forward-fit core for Virginia-class SSNs.

This alternate core became known as the NGR (Next Generation Reactor) or NGR-93 (because the fuel is 93 percent enriched). The last NGR task named in Naval Reactor's FY 2012 Congressional budget request was to "develop test predictions and related analysis for Next Generation Reactor new construction testing." Subsequent year budget requests provided no new details. Somewhere in the Virginia SSN construction cycle, the NGR will be introduced to the fleet. NGR won't have all of the higher performance promised by the TTC, but it probably will equal or exceed the performance of the original S9G core designed in the 1990s.

S1B

S1B will be a life-of-the boat reactor for the new Columbia-class (previously known as the Ohio replacement) SSBN, which will have a 42.5-year service life. The S1B will have the longest design life of any reactor ever developed by the US Navy.

Research, development, and design for the class of SSBNs that will replace the Ohio class began almost a decade ago. The goal is to provide a new reactor plant to maximize operational availability and reduce acquisition and life cycle costs. The S1B reactor is expected to support more than 40 years of operation, which reportedly will enable the US Navy to operate two fewer submarines than the Ohio class to fulfill its missions (NNSA 2011; NNSA 2012).

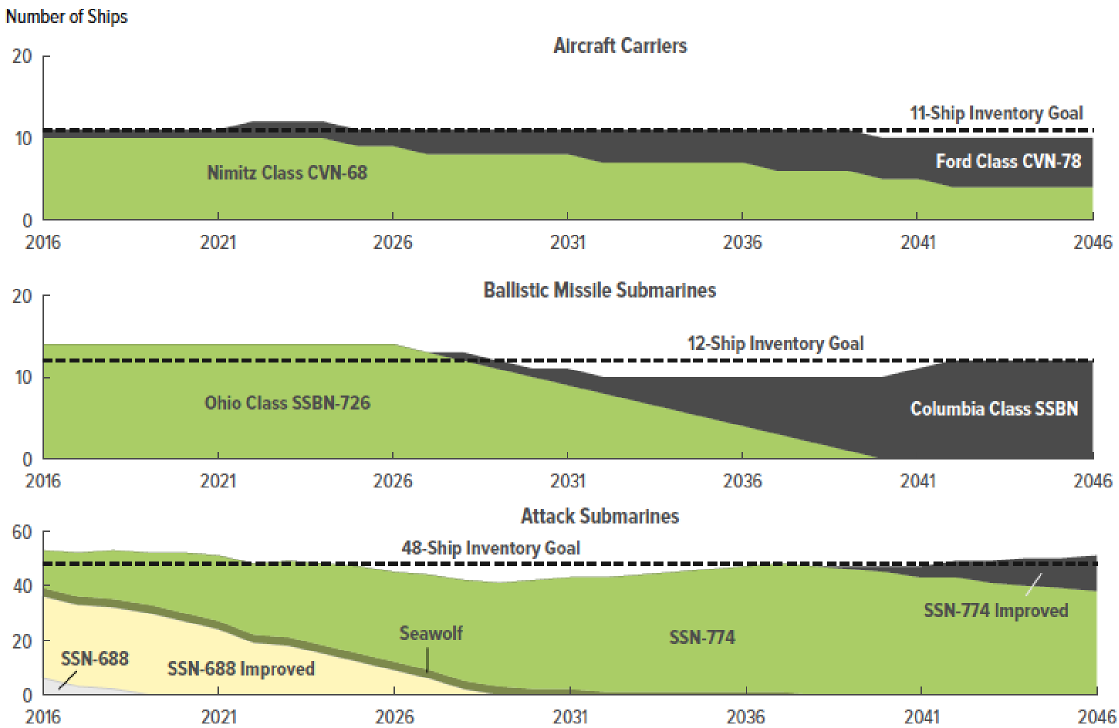
Recapitalizing the US Nuclear Fleet

The large number of nuclear-powered ships approaching the end of their service life (see Table 2), coupled with the long lead time and high cost to design, develop, and construct replacement ships, is placing increasing pressure on the fleet to meet operational commitments. Therefore, the Navy is seeking to recapitalize a large portion of its nuclear-powered fleet with vessels that are more capable than their predecessors.

The Congressional Budget Office analyzed the Navy's 2017 long-range shipbuilding plan (OPNAV 2016) for a 308-ship combatant fleet, concluding that significant gaps will emerge (CBO 2017).

As indicated in Figure 1, the shortfall in CVNs develops in 2038, due to a mismatch between the schedule for retirement of Nimitz-class CVNs

Figure 1: Annual Inventories Under the Navy's 2017 Plan Versus Goals for Selected Categories of Ships.



Source: CBO 2015

at the end of their service life and the planned budget for construction of the replacement Ford-class CVNs.

The shortfall in SSBNs, resulting in a fleet that goes down to 10 SSBNs, develops earlier, primarily because the Navy deferred the start of procurement of the Columbia-class SSBN by two years and, under current plans, the budgeted construction rate for following years will not be adjusted to fill the shortfall until 2042, after the last Ohio-class SSBN has retired. Rear Adm. Richard Breckenridge, director of undersea warfare, reported in 2013 that "in order to sustain 10 operational SSBNs from now through the introduction of the new SSBN, we must complete refueling overhauls for all 14 Ohio SSBNs and operate the 12 newest of them to their full 42-year extended life" (Breckenridge 2013).

The significant decade-long shortfall of SSNs, with the SSN fleet dropping to a minimum of 41 SSNs in 2029, will further challenge the operating life of their planned life-of-the-boat reactor cores by requiring higher operating tempos.

The very high procurement price for replacement nuclear-powered vessels and the high price for midlife refueling and complex overhauls (RCOHs) of CVNs create a budgetary challenge for the Navy and Congress. Representative unit prices are summarized in Table 4.

CVNs

The Navy's 2017 long-range shipbuilding plan (OPNAV 2016) indicates that Ford-class CVNs, procured at approximately four-year intervals, will replace Nimitz-class CVNs on a one-for-one-basis. Among US shipyards, only Newport News Shipbuilding is capable of building a CVN. This shipyard also is responsible for the midlife RCOH of the current fleet of Nimitz-class CVNs. The Congressional Research Service (O'Rourke 2017b) estimated that the lead Ford-class CVN, USS *Gerald R. Ford*, could cost about $12.9 billion, which is almost double the cost of the last Nimitz-class CVN commissioned in 2009 (not adjusted for inflation). However, Congress capped the price for the second Ford-class CVN, USS *John F. Kennedy*, at $11.5 billion.

Submarines

There are only two US shipyards capable of building a nuclear-powered submarine: Newport News Shipbuilding and General Dynamics Electric Boat. Many submarine maintenance activities can be performed at four

Table 4: Representative Replacement Nuclear-Powered Vessel and CVN Midlife RCOH Prices

Ship type	Ship Class	Estimated Unit Price, in $bn	Basis
CVN	Ford-class, new construction	11.5	Congressionally mandated price cap for 2nd ship in class.
CVN	Nimitz-class, RCOH	2.8	2017 contract value for USS *George Washington* RCOH.
SSBN	Columbia-class, new construction	6.5	Congressional Research Service estimate for boats 2–12.
SSN	Virginia-class, new construction	2.0-2.6	Current actual price is about $2.6 billion. Navy's target for future units is $2 billion.

Legend: Ship designations: CVN = aircraft carrier, nuclear; SSBN = strategic ballistic-missile submarine, nuclear; SSN = attack submarine, nuclear. RCOH = refueling and complex overhauls.

Sources: Peter Lobner; GovConWire; O'Rourke 2016; O'Rourke 2017a; O'Rourke 2017b.

Table 5: Submarine Shipbuilding Plan (FY-2017 – 2030, amended)

FY	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
SSN	VA BLK IV		VA BLOCK V					VA BLOCK VI					VA BLK VII		
	2	2	2	2	2	2	2	1	2	1	1	1	1	1	22
SSBN					COLUMBIA Class BLOCK I					COLUMBIA Class Follow-on Ships					
					1			1		1	1	1	1	1	7
TOTAL	2	2	2	2	3	2	2	2	2	2	2	2	2	2	29

Legend: Ship designations: SSBN = strategic ballistic-missile submarine, nuclear; SSN = attack submarine, nuclear.

Source: Program Executive Office, Submarines 2017.

other nuclear-capable naval shipyards. Table 5 summarizes the FY 2017 procurement plan, by fiscal year and block, for Virginia-class SSNs and Columbia-class SSBNs (OPNAV 2016). (A "block" is a procurement batch; different blocks of the same vessel sometimes have distinctly different characteristics.) Between FY 2017 and FY 2030, only two submarines will be procured per year in every year except 2021, when there will be three.

Figure 2 illustrates the impact of that procurement schedule on the size of the submarine fleet between 2017 and 2046. For the next 30 years, the SSN fleet will be smaller than it is in 2018. The dedicated SSGN fleet will be gone by 2028 and the future SSBN fleet will be smaller than it is in 2018.

SSBNs

Twelve Columbia-class SSBNs will replace the 14 Ohio-class SSBNs. The Columbia-class SSBN will have a life-of-the-boat reactor, eliminating the need for a midlife refueling. This will save big blocks of time in the middle of the SSBN fleet's life cycle, enabling fewer Columbia-class SSBNs to support the same level of patrols assigned to the fleet of 14 Ohio-class SSBNs. The Congressional Research Service reported that the lead boat may cost $8.2 billion in 2017 dollars (O'Rourke 2017a). Boats 2-12 are expected to have an average unit procurement cost of $6.5 billion in constant FY 2017 dollars. However, the Government Accountability Office reported that technical risks in the Columbia-class SSBN program could lead to significant cost escalation (GAO 2017).

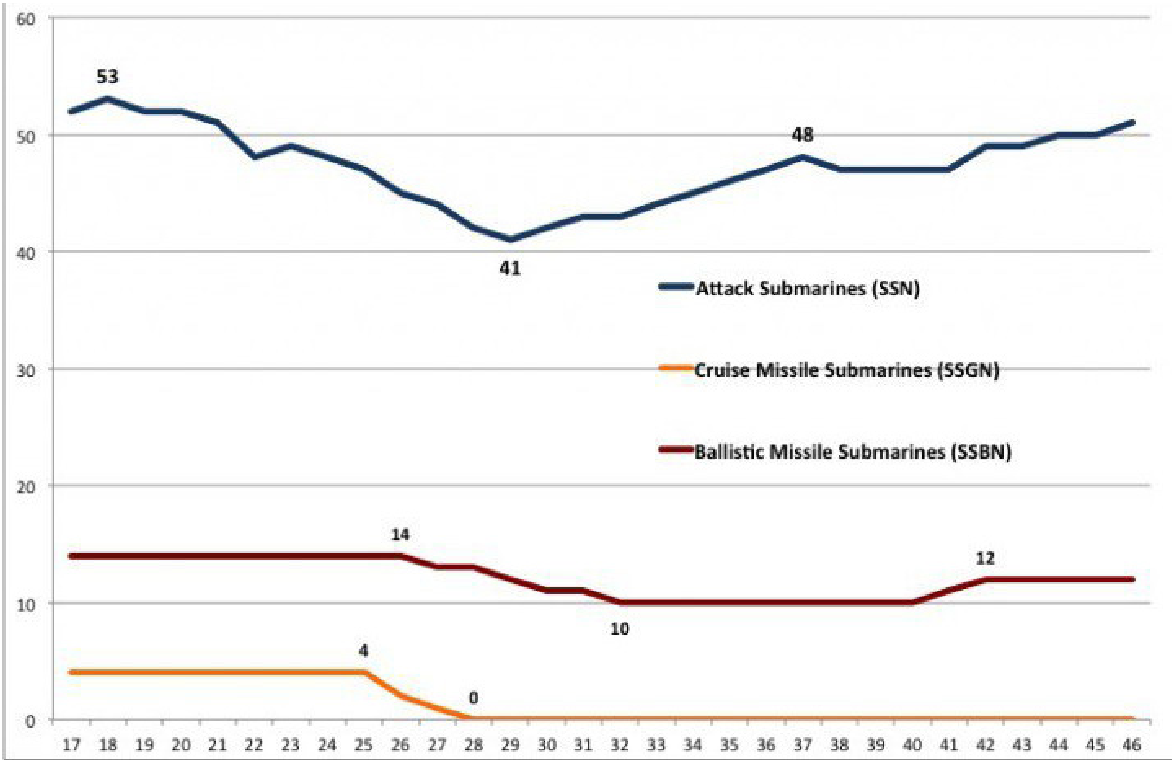
SSGNs

The Navy's 2017 shipbuilding plan shows that the four Ohio-class SSGNs will not be replaced. Their SSGN function will be partially replaced by a larger number of Virginia-class Block V, VI, and VII multimission SSNs, each of which will carry far fewer cruise missiles than an Ohio-class SSGN.

SSNs

The Navy's current fleet requirement is for 48 SSNs. The Los Angeles-class SSNs currently are being replaced by Virginia-class SSNs, but on a less than one-for-one basis. The replacement Virginia-class SSNs currently are being built at a

Figure 2: 30-year Trends of the Numbers of SSNs, SSBNs, and SSGNs in the US Submarine Fleet, 2017-2046.



Source: Freedberg 2016

rate of two per year, which is projected to drop to one per year in the mid-2020s. The net result is a long-term decline in the size of the SSN fleet. USS *Colorado* (SSN-788), which is part of Block II, cost $2.7 billion when delivered in March 2018 (AP 2018). The Navy aims to get Virginia-class SSN procurement costs down to $2 billion per unit (O'Rourke 2016), which may be feasible for boats in Blocks III and IV. The boats in Blocks V–VII will gain a new 70-foot (21.3-meter) hull section aft of the sail to house vertical launch cells for cruise missiles and other devices. The unit cost of these boats therefore will likely be more than $2 billion.

Expanding the Navy's Fleet

In December 2016, the Navy announced plans to increase the US fleet from the current authorized limit of 308 vessels to 355 vessels. The Heritage Foundation's *2017 Index of US Military Strength* (Wood 2017) reported that the Navy's actual fleet size in early 2017 was 274 vessels. It will take decades and great cost for the Navy to reach the 355-ship target. Figure 3 illustrates that there will be a huge cost premium to achieving the 355-ship target faster.

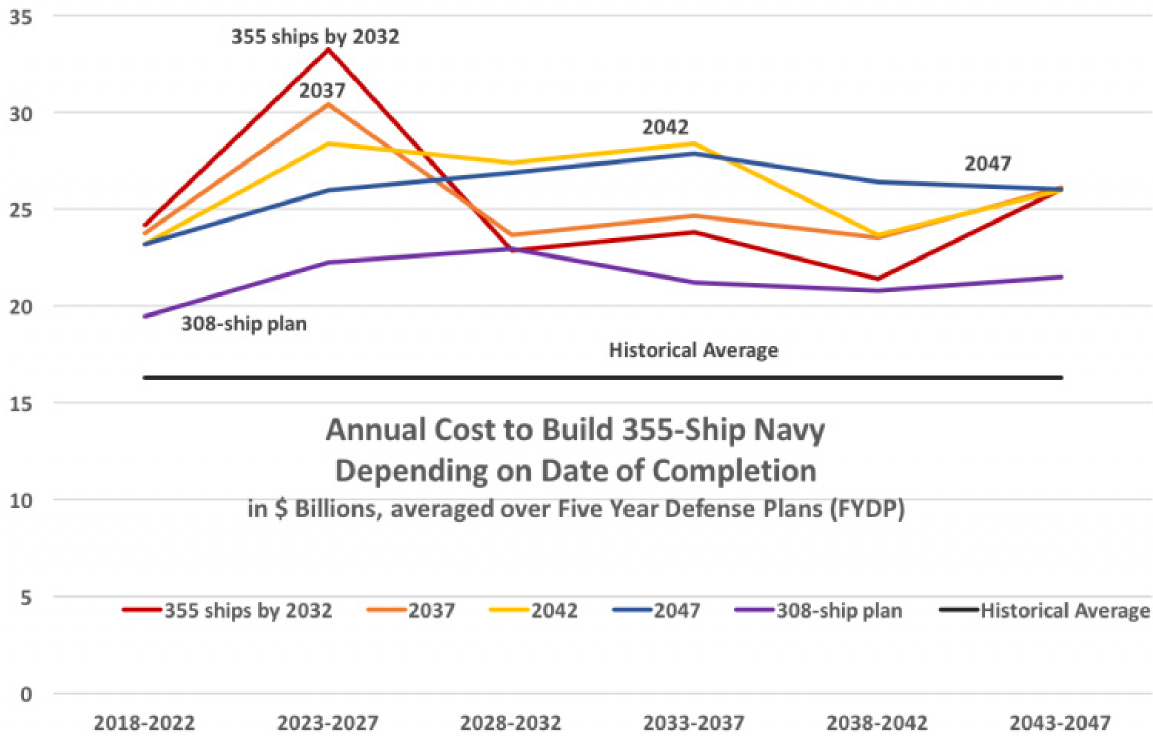
The Navy has examined the possibility of increasing the rate of Virginia-class SSN construction, considering the availability of shipbuilder facilities, workforce readiness and ability to ramp up to meet higher construction rates, and the health of the supplier/vendor industrial base (Program Executive Office, Submarines 2017). Other analyses have looked at budget savings from reducing the size of the Columbia-class SSBN fleet to as few as eight boats (CBO 2013) and defining aircraft carrier options other than the Ford-class CVN (Martin and McMahon 2017).

The Current US HEU Inventory

In 2016, the Obama White House issued a fact sheet (Office of the Press Secretary 2016) reporting that the US HEU inventory was 585.6 metric tons as of September 30, 2013. Of that amount, 499.4 metric tons of HEU were for purposes including nuclear weapons, naval propulsion, nuclear energy, and science. Of the remaining 86.2 metric tons, 41.6 metric tons were available for potential down-blending to LEU or, if that were not possible, disposal as low-level waste. The rest of the material, totaling 44.6 metric tons, was in spent reactor fuel.

The HEU for current naval reactors comes from two sources—the part of the national HEU stockpile

Figure 3: Annual Cost to Build 355-Ship Navy Depending on Date of Completion.



Source: CBO 2017

reserved for Naval Reactors, which has an enrichment level of 97 percent, and HEU returned from decommissioned nuclear weapons, which is enriched to 93 percent.

In July 2016, the NNSA reported that the HEU inventory allocated for naval reactors should be sufficient for projected Navy needs until 2064 (NNSA 2016). For initial work on LEU development and reactor core production, the Navy could use a relatively small amount of HEU down-blended with natural or depleted uranium to obtain 19.75 percent enrichment. Having the end of the existing naval reactor HEU inventory in sight—albeit 46 years away—might motivate the Navy to develop LEU-fueled reactors and refueling cores, thereby greatly extending the longevity of the nation's HEU stockpile.

The Current Naval Nuclear Fuel Cycle and Modifications for LEU Fuel

The current naval nuclear fuel cycle is a once-through open cycle. Fuel manufacturing occurs at the front end of the cycle. Fuel utilization occurs aboard a naval vessel. Storage of spent fuel occurs at the back end of the fuel cycle. The back end of the fuel cycle currently does not include reprocessing of naval spent fuel to recover uranium for reuse in a closed fuel cycle. This may change, however, if a Senate proposal to recycle spent naval fuel becomes part of the FY 2019 energy and water appropriations bill.

In the United States, the front end of the naval nuclear fuel cycle begins with the existing HEU stockpile and HEU from retired nuclear weapons.

Nuclear Fuel Services (NFS), in Erwin, Tennessee, has been the sole manufacturer of nuclear fuel for the US Navy's fleet of nuclear-powered vessels since 1964. Currently, NFS manufactures new HEU cores for Virginia-class SSNs and Ford-class CVNs. It also manufactures HEU refueling cores for Ohio-class SSBNs and Nimitz-class CVNs. NFS also provides various services to help develop materials and manufacturing processes for future Naval Reactors programs.

As described in Naval Reactors' 2016 LEU conceptual plan (NNSA 2016), a new manufacturing line would be developed for LEU fuel, which would be based on a fuel system that was substantially different from ones used in the current HEU fuel manufacturing processes.

Test Reactors and Prototypes to Support Reactor Development Programs

Test Reactor

The Department of Energy's Advanced Test Reactor (ATR) is a materials test reactor built in 1967. The ATR, a pressurized water reactor with a rated power of 250 megawatts thermal, offers high thermal-neutron flux and large test volumes. It is the primary national facility for performing material irradiation testing. The facility is Naval Reactors' main source of data on the performance of reactor fuel, poisons, and structural materials under irradiated conditions. The ATR will be an important resource for developing LEU fuel (NNSA 2016) but would need to be upgraded. With 51 years of operation already to the ATR's credit, it seems that Naval Reactors and DOE should be planning for a replacement for the ATR.

Land-Based Prototypes

Naval Reactors has two aging, land-based prototype reactors known as S8G and MARF (Modifications and Additions Reactor Facility). Both are located at the Kenneth A. Kesselring site in West Milton, New York. The S8G prototype is undergoing a major overhaul from 2018 to 2021, after which it will support development of the S1B reactor for the Columbia-class SSBN and provide naval nuclear operator training through 2041. MARF is scheduled for defueling and layup starting in FY 2018.

NR's 2016 conceptual plan for developing an LEU-fueled naval reactor (NNSA 2016) called for development of a new land-based LEU prototype reactor. There are several examples of naval reactors that did not have dedicated prototypes, including the S9G for Virginia-class SSNs, the Next Generation Reactor core for later Virginia-class SSNs, and the A1B for the Ford-class CVN. However, Naval Reactors noted that the Navy "has always demonstrated major new fuel technologies in a prototype reactor core before deploying these technologies in a warship. The prototype test proves that the fuel works in an actual naval core and demonstrates the real world fuel performance and core lifetime" (NNSA 2016).

Considering the important national-security implications of the new LEU fuel, a new prototype reactor offers a prudent path for testing the advanced fuel system in an operational environment and for supporting the fleet of LEU-fueled ships in later years. Naval Reactors should evaluate the practicality of using MARF to augment and accelerate LEU fuel and reactor material testing.

A Retrospective Look at Refueling US Naval Reactors

The first SSN, *Nautilus*, was refueled four times during its service life. Several later classes of SSNs and SSBNs were refueled two or three times. It wasn't until the mid-1960s, when the later Permit-class SSNs and the newer Sturgeon-class SSNs entered service, that a submarine reactor required only a single refueling during the service life of the boat. The first group of Los Angeles-class SSNs (the "Flight I" boats), which started entering the fleet in 1977, and the Ohio-class SSBNs, which started entering the fleet in 1981, also required a single refueling during their service life.

The era of the life-of-the-boat reactor arrived with the second group of Los Angeles-class SSNs (the "Flight II" boats). This reactor, the S6G, with a long-life core, the D2W, was designed for an assumed SSN operating tempo that was translated into an expected utilization rate of the reactor over its intended service life. If an SSN operates at its assumed tempo, the reactor will not require refueling during the submarine's service life. But if the submarine is operated at a higher operational tempo (that is, more or longer deployments per year), then reactor utilization may be higher than expected and the reactor will reach the end of its life before the SSN reaches the end of its service life.

Other submarines designed and operating with life-of-the-boat reactors are the Seawolf-class and the Virginia-class SSNs. The new Columbia-class SSBNs are being designed with a life-of-the-boat reactor for a service life of more than 40 years.

The Navy has a long history of operating naval reactors that required one or more refuelings during the service life of the ship. The Navy's operational plans always have adapted to the EOCs for these ships. Fueling ships with LEU will require the Navy to implement EOCs that may seem to be a bit of a throwback to the 1960s and 1970s, when it was common for submarines to require multiple refuelings during a service life of 25 to 30 years. However, the US nuclear submarine fleet was much larger then—there were 115 nuclear submarines in 1977 as opposed to 68 today—and able to absorb the operational interruptions of more frequent refueling.

Also in the 1960s and 1970s, the nation had a more extensive nuclear-qualified shipyard infrastructure and a larger, qualified workforce to support more frequent refueling. Three nuclear-qualified private shipyards from that period no longer are supporting the current US naval nuclear fleet. In addition, one nuclear-qualified naval shipyard has been retired and one no longer is used for new construction. As LEU-fueled ships enter the fleet, the nation's nuclear-qualified shipyard infrastructure will need to be expanded to meet the demands of EOCs with more frequent reactor refueling.

The decline of the current US fleet to a total of 53 SSNs and SSBNs by 2028 could complicate a move to LEU fuel. A smaller submarine fleet increases the demands on each individual boat and complicates the scheduling of overhauls and refuelings. If LEU-fueled ships enter the fleet, the Navy will need to develop more-efficient refueling processes and the associated infrastructure to minimize the impact of refueling on the operational availability of its ships.

Since the 1960s, US submarine reactor refuelings have required cutting a large patch out of the hull, above the reactor; inserting fresh fuel; restoring the hull patch to its original position; and welding it in place. As part of the submarine's pressure hull, the hull patch is subject to strict quality procedures known as SUBSAFE. In contrast, French submarines, with relatively shorter-lived LEU reactor cores, are refueled via a large, removable hatch in the top of the hull (called a brèche) that reduces the overall time needed for refueling. This approach appears to be worthy of consideration for a future US LEU-fueled submarine.

A Possible Path Forward

The challenges for introducing LEU fuel to the US nuclear fleet are daunting, especially in a budget climate in which all military services are competing for limited funds. Within the Navy, high-priority programs that have national-security implications compete against each other. And within Naval Reactors, major programs such as recapitalizing the S8G land-based prototype reactor in New York and the Expended Core Facility/Dry Storage Facility in Idaho are priorities that are likely to win out over an LEU fuel program that Naval Reactors characterized as "not directly producing a more militarily desirable reactor design."

How then could the United States pursue LEU fuel in naval reactors? Blending funding from multiple stakeholders is one approach that could have value. For example, NNSA's Office of Defense Nuclear Nonproliferation (DNN) could contribute funding to the Navy's LEU fuel program, primarily to develop and qualify new fuels and technologies needed to support the Navy's conversion efforts. Specifically, DNN has been the leader, under its Convert Program, in converting civilian research and test reactors from weapon-grade fuel, including developing and qualifying new fuels and technologies to support conversion efforts domestically and abroad. A broad interpretation of the term "domestically" could allow DNN to collaborate technically and financially with Naval Reactors to develop and qualify new LEU naval fuels and technologies needed to enable deployment of LEU-fueled reactors in the US nuclear aircraft carrier and submarine fleets.

Since the United States and the United Kingdom share some submarine reactor technologies under the US-UK Mutual Defense Agreement, most recently updated and agreed in July 2014 (US-UK Nuclear Agreement 2014), an added benefit of a US LEU fuel solution for naval reactors is that it also could apply to future UK nuclear submarine reactors.

While the Navy probably will not be enthusiastic about switching from HEU to LEU fuel, budget and technical assistance from DNN could help ease that transition and allow the Navy to focus its own budget on deployment of the LEU fuel in the fleet and development of new classes of ships designed from the start to use LEU fuel. One potential drawback to this approach is the Navy's historical antipathy to any outside interference in the nuclear navy.

Still, it may be possible in a budget-constrained environment to convince the major stakeholders of the wisdom of collaboration. Naval Reactors would prepare a detailed program plan and budget for LEU fuel implementation, building on the 2016 conceptual plan. A directive from the president, the secretary of energy, and the secretary of defense or specific instructions from Congress likely would be needed to enforce multiple-stakeholder funding and collaboration.

For the first phase of this program, DNN funding could be applied to the design and development of the advanced LEU fuel system and modernization of the ATR to enable naval LEU fuel testing and qualification. Naval Reactors funding could be applied to the balance of the development tasks, including detailed computer analysis and simulation of LEU fuel behavior and whole propulsion plant performance, and design of a new LEU prototype reactor.

If the first phase establishes the technical and operational feasibility of using LEU fuel in US naval reactors and qualifies the new fuel system(s), and if the collaborating funding organizations (Naval Reactors, DNN, and the Navy) agree to the solution, then the second phase of the program could fund deployment of the LEU fuel as well as construction and operation of the land-based LEU prototype reactor by Naval Reactors. The Navy would manage the timeline for fuel development and deployment with the goal of creating two ship classes fueled by LEU:

(1) Ford-class aircraft carrier

Refuel the already built CVNs with LEU cores starting with the lead ship, USS *Gerald R. Ford*, in about 2042. Install original LEU cores in new-construction ships in this class as soon as practical. After the earlier Ford-class carriers have been refueled with LEU cores, all Ford-class carriers would be operating with LEU cores by about 2060.

(2) SSNX submarine

This new submarine class is the follow-on to the Virginia-class SSN. The SSNX would be designed from the start with an LEU core. The Navy would manage Virginia-class SSN procurement as needed to transition smoothly to procurement of the LEU-fueled SSNX, with delivery of the first SSNX boat by about 2042. The procurement goal would be to keep the SSN fleet at an acceptable size during the transition to production of the LEU-fueled SSNX-class boats.

This approach assumes that Virginia-class SSNs and Columbia-class SSBNs will simply be the legacy HEU-fueled fleet, all with life-of-the-boat cores. The last HEU-fueled boats would reach the end of their service lives in the 2080s.

The Navy would also manage the modernization of its land-based infrastructure for aircraft carriers and submarines and develop suitable vessel EOCs as needed to support basing, maintenance, and overhaul of LEU-fueled ships in the fleet.

Conclusion

As outlined above, transitioning the US nuclear fleet to LEU-fueled reactors will not be easy, and it will be a costly and lengthy endeavor. The obstacles, however, are surmountable. With regard to the cost, one possibility is to draw part of the needed funding from stakeholders other than Naval Reactors.

The first LEU cores should be targeted for Ford-class aircraft carriers and SSNX submarines. In particular, the goals should be to refuel the USS *Gerald R. Ford* with an LEU core during its midlife refueling overhaul in about 2042 and deliver the first SSNX with an original LEU core in about the same time frame. Meeting these targets would enable the US to have all aircraft carriers fueled with LEU by about 2060 and to retire the last submarines with life-of-the-boat HEU cores in the 2080s.

If the Navy fails to adopt LEU-fueled reactors, it will face an even more difficult challenge in the 2060s, when the inventory of HEU available for naval reactors may be depleted.

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