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Replacing Highly Enriched Uranium in Naval Reactors

SUMMARY

Highly enriched uranium (HEU) is the simplest nuclear material to use for an improvised nuclear device, making it a target for terrorist groups seeking to inflict mass destruction. This paper examines the current status of HEU in naval propulsion programs worldwide, with a specific focus on the U.S. Navy's program. It includes a technical assessment of less risky low-enriched uranium (LEU) alternatives and recommendations to enable conversion to such alternate technologies.

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Executive Summary

Minimization or elimination of globally held stockpiles of highly enriched uranium (HEU)¹ has been a long-standing U.S. policy goal since the Carter administration in the late 1970s. Most states recognize that elimination or minimization of HEU would have significant benefits for global nonproliferation and counterterrorism efforts. These concerns have driven several efforts to eliminate or minimize HEU use in several applications.

Significant progress has been made in reducing the use of HEU in civilian research reactors, in the preparation of isotopes used for medical purposes, and even in the elimination of weapons stockpile HEU by programs involving blending down the weapons grade HEU to low enriched uranium (LEU) fuel for civilian power reactors. The largest remaining non-weapons use of HEU is as fuel for naval propulsion reactors. In contrast to the attention given to other HEU minimization efforts, there has been relatively little international effort to eliminate or minimize the naval propulsion use. The topic has been addressed in some studies, particularly in the period shortly after the 9/11 attacks, and there has been some focus on the issue in the international arena, such as discussions at the two International Symposia on HEU Minimization.²

One of the major reasons for lack of progress in reducing HEU use in naval propulsion is that these are—except for the Russian ice breaker program—military programs, and the use of HEU, particularly for submarines, has historically been perceived to have a number of significant advantages. In addition, the non-weapons uses of HEU, such as for submarine propulsion, present a unique set of problems for the nonproliferation regime because, as is discussed in the body of this paper, there is a “loophole” in the Treaty on the Non-Proliferation of Nuclear Weapons (NPT).

The Russian Federation and the United States are the world’s largest holders of HEU, each of which has well over 500 metric tons (MT) of HEU.^{3,4} By comparison the next largest stock of HEU is the approximately 18 MT held by China. The sum total of HEU in all other states is on the order of 70 MT, a small fraction of the U.S./Russian total.

The United States holds the largest declared reserve of HEU designated for naval reactors, approximately 140 MT. In addition, the U.S. Navy and United Kingdom’s Royal Navy almost exclusively use an HEU enrichment that is as high as or higher than that used in nuclear weapons. Other navies, such as the Russian Federation and the Indian Navy, typically use HEU that is enriched in the 40 percent to 50 percent range, approximately one half that of the typical enrichment for nuclear weapons.⁵ Finally, the remaining navies (France and China) that have nuclear-powered vessels use LEU fuel, most of which is enriched to a level of less than 10 percent.

Currently, all marine propulsion reactors are military with the exception of the Soviet/Russian fleet of icebreakers/Arctic supply ships. Although the Soviet Union built its first icebreaker initially using an LEU core, it later retrofitted that vessel with HEU as well as all icebreakers that followed. These vessels are still operated by the Russian Federation. Except for the Soviet Union, early attempts at nuclear-powered commercial vessels elsewhere proved to be uneconomical; Japan, Germany, and the United States at one time built nuclear-powered commercial vessels fueled by LEU. These vessels are no longer in service.

¹ HEU is by definition uranium that is enriched in fissile U-235 to a level of greater than or equal to 20 percent. The remainder is primarily uranium 238 with a trace of uranium 234. LEU is any enrichment level above the natural level (approximately 0.7 percent) and less than 20 percent enriched. The definition is somewhat arbitrary. It is typically assumed that HEU may be useful for a nuclear yield-producing weapon and that LEU is not useful. However, it should be kept in mind that the 20 percent enrichment level is not a bright line based on a physical certainty. Rather, it is a practical use definition based on assumptions that a yield-producing device made from LEU would be too large to be realistically developed as a nuclear weapon.

² The first Symposium was held in Oslo, Norway, in 2006, sponsored by the government of Norway and the International Atomic Energy Agency (IAEA). The second Symposium was held in Vienna, Austria, in 2012, sponsored by the governments of Austria and Norway and the IAEA.

³ A metric ton (MT) is 1,000 kilograms or about 2,200 lbs.

⁴ Data for this report was collected through 2015.

⁵ This is not meant to imply that the HEU used by the Russian Federation could not be used in a nuclear weapon.

The nuclear-powered vessels of the French Navy are of particular note. Although the earliest French submarines were powered by LEU fueled reactors, a few vessels were fueled using HEU before the French Navy ultimately decided to return to the use of LEU in its modern naval reactors. Currently, all of France's submarines and nuclear-powered aircraft carrier use LEU fuel.

U.S. Navy Assessments

Congress has recognized that LEU use by the U.S. Navy would be a significant step in achieving the United States' nonproliferation and counterterrorism goals. Twice it has asked the Navy to report to Congress on the prospects for using LEU in naval propulsion reactors. The Navy's first report to Congress in 1995 examined the issue from a number of perspectives: technical feasibility, environmental considerations, economic considerations, and proliferation considerations. The report concluded that there were no advantages to LEU use, and that there were serious penalties for LEU use, particularly economic and environmental. In 2013 Congress asked the Navy to update its 1995 report. Unfortunately this led to a rather cursory effort by the Navy in its 2014 report to Congress.

The Navy's 1995 and 2014 reports can be criticized from a number of perspectives, as discussed in detail in this report. However, detailed analysis is not possible in most areas because information on naval reactors, their fuel, and submarine design and operations are generally classified subjects. Furthermore, it is not clear what the Navy did to prepare its reports to Congress. Although the Navy alludes to studies underlying its 1995 and 2014 reports, these studies were not provided, offering no chance to examine the details and evaluate them.

What is clear from the Navy's reports and from open literature is that naval vessels clearly can be powered by LEU. LEU cores can provide the same (or greater) power levels than HEU cores; however, the energy density of the fuel is lower than an equivalent HEU core. Thus an LEU core that will fit into the same space as an HEU core and produce the same power would not contain as much fissile U-235 and therefore would not last nearly as long as an HEU core before requiring refueling. In order to last the 33+ years that the Navy believes is achievable using life-of-the-ship HEU cores, several refuelings would be required for an LEU fueled reactor that could fit in the same reactor compartment. The Navy admits that an LEU life-of-the-ship core could be built for an SSN, but it would be too large to fit in the current SSN design, therefore requiring a redesigned submarine that would potentially be less operationally capable. The Navy has also argued that for the SSBN/SSGN⁶ and aircraft carriers (CVNs) an LEU life-of-the-ship reactor would require vessel redesign. However, these arguments don't seem very persuasive because in another part of the same study the Navy admits that an LEU life-of-the-ship core could fit into the then-current SSBN/SSGN hull. Furthermore, although LEU cores may require more space, it is hard to believe LEU reactors could not fit into CVN's hulls.

In its 1995 report, the Navy evaluated cost factors for two options: (1) LEU cores in the design space with refueling; and (2) life-of-the-ship LEU cores. Although the Navy's analysis is subject to well-deserved criticism, the 1995 report did provide a framework for some consideration of most of the major issues and of the costs involved in using LEU fuel. Unfortunately, the 2014 report by the Navy to Congress did not update any of these figures or studies from its 1995 report even though the Navy was tasked to do so.

In what some have described as an optimistic change in the Navy's attitude toward using LEU fuel, the Navy stated in its 2014 report that it would be willing to undertake a serious program to develop LEU cores. However, there is no indication that the Navy would do this for any reason other than to keep its R&D base active and vital. The Navy fears, probably correctly, that the R&D infrastructure will wither and decay once the current design work is finished.

The U.S. Navy has an enviable record for safety and performance of its naval reactors, but it appears to be unwilling to give Congress a complete picture of the consequences of using LEU cores. In part that may be due to the somewhat understandable concern that a study supporting the Navy's use of LEU as a viable option would invariably result in the directive to use LEU despite whatever arguments the Navy might offer in support of HEU use.

⁶ Submarines are generally grouped as attack (SSN) or ballistic missile (SSBN or SSGN) submarines.

Because the Navy has had at least two opportunities to address the LEU issue and arguably has failed to produce an unbiased analysis of the potential for LEU use, one of the recommendations of this study is that an independent panel of experts be tasked with a review and perhaps further analysis of the Navy's studies of these issues. In order to perform that task, the experts would necessarily need to have full access to all the Navy's data regardless of classification level.

HEU vs. LEU in Other Countries

Going beyond what could be a unilateral effort by the United States to forgo the use of HEU in propulsion reactors, there is, of course, the broader issue of what position other HEU-using navies would take on conversion to LEU. The Royal Navy might be induced to follow the U.S. lead if the U.S. were to adopt LEU use, particularly if there was an exchange of information with the United States as has been done in the past on naval reactor issues. However, it is doubtful that the Russian Federation or India would eliminate their use of HEU absent an overriding reason or incentive to do so. Whether or not a binding and verifiable international instrument could be developed for states to agree to forgo the use of HEU after some future date is an interesting issue. Another interesting issue is how HEU use by the world navies would be affected, or could be affected, by international efforts to eliminate HEU.

Another interesting issue is how HEU use by the world navies would be affected, or could be affected, by international efforts to eliminate HEU.

Considerations of eliminating the use of HEU in propulsion reactors call into question how HEU use in naval reactors relates to a potential Fissile Material Cutoff Treaty (FMCT). Although the FMCT concept has been discussed for decades, there is no consensus on the specifics of a proposal. It is apparent that the U.S. Navy believes that an FMCT would only prohibit the production of fissile material for use in nuclear weapons, allowing for the continued production of HEU for other purposes, such as for naval propulsion fuel. The Navy's interpretation is consistent with statements by a series of U.S. presidents who have repeatedly caveated their remarks regarding the elimination of the production of fissile material by specifically referring only to fissile materials used for nuclear weapons. Other states, particularly many of the non-nuclear weapon states (NNWS) under the NPT may have a totally different view of what the scope of the FMCT should be and they may favor a total ban on HEU production regardless of its intended use.

This study has developed in some detail a picture of the world's nuclear navies in order to enhance the understanding not only of the scope and magnitude of the HEU problem, but to illustrate historical trends and to attempt to illustrate post-Cold War developments. Although there was perhaps a "Golden Age" in the immediate post-Cold War period where the numbers of nuclear-powered vessels decreased in the United States and the Russian Federation, the new century has seen the development of naval nuclear-powered submarines by India and Brazil and an increase in the size of the Chinese nuclear submarine force. In addition, other countries have expressed an interest in nuclear submarines as regional arms races appear to take hold in Asia and the Indian Ocean area. The current decade has also seen a return of some aspects of the Cold War vis-à-vis the Russian Federation, where increased Russian military spending and a more combative approach to Europe and the United States could potentially trigger a new arms race—an open issue that may still be peacefully resolved.

Leasing or outright sales of nuclear-powered submarines has become an aspect of current military expansion. It is not a new issue, but is one that has arguably received too little attention from the international community. The Indian government leased a nuclear submarine from the former Soviet Union for a three-year period in the late 1980s. This lease received little attention at the time for several reasons, including the crewing of the reactor by Soviet officers and sailors, and the news focus on other major events at the time, such as the collapse of the Soviet Union. However, at about the same time Canada was considering modernizing its submarine force by purchasing nuclear-powered submarines from either France or the United Kingdom. India has now built its own nuclear-powered submarine and has a modern Russian nuclear submarine on a ten-year lease and it is totally crewed by India. Reports are that India is considering leasing another nuclear-powered attack submarine from the Russian Federation and that Pakistan may be considering leasing nuclear submarines from China. Currently, France is assisting Brazil in its nuclear submarine program, albeit by most reports not in the development of the nuclear reactor. The fact that these transactions are arguably legal under international agreements is a cause for significant concern, particularly if the practice becomes more widespread. Although the activities to date may have been viewed without too much alarm, how would the international community react to Iran or other states attempting to lease or purchase nuclear submarines?

Key Findings

Significant issues that became apparent during this study were:

- The deficiencies of the U.S. Navy's reports to Congress in 1995 and 2014.
- The scale of the hazards and concerns resulting from the proliferation of naval nuclear submarine programs including:
 - The NPT “loophole” that allows for un-safeguarded non-weapons use of HEU, and
 - The leasing or even potential outright sales of nuclear vessels fueled with HEU.
- Whether the U.S. Navy's use of life-of-the-ship HEU cores, although economically attractive, is in reality a potential long-term problem. Has the Navy pushed its HEU cores into an unknown and potentially dangerous area, departing from its usual conservative approach to embark on an arguably non-conservative venture beyond what is reasonably knowable about fuel materials properties— potentially resulting in costly retrofits that would have significant operational and economic consequences?

Recommendations

These issues resulted in a series of recommendations as follows:

- Because the Navy's 2014 report has proved to be deficient in a number of ways, Congress should request that the Navy prepare a new report that includes true updates, including cost revisions, on at least the subjects considered in the 1995 report.
- Congress should request a complete set of briefings on the advanced fuel concept obliquely referred to by the Navy in its 2014 report and its affect on use of LEU fueled reactors.
- Congress, perhaps working in conjunction with one of the national academies, should support a study by non-Navy, or Navy contractor, experts on the issue of LEU conversion. Such a study would have to have access to all Navy and Navy-contractor material on these issues.
- Congress and/or the Navy should consider how information could be exchanged with the French on their experiences with LEU use in submarines. It should be noted that there is some precedent for such an exchange given our early-program exchanges with the United Kingdom, which included the exchange of design information and access to facilities.
- It is quite possible that the Navy's 1995 and 2014 Reports to Congress do not disclose all of the concerns that the Navy would raise if it were to feel more threatened by the reality of an order to convert to LEU use. Congress would probably be reluctant to force LEU use if there is any argument that a shift to LEU would have a significant negative effect on the Navy's operational capability. Therefore Congress should ask for an expanded assessment of the tactical impacts vis-à-vis potential threats that would be anticipated if the Navy were to unilaterally shift to LEU use.
- The issue of whether the fuel elements for the Navy's life-of-the-ship cores, which are now only in the early portion of their service life, have been adequately tested should be addressed. This issue should be reanalyzed by the Navy and the results of the Navy's analysis should be reviewed by an independent panel of experts who have access to all the Navy's tests and studies.
- The issue of the long-term health of the Navy's nuclear propulsion program, including its R&D program, needs to be reviewed. Is the country heading into a “graying” area of decline like that experienced by the nuclear weapons complex? Are vital skills, methods, etc., such as refueling technologies, being lost? If so, what can or should be done to address these issues that should be considered at a national level?
- The nuclear propulsion infrastructure should similarly be examined to determine if funding is sufficient for future needs—particularly if LEU design and use were to be undertaken.

- The issue of using LEU fuel for the *Ohio*-class replacement SSBNs should be revisited. Although timing may be critical, the size of the hull of the SSBN should allow for LEU life-of-the-ship cores.
- A study should be undertaken to fully explore the political ramifications of continued military HEU use on the prospects for a Fissile Material Cutoff Treaty and any potential feedback to the non-weapons military exemption of the Nuclear Nonproliferation Treaty from the continued use of HEU.
- A study should be undertaken to explore whether there could be an international agreement, perhaps reminiscent of the naval construction limitation treaties of the post-WWI period, to eliminate the use of HEU in naval propulsion reactors. Could an agreement be reached that would be verifiable?

Introduction

This study addresses one aspect of potential global efforts to deal with the problem of HEU.⁷ Huge stockpiles of HEU were accumulated by the nuclear weapon states during the Cold War, primarily by the Soviet Union and the United States. The principal use of HEU during the Cold War was for nuclear weapons, with the secondary use being for nuclear reactors. Nuclear propulsion reactors, in particular naval propulsion reactors in submarines, were and are the most extensive non-weapons consumers of HEU.

Even before the end of the Cold War, the production, stockpiling, and use of HEU received long-term recognition as a nonproliferation threat, given the relative ease with which HEU can be used in producing a nuclear weapon. The International Atomic Energy Agency (IAEA) safeguards regime and member states of the NPT⁸ have long dealt with the nonproliferation issues and nuclear security issues posed by the enrichment of uranium that is necessary for the production of HEU.

Although recognized during the Cold War, the threat that non-state actors⁹ could acquire and use HEU in a relatively simple gun-type nuclear weapon has emerged as a significant concern in the post-Cold War environment.

The proliferation concerns coupled with the non-state actor threat have led to the current view of many states that HEU is so dangerous that the world should focus on eliminating HEU, banning its production, converting it to less dangerous levels of enrichment, and finding alternative materials and techniques for those current processes and equipment that use HEU.

This study examines the use of HEU in naval propulsion reactors and the feasibility of replacing HEU with LEU. The study focuses on the LEU/HEU decision in the United States, but the problem and potential solutions are also considered in an international context.

This study was sponsored by the Nuclear Threat Initiative.

⁷ HEU is by definition uranium that is enriched in fissile U-235 to a level of greater than or equal to 20 percent. The remainder is primarily U-238 with a trace of U-234. LEU is any enrichment level above the natural level (approximately 0.7 percent) and less than 20 percent enriched. The definition is somewhat arbitrary. It is typically assumed that HEU may be useful for a nuclear yield-producing weapon and that LEU is not useful. However, it should be kept in mind that the 20 percent enrichment level is not a bright line based on a physical certainty. Rather, it is a practical use definition based on assumptions that a yield-producing device made from LEU would be too large to be realistically developed as a nuclear weapon.

⁸ A copy of the text of the NPT is available at www.un.org/en/conf/npt/2010/npttext.shtml.

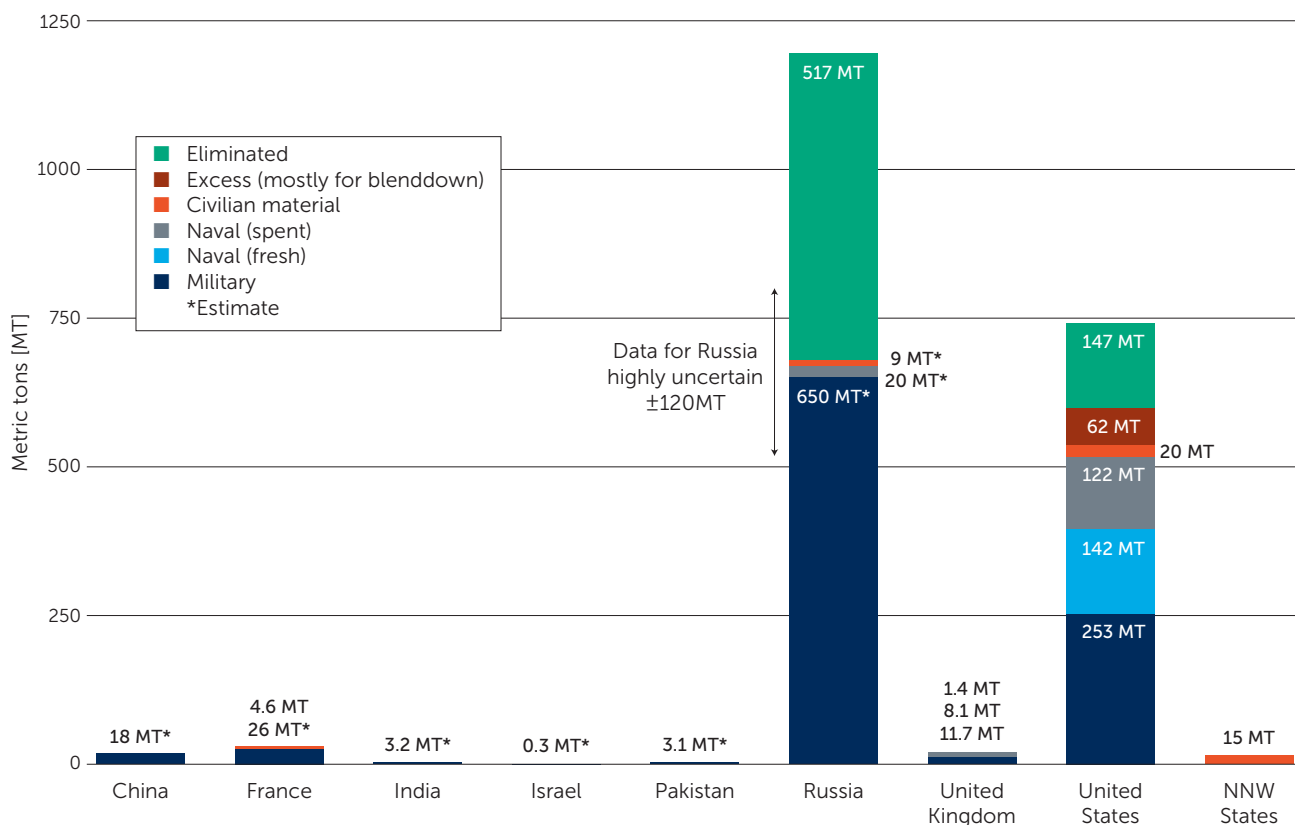
⁹ *Non-state actor* is a term generally preferred to *terrorist*. Generally *non-state actor* will be used in this study.

The Risks of HEU

HEU is one of the most dangerous materials on earth and is a major target for non-state actors seeking to inflict massive damage. HEU is stored at hundreds of sites in dozens of countries around the world. Since the end of the Cold War, various HEU minimization and reduction programs have been implemented along with increased security efforts for facilities and operations using HEU. Efforts to convert research reactors from HEU to LEU use have achieved significant success in eliminating HEU in diverse geographic areas where the security of HEU was problematic. Efforts are still ongoing in these conversion efforts as well as efforts to eliminate the use of HEU in other applications, such as the production of medical isotopes. Additionally, the United States and the Russian Federation have attempted to address some aspects of the large standing stockpiles of HEU that resulted from the dismantlement of Cold War-era nuclear weapons. The Megatons to Megawatts program and the U.S. declaration of excess weapons HEU have allowed significant quantities of HEU to be downblended from weapons levels (over 90 percent enrichment) to commercial reactor fuel LEU levels (typically 3–5 percent enrichment), thus removing this material as a proliferation or terrorist threat.

However, huge stocks of HEU still remain, particularly in the Russian Federation and United States. Figure 1 below, taken from the Global Fissile Material Report 2015, shows the worldwide estimates of HEU by country.

Figure 1. World HEU Estimates



Source: “Global Fissile Material Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production,” Eighth annual report of the International Panel on Fissile Materials (2015), available at www.fissilematerials.org.

Note: To put the numbers in Figure 1 in perspective it is useful to consider the term *Significant Quantity* (SQ) used by the IAEA. The SQ is often misunderstood and/or often misused as the minimum amount of material needed to build a nuclear weapon. However, the SQ is actually a term used by the IAEA to represent an amount needed for a state to be considered to have the ability to build nuclear weapons. The SQ may, in fact, be well in excess of the amount needed for a single nuclear weapon. The SQ for U-235 is 25 kilograms. Thus a metric ton (MT), the base term in Figure 1, represents on the order of 40 SQs.

As Figure 1 shows, the U.S. has set aside 142 MT of HEU as fresh fuel for naval purposes, while the Russian Federation and United Kingdom set aside 20 MT¹⁰ and 8.1 MT respectively. As we will discuss further below, the U.S., U.K., the Russian Federation, and India are the only nations that currently use HEU in naval reactors. Therefore, as can be seen by Figure 1, if the HEU used for naval fuel was eliminated, it would represent an amount far in excess of the HEU existing in the rest of the world—a clear illustration of why eliminating the use of HEU in naval reactors is such an important goal for nonproliferation and global nuclear security.

¹⁰ Given the number of remaining Russian Federation submarines this number appears to be low. Russian Federation figures for fresh naval fuel are not generally thought to be very transparent. Those in Figure 1 appeared to be too low but could in reality be on the same order of magnitude as the U.S. naval fuel reserve.

HEU and the NPT

When the NPT was negotiated in the 1960s, the defined nuclear weapon states (NWS) as well as the NNWS deliberately confined the scope of the NPT to nuclear weapons and nuclear weapons technology.¹¹

One reason was the fact that the NNWS desired to keep open future options to use special fissionable material and source material for purposes other than nuclear weapons. NWS and NNWS, for example, were considering, or had already seriously considered, peaceful nuclear explosives (PNEs) for a number of uses in massive engineering projects, such as a building a second Panama Canal across Nicaragua, and they wanted to preserve these options.¹² In addition, the NNWS saw potential in the use of nuclear power for applications, such as commercial shipping. The deliberate omission from the NPT text of uses of special fissionable material or source material for purposes other than nuclear weapons and nuclear explosive devices preserved all other uses, such as nuclear propulsion.¹³

However, the special fissionable and source nuclear materials required for non-weapons-related nuclear uses were still subjected to the NPT mandated safeguards regime. Pursuant to Article III of the NPT, each NNWS is required to execute a safeguards agreement with the IAEA, which states in part:

Each [NNWS] undertakes to accept safeguards ... for the exclusive purpose of verification of the fulfillment of its obligations assumed under this Treaty ... Procedures for the safeguards required by this Article shall be followed with respect to *source or special fissionable material* whether it is being produced, processed or used in any principal nuclear facility or is outside any such facility. The safeguards required by this Article shall 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.*¹⁴

As noted by a number of commentators¹⁵ the restriction of use to nuclear weapons and nuclear explosive devices created a “loophole” that potentially allowed NNWS arguably to produce and even use weapons-usable material for purposes other than nuclear weapons.¹⁶ The fear is, of course, that HEU or other source or special fissionable material possessed under the loophole would ultimately be used in a weapons program and that the breakout time¹⁷ would be greatly reduced, particularly if the clandestine nuclear weapons program had developed a viable nuclear weapons design that could use the “loophole” material. It was thought that the loophole might be exploited by NWS to export technology and even HEU to NNWS for use in submarines, or even provide them with complete submarines.¹⁸

Concern about the production and removal from IAEA oversight for military activities has become an increasing concern, although as yet no state has exercised this option.¹⁹ A potential solution has been suggested that involves IAEA Board of Governors’ approval for removal of the material initially from safeguards with an appropriate accounting approach for the

¹¹ Article I of the NPT defines this scope as “nuclear weapons or other nuclear explosive devices.”

¹² Although PNEs are “other nuclear explosive devices,” Article V preserves the PNE benefit for NNWS use by setting out provisions to make them available to NNWS. The agreement by most states to the Comprehensive Test Ban Treaty (CTBT) has essentially eliminated any further consideration of PNEs.

¹³ James Clay Moltz, “Viewpoint: Closing the NPT Loophole on Exports of Naval Propulsion Reactors,” *The Nonproliferation Review* (Fall 1999): 108–114, available at www.nonproliferation.org/wp-content/uploads/npr/cmoltz61.pdf. NNWS Japan and Germany did in fact construct commercial nuclear powered vessels.

¹⁴ Article III of the NPT, emphasis added.

¹⁵ See, for example, Moltz, “Closing the NPT Loophole.”

¹⁶ Typically discussions of the “loophole” focus on HEU and naval reactors, but the “loophole” would also be applicable to plutonium or any other fissile material that could be used for space reactors, radioisotopic generators (RTGs), etc.

¹⁷ Generally the time between the loss of safeguards control and the actual production of a nuclear weapon by a NNWS.

¹⁸ Moltz, “Closing the NPT Loophole,” 108.

¹⁹ Sébastien Philippe, “Bringing Law to the Sea: Safeguarding the Naval Nuclear Fuel Cycle,” *Bulletin of the Atomic Scientists* (2014), available at <http://thebulletin.org/bringing-law-sea-safeguarding-naval-nuclear-fuel-cycle7418>.

material, including quantities and composition, followed by a reapplication of safeguards once the material is no longer in use. In addition, it has been suggested that IAEA should develop a safeguards regime that is specific to naval reactors, noting that the classification that most states use to protect naval reactor information would be an additional burden for such a regime.²⁰

Although there has been significant attention paid to the NPT loophole, relatively little attention has been paid to the leasing of complete nuclear submarines by the Soviet Union/Russian Federation to India.

As discussed above, Brazil is generally considered the major prospective test case for how to deal with naval nuclear propulsion reactors in NNWS.²¹ Although Iran has threatened to exercise its right to build a nuclear submarine,²² most commentators believe that Iran's statements are an idle threat made to influence the ongoing P5+1 negotiations regarding Iran's broader nuclear safeguards issues and bolster Iran's claims that it needs to enrich to higher levels than required for typical power reactor.

Although there has been significant attention paid to the NPT loophole, relatively little attention has been paid to the leasing of complete nuclear submarines by the Soviet Union/Russian Federation to India. From 1988 to 1991 India leased and operated a Soviet *Charlie*-class SSGN designated by the Indian Navy as INS *Chakra*. Under the terms of the lease the HEU-fueled reactor was operated by Soviet naval personnel and Indian and Soviet personnel used the vessel to train Indian naval personnel in nuclear submarine operations.²³

The Indian Navy has leased another complete nuclear submarine. The INS *Chakra* (same name as the initial leased vessel) is a Russian *Akula*-class SSN leased for a 10-year period for a sum that has been reported as USD \$900 million.²⁴ Although the lease agreement was signed in 2004 the transfer was delayed for a number of reasons, including an accident in 2008 that killed 20 Russian crew members when a fire suppression system inadvertently activated and suffocated them.²⁵ In contrast to the earlier lease of the old *Charlie*-class vessel *Chakra*, the new *Chakra* is crewed entirely by Indian naval personnel. There are also reports that India may lease a second nuclear submarine from Russia.²⁶ These submarines, coupled with indigenously built nuclear-powered submarines, will give the Indian Navy a significant long-range submarine force, including missile capability. Predictably Pakistan has shown interest in potentially leasing Chinese nuclear submarines to offset the Indian Navy's perceived sea control advantage.²⁷

²⁰ Ibid.

²¹ Sharon Squassoni and David Fite, "Brazil as Litmus Test: Resende and Restrictions on Uranium Enrichment," Arms Control Association (2005), available at www.armscontrol.org/act/2005_10/Oct-Brazil.

²² "Iran Plans Nuclear Powered Submarine: Report," Reuters (June 12, 2012), available at www.reuters.com/article/2012/06/12/us-iran-nuclear-submarine-idUSBRE85B17Q20120612.

²³ "The Great Indian Nuclear Submarine Saga," Defencyclopedia (2014), available at <http://defencyclopedia.com/2014/05/17/the-great-indian-nuclear-submarine-saga/>.

²⁴ "India to Induct Russia-Made Nuclear-Powered Nerpa Nuclear Submarine into Navy Today," NDTV (April 4, 2012), available at www.ndtv.com/article/india/india-to-induct-russia-made-nuclear-powered-nerpa-nuclear-submarine-into-navy-today-193609. See also Yogesh Joshi, "Leased Sub Key to India's Naval Modernization," World Politics Review (2012), available at www.worldpoliticsreview.com/articles/12014/leased-sub-key-to-indias-naval-modernization.

²⁵ "Submarines: India Seeks Another Russian Rental," Strategy Page (2013), available at <https://www.strategypage.com/htmw/htsub/20131103.aspx>.

²⁶ "India May Leased Second Nuclear Submarine from Russia," DailyMail.com India (October 20, 2013), available at www.dailymail.co.uk/indiahome/indianews/article-2469323/India-lease-second-nuclear-submarine-Russia.html. See also, "The Great Indian Nuclear Submarine Saga."

²⁷ C. Raja Mohan, "Chinese Takeaway," *The Indian Express* (November 24, 2014), available at <http://indianexpress.com/article/opinion/columns/chinese-takeaway-10>.

Although the naval nuclear propulsion concerns with India and Pakistan have involved leases and non-NPT states, in the late 1980s there was a potential that France or the United Kingdom would sell nuclear-powered submarines to Canada, a proposal that was opposed by the United States, but that clearly showed that NWS and NNWS might exercise the NPT loophole.²⁸

Although efforts have been discussed to close the NPT loophole, for example by international agreement to a regime analogous to the Missile Technology Control Regime,²⁹ there does not appear to be any current efforts that will close the loophole for naval reactors or any other non-nuclear weapons use. In fact, it is arguable that the current efforts to establish a safeguards regime that is responsive to the problem will, if successful, lessen any potential incentive to close the loophole. NNWS mistrust of the NWS motives for closing the loophole is also a significant factor that would probably block any efforts to modify the NPT or develop a new treaty that would have the same effect.

²⁸ John F. Burns, "Canada Considers 10 Nuclear Subs to Patrol Arctic," *New York Times* (May 3, 1987), available at www.nytimes.com/1987/05/03/world/canada-considers-10-nuclear-subs-to-patrol-arctic.html. See also, Moltz, "Closing the NPT Loophole," 110. It should be pointed out that before Canada decided against the nuclear submarine option, the Canadian government sought to allay NPT "loophole" concerns by offering to agree to extended oversight on the material that would be used in the submarine program. Because the program did not proceed, the exact details of how such an agreement would work were never solidified.

²⁹ Moltz, "Closing the NPT Loophole," 111.

Safeguarding HEU

HEU is a special fissionable material and therefore is subject to the various IAEA safeguards regimes. However, it is important to understand that while essentially all HEU in NNWS is safeguarded, almost no HEU in NWS (almost all of the enormous global holdings) is safeguarded.

The manner in which the IAEA has established its safeguards programs is through the issuance of various Information Circulars (INFCIRCs) and bilateral agreements with each of the states subject to safeguards.³⁰ When discussing the application of safeguards it is useful to consider the safeguards system as having three phases.

The first safeguards phase, from approximately 1961 to 1971 (prior to the NPT), was established by INFCIRC/26 (reactors up to 100 MW thermal) and INFCIRC/66 (removing the cap on reactor size) and their respective addenda or revisions. The INFCIRC/26 and INFCIRC/66/Rev. 2 safeguards obligations are often referred to Item-Specific or Facility-Specific safeguards because the obligation only relates to a limited number of facilities that are agreed to by the state and the IAEA. It is important to understand that this level of safeguards applies to all IAEA Member States regardless of whether or not they are NPT members. Thus India, Israel, and Pakistan are bound by these pre-NPT obligations but the implementation of safeguards only applies to a limited number of specified facilities.

The second phase of safeguards, from 1971 to 1995, is the comprehensive or full scope safeguards phase defined by INFCIRC/153, which sets out the obligations of NPT states under safeguards. The comprehensive safeguards regime is not only related to safeguards, but has become a reference standard for bilateral agreements and for other contractual agreements, such as those executed by members of the Nuclear Suppliers Group (NSG), which typically require recipients of items subject to the NSG agreement to accept comprehensive safeguards as a condition on the equipment buyer.

The third and final phase of safeguards, from 1995 to the present, is regarded as the period of strengthened safeguards in which the IAEA Member States executed additional safeguards agreements pursuant to INFCIRC/540. This agreement is referred to as the Model Additional Protocol and gives the IAEA enhanced state-wide inspection ability.

The safeguarding of naval propulsion fuel appears to provide significant challenges to the safeguards system. With the exception of India, all states operating nuclear-powered vessels are NPT members and NWS under the NPT. Therefore, although the issue is now being considered with regard to the Brazilian program, the Indian naval propulsion program has received relatively little attention because it is not covered by India's pre-NPT safeguards agreements and, as a non-nuclear weapon program, would be subject to the "loophole" exclusion even if India were an NPT member.

As the Brazilian program progresses further cooperation and better engagement between the IAEA and Brazil will be needed in order to ensure that any material used for a Brazilian nuclear-powered submarine is properly protected against potential diversion.

However, safeguards questions still need to be addressed. NWS under the NPT are obligated to ensure safeguarding of any materials transferred to another state. The Soviet Union and Russian Federation have exploited the non-weapons loophole of the NPT to lease submarines to India. Once in India, no safeguards apply. India has agreed with the IAEA on an expanded list of facilities and a series of India-specific arrangements. Along with the U.S.-India nuclear agreement, an agreement with the NSG, and an acceptance of the Model Additional Protocol, it has a relatively high level of safeguards.³¹ However, neither the leased Russian submarine (see the Indian section) nor the indigenous Indian nuclear powered submarine are covered.

³⁰ See generally, IAEA, *The Evolution of IAEA safeguards*, International Nuclear Verification Series No. 2 (Vienna, 1998), available at www-pub.iaea.org/MTCD/publications/PDF/NVS2_web.pdf.

³¹ World Nuclear Association, "Nuclear Power in India," updated as of December 2014, available at www.world-nuclear.org/info/Country-Profiles/Countries-G-N/India/.

HEU Use in Non-Weapons Military and Non-Military Applications

Understanding the history of HEU use in non-weapons military and non-military applications is important in order to understand its impact on the considerations for eliminating HEU use in naval/military propulsion. Other past and current uses of HEU are particularly important when elimination of naval HEU use is considered in a context of ceasing the complete production of HEU as some have suggested should be done in a prospective FMCT.

In the earliest years of the nuclear era, uranium was considered to be a scarce asset and ideas for using it were confined to nuclear weapons programs. It was believed that only three sources of uranium existed worldwide, in Canada, the Belgian Congo, and Czechoslovakia.³² Even when expanded uranium exploration made it apparent that uranium could be economically recovered from other areas, the limitations on enrichment capacity and nuclear weapons arms race kept it initially confined to use in nuclear weapons. As noted in a later section, the limited supply of enriched uranium almost completely killed the early U.S. naval nuclear program because many worried that diverting uranium and scientists from bomb-making was unwise.

Once HEU became available for use outside the weapons/military complex it was used for a range of applications. It was preferred to LEU in these applications for essentially the same reasons that the U.S. Navy prefers HEU for use in naval propulsion. In the case of reactors, HEU-fueled reactors are smaller and lighter than comparable LEU-fueled reactors. Therefore in the 1950s when reactor applications were considered, for example, for **aircraft** and **cruise missiles** (by the United States and Soviet Union), they were powered by HEU fuel. **Research reactors** similarly could be made with smaller HEU cores, but here another significant HEU advantage came into play. When high neutron density³³ was a desired goal in research reactors it was easier to use an HEU core, and although most research reactors contained only a few kilograms of HEU there were, and are, materials test reactors and critical assemblies specifically designed for a high neutron flux that have cores with significantly more HEU than the typical research reactor.

In the case of reactors, HEU-fueled reactors are smaller and lighter than comparable LEU-fueled reactors.

HEU has also historically been associated with **fast reactors**, in particular with what are known as fast breeder reactors (FBRs), reactors that produce more fissile material than they consume while at the same time producing useful power.³⁴

The United States and Soviet Union both operated HEU **reactors in space** for missions³⁵ that had power requirements that could not be satisfied by either solar power or by the use of Radioisotope Thermoelectric Generators (RTGs).³⁶

³² Robert Bothwell, "From Radium to Uranium." In *Eldorado: Canada's National Uranium Company: The Official History of Eldorado Nuclear Ltd.* (Toronto: University of Toronto Press, 1984).

³³ Described as "neutron flux," which generally is given in neutrons/cm²-second. A typical TRIGA research reactor might have a flux of 3×10^{13} neutrons/cm²-second.

³⁴ Fast reactors are those reactors where most of the fissioning occurs at energies well above the thermal energy range where neutrons are at or near the speed of gas molecules at reactor core temperature. Typical civilian power reactors are thermal reactors with most of the fission's occurring at thermal energies.

³⁵ The Soviets frequently launched small reactors into low Earth orbit during the Cold War. The reactors powered radars used to track principally U.S. naval vessels. These Radar Ocean Reconnaissance Satellites (RORSATs) were designed to boost to a higher altitude parking orbit in order to decay at the end of their useful lives. At least twice RORSATs failed to boost and returned to Earth. Cosmos 954 rained debris along a long swath of the Great Slave Lake in Canada after it partially burned up on reentry in 1977.

³⁶ RTGs are powered by highly active radionuclides, such as strontium 90 (typically used by the Soviet Union/Russian Federation) or plutonium 238 (typically used by the United States). These systems use the energy from the radioactive decay products to produce electric power. They are often referred to as "nuclear batteries."

Currently, the United States and Russian Federation, and perhaps China and others, have the capability of using HEU-fueled reactors in space. The amount of HEU used by these reactors is typically much less than the amount used in submarine reactors but is more similar to the quantities used in research reactors. Where submarine reactors typically produce between 50 and 200 MW, space reactors are two orders of magnitude less, typically producing 1 MW or less.

Although space reactors are typically not discussed in plans to convert from HEU to LEU, they do represent a system that has historically, albeit infrequently, consumed HEU. More importantly, in contrast to ships and submarines, the weight penalty for using LEU in space reactors is extremely significant, a factor that would make replacement with LEU very difficult.

A number of nations have acquired and used HEU for valid **scientific research efforts**. Typically the quantities used are rather small and many of the states satisfy their NPT obligations under the Small Quantities Protocol.

Russia is the only nation that operates non-military maritime propulsion reactors that use HEU. Its fleet of nuclear-powered icebreakers/Arctic resupply vessels is used to clear the “northern-route shipping lane from the Atlantic to the Pacific across Russia’s northern arctic coast.”³⁷ Its commercial nuclear fleet includes five currently operating icebreakers and two that

are out of commission while being repaired. All five of the vessels are currently powered using HEU fuel enriched from 30–90 percent U-235.³⁸ It has not always been that way; the first Soviet icebreaker, the *Lenin*, was initially powered with LEU. However, following an accident that required replacement of the core, it was subsequently fueled with HEU.³⁹ Although there is discussion that the next generation of Russian icebreakers and Arctic resupply ships may be fueled with LEU,⁴⁰ a great deal of concern surrounds both these reactors and Russia’s floating nuclear power plants, particularly because Russia has begun more actively seeking buyers to purchase or lease the vessels, a possibility that is certain to present further challenges to international safeguards.

Russia is the only nation that operates non-military maritime propulsion reactors that use HEU.

In the limited history of **commercial nuclear-powered ships**, the Soviet Union/Russian Federation’s HEU powered icebreakers/Arctic supply ships are unique in their use of HEU. Other nations have designed commercial nuclear-powered ships that use LEU fuel. The first was the *Savannah*, the

sole U.S.-built commercial cargo ship that was built for demonstration purposes only. Following that came the *Otto Hahn*, a German built nuclear-powered cargo vessel that operated from 1968–1979.⁴¹ Finally, the Japanese designed *Mutsu* was the last nuclear-powered commercial vessel, which was decommissioned in 1992 following a tumultuous 23-year history plagued by technical and public opinion problems and never commercially operated on the high seas.⁴² Although all three of these vessels were initially designed to demonstrate the possibilities of peaceful nuclear energy, they were not economical and the countries that built them chose not to build any more nuclear-powered commercial vessels.

Finally, HEU has been used extensively in the preparation of **medical isotopes**. Molybdenum (Mo) 99 is a fission fragment that decays to technetium (Tc) 99m.⁴³ Tc 99m is one of the most commonly used radionuclides for medical diagnostic purposes. To prepare Mo 99, HEU is exposed to a neutron flux (typically in a small research-size reactor) and the Mo 99 is then chemically separated from the other fission fragments. The Mo 99 is then loaded onto a chemical ion exchange column and shipped to a hospital or distribution point near to where the daughter Tc 99m is to be used. When needed, the shorter-

³⁷ Christine Egnatuk, “Chapter 5—Russia: Icebreaker Ships and Floating Reactors.” In *Nuclear Terrorism and Global Security the Challenge of Phasing Out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013), 66–81.

³⁸ The wide range exists because there are conflicting reports in this matter. Specifically, the Murmansk Shipping companies, which produces the icebreakers, reports 30–40 percent U-235. However, a report to the Norwegian Port Authority prior to an icebreaker arrival claimed 90 percent U-235 at one point, creating some doubt among experts. *Ibid.*, 74.

³⁹ Ole Reistad and Povl L. Ølgaard, “Russian Nuclear Power Plants for Marine Applications,” *Nordic Nuclear Safety Research (NKS) Report*, NKS-138 (April 2006), 15.

⁴⁰ Egnatuk, “Russia: Icebreaker Ships and Floating Reactors,” 78.

⁴¹ Peter von Dobschuetz, “Dismantlement of *NS Otto Hahn*,” International Atomic Energy Agency, Vienna.

⁴² Ronald E. Yates, “Setbacks Submerge Japan’s Nuclear Ship,” *Chicago Tribune* (September 2, 1990), available at http://articles.chicagotribune.com/1990-09-02/news/9003130692_1_reactor-radiation-ship.

⁴³ The small “m” is a reference to the fact that the principal decay comes from a “metastable” energy level in the technetium 99. The metastable state is at a higher level than the ground state of the isotope.

lived Tc 99m is eluted off the column in a process that is known as “milking,” giving rise to the distribution column unit being called a “Moly Cow.”

Inroads have been made in replacing HEU with LEU in a number of these applications. Research reactor cores have been successfully redesigned to use LEU without too significant a loss of neutron flux levels and a worldwide replacement program has been converting research reactors to LEU use. However, more than 120 HEU-based research reactors and critical assemblies still are in use with approximately half of the total in the Russian Federation.⁴⁴

LEU, although less efficient and producing more radioactive waste, has been successful as an HEU replacement in the production of medical isotopes.⁴⁵ For better or for worse, many of the older ideas about the use of HEU-based reactors for aircraft and smaller vehicle propulsion are no longer considered viable options. In the area of FBRs there are options of using plutonium to replace HEU, but this replacement itself has a number of unattractive features from nonproliferation and terrorism perspectives.

In summary HEU can be replaced, albeit with difficulty, in all of the non-weapons applications. Replacing HEU in space reactors is probably the most challenging due to the enormous penalties paid to launch the increased weight of an equivalent power output LEU-fueled space reactor.

⁴⁴ International Panel on Fissile Materials, “Facilities: Research and Isotope Production Reactors,” available at http://fissilematerials.org/facilities/research_and_isotope_production_reactors.html.

⁴⁵ However, the importation of LEU produced medical molybdenum 99/technetium 99m has encountered some tariff opposition and regulatory prohibitions on its use in various states for what appear to be protectionist and unfounded non-technical reasons.

Comparing Research Reactors, Power Reactors, and Naval Reactors

In the post-Cold War period there has been a significant amount of success in converting research reactors from HEU fuel to LEU fuel. The Department of Energy (DOE) has had a program for the Reduced Enrichment for Research and Test Reactors (RETRs) since 1978.⁴⁶ According to DOE's National Nuclear Security Administration (NNSA), their office of Global Threat Reduction Initiative (GTRI) has converted seven HEU research reactors to LEU use since 2004 at places like Texas A&M University, Washington State University, and Idaho National Laboratory.⁴⁷ GTRI has also been helping develop LEU fuel for the high-performance research reactors and high-flux test reactors that still currently use HEU.

Critics of HEU naval reactors have often argued that a similar program could be undertaken to convert naval reactors into LEU reactors assuming that the fuel can just be replaced without major alterations. This argument is totally flawed and it is important to understand why this successful conversion program for research reactors has little to no application to the prospect of converting naval reactors to LEU fuel. It is also important to understand the similarities and contrasts between naval nuclear propulsion reactors, research reactors, and the power reactors used in shore-based power stations.

In comparison to power reactors, naval nuclear propulsion reactors are small reactors. In comparison to research reactors, they are relatively large reactors. Their power rating is typically somewhere between 50 MW and 200 MW,⁴⁸ whereas research reactors are typically less than 10 MW and modern power reactors are on the order of 3,000 MW.⁴⁹ Schematically naval propulsion reactors somewhat resemble scaled-down versions of pressurized water reactors (PWRs) used in power stations, with the reactor having a primary coolant loop, heat exchanger, and steam generator that produce steam for a turbine. In some naval applications the steam turbine is directly coupled to the drivetrain (the gearing, shaft(s), etc. that ultimately turn the ship's screw(s) or propeller(s)), but in others (like a shore power station) it is used to produce electricity to drive an electric motor that in turn is coupled to the vessel's drivetrain.

Naval reactors need to be rugged, quiet, etc. These requirements lead designers to use different fuel, rugged support structures, etc. from those used in power reactors in order to withstand a very different environment in which the reactor must be capable of always operating through rapid power changes and surviving shocks in battle damage. These differences between naval reactors and civilian power reactors are often not understood even by nuclear engineers who have not been exposed to naval propulsion reactors. For example, all reactors produce xenon isotopes in normal operation. Once a reactor is shut down either intentionally or via an unintentional SCRAM (emergency shutdown), a radioactive xenon poison builds up, which can prevent civilian power and research reactors from going critical until the poison (which is itself radioactive) has decayed away. Naval reactors can never be put in the position of being unable to override xenon build up, a fact that requires naval reactor cores (whether they use LEU or HEU) to contain more excess reactivity than other types of reactors and therefore they require refueling earlier in their lifecycle than would be done if their cores were operated in a civilian power production mode and could be allowed to burn longer.

⁴⁶ Argonne National Laboratory, "Reduced Enrichment for Research and Test Reactors," available at www.rertr.anl.gov/index.html.

⁴⁷ Department of Energy, National Nuclear Security Administration, "Domestic U.S. Reactor Conversions: Fact Sheet," available at <http://nnsa.energy.gov/mediaroom/factsheets/reactorconversion>.

⁴⁸ Typically power levels are classified by the maximum thermal power capability of the core. Typically this is denoted as megawatts (MW) or thermal megawatts (MWt) in order to distinguish it from the electrical power output, which is typically given in megawatts-electrical (MWe).

⁴⁹ In contrast to naval reactors, civilian nuclear power plants are typically described by their megawatt-electrical power output. A rule of thumb is that the thermal energy produced in a civilian nuclear power plant is three times the electrical energy output (i.e., the efficiency is approximately 33 percent). Thus a typical modern nuclear power plant rated at 1000 MW electrical would be a 3,000 MW thermal plant. Research reactors are also typically rated on their thermal power output.

Research reactors are typically very low power reactors that are not associated with any type of steam production or power production. Many employ no coolant pumps, instead providing cooling and moderation by immersing the small reactor core in a pool of water. In such an “open pool” design, the core is exposed and visible where it is typically suspended from a traveling bridge structure. The pool of water acts as both the moderator and coolant. The volume of the pool is large enough, and the reactor power low enough, that even full power operation doesn’t lead to a significant rise of pool temperature and the air/pool interface is sufficient to dispose of the heat generated.⁵⁰

The General Atomics’ TRIGA (Training, Research, Isotopes, General Atomics) reactor is a typical small research reactor.⁵¹ The TRIGA reactor was originally designed to be able to operate with HEU and a steady power of up to 16 MWt. Currently, TRIGA reactors, such as the ones at Texas A&M University and University of Texas at Austin, operate with LEU fuel and powers of 1 MWt and 1.1 MWt respectively.⁵²

A significant difference between naval reactors and research reactors is in the characteristics of the fuel. Even though both may use HEU, there can be major differences in the thermal expansion coefficient of the fuel and how the expansion feeds back to affect the core’s power level. In HEU cores, such as the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, where the fuel is enriched at 93 percent, the reactor power load is of 85 MWt.⁵³ At this load, while significantly higher than the TRIGA, the reactor is still operating at relatively low power and under less stress than the naval reactors. This fuel also operates at a lower temperature than naval reactor or a power reactor. The HFIR’s inlet water temperature is of 120°F and the outlet is at 156°F, which are significantly lower than analogous temperatures in naval and power reactors. These lower temperatures give the HFIR, much like a TRIGA, a very large negative reactivity feedback coefficient. As the temperature increases, the fuel becomes less reactive and the power level stabilizes. All U.S. reactors are built with this capability, but the higher the operating temperature, the lower the coefficient becomes. If a similar reactor were fueled with LEU, the results would not be as noticeable as with HEU.

A comparison of research reactor conversion to naval reactor conversion is inappropriate — equivalent to comparing apples and oranges.

Research reactors were usually designed to provide a maximized neutron flux for scientific research, often being designed to allow small experiments to be exposed to neutron levels as high as they would see in the much higher-powered power reactors. Creating a high neutron flux was simplified by the use of HEU, which allowed the construction of a small core with a relatively high neutron flux. There was never any question about whether research reactors could be redesigned using LEU to operate at the low power levels; the “trick” in redesigning for LEU cores was to create low power LEU cores that could match the high neutron flux desirable for research purposes. Weight, size of core, shielding, shock mitigation, and all the other attributes that are necessary considerations in a naval propulsion core conversion are not impediments to the use of LEU in a research reactor. Thus a comparison of research reactor conversion to naval reactor conversion is inappropriate — equivalent to comparing apples and oranges.

Although naval reactors resemble small PWRs, one noticeable difference from typical power reactors is in the construction of the fuel elements. Naval reactor fuels are not typically like the uranium dioxide (UO₂) pellets clad in zirconium alloy that is used in fuel elements in power reactors. Naval reactors tend to use uranium-metal alloys such as a uranium-zirconium or uranium-aluminum alloy (e.g., 15 percent uranium with 93 percent enrichment) or a metal-ceramic.⁵⁴ However, like all reactor fuel, the naval reactor fuel must be designed to retain its integrity (i.e., contain all fission fragments) throughout its

⁵⁰ Typically the systems may use a small diffuser that circulates pool water down over the core to inhibit short-lived radioactive nitrogen from being a problem at the surface of the pool. The nitrogen activity is produced by reactions on oxygen nuclei in the water around the core but it is so short-lived that it can be easily prevented from reaching the surface until the radioactive nitrogen has decayed away.

⁵¹ Due to its simplicity the TRIGA was often provided to other nations during a time when the Soviet Union and the U.S. both were prone to provide nuclear technology as part of their “peaceful” Cold War ideological competition. One of the few well documented thefts of HEU occurred from a U.S. supplied reactor in Kinshasa, Democratic Republic of Congo, in the 1970s. One fuel rod was recovered in Italy in 1999 and the other remains missing. See, Chris McGreal, “Missing Keys, Holes in Fence and a Single Padlock: Welcome to Congo’s Nuclear Plant,” *The Guardian* (November 23, 2006), available at www.theguardian.com/world/2006/nov/23/congo.chrismcgreal.

⁵² International Atomic Energy Agency (IAEA), “Research Reactor Technical Data,” available at <http://nucleus.iaea.org/RRDB/RR/TechnicalData.aspx?Rid=517>.

⁵³ Oak Ridge National Laboratory, “High Flux Isotope Reactor,” available at <https://neutrons.ornl.gov/hfir>.

⁵⁴ Magdi Ragheb, “Nuclear Naval Propulsion.” In *Nuclear Power: Deployment, Operation and Sustainability*, ed. Pavel Tsvetkov (InTech, 2011), available at www.intechopen.com/books/nuclear-power-deployment-operation-and-sustainability/nuclear-naval-propulsion.

life. As will be discussed further below, the issue of long-term fuel survivability in the life-of-the-ship reactors now being built by the U.S. Navy could be a significant limiting factor in naval propulsion reactors.

In summary, while naval reactors and research reactors may seem like similar technologies at first glance, especially with both having a long history of using HEU fuel, a closer analysis shows that the two use completely different engineering approaches and design features. Operating pressures and temperatures, the design of the fuel elements, reactor temperature coefficients, core layout, and the need for naval reactors to be designed to operate over wide power ranges, etc. are just some of the many different engineering facts that distinguish naval reactors from research reactors. It is a major engineering fallacy to compare the two as similar technologies, and even worse to assume that what has and can be done to research reactors, such as LEU conversion, can be equally applied to naval reactors.

The History of HEU in Submarines and Surface Warships

In the last seven decades of nuclear technology, by far the most significant non-weapons use of HEU is naval propulsion reactors. In this study we trace the use of both HEU and LEU in maritime propulsion both to define the scope of the problem and to understand the potential for eliminating HEU use.

This study examines the history of HEU use in propulsion reactors by country. Historically NWS have been the principal users of nuclear reactors for naval propulsion. The initial vessel, the U.S. submarine *Nautilus*, kicked off the development of naval reactor propulsion in the early 1950s. The United States was soon followed by the Soviet Union, the United Kingdom, France, and China, all of whom operated nuclear-powered submarines, and in some instances nuclear-powered surface vessels, during the Cold War. Although the end of the Cold War brought about a significant decrease in the number of nuclear-powered submarines and warships, nuclear-powered military vessels still continue to play an important role in the naval strategy of these countries. In addition to submarines and warships, the United States, Germany, Japan, and the Soviet Union developed commercial nuclear-powered surface vessels. All of these commercial vessels were powered by LEU-fueled reactors with the exception of the later generation Soviet icebreakers/supply ships.

In addition to the choice to go nuclear, foreign navies have had to determine what level of uranium enrichment to use in their programs. This decision appears to have been based on one of four considerations: (1) the need for expediency, as with the Soviets; (2) economic issues, as with the French; (3) the example provided by the technology of another state's program, as is the case of the Chinese, Indians, British, and perhaps the Brazilians; or (4) the desire for maximum operation endurance and flexibility, as with the Americans.

Regardless of the reasons behind a nation's choice to go nuclear, the number of states using nuclear-powered warships continues to grow. In recent years India has operated leased Russian nuclear submarines, and it has now developed its own nuclear submarine. Brazil also has an ongoing nuclear submarine development program and Argentina has scattered parts of a nuclear submarine program.⁵⁵

The U.S. currently has the world's largest nuclear submarine force (all U.S. submarines use nuclear propulsion) and has the second largest total number of submarines.⁵⁶ The Russian Federation has the second largest number of nuclear submarines and the fourth largest number of total submarines. China has the third or fourth largest nuclear submarine force⁵⁷ and the third largest number of submarines of all types.

In the following subsections we review the naval nuclear reactor programs of each country that has developed a naval nuclear capability. It should be understood at the outset that when considering any states' naval nuclear propulsion program that the information is invariably considered highly classified by the state, and therefore, what is available from open source literature may be of questionable accuracy and can be contradictory.

Appendix A contains open source descriptions of past and present vessels and reactors operated by navies of the United States, Russian Federation, United Kingdom, France, China, India, and Brazil and Argentina.

⁵⁵ Brazil's program presents a special challenge to the IAEA's safeguards regime as it potentially could be a military, but non-weapons-related use of nuclear material thus possibly removing the material from its safeguards obligations during its military use.

⁵⁶ Surprisingly, North Korea has the world's largest submarine force, all of which are conventionally powered.

⁵⁷ Exact numbers of submarines possessed by China that are truly operational is not well known. The number of nuclear submarines possessed by China, the United Kingdom, and France are close a number (about a dozen) and whether a state is third, fourth, or fifth in the list depends on the fluctuating numbers of submarines in and out of commission, at sea trials, etc.

The United States

The U.S. nuclear submarine program is the oldest and most advanced in the world, including approximately 25 different classes of submarines and at least 18 different reactor designs.⁵⁸ Additionally, while only one commercial U.S. nuclear vessel, the *Savannah*, has ever been constructed, the U.S. Navy has developed at least nine different classes of military surface vessels including both nuclear-powered aircraft carriers and cruisers. However, unlike many other national nuclear propulsion programs, the U.S. program has pursued almost exclusively PWR reactor plants using weapons grade (greater than 90 percent) HEU fuels, characteristics attributed by most experts to the unique leadership and development of the U.S. program.

The U.S. nuclear submarine program is the oldest and most advanced in the world.

Similar to the Soviet and later Russian nuclear propulsion program, the U.S. program focused most of its efforts on nuclear propulsion submarines, and as such the U.S. program is best described in terms of the four generations of nuclear submarine development. In order to best understand this development, it is important to first understand the convention by which U.S. naval nuclear reactor designs designated. The designation includes three letters that specify the type of reactor (“A”—

Aircraft Carrier, “S”—Submarine, “D”—Destroyer, “C”—Cruiser), the generation number of the reactor, and the contractor that designed the reactor (“B”—Bechtel, “C”—Combustion Engineering, “W”—Westinghouse, “G”—General Electric). As such, the sixth generation submarine reactor designed by General Electric is designated S6G, the specific reactor design used in all *Los Angeles*-class submarines.

Early History

The U.S. nuclear submarine program began on March 20, 1939, when a physicist from Columbia University, Ross Gunn, requested \$1,500 to conduct research on a nuclear “fission chamber” that would generate steam to operate a turbine for a submarine power plant.⁵⁹ In that first research effort, Gunn concluded that nuclear-powered submarines had several possible advantages, namely the ability to operate submerged without oxygen. However, he also concluded that many unknowns remained, particularly the means for separating the U-235 atoms necessary for nuclear fission. These early efforts at nuclear naval propulsion were halted because the United States devoted greater resources to developing a nuclear bomb, fearing that Germany would develop one first.

Following WWII, research began again, this time much more seriously. It is important to note that at this point in the development of the U.S. program, the quantity of fissile material possessed by the U.S. government played a vital role decision-making. Specifically, it was initially projected that U.S. naval reactors would require annual refueling. As such, despite the many advantages of nuclear propulsion submarines, the idea still received a great deal of resistance simply because many worried that its development would distract attention and divert material from nuclear weapons development.⁶⁰ This factor heavily influenced early submarine design, particularly with regard to the enrichment of early submarine fuel and these early concerns ultimately had longer-lasting effects that still influence design decisions today.

The first two nuclear naval propulsion designs were developed concurrently by the contractors Westinghouse Company and General Electric (GE), with each company initially pursuing different approaches to a naval nuclear reactor. Initially GE developed a liquid metal cooled reactor concept, whereas Westinghouse developed a PWR concept. The PWR was ultimately to become the forerunner of the modern U.S. naval nuclear reactor designs. Initially, however, the decision was not clear, and the liquid metal concept was not fully rejected at this point. Ultimately the PWR design was chosen, and was designated as the Submarine Thermal Reactor (STR). This STR was later designated S1W and became the basis for the S2W reactor plant placed in the world’s first nuclear-powered submarine, the *Nautilus*.⁶¹

⁵⁸ A complete listing of all U.S. Submarine and Reactor designs is found in Appendix A.

⁵⁹ Norman Polmar and Kenneth J. Moore, *Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines* (Washington, DC: Brassey’s, 2004), 50.

⁶⁰ *Ibid.*, 53

⁶¹ Susan M. Stacy, “Neutrons: Fast Flux, High Flux, and Rickover’s Flux.” In *Proving the Principle: A History of the Idaho National Engineering and Environmental Laboratory, 1949–1999* (Idaho Falls, ID: Idaho Operations Office of the Department of Energy, 2000), 51–53.

First Generation Submarines

The first generation of nuclear submarines includes the first successful U.S. nuclear propulsion reactor S2W, that powered the *Nautilus*, as well as its immediate successors, the S3W and S4W reactors, which powered numerous submarine classes, including the *Skate*, *Sargo*, *Halibut*, *Swordfish*, and *Seadragon*-classes. Additionally, the earliest GE nuclear propulsion designs, S1G and S2G, which developed the liquid metal coolant concept, are also considered to be part of the first generation, even though S2G was only used in one operational submarine, *Seawolf*.

This first nuclear propulsion reactor plant was called the Submarine Thermal Reactor. On March 30, 1953, the STR was brought to power for the first time; it later achieved a 96-hour sustained full power run, simulating a crossing of the Atlantic Ocean, and eventually was designated S1W, the prototype design for the reactor plant placed in the *Nautilus*.⁶²

As discussed above, during the early history of the U.S. nuclear program, naval nuclear reactors competed directly with the U.S. nuclear weapons program for fissile material. The *Nautilus* was initially fueled with 20 percent U-235; however, as the supply and processing of uranium improved, more U-235 was available and *Nautilus* was refueled with 40 percent U-235 in 1957.⁶³ In fact, the increasing endurance achieved with each subsequent core, starting with 62,000 miles and ending with 150,000 miles for its third core, indicates that the enrichment of the uranium fuel within the *Nautilus* continued to increase throughout its life.⁶⁴

Concurrently with construction of the STR PWR, GE continued developing its own liquid metal coolant concept, which ultimately became the Submarine Intermediate Reactor (SIR). The SIR was later redesignated S1G and became the model for S2G, which powered the first *Seawolf* submarine. It is important to note that the S1G design is likely to represent the first U.S. design with fuel enriched to 90 percent U-235, given the importance placed on compactness for the design.⁶⁵ However, although liquid sodium coolant has better heat transfer characteristics, it was ultimately decided that the design had too many technical and safety considerations. As such, in 1958, the S2G reactor was removed from the *Seawolf* and replaced with a PWR, designated S2Wa.⁶⁶

Following the *Nautilus* and the *Seawolf*, it was determined that those two designs were too expensive for series production, and the decision was made to place a new small PWR in a modified *Tang*-class design.⁶⁷ This newer design was designated S3W, with S4W shortly following with the same reactor and slightly different equipment configuration. Only five of these reactors were built; however, they carried out much of the initial under-ice operations responsible for mapping the Arctic seabed and represent the first truly successful operational naval propulsion reactors for the U.S. program. Finally, although very little is available in the open-source literature, it is expected that uranium enrichment for the S3W and S4W reactor cores had already reached greater than 90 percent U-235 because many of the issues previously limiting the quantity of enriched uranium available had been resolved by that point.

One additional project that should be mentioned in discussion of first generation reactor designs is the nuclear radar picket *Triton*. Following its pursuit of liquid metal cooled designs, GE next began design of a two-reactor propulsion plant that would ultimately power the *Triton* nuclear radar picket. The prototype for this design, S3G, was constructed in West Milton, New York, and the similar S4G reactor was installed in the *Triton*. Unfortunately, although the *Triton* was quickly made redundant by aircraft radar pickets and no additional two-reactor propulsion systems were used in U.S. submarines, the experience gained through these designs was used for later surface vessel reactor designs.⁶⁸ Additionally, the *Triton* has the auspicious honor of completing the world's first submerged around-the-world cruise.

⁶² Ibid.

⁶³ Norman Friedman, *Submarine Design and Development* (Annapolis, MD.: Naval Institute Press, 1984), 134.

⁶⁴ Norman Polmar, *The American Submarine* (Annapolis, MD: Nautical & Aviation Publishing Company of America, 1983), 113.

⁶⁵ Friedman, *Submarine Design and Development*, 134.

⁶⁶ Polmar and Moore, *Cold War Submarines*, 60–61.

⁶⁷ Polmar and Moore, *Cold War Submarines*, 63.

⁶⁸ Polmar and Moore, *Cold War Submarines*, 65.

Second Generation Submarines

Following the lessons learned from the first generation of U.S. propulsion reactors, the second generation designers certainly placed a greater premium on sound silencing, as is evident by the design improvements made for the S5W design as well as the successful development of the S2C and S5G designs. The S5W reactor design, in particular, became the workhorse of the second generation of submarines, powering a number of classes, including the *Skipjack*, *George Washington*, *Permit*, and *Sturgeon* among others.⁶⁹ Although the S2C and S5G designs that powered the *Tullibee* and *Narwahl* respectively were only used in one vessel each, the designs were nonetheless important for the concepts they proved that became important in later designs.

Although the earliest class of submarines to use the S5W design, the *Skipjack*, demonstrated small improvements in its design, the S5W propulsion plant used in the *Thresher* was particularly significant for several reasons. To begin with, it included the first efforts to reduce the narrow-band machinery noises that easily set submarines noise apart from other marine noise.⁷⁰ Additionally, the *Thresher*-class included the first efforts at rafting, a design technique developed by the Royal Navy, whereby machinery noise and vibrations are decoupled from the hull of the submarine. Finally, the *Thresher*-class was

This accident, the first of its kind in the U.S. nuclear Navy, brought on numerous changes in the reactor safety features.

important because of changes made following the loss of the flagship vessel, the *Thresher*, during sea trials on April 10, 1963. Investigators believe that *Thresher* experienced uncontrollable flooding due to a piping failure at near test depth. A failure of the emergency ballast blowing system and the loss of power due to a reactor SCRAM prevented *Thresher* from reaching the surface or being able to control its depth and the hull was eventually crushed when the vessel sank. This accident, the first of its kind in the U.S. nuclear Navy, brought on numerous changes in the reactor safety features of the S5W design to minimize the chance of unnecessary protective actions. Furthermore, although not important to reactor design, the accident also caused several important changes in the Navy's SUBSAFE program, by which the maintenance and equipment used to ensure submarine safety is treated with much greater scrutiny.⁷¹

Although most of the submarine classes in the second generation used the S5W reactor, the *Tullibee* used a different design—the first to be designed by the Combustion Engineering design firm of Windsor, Connecticut, with the assistance of the Naval Reactors design branch. The S1C prototype reactor and its successor, the S2C reactor that ultimately powered the *Tullibee*, used an electric drive rather than a steam turbine, significantly reducing propulsion noise, an important design innovation that has since been considered for several other designs.⁷² Additionally, because the *Tullibee* was designed for research and anti-submarine warfare (ASW) capabilities, the S2C design was developed to be very small, but very capable, with an expected 93 percent U-235 enriched core that produced 1/6 the power of the S5W reactor plant.⁷³ However, although the *Tullibee* was considered a very capable platform, its limited speed ultimately led to the decision to produce no other vessels in the class.

Finally, following the S5W and S2C reactor designs, the final reactor design of the second generation was the S5G reactor. Unlike the other 36 *Sturgeon*-class vessels produced from 1967–1975, the *Narwahl* was reconfigured to instead carry the S5G reactor.⁷⁴ Continuing its trend for developing more revolutionary designs, GE finally achieved broad success with the S5G reactor, which is known for its natural circulation capability, whereby coolant circulation within the primary circuit is achieved without the use of pumps. This natural circulation technology was successfully proven on the *Narwahl* and subsequently used in future reactor designs, particularly the important *Ohio*-class S8G design.

⁶⁹ *Jane's Fighting Ships*, series of annual editions 1965–2014.

⁷⁰ Polmar and Moore, *Cold War Submarines*, 151.

⁷¹ Polmar and Moore, *Cold War Submarines*, 152.

⁷² Polmar and Moore, *Cold War Submarines*, 153.

⁷³ Polmar and Moore, *Cold War Submarines*, 153.

⁷⁴ Polmar and Moore, *Cold War Submarines*, 155.

Third Generation Submarines

The third generation⁷⁵ of U.S. submarines represents most of the current operational submarine fleet, including the S6G and S8G reactors that power the *Los Angeles*- and *Ohio*-classes respectively. This generation represented a significant shift in the method by which U.S. submarines were designed, focusing much greater attention on developing fewer new designs in order to cut costs, as compared to first and second generation submarine designs, which included a number of “one-off” designs and submarine classes with fewer vessels. This shift is partly explained by the waning influence of Vice Admiral Hyman Rickover, who had for years as the “Father of the Nuclear Navy” played an important personal role in ensuring that the nuclear navy got the resources he thought necessary to support its development programs. Additionally, the third generation period was one in which as U.S. influence continued to expand abroad, the battle for defense budget resources intensified, placing every expenditure under greater scrutiny.

The battle for resources became especially important in the design of the S6G reactor that ultimately powered the *Los Angeles*-class attack submarine. In the late 1960s, three separate new programs were being simultaneously developed to replace the *Sturgeon*-class: (1) the CONFORM program, (2) The *Los Angeles*-class design, and (3) the *Lipscomb* Turbine Electric-Drive Submarine (TEDS) program.⁷⁶ Ultimately, the pressure to cut costs imposed by the Vietnam War as well as Rickover’s influence resulted in the adoption of the *Los Angeles*-class as the primary third generation attack design. The CONFORM program was eventually discontinued and the *Lipscomb* TEDS design was halted after the construction of only one vessel.

The S6G reactor plant that powered the *Los Angeles*-class was based on the larger D2W reactor design used for surface vessels and rated at 148 MWt.⁷⁷ The primary design consideration behind the *Los Angeles*-class submarine and its associated S6G reactor design was speed. Speed became such an important factor with this design for two reasons: (1) Soviet attack submarines at that time were found to be much faster than expected, and (2) the *Thresher*- and *Sturgeon*-classes were ultimately slower than desired, considering that the S5W reactor design used was initially design for the *Skipjack*, a much smaller vessel.⁷⁸ With a projected maximum speed of 33 knots and a maximum depth of 950 feet, the *Los Angeles*-class did meet the requirements for the third generation U.S. submarines. However, for this small increase in speed, the costs of the *Los Angeles*-class greatly increased, leading to several challenges to the design in the 1970s. In the end, despite these challenges, Rickover once again used his influence to ensure that *Los Angeles*-class remained the choice of the U.S. Navy.

Following the *George Washington* and *Ethan Allen*-classes of ballistic missile submarines, the *Ohio*-class or *Trident*-class submarine and its associated S8G reactor represented the next step in development that started with the S5G reactor design proven aboard the *Narwahl*. The desired characteristics for the S8G reactor design certainly presented challenges. Having concluded that the next generation of ballistic missile submarines should carry 24 SLBMs, the next generation of ballistic missile submarines would need to be larger and its reactor more powerful. As such, the S7G prototype and its successor the S8G are capable of using natural circulation at low speeds to reduce noise emission. Additionally, a single large propulsion turbine was used instead of reduction gears, increasing the size of the propulsion train, but further reducing the noise emitted.

It should also be noted that the S7G prototype initially contained an interesting design feature, whereby core reactivity was controlled by stationary gadolinium-clad tubes that were partially filled with water.⁷⁹ A higher water level in the tube within the core slowed down the neutrons allowing them to be captured by the gadolinium tube cladding rather than the uranium fuel, leading to a lower power level. The design constituted a novel new fail-safe control system. The pump needed to run continuously to keep the water level pumped down. Upon an accidental loss of pump power, all the water would flow back into the tube, shutting down the reactor. Official sources behind the reasons for the use of gadolinium tubes are

⁷⁵ Unless otherwise noted, all information included in this section was sourced primarily from Norman Polmar and Kenneth J. Moore, *Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines* (Washington, DC: Brassey’s, 2004), which is the best open-source resource on Third Generation Submarine design development.

⁷⁶ Polmar and Moore, *Cold War Submarines*, 269.

⁷⁷ Polmar and Moore, *Cold War Submarines*, 268.

⁷⁸ Polmar and Moore, *Cold War Submarines*, 268.

⁷⁹ Magdi Ragheb, “Nuclear Naval Propulsion.” In *Nuclear Power: Deployment, Operation and Sustainability*, ed. Pavel Tsvetkov (InTech, 2011), available at www.intechopen.com/books/nuclear-power-deployment-operation-and-sustainability/nuclear-naval-propulsion.

unknown. There is significant speculation that the design was developed to determine the feasibility of other reactivity control measures in the event that the Navy was no longer able to obtain the materials necessary to continue producing control rods. Ultimately, the gadolinium tubes were replaced with standard control rods in the late 1980s when the core was refueled.⁸⁰

Aside from the *Los Angeles*-class and *Ohio*-class, the S5Wa reactor that was included in the *Glenard P. Lipscomb* (SSN 685) should also be mentioned when discussing the third generation of U.S. designs. The *Lipscomb*, also designated as TEDS, continued the work started with the *Tullibee* to develop a quieter submarine by using an electric propulsion system and removing the need for reduction gears. Unfortunately, the inefficiency of electric propulsion systems reduced the power output of the S5W reactor, resulting in a top submerged speed of only 23 knots for the *Lipscomb*, as well as several problems with overheating, which played a large role in discontinuing the S5Wa design.⁸¹

Fourth Generation Submarines

In the 1980s, the U.S. Navy began to pursue a new generation of attack submarines. This new generation, often considered the fourth generation, includes the *Seawolf*- and *Virginia*-classes, with some experts including the new SSGN-class as well, which was produced through conversion of several existing *Ohio*-class ballistic missile submarines. The designs and development of this new generation reflect a number of important shifts in the geopolitical situation of the world in the 1980s. First, the long-held American dominance in the area of submarine quieting changed drastically as several Soviet design improvements allowed their *Akula*-class submarine to reach, if not surpass, U.S. levels of submarine quieting. This concern was relatively short-lived, though, as the collapse of the Soviet Union in the early 1990s removed the Soviet threat. Nevertheless, the *Seawolf*-class submarine, designed for improved quieting, had already been designed and funded at that point. Moreover, as the collapse of the Soviet Union removed the greatest potential foe of the United States, it also started the necessary process of considering what shape the U.S. submarine force would take in a post-Soviet world and which new capabilities would be necessary for that force. As such, one of the key elements of the fourth generation of U.S. submarines is flexibility—the flexibility to respond to numerous different threats with different capabilities—as is demonstrated through many of the design elements in the *Virginia* and SSGN-classes.

The *Seawolf*-class represents the first of the fourth generation submarines and the last of the Soviet era submarines classes. Designed to be the most capable attack submarine ever built, it includes a more powerful S6W reactor, a jet-pump propulsor instead of a normal exterior propeller, and eight torpedo tubes with the capability to carry about 50 torpedoes.⁸² Not surprisingly, given all the advances included into the *Seawolf*-class design, it is not surprising that it is considered the most expensive U.S. submarine ever built, with some estimates reaching approximately USD \$16 billion for the three submarines that were ultimately built.⁸³ However, in the end it was concluded following the collapse of the Soviet Union that the *Seawolf*-class was no longer necessary, leading to a discontinuation of construction. Currently, one *Seawolf*-class submarine, the *Jimmy Carter*, is in use as the Navy's special operations submarine platform.⁸⁴

Following the high cost of the *Seawolf*-class, the *Virginia*-class was designed with much greater attention to costs and the capabilities necessary to respond to contemporary threats. Given those considerations, the *Virginia*-class includes a jet-pump propulsor, like the *Seawolf*, but is considerably smaller than either of its predecessors, the *Seawolf* or the *Los Angeles*, with only four torpedo tubes. It is important to note though that, consistent with the desire to achieve a more capable, flexible platform, the *Virginia*-class also includes 12 vertical launch tubes for Tomahawk missiles. Additionally, the S9G reactor that powers the *Virginia*-class holds the distinction of being the first U.S. reactor with a 30-year life-of-core reactor.⁸⁵

The final “class” of the fourth generation can't really be considered a new class, but rather a mission conversion for the *Ohio*-class submarine. Specifically, the new class converted the tubes previously devoted to ballistic missiles for a number of

⁸⁰ Ibid.

⁸¹ Polmar and Moore, *Cold War Submarines*, 269.

⁸² Polmar and Moore, *Cold War Submarines*, 309.

⁸³ Polmar and Moore, *Cold War Submarines*, 313.

⁸⁴ *Jane's Fighting Ships*.

⁸⁵ Office of Naval Reactors, “Report on Low Enriched Uranium for Naval Reactor Cores: Report to Congress January 2014” (Washington, DC: 2014), hereinafter 2014 Report.

new purposes, including the launch of Tomahawk cruise missiles as well as the release of Navy seals. Although other small improvements were made to the *Ohio*-class vessels converted for use as SSGNs, generally the submarine design is the same, demonstrating how pressures, such as limited resources and expanding missions, have influenced the development of U.S. submarines in the modern era.

Surface Warships

The United States has quite an extensive history in developing surface nuclear propulsion reactors. However, unlike Russia and the Soviet Union before it, the United States only built one commercial nuclear merchant ship—the *Savannah*. It was designed as a national showpiece and not as an economical merchant vessel. In the military sphere, the United States was much more active, developing a number of propulsion reactors for surface ships. Initially, the “nuclear revolution” was envisioned to power a large array of surface vessels, including cruisers, destroyers, and aircraft carriers. In fact, Section 1012 of the FY2008 Defense Authorization Act (H.R. 4986) requires that any future U.S. Naval combatant ships be constructed with integrated nuclear propulsion plants, unless the Secretary of Defense notifies Congress that nuclear propulsion for the given class of ship is not in the national interest.⁸⁶ However, despite this law, currently the U.S. Navy only possesses nuclear-powered submarines and aircraft carriers, with no serious intentions to expand the variety of nuclear vessels at this point.

It has not always been the case that only aircraft carriers and submarines used nuclear propulsion. In 1961, the Navy’s first nuclear-powered cruiser, the *Long Beach* (CGN-9) was commissioned. Subsequently an additional eight nuclear-powered cruisers were built. These cruisers, which were procured to escort the Navy’s nuclear-powered carriers, were generally successful. However, the high cost of nuclear-powered cruisers resulted in a conventionally powered design being chosen to replace them. Procurement costs of nuclear-powered designs would have been 30–200 percent greater than the conventional designs.⁸⁷ No further nuclear-powered cruisers have been built, and the nine nuclear cruisers were retired in the 1990s, leaving the Navy with only nuclear-powered aircraft carriers and submarines.

There were initial challenges in scaling up the STR design used as the prototype for the *Nautilus*, and, therefore the first nuclear-powered aircraft carrier, the *USS Enterprise*, initially contained eight A2W reactors. Subsequent surface vessel designs overcame these challenges, and contemporary aircraft carriers only contain two larger reactors, as was designed with the A4W reactors in the *USS Nimitz*. However, given that the first aircraft carrier reactor design was in development concurrently with the second generation of submarine reactor designs, all aircraft carrier reactors were expected to have used highly enriched uranium fuel, in excess of 90 percent U-235. Regarding aircraft carrier reactor design, it is important to note that all consideration by the U.S. Navy given to alternative enrichment levels for naval propulsion reactors has been concerned with the impacts on submarines, despite the very different reactors and operational parameters for aircraft carriers.

At the present time U.S. nuclear Navy force levels appear to be stable or perhaps declining slightly. Nuclear-powered aircraft carriers and submarines continued to be built but the Navy is under serious financial pressures. It appears highly doubtful that any of the future construction large aircraft carriers would be conventionally powered and although the Navy might experiment with new conventional submarine technologies, such as the air independent propulsion (AIP) technology it appears certain that most, if not all, future submarines will be nuclear powered.

The Soviet Union/Russian Federation

The Soviet naval nuclear power program, and its subsequent Russian successor, is one of most expansive naval nuclear programs ever developed, including not only military naval applications, but also civilian naval applications, such as naval icebreakers and, more recently, floating nuclear power plants (FNNPs), in total reaching more than approximately 260 naval nuclear vessels constructed since the program’s inception in 1958.⁸⁸ Similar to the U.S. naval reactor design, Soviet nuclear reactor design underwent a series of progressions as designers searched for better designs, in terms of both capability and

⁸⁶ Ronald Rourke, *Navy Nuclear-Powered Surface Ships: Background, Issues, and Options for Congress*. (Ft. Belvoir, VA: Congressional Research Center, 2010).

⁸⁷ *Ibid.*

⁸⁸ Nils Bohmer, Alexander Nikitin, Igor Kurdik, Thomas Nilsen, Michael H. McGovern, and Andrey Zolotov. *The Arctic Nuclear Challenge* (Oslo, Norway: Bellona Foundation, 2001) 3.

safety. However, unlike U.S. designs that maintained a relatively consistent enrichment for its naval reactors,⁸⁹ Soviet designs have employed a wide variety of enrichment levels. This development is explained by the initially less deliberate manner by which new Soviet nuclear reactor designs were developed, owing much to the pressure placed on Soviet designers to design and produce reliable and safe naval reactors at rates necessary to maintain pace with the United States during the Cold War.

Beyond inconsistent enrichment levels for fuel design, the Cold War naval nuclear arms race left a much more serious legacy in terms of the disposition of spent fuel from naval nuclear reactors, and more specifically the security surrounding that spent fuel. Given these considerations, Russia has in recent years considered options to improve both the security and marketability of its naval reactors, including the possibility of developing an LEU-fueled icebreaker or FNNP. However, significant uncertainty still remains whether these plans will be implemented given recent financial troubles that have slowed the pace of modernization. Furthermore, even without financial troubles, it is difficult to predict decisions regarding Russia's naval nuclear program, given how little information is available regarding the program or any future plans for its development.

History of Military Naval Nuclear Development

Russia's military naval nuclear development includes both submarines and surface ships, such as nuclear-powered cruisers and communications vessels. However, the major focus of the Soviet naval nuclear program has always been submarines, given the additional capabilities provided by nuclear propulsion submarines, the challenges of their development, and the desire to keep pace with American development. Nuclear submarine reactor design is often characterized in terms of four generations, with the first generation in production from 1955–1966, the second generation from 1963–1992, the third generation from 1976–present, and the fourth generation commencing in 1993. All the designs of the major generations were pressurized water reactors (PWR), but several more novel prototype designs and liquid metal cooled reactors (LMR) were designed and produced. However, none of these more novel designs are known to be in operation today. Additionally, it is important to note that many of the early Soviet designs focused heavily on redundancy, as is demonstrated by early designs, including two reactors. In fact, this focus on reliability and safety, driven by the Soviet need to play “catch up” in terms of naval reactor research, had a number of important effects, first of which was the decision to use fuel systems containing fuel of lower enrichment than that used in American designs.⁹⁰ As Soviet designers developed and tested new designs, they also became more comfortable ensuring safety and reliability at higher enrichment levels as is demonstrated by the progression of Soviet reactors designs.

First Generation Submarines

The first generation of submarine reactors, which operated in *November*, *Hotel*, and *Echo I and II* class submarines, is characterized by the VM-A reactor design. Given the time period often attributed to first generation designs, the *November*- and *Papa*-class designs could be included as well. However, these are both liquid metal cooled prototype designs and should therefore be considered separately from VM-A designs given their drastically different designs. Aside from small configuration differences, all the VM-A reactors were fairly similar; all were PWRs with vertical europium control rods used for reactivity control. One of the important design features of the VM-A design was the decision to place all connecting piping to the core above the upper edge of the core, thereby preventing the possibility of accidentally draining a portion of the core as occurred with one the early Soviet icebreaker designs.⁹¹ Only limited information is publicly known about the fuel type of VM-A reactors, a disconcerting fact, considering that many of the spent cores still await dismantlement in bases on the Kola Peninsula, far from a dismantlement facility, or were disposed of by dumping them in the Kara Sea.⁹² The limited information available indicates that VM-A cores were operated using fuel assemblies of varying enrichment levels, up to 20 percent U-235, in uranium-aluminum alloys with a suspected stainless steel cladding material.

⁸⁹ See Appendix A, Table A-1. U.S. Naval Reactors, which lists U.S. submarine and reactor designs.

⁹⁰ Ole Reistad, Morten Bremer Mærli, and Nils Böhmer, “Russian Naval Nuclear Fuel and Reactors: Dangerous Unknowns,” *The Nonproliferation Review* 12:1 (2005), 163–197.

⁹¹ Part of the core of the icebreaker *Lenin* was inadvertently drained in 1966 when a rupture occurred in piping below the top of the core, causing significant damage to some of the fuel elements. Reistad et al., *Dangerous Unknowns*, 169.

⁹² Until the early 1990s the practice was to dump all damaged submarine reactors in the Kara Sea, northeast of the Barents Sea in the Arctic Ocean.

Second Generation Submarines

The second generation of Soviet submarine reactor designs, the VM-2 and VM-4 reactor designs includes the designs for the *Victor I-III*, *Yankee*, *Charlie I-II* and *Delta I-IV*-class submarines. Less is known about the technical specifications of the second generation reactor design, and in some cases conflicting information exists, further confusing the issue. However, it is generally agreed that the Second Generation designs are more capable than the first generation, with greater core lifetimes, better reliability, and smaller core sizes. This is confirmed by design change noted in the *Charlie*-class, where the vessel only included one reactor as opposed to two reactors in all previous designs. Despite these improvements, it is clear that the second generation designs were still far from mature, as was demonstrated by several cases of fuel swelling in *Yankee*-class submarines, where it was necessary to have personnel enter the reactor compartment to manually insert the stuck control rods.⁹³ Additionally, evidence from the *Kursk* sinking in 2001 seems to indicate that the second generation designs lacked the very basic safety feature that prevents control rods from falling out in the event the reactor is inverted.⁹⁴ In terms of the enrichment of fuel assemblies for the second generation reactors, some conflicting opinions exist. However, it seems that most researchers have concluded that the VM-2 and VM-4 designs contained fuel assemblies with approximately 20 percent U-235, similar to what is known to have fueled the first generation designs.

Compared to the first and second generation reactor designs, even less is known about the third generation design.

Third Generation Submarines

Compared to the first and second generation reactor designs, even less is known about the third generation design, which typically includes the *Typhoon*, *Sierra*, *Oscar*, *Akula*, and *Mike*-class submarines. To begin with, a great deal of inconsistency exists in the nomenclature used for the third generation reactor system. However, generally it is agreed that the third generation is characterized by the VM-5 reactor with the OK-650 core. Additionally, furthering the confusion, the Soviet surface-based nuclear system, KN-3, which was operated on the *Kirov*-class missile cruiser, is often considered part of the third generation, but it seems to bear little resemblance to the VM-5 reactors system. However, despite the uncertainty regarding this generation, it is possible to conclude that the third generation reactors designs were more powerful than previous generations (70 MW to 190 MW).⁹⁵ Additionally, the use of titanium hulls for some third generation designs played an important role, given its reduced displacement but increased strength. Regarding the fuel enrichment of third generation reactor designs, many researchers have weighed in on the topic with a wide range of conclusions, anywhere from 21–45 percent U-235.⁹⁶ Neither the Soviet government nor its Russian successor has ever publicly released any information regarding the enrichment of these third generation designs. The best indication available comes from a Soviet statement in response to concerns about the submarine *Komsomolets*, which sank in the Barents Sea in 1989, and that was characterized as “modestly enriched fuel.”⁹⁷

Besides the three generations of Soviet reactor designs already mentioned, there exists a wide variety of other nuclear platforms that, although they represent a much smaller proportion of the entire Soviet nuclear fleet, actually represent a greater variety in terms of reactor design and fuel enrichment. The most important group to mention outside the first three generations is sometimes called the fourth generation, but could be more accurately called the post-Soviet generation, which includes the two most recent classes added to Russia’s submarine fleet, the *Borei*-class and the *Yasen*-class. However, aside from being completed in the post-Soviet era and some small changes, including a more advanced propulsion system, the reactor systems of these two classes otherwise closely resemble the third generation designs, including its OK-650 core and consequent fuel enrichment.

⁹³ Ole Reistad and Povl L. Ølgaard, “Russian Nuclear Power Plants for Marine Applications,” 33.

⁹⁴ Ibid.

⁹⁵ Reistad et al., *Dangerous Unknowns*, 180.

⁹⁶ Pavel Podvig, “History of Highly Enriched Uranium Production in Russia,” *Science & Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives* 19, no. 1 (2011), 46–67.

⁹⁷ Steinar Høibråten, Per E. Thoresen, Are Haugan, “The Sunken Nuclear Submarine *Komsomolets* and Its Effects on the Environment” *Science of the Total Environment* 202, nos. 1–3 (August 25, 1997), 10.

Without a doubt, the most interesting, and perhaps most concerning, Soviet nuclear designs were those created for some of the Soviet Union's more novel platforms, including its LMR submarine designs and nuclear icebreaker designs. Although most of Russia's current fleet of naval reactors is powered by HEU, defined by the IAEA as greater than 20 percent U-235, it is important to note that all of the LMR designs as well as the nuclear icebreaker designs include fuel of much higher enrichment levels, near 90 percent U-235, a significant enrichment level given its potential for use directly in a nuclear weapon. More importantly, unlike all the Russian submarine uses of HEU, the Russian nuclear icebreaker fleet is civilian operated, a concern shared by many in the international community.

As compared to the more than 250 nuclear-powered naval vessels, both military and civilian, that have been built in the Soviet Union and Russia since the inception of the Soviet naval nuclear power program, the current Russian nuclear fleet, totaling somewhere around 50 vessels, is relatively modest, representing only 20 percent of Soviet naval nuclear reactors are no longer operating. These data are especially important considering that most of these reactor cores contained HEU, and, especially following the collapse of the Soviet Union, were often poorly guarded. Although some instances of relative transparency exist,⁹⁸ much of the information on Russia's naval nuclear program, including disposition of spent fuel, has

More importantly, unlike all the Russian submarine uses of HEU, the Russian nuclear icebreaker fleet is civilian operated, a concern shared by many in the international community.

been primarily obtained through information gleaned from investigations of nuclear material thefts or radiological incidents that occurred both during and after the Soviet Union. As such, it is not at all surprising that researchers in the field of nonproliferation and nuclear security have expressed concern both with the enrichment of future reactors, civilian and military, as well as the disposition of such fuel.

However, despite these concerns, much like the U.S. Navy, it seems unlikely that the Russian Navy will convert its military naval reactors to LEU anytime soon. Like the U.S. Navy, the Russian Navy doesn't see any reason to give up the advantages of HEU, especially because Russia has been operating with its current level of enrichment for decades and does not desire to make a drastic change without good cause. Furthermore, some of the stronger arguments for conversion that were present in the 1990s and 2000s—that the security problems with fresh and spent HEU fuel in Russia necessitated conversion—no longer exist, in part thanks to U.S. assistance in strengthening Russia's material protection, control, and accounting (MPC&A) efforts. On the other hand, the possibility of converting Russia's fleet of nuclear icebreakers and FNNP to use LEU seems more likely. Not only would this make both platforms more commercially appealing, by easing the restrictions imposed by the NSG, but it would also bring Russia's civilian nuclear industry better in line with the IAEA's

requirements and recommendations regarding use of HEU. This possibility seems to be confirmed by the design used for the new Russian prototype naval reactor design, the RITM-200, which is currently operating using LEU.⁹⁹ This is encouraging, given that this is the reactor design expected to be adopted for the next generation of Russian icebreakers. However, it is important to note that this is based entirely on the ability of the Russian government to complete development of the new design as well as construct a new fleet of icebreakers to replace the current fleet, which is fueled by HEU.

Unfortunately, given Russia's current fiscal difficulties and the size of the icebreaker fleet (seven vessels) that would need to be replaced, it is unlikely the conversion will begin in the near-term. Furthermore, although some have taken it as an encouraging sign that the RITM-200 could also represent a potential option for the next generation of LEU Russian military reactors, the design for the RITM-200, known as a "cassette design" easily accommodates different fuel arrangements with varying enrichment levels, thereby making it possible for use with LEU or HEU. As such, most believe that this does not represent much optimism in terms of converting Russian military reactors to LEU and some actually express pessimism that the next generation of icebreakers may remain HEU fueled.

⁹⁸ One of the best instances of transparency regarding the topic of naval reactor disposition is the 1993 Yablokov Report, (Reistad et al., *Dangerous Unknowns*, 164), which provided the first open information on the dumping of reactors and radioactive waste in the Kara Sea (north of the Kola Peninsula in northwest Russia).

⁹⁹ Egnatuk, "Russia: Icebreaker Ships and Floating Reactors."

The United Kingdom

Not long after the United States launched the *Nautilus*, the United Kingdom embarked on its own naval nuclear propulsion program. The engineering portion of the program was heavily integrated with the U.S. program, and Rolls-Royce and Vickers engineers frequently engaged in exchanges with the Rickover-run U.S. program. In fact, the U.K. program was supplied with technical design information on the Westinghouse S5W plant that was ultimately used in designing the first U.K. nuclear attack submarine, *Dreadnought*.

The U.K. developed its own reactor for the *Valiant*-class SSNs and follow on SSNs of the *Churchill*-class, *Swiftsure*-class, *Trafalgar*-class, and the new *Astute*-class. Rolls Royce and Vickers have also built SSBNs of the *Resolution*-class and current service *Vanguard*-class.

The United Kingdom's current nuclear submarine force consists of four *Trafalgar*-class SSNs and two *Astute*-class SSNs and four *Vanguard*-class SSBNs. All U.K. submarines are reported to be fueled with HEU in 90 percent plus enrichment range, essentially the same fuel used in U.S. naval propulsion reactors.

France

Despite its small size, the French naval nuclear propulsion program is one of the most advanced in the world, owing much of that to the unique manner by which it developed. Specifically, unlike most of the other national programs, which received great deals of technical support either from the U.S. or Soviet programs, the French program developed more independently, with a few exceptions that will be discussed later. Most interestingly, unlike every other national program, the enrichment of French naval nuclear propulsion fuels started low, then increased into the range of HEU, and subsequently returned to lower enrichment levels (~7 percent U-235).¹⁰⁰

Unlike the U.S. and Soviet naval nuclear propulsion programs, the smaller size and limited resources of the French program dictated a slower and more deliberate development. Although the U.S. and Soviet programs, which are often described in terms of several generations, each including numerous classes of submarine and reactor designs, the French program in total currently includes only four submarine classes, and one aircraft carrier class. Therefore, the French program is better described in terms of the enrichment decisions made that unite each group of vessels. As such, the French development should be divided into three phases: (1) The first phase includes the early French prototype designs up through the earliest vessels of the *Redoubtable*-class; (2) The second phase includes the HEU-fueled vessels of the *Redoubtable*-class; and (3) The last phase includes all the contemporary LEU-fueled classes, such as the *Rubis*-class, the *Triomphant*-class, the *Barracuda*-class, and the only French nuclear propulsion aircraft carrier, the *Charles de Gaulle*.

Creating a Nuclear-Powered Force de Frappe

The first decade of French naval nuclear development was without a doubt the most dynamic period in the program, considering the great challenges the program faced as its leaders attempted to reproduce the successes of the U.S. and Soviet programs with much fewer resources. Unlike the British program, which received substantial technical assistance from the United States throughout its development, and the Chinese program, which received a great deal of technical support from the USSR until the Sino-Soviet split in the early 1960s, the French program received comparatively little support. The United States provided a large share of the assistance to the French program, and, while opinions differ on the specific amount,¹⁰¹ most experts agree on the reasons such little support was given. To begin with, given its proud history of submarine development, France did not want to give up the independence of its military program to the U.S. in exchange

¹⁰⁰ Rebecca Ward, "USA and France: Naval Propulsion." In *Nuclear Terrorism and Global Security the Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013), 182.

¹⁰¹ Ward's chapter, "USA and France," 177–195 indicates that the French program may have received significant technical assistance from the United States. However, Andre Gempp, former director of the Coelacanth Project that developed the first French naval nuclear reactor, indicated otherwise that the French only received enriched uranium from the United States.

for technical assistance. This desire ultimately resulted in the first French attempt at naval nuclear propulsion, initially designated Q.244.¹⁰²

The Q.244 was the first French attempt to develop its own indigenous nuclear deterrent, often called the *Force de frappe* during the early years of the French nuclear program. Given the announcement of the world's first nuclear propulsion submarine, the *Nautilus*, in January 1955, France began development of its own nuclear propulsion submarine, designated Q.244, which was intended to eventually serve as the first French ballistic missile submarine. However, unlike the U.S. nuclear program, the French program had not yet developed uranium enrichment capability, meaning that the Q.244 was designed to use natural uranium fuel and heavy water as the moderator. Construction of the vessel progressed substantially before it was determined that the large core size and operating characteristics of a natural uranium reactor made it unsuitable for a submarine, and the Q.244 was set aside.¹⁰³ Despite this setback, given its large size, the Q.244 did go on to play an important role in the development of the French ballistic missile launcher technology as a conventionally powered experimental ballistic missile submarine, on which many of the earliest French ballistic missiles were tested.

Following the failure of the Q.244, some elements within the U.S. military approached the French with a proposal for technical cooperation. Once again, the French were hesitant given their desire to maintain military autonomy. Furthermore, this hesitancy was compounded by the fear within some U.S. sectors that any technical assistance provided to the French would be subsequently be leaked to the Soviets.¹⁰⁴ As a result, at least officially, the only assistance provided to the French was 440 pounds of enriched uranium. However, this assistance came with an important provision: the uranium could only be used for terrestrial purposes.¹⁰⁵ The French agreed with these terms, having no other means to obtain enriched uranium at that point, and, as such, construction began on a land-based prototype designated *Prototype à Terre* (PAT), based in Cadarache, which ultimately became the prototype for the first French submarine, the *Redoubtable*.¹⁰⁶ Interestingly, given the provision placed on the use of the fuel, the decision was made to construct the PAT in a manner to replicate all aspects of a submarine-based reactor, including placement in a large pool of water, very similar to how the *Nautilus* was originally designed. Some opinions diverge on the initial enrichment of this fuel, provided by the United States, and on the enrichment of the subsequent *Redoubtable*-class cores that followed. However, most opinions agree that one or more of the *Redoubtable*-class vessels were initially fueled with LEU.

Despite the efforts of the United States to prevent a French nuclear propulsion submarine, France successfully developed its own HEU production capability in 1967 when it completed the construction of the final two gaseous diffusion plants at the Pierrelatte enrichment facility.¹⁰⁷ Given that the *Redoubtable* was launched in March 1967 and its first criticality was reached in January 1969, this timeline suggests that at least the first vessel of the class was fueled with LEU.¹⁰⁸ However, with a fully operational enrichment capability, the later vessels of the *Redoubtable*-class were certainly fueled with HEU.

Transitioning to HEU

Compared to the dynamic first phase of French naval nuclear development, the second phase acts as more of a transition. Specifically, following the successful development and construction of an indigenous French enrichment capability at Pierrelatte, it is expected that most of remaining *Redoubtable*-class submarines operated with HEU fuel, expected to be enriched to approximately 90 percent U-235. It is known that the last vessel of the class, the *Inflexible* was fueled with HEU, thereby leaving the French Navy entirely LEU-powered in 2008 when *Inflexible* was decommissioned.¹⁰⁹ It is important to

¹⁰² Andre Gempp, "La Mise en Place et le Developpement des Sous-Marins Nucleaires," (speech presented at the Institute of Comparative Strategy, n.d.), available at www.institut-strategie.fr/ihcc_nuc1_Gempp.html.

¹⁰³ Ibid.

¹⁰⁴ Nuclear Submarine "Le Redoutable S 611" *Submarine Museum*, Cherbourg, France, available at <http://sous.marins.musees.free.fr/index.php/france/le-redoutable>.

¹⁰⁵ Andre Gempp, "La Mise en Place et le Developpement des Sous-Marins Nucleaires."

¹⁰⁶ Jean-Luc Delaetter, "The Genesis of Nuclear Propulsion in France," in *1899/1999, A Century of Subsea Construction*, available at www.sous-mama.org/la-genese-de-la-propulsion-nucleaire-en-france-blog-254.html.

¹⁰⁷ "Pierrelatte: Uranium Enrichment Plant" (information pamphlet released the French Atomic Energy Commission (CEA)), available at www.francetnp.fr/IMG/pdf/A_-_Pierrelatte.pdf.

¹⁰⁸ Nuclear Submarine "Le Redoutable S 611."

¹⁰⁹ Ward, "USA and France," 182.

note that despite the efforts France undertook to develop such a capability, it was not long before major portions of the facility were shut down, with the commercial Eurodif facility meeting the production needs in its place. As such, only the highest enrichment line at Pierrelatte remained operational until it too was shutdown in 1996, as will be discussed in greater detail in the next section.

Economic Constraints and a Return to LEU

The third and final phase of the French naval nuclear propulsion development represents a decision unique among all the national nuclear propulsion programs: the decision to voluntarily eschew the use of HEU for its naval reactors by designing all the contemporary naval nuclear vessels using LEU. Specifically, this group includes the submarine *Rubis* and *Triomphant*-classes, the aircraft carrier *Charles du Gaulle*, and the yet-to-be-completed *Barracuda*-class submarines. The specific reasons for pursuing this path are discussed below; however, it is important to note that the tactical, operational, and economic effects of using LEU were considered in this decision, and, as such, a great deal could be learned regarding the advantages and disadvantages of HEU fuel from this decision.

The *Rubis*-class was the first in this phase to incorporate the use of LEU in its CAS-48 reactor, an interesting decision considering that the enrichment plant at Pierrelatte hadn't yet been operating a decade when design of the *Rubis* began. Furthermore, despite the decision to initiate LEU use for the *Rubis* design, the remaining vessels of the *Redoubtable*-class continued to be constructed with HEU. However, with more context, it is possible to understand the decision of the French Navy. To begin with, the founding of Eurodif in 1973 by the nations of Belgium, France, Iran, Italy, and Spain, and subsequent construction of an enrichment plant, completed in 1979, demonstrated to France that the low-enrichment non-military lines at the military enrichment plant at Pierrelatte were no longer necessary. As such, the high costs of operating the plant combined with the relatively low output (~100 kg/yr)¹¹⁰ ultimately made the plant economically unviable. Therefore, given that HEU is not required for any other military uses in France, the decision to return to the use of LEU for naval propulsion reactors eliminated the need for the costly enrichment plant. Additionally, members of the French military have indicated that the French Navy serves a very different role from the U.S. Navy; a role that relies less on the ability to project force worldwide and therefore would require lighter operational tempos and fewer refuelings. As such, it can be seen that in the case of the French naval nuclear propulsion program, the decision to return to the use of LEU was reasonable.

Beyond the rationale behind the decision to return to LEU use, the manner by which the French Navy designed its new LEU-fueled cores deserves particular attention for its successes in overcoming some of the major challenges associated with the use of LEU in naval propulsion reactors. Specifically, the decision to use an integrated reactor design, whereby the steam generator is placed within the reactor pressure vessel, was very successful in minimizing the increase in core size for an LEU core, and is replicated in almost all contemporary small reactors. Furthermore, the use of caramel fuel, developed for research reactor design, provided the possibility for greater fuel density, thereby also assisting to minimize the increased size of an LEU-fueled core. Together, these design improvements allowed the *Rubis* CAS-48 reactor design to operate with an average of 7 percent enriched fuel for 7–10 years between refuelings.¹¹¹ Following this initial success, the CAS-48 reactor design was successfully scaled up to power the larger *Triomphant* and *Charles de Gaulle*-classes, and this larger reactor, designated K-15, has most recently been modified to power the *Barracuda*-class submarine, using fuel enriched to ~5 percent U-235 and achieving much greater core lifetimes.

¹¹⁰ Ward, "USA and France," 189.

¹¹¹ Ward, "USA and France," 188.

China

Although the Peoples' Liberation Army Navy (PLAN)¹¹² submarine force is now probably the third or fourth largest in the world,¹¹³ there is little public information available about the force. Much less is known about the Chinese nuclear propulsion program than about those of the United States and the Russian Federation.

The PLAN began its nuclear submarine program in the late 1950s. From its inception, the overall program has been known as the 09 Program and therefore the various PLAN submarine designs are commonly known by the program number plus a digit signifying the class, such as 091, the *Han*-attack class SSN, 092 the *Xia*-class SSBN, etc. They are also known by their pennant or hull numbers and their assigned NATO class names.¹¹⁴

Project 09 started in 1958 at the Chinese Institute of Atomic Energy at the beginning of the Great Leap Forward (1958–1961). Project 09's initial task was to understand what would be involved in a nuclear submarine program. It began its work with research by Chinese engineers and scientists into the U.S. and Soviet programs and it focused on PWR designs.¹¹⁵

The PLAN nuclear propulsion program suffered a number of technical and political setbacks. The Sino-Soviet rift forced the Chinese to create virtually each and every element of the nuclear propulsion program and to design the submarines based on what would have been considered extremely primitive methods. For example, early in the program all reactor calculations had to be performed by a team using hand calculators because computers were not available. Essential calculations sometimes took months.¹¹⁶

In addition to the general political winds, domestic political battles for control of the program led to intermittent starts and stops, suspensions, and direction changes. In addition to the battles between political figures and various institutes competing for influence, the overall program and the personnel were subject to the vagaries of not only the Great Leap Forward, but to the Cultural Revolution (1966–1976), which saw many of the individual engineers and scientists persecuted. In the early 1960s it appeared that Project 09 might be cancelled, but it continued at a reduced pace before resuming a more robust program in 1965.¹¹⁷

Chinese physicists and engineers studied the propulsion reactors used in the German commercial vessel *Otto Hahn* and the Soviet icebreaker *Lenin*. The *Otto Hahn* design had the backing of Qinghua Institute design team, but the *Lenin* design received PLAN and ministry backing and prevailed in 1965.¹¹⁸

Project 09 completed the construction of a land-based plant in 1970 and it began testing in late spring.¹¹⁹ Meanwhile construction of the SSN 091 (*Han*) began in 1968. The lead hull underwent sea trials from 1972–1974, entering service in 1974. During trials 091 experienced a number of problems, including reports of overexposure to crew members.¹²⁰ The reactor for the 091 was rated at 48 MWt, delivering 12,000 horsepower for a speed of 26 knots with an efficiency of ~ 18 percent.¹²¹

¹¹² Referred to herein as PLAN or Navy.

¹¹³ North Korea has the world's largest submarine force, all of which are conventionally powered submarines. The United States has largest nuclear submarine force (all U.S. submarines use nuclear propulsion) followed by the Russian Federation. Due to its penchant for operating redundant cores, the Russian Federation has about the same number of cores at sea as the United States. China has the third largest overall submarine force (larger than that of the Russian Federation), and has the third or fourth largest nuclear submarine force similar in number to France and the United Kingdom. Although growing, it is unclear which Chinese units are actually operational.

¹¹⁴ The NATO name for the 0901 is by the lead vessel *Han*, with the five *Han*-class SSNs referred to by their pennant or hull numbers as 401 through 405.

¹¹⁵ John W. Lewis and Xue Litai, "China's Strategic Seapower: The Politics of Force Modernization in the Nuclear Age" (Stanford, CA: Stanford University Press, 1994), 23.

¹¹⁶ *Ibid.*, 27.

¹¹⁷ *Ibid.*, 27–30.

¹¹⁸ *Ibid.*, 30–32.

¹¹⁹ *Ibid.*, 45.

¹²⁰ *Ibid.*, 109–110.

¹²¹ Lewis and Litai, "China's Strategic Seapower," 115. Note that other reports indicate the power level of the Han reactor is 90 MW.

The next submarine designed and built by the PLAN was the 092 SSBN. Development of the 092 started in 1967 with the missile and the submarine development running concurrently. Construction of the 092 started in 1971 at the same shipyard where the 091 was built. It was launched in 1981; the long construction period resulted in part from ongoing political instability. The reactor for the 092 was a scaled up version of the 091 reactor with a thermal power of 58 MWt developing 14,400 horsepower that gave the 092 a speed of 22 knots with the same 18 percent efficiency.¹²²

The PLAN currently has about 15 nuclear submarines in operation, under construction, or planned. Six of these are SSBNs and nine are SSNs. The original type 091 *Han*-class SSNs consisted of four boats, three of which are reported to still be operational. The follow-on type 092 *Xia*-class SSBN may have originally consisted of two units, one of which may have been lost in an accident leaving one currently in operation. There are reportedly six types 093 *Shang*-class SSNs. Two are operational and there are reports that four more are in various stages of construction. The type 094 *Jin*-class SSBN consists of five units. Three are reported as operational and two planned or in construction. One type 094 SSNs reportedly was launched in 2012.¹²³

To date all Chinese nuclear submarines are believed to be LEU fueled.

To date all Chinese nuclear submarines are believed to be LEU fueled. However, although the use of LEU in earlier designs seems to be well established, there does not appear to be any definitive source that shows that newer designs are continuing to use LEU cores. HEU technology is certainly well within China's technical abilities and available HEU stocks. Should the Chinese perceive it to be in their interest to use HEU cores, they would undoubtedly do so.

The disposition of the Chinese nuclear submarines has historically been that most have been assigned to the North Fleet at Quintao (near the Huludao shipyards where the 091, 092, and 094-classes were built), but the construction of new bases on Hainan Island seems to indicate that units, particularly SSBNs, are or will be shifted to the South Fleet.

Although the PLAN does not have any nuclear-powered surface vessels, China now is testing its first aircraft carrier (a unit obtained from the Ukraine and refitted in China) and can be expected to develop its own aircraft carrier designs. Undoubtedly Chinese designers will consider the option of nuclear power for domestically built Chinese carriers in order to make them less dependent on refueling and to increase their aviation fuel capacity. As a final comment it should be noted that from time to time there are statements about leapfrog advances in submarine reactor technology by China.¹²⁴ Most thoughtful commentators give little credibility to reports that, for example, newer Chinese submarines are using pebble bed reactors or high-temperature gas cooled reactors for propulsion.

India

The Indian nuclear program, both military and civilian, has had a tense history because India is neither a member of the NPT nor a member of the CTBT.¹²⁵ This has limited the amount of technology and material that India has been able to import and has stunted some of their development in the field. As of October 2014, India has 14 active submarines, and one undergoing sea trials. Of these, two are nuclear powered. The first nuclear submarine is a Russian *Akula* class on lease for ten years since 2012, and the second is an indigenous design, the *Arihant* class, which is currently undergoing sea trials and expected to be commissioned by early 2016.¹²⁶

India is interested in increasing its naval strength for multiple political reasons. Aside from the obvious pressure placed on Pakistan's submarine fleet, China's increased presence in the Indian Ocean and South China Sea has India worried about

¹²² Ibid., 115–117.

¹²³ From *Jane's Fighting Ships* (2014–2015), 128–130. See Appendix A, Table A-5. Chinese Naval Reactors.

¹²⁴ See, for example, discussion in Shing-you (Sandra) Fong, "China: Reactors and Nuclear Propulsion," in *Nuclear Terrorism and Global Security the Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013), 104.

¹²⁵ "Country Profiles: India," Nuclear Threat Initiative, available at www.nti.org/country-profiles/india/.

¹²⁶ "Jane's World Navies: India," *IHS Jane's Fighting Ships* 2013–2014, 116th ed., ed. Commodore Stephen Saunders (Englewood, CO: IHS Global Inc., 2013), 2, 5, 26; Ajay Banerjee, "Satisfied with nuclear sub Arihant trials: Navy Chief," *The Tribune India*, April 30, 2015, available at <http://www.tribuneindia.com/news/satisfied-with-nuclear-sub-arihant-trials-navy-chief/74351.html>.

Chinese maritime influence.¹²⁷ Also, India's international status as a non-signatory state to the NPT led to several political tensions and for India to suffer a shortage of uranium fuel.¹²⁸ In 2005 India signed an initiative with the United States that would allow India to conduct trade with nuclear technology and materials under specific conditions. After negotiating a limited safeguards agreement with the IAEA in 2008, the NSG lifted the ban on India, allowing nuclear trade with members of the NSG. A month later India signed a bilateral agreement for nuclear trade with the United States and as of September 2014, India has signed similar agreements for nuclear material with seven other countries.¹²⁹

Development of the Arihant Class and the Russian Leases

The *Arihant* class submarine is an indigenously built nuclear submarine capable of carrying 12 vertically launched nuclear missiles.¹³⁰ This boat signifies and shows the shift of the Indian Navy toward a more aggressive and competitive strategy as a response to Chinese pressure in the Indian Ocean. The Indian Navy commissioned its first nuclear-powered attack submarine to use the boat's range and endurance to increase the reach of the Navy in the Indian Ocean.¹³¹ This sea denial role is the largest incentive for the development of Indian nuclear submarines.¹³²

The *Arihant* is reported to have cost approximately USD \$2.9 billion and the project was launched in 2009. An 85 MW PWR powers it, which in turn drives one or two 35 MW steam turbines. It is reported to have 13 fuel assemblies, each containing 348 fuel rods, at an enrichment of 40 percent. The reactor went critical in August 2013.¹³³ The Bhabha Atomic Research Center (BARC) at Kalpakkam designed this PWR, and operated a 20 MW prototype of the submarine reactor since 2003 for several years before building the 85 MW PWR.¹³⁴

The Indian Navy currently operates a Russian *Akula-II* (Project 791) nuclear attack submarine, the *INS Chakra*, that was leased for ten years starting in April 2012.¹³⁵ This SSN has a 190 MWt VM-5/OK-659B PWR, a 32 MWe steam turbine, and two 2 MWe turbogenerators.¹³⁶ Following the commissioning ceremony of the *INS Chakra*, the Indian government and navy announced their interest in leasing a second nuclear-powered submarine from Russia. The proposed lease was for USD \$1.5 billion, and the design was supposed to include elements of the newer *Yasen* class SSGN.¹³⁷ There have been no updates on this.

Challenges and Setbacks

The development of a conventional submarine fleet by the Indian Navy has been tumultuous and challenging. Poor safety, budget management, and several accidents causing several fatalities have been prevalent, especially in the last few years. Of these accidents and delays, the nuclear submarines have not been exempt.

The *INS Chakra's* delivery was actually delayed by approximately three years for two reasons. The first delay was caused by differences in the cost of the lease. Originally the lease was signed for USD \$700 million, but was later increased to USD \$920 million. This caused some dissent and delays in the delivery of the submarine. The second delay was caused by an on-board accident in the pre-delivery trials. This accident occurred during the sea trials of 2008 in the Sea of Japan.¹³⁸

¹²⁷ Ibid.

¹²⁸ "Nuclear Power in India," World Nuclear Association, available at www.world-nuclear.org/info/Country-Profiles/Countries-G-N/India/.

¹²⁹ "Country Profiles: India," Nuclear Threat Initiative, available at www.nti.org/country-profiles/india/.

¹³⁰ Ibid.

¹³¹ "Jane's World Navies: India," 2, 5, 26.

¹³² Ibid.

¹³³ T.S. Subramanian, "In a First for India, Nuclear Sub's Reactor Activated," *The Hindu*, August 11, 2013, available at <http://www.thehindu.com/news/national/in-a-first-for-india-nuclear-subs-reactor-activated/article5009164.ece>.

¹³⁴ "Nuclear Power in India," World Nuclear Association, available at www.world-nuclear.org/info/Country-Profiles/Countries-G-N/India/.

¹³⁵ "Jane's World Navies: India."

¹³⁶ "Nuclear Powered Ships," World Nuclear Association, available at www.world-nuclear.org/info/Non-Power-Nuclear-Applications/Transport/Nuclear-Powered-Ships/.

¹³⁷ "Jane's World Navies: India."

¹³⁸ Ibid.

The development of the second *Arihant* class submarine has also been affected with accidents. In 2011, as the *Arihant* was undergoing criticality tests, an accident occurred when the valves of the dry dock gate malfunctioned as the *Arihant* was attempting to dock,¹³⁹ and killed four naval personnel. In March 2014, a civilian subcontractor was killed, during the testing of the *Arihant* class submarine, *Aridaman*, in Vishakhapatnam.¹⁴⁰

Future of Indian Nuclear Fleet

The Indian Navy has many political and strategic motivations for pursuing a strong nuclear submarine fleet. Due to previous constraints on the import of nuclear materials and technology, the Indian Navy is just now starting to develop its first indigenous nuclear submarines. These submarines, despite some of the challenges and setbacks, are going to play larger roles in the Indian Ocean and South China Sea theaters as both China and India try to increase their influence in these regions.¹⁴¹ India possesses the capability to enrich uranium indigenously, and has thus developed an HEU submarine that operates at 40 percent enrichment. Although still in its infancy, the Indian Navy is only going to expand its fleet of nuclear submarines; whether it will keep with the HEU submarines in its next generation or pursue LEU cores is yet to be determined.

In addition to submarines, India is reported to be considering expanding its aircraft carrier capability. It currently operates one aircraft carrier, which is conventionally powered. If it builds more carriers, it will probably consider whether they should be nuclear-powered. There are some obvious incentives for India to use nuclear power if it builds more aircraft carriers, but it is unclear whether India would pursue that path.

Argentina and Brazil

Argentina and Brazil are two nuclear South American states that have fought for political power, influence, and hegemony in the continent for decades. They are both NPT members and parties to the Latin America nuclear-weapon-free zone as established by the Treaty of Tlatelolco (1967), and members of the NSG. Neither country has signed the IAEA Additional Protocol¹⁴² and currently both countries are looking for bilateral nuclear cooperation agreements. Brazil has stated that it wants to have an operating nuclear submarine by 2023.¹⁴³ Argentina has agreed to collaborate with Brazil in this and endeavor and has also shown interest in developing nuclear propulsion for its own navy.¹⁴⁴ A brief history of each country's nuclear naval reactor development, both unilateral and bilateral, with notable reactor designs and submarine fleet data, is included below.

Argentina

As of January 2014, the Argentinian Navy (Armada de la República Argentina) submarine force consisted of two TR-1700 diesel-electric submarines and one Type 209 diesel-electric submarine. Argentina has shown interest in developing nuclear propulsion for its navy intermittently and in 2008 it announced and discussed the possibility of cooperation and development in a joint project with Brazil. Brazil announced in 2009 its plan to build a nuclear submarine by 2020.

In June 2010 Nilda Garré, then defense minister, revealed Argentinian plans to develop a nuclear submarine by 2015.¹⁴⁵ The Argentinian Ministry of Defense later announced that such a program would take at a minimum 15 years to develop, and to date there have been no advances in the development of the program. However, although perhaps not directly related to

¹³⁹ Suman Sharma, "4 Killed in India Nuclear Submarine Accident," New Delhi Agency DNA, May 19, 2011, available at www.dnaindia.com/india/report-4-killed-in-india-nuclear-submarine-accident-1545013.

¹⁴⁰ "Jane's World Navies: India."

¹⁴¹ See "Rattled by Chinese Submarines, India Joins Other Nations in Rebuilding Fleet," Naval Open Source INTelligence, December 10, 2014, available at <http://nosint.blogspot.com/2014/12/rattled-by-chinese-submarines-india.html?spref=tw&m=1>.

¹⁴² "Country Profiles: Brazil," Nuclear Threat Initiative, available at www.nti.org/country-profiles/brazil/; "Country Profiles: Argentina," Nuclear Threat Initiative, available at www.nti.org/country-profiles/argentina/.

¹⁴³ "Country Profiles: Brazil," Nuclear Threat Initiative.

¹⁴⁴ Ibid.

¹⁴⁵ "Jane's World Navies: Argentina," *IHS Jane's Fighting Ships* (2014), 2, 9, 12.

its submarine program Argentina's National Atomic Energy Commission (CNEA) in February 2014, began construction on its small modular reactor (SMR), the 27 MWe CAREM (Central Argentina de Elementos Modulares). This reactor has a 100 MWt output and is fueled by 3.4 percent enriched fuel with burnable poisons and is being developed and constructed by the state-run company INVAP.¹⁴⁶ Some sources cite the statement by Nilda Garré and indicate that this reactor could have military applications, and could be the starting point for the Argentinian nuclear propulsion reactors.¹⁴⁷

Brazil

Currently, the Brazilian Navy (Marinha do Brasil) submarine force consists of five Type 209 diesel-electric submarines.¹⁴⁸ Brazil has shown interest in nuclear submarine technology since 1979. Its commitment to expanding the fleet with nuclear submarines solidified in May 2004 when it announced a budget allocation of USD \$7.8 million for developing and completing a land-based prototype reactor.¹⁴⁹ By September 2005, Brazil had indigenously completed the 2131-R, a 50 MW land-based prototype reactor for eventual installation in a nuclear-powered attack submarine.¹⁵⁰ This reactor is reported to be fueled with 18–19 percent enriched uranium that will be enriched by Brazilian company Industrias Nucleares do Brasil and will be fitted in a 9.8 meter hull with a PWR loop-type system.¹⁵¹ The Brazilian Navy in collaboration with Brazilian company Nuclebras Equipamentos Pesados SA (NUCLEP) developed the reactor.¹⁵² In 2009 Brazil announced a joint venture with France for developing the non-nuclear components of its SN-BR (Submarino com Propulsão Nuclear Brasileiro) nuclear-powered attack submarines. July 6, 2012, officially began the development of the first SN-BR with preliminary designs showing a 96 meter hull, 4,000 tonne submerged displacement, and a 24 kiloton capability. The Brazilian Navy expects to have it operational on sea trials by 2023, and fully operational by 2025 with the second SN-BR operational by 2030, and four total by 2047.¹⁵³

In recent years Brazil and Argentina have made great strides in developing nuclear technology.

Proliferation Concerns

In recent years Brazil and Argentina have made great strides in developing nuclear technology. The international community has, however, expressed some concerns about the possible diversion of material that could lead to the covert development of nuclear weapons and with the difficulties these programs would pose to effective IAEA monitoring.¹⁵⁴

Other States' Naval Nuclear Propulsion Programs

North Korea

As noted above, North Korea is reported to have the world's largest submarine force, all of which are conventionally powered, with many of its force being considered "midget submarines." However, there is little indication that North Korea currently has the ability to build its own nuclear-powered submarines. North Korea might, however, be interested in an India-like leasing operation if either China or Russia were willing (thought to be unlikely) to lease them a vessel.

¹⁴⁶ "Nuclear Power in Argentina," World Nuclear Association, available at www.world-nuclear.org/information-library/country-profiles/countries-a-f/argentina.aspx; "Jane's Sentinel Security Assessment—South America: Defence Production R&D, Argentina." IHS Jane's Fighting Ships (2014), 1.

¹⁴⁷ "Construction Start of Small Modular Reactor in Argentina," World Nuclear Industry Status Report (February 12, 2014), available at www.worldnuclearreport.org/Construction-Start-of-Small.html.

¹⁴⁸ "Jane's World Navies: Brazil," IHS Jane's Fighting Ships (2014), 2, 21.

¹⁴⁹ "Brazil Accelerates Reactor Work for Nuclear Submarine Program," *Sea Power* 47, no. 7 (2004): 44.

¹⁵⁰ "Brazil's PROSUB Infrastructure Takes Shape," *Jane's Defence Weekly* (2013); "Jane's Sentinel Security Assessment—South America: Defence Production R&D, Brazil." IHS Jane's Fighting Ships (2013).

¹⁵¹ Togzhan Kassenova, *Brazil's Nuclear Kaleidoscope: An Evolving Identity Report* (Washington DC: Carnegie Endowment for International Peace, 2014).

¹⁵² Tim Fish, "Steel Cutting Begins for First Brazilian Scorpene," *Jane's Defence Weekly* (2010), 1.

¹⁵³ "Jane's Sentinel Security Assessment—South America: Procurement, Brazil." IHS Jane's Fighting Ships (2014), 14–15.

¹⁵⁴ Togzhan Kassenova, *Brazil's Nuclear Kaleidoscope*, 38–39; Liz Palmer and Gary Milhollin, "Brazil's Nuclear Puzzle," *Science* 306, no. 5696 (2004): 617.

Japan and South Korea

Japan, as noted above, previously built a commercial LEU-powered vessel. Both Japan and South Korea are capable of building nuclear-powered submarines or surface vessels should an arms race breakout in Asia.

Pakistan

While Pakistan might have the ability to build nuclear-powered submarines to challenge India, its nuclear infrastructure and economic base make it unlikely that Pakistan will venture into nuclear naval propulsion in the near future.

Iran

Iran deserves special mention in this area due to its problems with the IAEA/NPT and its assertion that it might undertake the development of submarine reactors. Iran's statements have raised concerns about the possibility that Iran could produce HEU under the guise of naval fuel, but would actually use the material for nuclear weapons. Most observers feel that the Iranian statements on this issue do not represent a serious commitment to a naval nuclear propulsion program. However, Iran's statements do demonstrate the need for developing a means to safeguard nuclear material for naval propulsion reactors in NNWS.

Germany, Canada, and Australia

Although **Germany** has quite a history of submarine development and has developed its own nuclear-powered commercial vessel, it is unlikely that Germany sees it in its strategic military plan to develop naval nuclear propulsion. Germany appears content to focus its efforts and resources toward becoming a leader in AIP technology for submarines. AIP allows non-nuclear submarines to operate quite silently submerged for long periods. **Canada**, like Germany, has the capability to develop nuclear submarines (and once intended to develop a nuclear submarine force by purchasing nuclear submarines or nuclear submarine technical assistance from France or the United Kingdom) but no longer sees it in its strategic interest to build nuclear-powered vessels. **Australia** is also capable of producing nuclear-powered submarines, but has not shown significant interest in doing so.

Current Status of LEU Use in Naval Reactors

Of the six countries currently using naval propulsion reactors, only France and China use LEU fueled reactors. Absent some great incentive to change, it is doubtful that the remaining four—the United States, the United Kingdom, the Russian Federation, and India—would be motivated to change from HEU fueled reactors. The Brazilian program, assisted by France and appears to be modeled on French reactor designs, is estimated to be an LEU based program.¹⁵⁵

Whether or not the navies using HEU could be persuaded to shift to LEU use is somewhat of a country-by-country consideration. For some countries the economics of the shift to LEU could be a driving factor, as it was for France. However, other countries may come to totally different economic conclusions. For the United States and presumably by the United Kingdom, whose nuclear propulsion program tends to track that in the United States, the economics of the situation might argue for continuing to use HEU in order to avoid research and development (R&D) costs for LEU fuels, reactors, and potentially new vessel designs to accommodate the use of LEU. This analysis might be valid for at least as long as HEU stocks remain available for submarine use and no new enrichment facilities are required.

Another question is whether those navies that currently use LEU might be convinced to shift to HEU use. Certainly this does not appear to be the case for France, but it is certainly possible that China might shift to HEU fueled reactors, particularly if it was to become convinced that this would offer its program an operational advantage.

¹⁵⁵ Gregg Thielman with Wyatt Hoffman, “Submarine Nuclear Reactors: A Worsening Proliferation Challenge” *Threat Assessment Brief* (The Arms Control Association, July 26, 2012). The article contains a photograph of a cutaway scale model of the future Brazilian nuclear-powered submarine at a trade fair in Rio de Janeiro in April 2011 on page 3. The photo depicts what appears to be a reactor with an integrated steam generator similar to that used in the French *Rubis*-class.

Nuclear Options for Future Naval Vessels

When a country considers whether or not to use nuclear propulsion for a specific type of vessel, there are a number of factors that go into the determination. Ignoring internal politics and issues of international prestige, and factors that may affect some smaller programs, the basic considerations are whether nuclear power provides an operational military advantage and whether that advantage is economically justifiable.

Once a decision has been made to embark on a nuclear power program, the decision as to whether to use LEU or HEU fuel often appear to have been based on one of four considerations: (1) the need to respond to an operational need or military expediency; (2) economic issues; (3) the example provided by the technology of another state's program or access to another state's technology; or (4) perhaps most significant to some states like the U.S., an evaluation that HEU offers important advantages in size and weight coupled with less need for refueling in comparison to LEU.

Although there are myriad factors that go into these considerations, the ability of the nuclear naval propulsion reactor to provide uninterrupted power over long periods of time is its chief operational advantage. Historically this has been the driving function in the development of nuclear-powered submarines, because until quite recently non-nuclear-powered submarines could not operate submerged for lengthy periods and could not generate submerged speeds comparable to nuclear-powered submarines. New submarine advances, particularly the AIP technology of Germany, have led to developing conventionally powered submarines that may be operationally competitive with, or even have advantages over, nuclear-powered submarines, such as quieter operational abilities. Although these new AIP submarines may be attractive to navies without nuclear-powered submarines or even to navies that have nuclear submarines to undertake specific operations exploiting their advantages and cost savings, it seems highly doubtful that the major nuclear submarine fleets of the United States, the United Kingdom, the Russian Federation, and China would totally forsake nuclear power for these newer conventional technologies.

At this point in time, and for the foreseeable future, it does not appear that the number of nuclear-powered vessels will grow significantly.

Similarly, it is doubtful that the United States and France would forsake nuclear-powered aircraft carriers for conventionally powered aircraft carriers. In addition to the essentially infinite range of the nuclear-powered carriers, not needing to carry large amounts of conventional fuel allows nuclear-powered carriers to carry more aviation fuel, a distinct operational advantage. Whether countries such as China and India with emerging aircraft carrier desires will opt for nuclear power for these vessels is an open issue. Beyond that, whether they would opt for HEU fueled reactors is questionable. In the case of India, it might be more likely that they might use a scaling up of their HEU fueled submarine reactor for an aircraft carrier. China would, at this point in time, appear unlikely to exercise an HEU option when its submarine experience has been with LEU fueled reactors.

During the Cold War both the United States and the Soviet Union/Russian Federation operated smaller surface combatants with HEU fueled reactors. For the United States, it was envisioned that complete carrier battle groups would consist of nuclear-powered vessels that use HEU. However, this proved economically impractical and all of the nuclear-powered cruisers have been retired. Absent an extreme change in the threat level on the world stage it appears unlikely that either the United States or Russian Federation would consider new non-carrier nuclear-powered warships.

In summary, at this point in time, and for the foreseeable future, it does not appear that the number of nuclear-powered vessels will grow significantly; conversely, it does not appear that the number will be reduced. However, as the Chinese and Indian nuclear-powered fleets grow, it may drive the United States and/or Russian Federation to expand their nuclear fleets. China and India's nuclear efforts also have the potential to trigger regional arms races in the Indian Ocean and Western Pacific.

Whether countries like Pakistan, South Korea, and Japan would feel threatened enough by Chinese and Indian nuclear efforts to embark on their own nuclear-powered submarines and/or surface warship construction is an open issue. Japan and South Korea certainly have the industrial base and nuclear capability to build such vessels. However, South Korea's major concern is the very local North Korean threat, which does not seem to require any of the potential advantages of nuclear-powered vessels. Japan, now faced with conflicts with the China over territorial claims in the South China Sea may be a more likely candidate for developing nuclear submarines. Pakistan does not have the industrial base to support significant nuclear submarine construction but may for reasons of parity with India be interested in leasing, or perhaps purchasing, nuclear submarines from China.

The U.S. Navy's Position on LEU Use in Naval Reactors

The question of LEU use by the U. S. Navy has been addressed by Congress several times since the end of the Cold War. In 1995, the U.S. Navy responded to direction by Congress to submit a report on the use of LEU fuel for naval reactors. The resulting 40-page “Report on Use of Low Enriched Uranium in Naval Propulsion June, 1995,”¹⁵⁶ contained four main analytical sections: (1) Technical Considerations; (2) Environmental Considerations; (3) Economic Considerations; and (4) Proliferation Considerations.¹⁵⁷

The 1995 Report has been analyzed and referred to by a number of commentators and the general consensus is that in 1995 the Navy was overwhelmingly opposed to the use of LEU for naval reactors.¹⁵⁸ It is impossible to find any support for the use of LEU in the Navy’s 1995 concluding statement that “[t]he 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.”¹⁵⁹ Although some of the Navy’s arguments supporting its conclusions are arguably slanted or skewed¹⁶⁰ and the analysis contained in the 1995 Report is not very transparent, it is difficult to argue for or against the report’s overall conclusions when many of the assumptions and data are simply not included in the report.

In response to Congress’ direction to update the 1995 Report, the Office of Naval Reactors in the Department of Energy¹⁶¹ prepared the “Report on Low Enriched Uranium for Naval Reactor Cores—Report to Congress January 2014.”¹⁶² The 2014 Report is considerably shorter than the 1995 Report, and although it is tempting after an initial reading to criticize the 2014 Report as being superficial and nonresponsive to the Congressional direction, to some extent such criticisms may be unfair.

The 2014 Report’s status as an update might explain some of the brevity of the 2014 Report, but it is difficult to read the 2014 Report without wondering what the Navy actually did to prepare the report. As the 2014 Report itself states, Congress requested the Navy to report

any changes in the estimated cost of fabricating HEU and LEU life-of-the-ship cores, the ability to refuel nuclear-propelled submarines and ships without extending the duration or frequency of major overhauls, and the overall health of the technology base that may be required to utilize LEU in Naval nuclear propulsion systems.¹⁶³

¹⁵⁶ Director, Naval Nuclear Propulsion, “Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion June, 1995” (1995), available at fissilematerials.org/library/onnp95.pdf (hereinafter 1995 Report).

¹⁵⁷ Ibid.

¹⁵⁸ See, for example, Chunyan Ma and Frank von Hippel, “Ending the Production of Highly Enriched Uranium for Naval Reactors,” *The Nonproliferation Ration Review* (Spring 2001), available at <http://cns.miis.edu/npr/pdfs/81mahip.pdf>.

¹⁵⁹ 1995 Report, Executive Summary, 1.

¹⁶⁰ As an example of the potential slanting, consider the fact that the 1995 Report makes no mention of the successful prior use of LEU fuel in civilian commercial nuclear powered surface ships such as the *NS Savannah* operated in the United States in the 1960s and 1970s, Germany’s *Otto Hahn*, Japan’s *Mutsu*, and the Soviet/Russian icebreaker *Lenin*, which was initially LEU powered. More glaringly, there is no discussion of the French *Rubis* class submarines, originally built in the 1970s with LEU cores.

¹⁶¹ Although it is led by active-duty naval personnel, management of the Naval Nuclear Propulsion Program (NNPP) has historically been under the Department of Energy and its predecessors (AEC and ERDA) and not the Department of Defense.

¹⁶² 2014 Report.

¹⁶³ Ibid.

This Congressional direction was almost totally ignored in the 2014 Report. Not only does the 2014 Report fail to update the 1995 Report, except for being mentioned in the repetition of the legislative language, the 1995 Report is remarkably not mentioned or referred to anywhere in the 2014 Report. Despite this, in many instances the language of the 1995 Report appears to be either directly copied from the 1995 Report without attribution or subtly reworded, again without attribution in the 2014 Report.

In addition to its failure to respond to all the topics requested by Congress, the 2014 Report is disappointing in a number of other aspects.¹⁶⁴ Although its brevity and lack of attribution to the 1995 Report make it difficult to compare the reports, a comparison is essential to understanding the Navy's current position on the use of LEU fuel for future naval propulsion reactors.

At least one commentator, Dr. Frank von Hippel of Princeton, has expressed some optimism that the 2014 Report reflects a change in the Navy's negative assessment and attitude regarding the use of LEU to replace HEU in naval propulsion reactors.¹⁶⁵ Others have expressed a less optimistic view.¹⁶⁶ Understanding the initial 1995 Report and then comparing the language in the 2014 Report is therefore essential in determining the Navy's current position on LEU use.

In 1995, the Navy's analysis considered two tracks or options. The first option was replacing HEU cores in submarines and aircraft carriers¹⁶⁷ with LEU cores that would fit in the existing design space (i.e., the same size reactor compartment, hull size, etc.)—an option that the Navy considered technically feasible. However, the LEU cores that could fit in the design space would not have a service life comparable to HEU cores and the submarines and aircraft carriers would need a number of core replacements (refuelings) during the life of each vessel. The second option was developing larger LEU cores that would last for the design life of the vessel, a “life-of-the-ship” option that would correspond to what in 1995 were the future planned lives for submarines and aircraft carriers. The larger life-of-the-ship LEU reactor cores would require more space and the resulting larger compartments, increased weight of shielding, etc. factors would cause most ships to increase in size and require new vessel designs.¹⁶⁸

Both of the LEU replacement options would have had one-time costs for developing new LEU core designs. However, the one-time design costs for the life-of-the-ship option were projected to be much greater because of the need to redesign the vessels. In addition, there were concerns that the increased vessel size would have led to a decrease in operational capabilities and performance and perhaps reliability and safety. By comparison, the multiple refueling option that could stay within current design space probably had little effect on performance, but it had very high costs spread over the life of the ship. Details of the analysis, cost, etc. are considered further below.

¹⁶⁴ For example, in addition to failing to update cost estimates from the 1995 Report, etc., the 2014 Report is strikingly silent on the use of LEU by other navies, particularly the French submarine fleet's total shift to LEU.

¹⁶⁵ Frank von Hippel, “United States Opens to the Possibility of Using LEU in Its Future Naval Reactors,” *International Panel on Fissile Materials (IPFM) Blog*, available at http://fissilematerials.org/blog/2014/04/united_states_opens_to_th.html. Dr. von Hippel has a long history of involvement in studying the minimization of the use of HEU and it would not be inappropriate to refer to him as a “leading light” on such issues whose views should not be taken lightly.

¹⁶⁶ Thomas Gray, “Revisiting the Conversion of U.S. Naval Reactors to Low Enriched Uranium” *Proceedings from the 55th Annual Meeting for the Institute for Nuclear Material Management*. (Deerfield, IL: Institute of Nuclear Material Management, 2014), available at www.inmm.org/source/proceedings/files/2014/a218_1.pdf.

¹⁶⁷ Although the Navy at one time had other nuclear-powered surface combatants (e.g., nuclear-powered guided missile cruisers) and was considering a more widespread use of nuclear power for other types of vessels, the production plans for other vessels were dropped, the cruisers were scrapped, and by 1995 only submarines and aircraft carriers remained in the U.S. nuclear fleet.

¹⁶⁸ Attack submarines (SSNs) were forecast to require increased hull diameters (but shorter overall length), whereas aircraft carriers were forecast to lengthen. However, the 1995 Report states that SSBNs could accommodate larger LEU cores in their current hull space.

Table 1 below, from the 1995 Report, compares the two LEU replacement options.

Table 1. Cost Comparison of Two Options for LEU Replacement of HEU in U.S. Navy Ships

	LEU Cores in Existing Design Ships	LEU Life-of-the-Ship Cores in Redesigned Ships
One-Time Costs	\$0.9 Billion	\$5.5 Billion
Increase in Annual Cost to Build and Maintain Baseline Force	\$1.77 Billion	\$1.1 Billion
Effective Reduction in Baseline Force/Annualized Replacement Cost	5 SSN/SSBNs, 1 CVN/ \$0.8 Billion	None/None
Total Increased Annual Cost	\$2.6 Billion	\$1.1 Billion

Source: Office of Naval Reactors, “Report on Low Enriched Uranium for Naval Reactor Cores: Report to Congress January 2014” (Washington, DC: 2014).

Although the budget numbers in Table 1 are from 1995 and would require updating, which was not done in the 2014 Report, the qualitative comparisons of the ratios would arguably remain about the same even when the inflation of costs is taken into account. Table 1 also illustrates one of the chief arguments that the Navy uses against the use of LEU cores. Use of the shorter-lived LEU cores that fit within the design space requires refueling (several during the life of the vessel) demands that ships be out of service for periods on the order of a year to a year-and-a-half for refueling. This leads to what is described in the table as “Effective Reduction in Baseline Force,” a figure that represents the extra submarines and aircraft carriers that would be required to maintain the same force at sea if the submarines and aircraft carriers did not require refueling (i.e., that they had life-of-the-ship LEU or HEU cores).

It should be noted that the U.S. program is the only one that appears to be currently using or contemplating life-of-the-ship cores. Other national programs have not indicated a strong interest in the concept, although they are undoubtedly aware that the United States is currently building the Virginia-class with life-of-the-ship core designed to last 33+ years. Although the stated rationale for these long-lived cores is to provide greater operational flexibility without the need for more frequent refueling, certainly the economic pressures the Navy faces in budget battles make the increased costs associated with the refuelings extremely undesirable. Conversely, the savings in betting on the viability of life-of-the-ship cores has played a role in the U.S. development of the longer core life concept. Other navies may either not feel they have mastered the technology needed for life-of-the-ship cores, or they may be satisfied with the status quo of their designs and to be unwilling to leap into an uncertain extended life fuel technology.

Although the Navy’s overall conclusion in 1995 that neither LEU option was palatable, it did express a preference between the two options. Table 1 was apparently the underlying basis for the Navy’s statement that:

Either option would be extremely costly. Of two unattractive choices, the case in which ships would be redesigned to accommodate larger life-of-the-ship LEU cores clearly would have the lesser long-term impact in both cost and ability of the industrial infrastructure to maintain the ships.¹⁶⁹

In both the 1995 and 2014 Reports, the Navy provided an arguably weak justification of the use of HEU based on support of U.S. nonproliferation policy. The Navy argued that its use of weapons surplus HEU fuel “provides a safe, economical way of removing this material from the threat of diversion, and postpones the need to obtain a new, costly enrichment facility for HEU.”¹⁷⁰ Certainly the cost savings of burning surplus weapons HEU are a significant savings to the country from an

¹⁶⁹ 1995 Report, 27.

¹⁷⁰ 2014 Report, 4. The Navy’s argument in 1995 was essentially the same.

economic point of view, but reducing the HEU material scavenged from weapons could also have been accomplished by a program similar to the Megatons to Megawatts program—blending down the HEU to LEU.

In neither of its reports to Congress does the Navy directly discuss the effect of a potential FMCT on the LEU replacement issue, although it did refer to the United States commitment to prohibit the production of HEU or plutonium for nuclear weapons purposes.¹⁷¹ A proposed FMCT may, or may not, exclude military use material.¹⁷² If the FMCT were to be enacted without a military exemption, eventually the stocks of HEU for naval reactors would be depleted. In that scenario the burning weapons grade HEU scavenged from dismantled nuclear weapons would provide a time cushion to an essential transition to LEU use.

In a glaring omission, particularly since the Navy expressed concern about the proliferation risk of increased plutonium in spent LEU, the Navy almost totally ignored the proliferation and security risks of unburned and burned HEU fuel.

The U.S. Navy's annual consumption of HEU can be roughly approximated by considering the number of reactors and applying some basic nuclear engineering rules of thumb.¹⁷³ Rough calculations show that the 142 MT of HEU set aside by the U.S. for naval fuel (see Figure 1 above) is sufficient to fuel U.S. vessels for 50 years or more.

In a glaring omission, particularly since the Navy expressed concern about the proliferation risk of increased plutonium in spent LEU, the Navy almost totally ignored the proliferation and security risks of unburned and burned HEU fuel¹⁷⁴ in both of its reports to Congress. Furthermore, both reports ignore the terrorism risk presented by HEU for use in an improvised nuclear device (IND). Certainly one might have expected that the Navy would have candidly discussed the high risks of diversion of unburned HEU fuel in comparison to the low risk of diversion of unburned LEU fuel. However, not only did the Navy fail to discuss these issues in its 1995 and 2014 Reports, the Navy actually argued in the 1995 Report that the security needs for LEU fuel would be greater than those for HEU fuel because more LEU cores than HEU cores would be used and more waste generated, leading the Navy to conclude that LEU and HEU security costs “are not judged to be significantly

different” and that the risks of theft or diversion “would not be materially different with different enrichments owing to application of compensatory security measures.”¹⁷⁵

The conclusion of the Navy's 2014 Report states that:

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.

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.¹⁷⁶

¹⁷¹ 1995 Report, 28.

¹⁷² All U.S. statements in support of the concept of an FMCT, including references in President Obama's Prague Speech have framed the issue in terms of elimination of the production of fissile material for use in nuclear weapons. Other states may not support such a limit and call for complete elimination of the production of such material regardless of its use (e.g., a total ban on production of HEU and separated plutonium).

¹⁷³ The 10 operating U.S. carriers have two reactors each and the 71 U.S. submarines have a single reactor. This means that there are approximately 90 reactors, each of which are on the order of 150 MW. A rule of thumb is that the burning of 1 gram of fissile material produces 1 MW-day of energy. Therefore the 90 reactors each operating at 150 MW for 180 days per year on average would burn 90 x 180 x 0.150 kilograms of fissile U-235 per year, or about 2.4 MT per year. Therefore the 142 MT of 90 percent plus HEU set aside for naval fuel shown in Figure 1 could be expected to last the U.S. Navy for more than 50 years without the need for the United States to produce any more HEU.

¹⁷⁴ Burned HEU fuel still contains HEU levels of enrichment and is both a proliferation and terrorist concern.

¹⁷⁵ 1995 Report, 30–31.

¹⁷⁶ 2014 Report, 5–6.

The Navy's position seems to be, as first stated in its 1995 Report, that while replacing HEU cores with LEU is technically feasible, it is a costly option that offers no technical advantages to the Navy and no advantages to the country from nonproliferation, cost, or environmental perspectives.

The second paragraph of the 2014 conclusion raises the tantalizing possibility of an "advanced fuel system" which apparently could allow more densely packed uranium fuels. If true, this might have an important effect on the ability to convert from using HEU to using LEU. Unfortunately there is no specific direction as to which kinds of "advanced fuel systems" could support this possibility. Certainly if advances in fuels would allow increased uranium loading, it results in smaller HEU and LEU cores, but there is no indication that this advanced fuel system would allow for an LEU life-of-the-ship core that could fit in the current design space for attack submarines (although the result might be different for an aircraft carrier).

More likely increasing the LEU fuel density would result in smaller and/or longer lived LEU cores than those studied in the 1995 Report, and therefore "advanced fuel system" LEU cores that could fit in the design space could have a longer life than 1995 estimates and therefore might result in fewer refuelings than those considered in the cost analyses of the 1995 Report. If a significant lengthening of LEU core life is indeed possible, albeit not to the extent of life-of-the-ship core life, it would have a significant effect on the cost estimates from the 1995 Report and in the relative cost shown in Table 1 above.

Is the second paragraph of the conclusion of the 2014 Report the basis for an optimistic assessment of a change in the Navy's position on LEU use or is it simply a statement that a "make-work" and/or "keep busy" projects with LEU fuel would be preferable to losing the R&D capability? The answer is unclear, but it is clear that the Navy is concerned that once its current work is finished the naval reactor R&D facilities will be hard-pressed to maintain a level of competency. The Navy and its prime naval reactor contractors, such as Knolls Atomic Power Laboratory and others, have a vested interest in maintaining a sustainable R&D program. A cynical view of the Navy's mention of the possibility of advanced LEU fuel in 2014 would be that although the Navy doesn't support the use of LEU fuel, some R&D work on the LEU concept is better than no R&D work at all. It should be noted that by raising the specter of work on LEU and an eroding naval reactor R&D base, the Navy would "win" if Congress were either to be in fear of the loss of the R&D capability or wanted to aggressively pursue LEU options.

Analysis of the Navy's Arguments on LEU Use

This section contains an analysis of the arguments made by the Navy in its 1995 and 2014 Reports to Congress. As noted above, the 1995 Report contained the basic analysis done by the Navy that resulted in its recommendations against the use of LEU for Naval propulsion reactors.

In its 1995 Report, the Navy prepared four main analytical sections: (1) Technical Considerations; (2) Environmental Considerations; (3) Economic Considerations; and (4) Proliferation Considerations.¹⁷⁷ To the extent possible from open sources, we will review the Navy's analytical conclusions using these same topic headings and following the same sequence used in the 1995 Report.

Technical Considerations

Essential Functional Requirements

The 1995 Report set forth eight criteria that are unique to naval reactors and distinguish them from land-based reactors. These criteria included: (1) compactness; (2) crew protection; (3) public safety; (4) reliability; (5) ruggedness; (6) maneuverability; (7) endurance; and (8) quietness. This list appears to contain all the essential requirements that are important for naval propulsion reactors.

State of LEU Technology

One of the failings of the 2014 Report was that it did not provide an update on the state-of-the-art of LEU technology as requested by Congress. As noted above, the Navy's failure to discuss the use of LEU by other navies, particularly by the French and Chinese Navies, is a glaring omission in both the 1995 and 2014 Reports.

The Effect of Using Low-Enriched Uranium on Naval Nuclear Propulsion Technology

Although the Navy was correct in stating that the U.S. Navy had no proven LEU fuel system for naval propulsion in 1995, its statement denying the existence of a proven fuel system "based on low-enriched uranium (LEU) in place of highly-enriched uranium (HEU)"¹⁷⁸ was at best inaccurate, and at worst a deliberate intention to mislead Congress. Quite obviously the statement ignores the fact that France and China had both operated LEU fuel systems in submarines prior to 1995.

However, even if we were to assume that there might have been some reason not to mention the French and Chinese programs in 1995 (e.g., not to bring in intelligence information), by 2014 the statement was undoubtedly incorrect and should have been updated.

Assumptions for the Navy's 1995 Report

The choice by the Navy to base the 1995 Report on 20 percent enrichment for the LEU fuel was arguably the best choice for presenting the best advantages of LEU fuel. However, stating that it has "the best chance of working in a Naval application" is once again implying that there is no viable LEU fuel option for submarines except ignoring both the French and Chinese developments. The additional analysis of one case using 5 percent enrichment was not inappropriate in the 1995 Report; the results fly in the face of proven success by using these enrichments.

There is little argument that choosing a light-water cooled and moderated reactor running at approximately the same temperatures and pressures as the Navy's HEU cores was an appropriate choice. However, basing the LEU reactor on

¹⁷⁷ 1995 Report.

¹⁷⁸ 1995 Report, 7.

the same fuel elements, fuel module design, materials, and fabrication methods in current use ignored the potential for increased fuel density and longer-lived LEU cores. There is little even now on the subject of submarine reactor fuels. One of the most quoted pieces on the topic is work done by an MIT graduate student, Thomas Ippolito, Jr., as part of his Master's thesis in 1990, five years before the Navy's 1995 Report.¹⁷⁹ Ippolito cited and considered many aspects of the French use of a high-integrity, more dense LEU fuel for submarines, a fuel often described as "caramel" fuel because the small uranium lumps look somewhat like caramel candy.

Ignoring Ippolito's work in 1995 might be understandable, but failing to address his work and the work of numerous commentators, probably most notably Dr. Frank von Hippel of Princeton and his colleagues who have stressed that higher density fuel might be possible and change the LEU calculus is inexplicable.

LEU in Current Design Ships

In its 1995 Report, the Navy appeared to use a simple ratioing of enrichment levels to determine that an LEU core would have a 7.5-year useful life. The basis of its analysis is never explicitly stated, but it appears that the Navy did not consider increasing the density of LEU fuel as part of its study. The Navy did this despite the fact that one of the few attempts to understand whether LEU cores could be used in submarines was Ippolito's work mentioned above.

In 1995 the last of the *Ohio*-class SSBN/SSGNs were still under construction. The Navy correctly pointed out that the approximately 20-year life of the reactor cores in the *Ohio*-class meant that they would need to be replaced before LEU cores could be developed for these vessels. The Navy briefly considered in its 1995 Report that the follow-on to the *Ohio*-class would be able to use a 40+-year life-of-the-ship core that the Navy anticipated would be developed. The Navy further stated that an LEU version of this anticipated life-of-the-ship core would have an endurance of about 10.5 years.¹⁸⁰ Again, no indication of the actual analysis was given and it appears to have been some form of ratioing based on enrichment levels.

The conclusion reached by the Navy in 1995 therefore was that LEU core future SSNs and SSBN would require three refueling overhauls if LEU cores replace the HEU cores in these vessels.

Although this analysis is difficult to challenge directly, other than noting that it apparently gives no credit to the option of increasing fuel density in the LEU cores, it has a significant flaw. It does not consider the potential that a life-of-the-ship core could be fitted into the SSBN profile instead of using shorter-lived LEU cores. Failure to consider SSBN life-of-the-ship LEU cores without redesign was done despite the fact the 1995 Report later admits that an LEU life-of-the-ship core "could probably be fit into this ship's [*Ohio*-class] 42-foot hull."¹⁸¹ That being the case, it would make little sense to design new SSBNs with smaller, shorter-lived cores requiring refuelings and it would seem rather improbable to carry forth this comparison for SSBNs as was done in Table 1 unless the unstated goal is to make the LEU option look less attractive.¹⁸² Clearly for future SSBNs even with the 1995 considerations, the HEU/LEU comparison should have been a straight up comparison of two life-of-the-ship cores rather than considering LEU cores that required refuelings.

In its 1995 Report, the Navy apparently did not consider that the life-of-the-ship fuel integrity problem, even for HEU cores, had been solved.¹⁸³ Long-life fuel integrity was a work in progress and the 1995 Report stated that for CVN cores "[t]he limiting technical consideration is corrosion of the cladding. Advanced cladding materials are in development and testing with the goal of realizing core lifetimes as long as 45 years."¹⁸⁴ How the Navy has resolved the fuel cladding issue, a problem that results primarily from the evolution of gaseous fission products as the fissile/fissionable material in the core is burned throughout the lifetime of the core, is undoubtedly classified.

¹⁷⁹ Thomas Ippolito, Jr., "Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design" (Master of Science thesis, MIT, 1990).

¹⁸⁰ 1995 Report, 9.

¹⁸¹ 1995 Report, 11.

¹⁸² However, the Navy does just that. In addition to Table 2 on page 9, the comparison also shows up in Table 5 on page 16, Table 6 on page 17, and Table 7 on page 23 of the 1995 Report.

¹⁸³ By the time of its 2014 Report, the Navy apparently considered the corrosion problem resolved as discussed in the previous section.

¹⁸⁴ 1995 Report, 9–10.

However, despite the lack of resolution cladding problem, the 1995 Report based its comparison on a comparison of life-of-ship cores for SSNs, SSBN, and CVNs that did not exist in 1995 against shorter-lived LEU cores.

The 1995 Report concludes its assessment of LEU cores in current designs by stating that such cores “would require more frequent refueling, resulting in a significant increase in life-cycle cost, far greater reactor servicing workload, reduction in ship availability to the fleet, increase in radiation exposure to shipyard personnel, and increase in the generation of radioactive waste.”¹⁸⁵ Several of these statements are simply not supported by the analysis in the report itself. Although it is correct that using less than life-of-the-ship cores in SSNs in the same design space would require more frequent refueling (assuming that a life-of-the-ship HEU core, something that is yet to be proven in practice, is achievable) the reduction in ship availability is arguably not as severe as the Navy states, increases in radiation exposure to shipyard personnel are not invariable consequences of using LEU, and the increase in the generation of radioactive waste may not be a significant.

LEU Life-of-the-Ship Cores

The second option considered by the Navy is the use of life-of-the-ship LEU cores. In this section of its 1995 Report, the Navy did note that simple enrichment ratios were not appropriate. Without any real analysis it noted that simple volumetric ratios would result in an LEU life-of-the-ship core that was three times the volume of an HEU core, taking into account fissioning of plutonium that would be created in the LEU cores.¹⁸⁶

Although it is once again difficult to argue with the Navy’s conclusion that vessel redesign would be required and that operational performance might be impacted, it is also fair to note that the Navy did not consider redesigns of components in its assessment of LEU reactors. The French Navy saves considerable space in the reactor compartment by using an integrated steam generator,¹⁸⁷ a concept that is now commonly employed in SMR designs for commercial power reactors.¹⁸⁸ One would have thought that had the Navy wanted to seriously consider LEU use in a design space, it should not nearly have scaled everything up, but should have looked instead to explore design concepts that would take better advantage of existing space.

The Navy concluded that for a 20 percent LEU core, a modern SSN would need to have an increased hull diameter, but inexplicably the whole length would shorten while the overall design got heavier.

Furthermore, as discussed above, the Navy admitted that an SSBN would probably not need to be changed to any great extent to use a life-of-ship LEU core. Surprisingly, the Navy felt that aircraft carriers were not large enough to accept a life-of-the-ship LEU core without an increase in hull length.¹⁸⁹ No details of any of Navy studies mentioned in the 1995 Report were given. The Navy may be correct in its analysis, but without access the analysis it is difficult to say how competently the analysis dealt with, or did not deal with, effective use of space in the SSN and CVN.

The Navy did make a point of indicating that the larger LEU core in a submarine or aircraft carrier would have more moving parts, such as control rods, that may be subject to failure and/or the need for ongoing maintenance.¹⁹⁰ This is a logical argument, but in order to determine the significance of the issue the Navy would need to examine reliability data for these components. This appears neither something the Navy has done nor an issue for which the Navy would be willing to provide data for open analysis.

The life-of-the-ship consideration of LEU cores concluded with a section on why cores with enrichment below 20 percent would not be suitable for naval propulsion reactors. One of the Navy’s key assessments was that in contrast to civilian

¹⁸⁵ 1995 Report, 10.

¹⁸⁶ 1995 Report, 10.

¹⁸⁷ In an integrated steam generator design, the steam generator is inside the pressure vessel. Eliminating the external steam generator saves a significant amount of space.

¹⁸⁸ SMRs are a relatively new commercial power concept and typically have thermal power levels that are in the same power range as naval propulsion reactors.

¹⁸⁹ 1995 Report, 11–12.

¹⁹⁰ 1995 Report, 12.

reactors, naval reactors cannot be designed to be easily disassembled and refueled.¹⁹¹ Once again, while the Navy's comments appear to be logical, they are overstated and ignore the fact that other navies are in fact using such designs. For example, the Navy states that naval reactors must be "compact and mobile, and cannot carry their refueling facilities around with them."¹⁹² However, refuelings are a shipyard function and a well thought out design using LEU would entail designing automated shipyard refueling capabilities that would maximize the use of automation to minimize refueling time and the radiation exposure potential from refuelings. No one would seriously consider that the vessel itself would attempt to "carry refueling facilities around with them."

In summary, the 1995 Report seems to go out of its way to overstate arguments against life-of-the-ship LEU cores, particularly with reference to cores employing enrichments comparable to the 3–5 percent enrichment in civilian power reactors. The Navy overemphasized the difficulty of designing cores that could be easily refueled and totally ignored the fact that other navies did not appear to share the U.S. Navy's opinion and were in fact operating cores that used uranium enriched to less than 10 percent. Even if the Navy was not totally aware of the foreign uses in 1995, the update required by Congress in the 2014 Report should have addressed the issue.

Environmental Considerations

The 1995 Report suggests that use of LEU fuel would cause negative environmental impacts because: (1) there would be an increase in the number of shipments of spent fuel; (2) the use of LEU fuel would create an increase in the volume of spent fuel requiring disposal; and (3) the increased number of refuelings needed with LEU fuel would potentially increase the occupational radiation exposure of shipyard workers.¹⁹³

In its 2014 Report the Navy appears to shift its environmental concerns about LEU. Perhaps the Navy recognized that some of the environmental concerns raised in the 1995 Report are subjective and subject to criticism. Rather than adopting the earlier concerns that seem to focus primarily on increased occupational exposure of workers, the 2014 Report stresses the cost required to deal with environmental impacts. Increased costs of new design storage containers, etc. now seem to dominate the environmental focus, replacing the 1995 Report's focus on increased hazards to shipyard workers.

Effect on Spent Fuel Shipping and Disposal

The Navy is unquestionably correct in its statements that the use of LEU cores in either of its options (LEU cores in the current design space requiring refueling, or life-of-the-ship LEU cores) would generate a larger volume of spent fuel. The Navy is also correct in noting that the characteristics of the LEU spent fuel would be different due to the production of larger amounts of radionuclides due to neutron absorption and other interactions on U-238. In comparison to an HEU core, U-238 presence would increase by a factor of approximately 10–30 depending on the HEU enrichment considered.¹⁹⁴

However, although these issues are not inconsequential, it should be kept in mind that the naval propulsion reactors, even larger ones with a 200 MWt capacity, are far smaller than the current typical 3000 MWt commercial power reactor. A modern large civilian power reactor therefore generates approximately a factor of 15 times the waste of a submarine reactor per fuel load and the fuel replacement in a commercial reactor is far more frequent than even the shortest-lived LEU cores considered in the Navy's reports to Congress.¹⁹⁵

Clearly the Navy is correct that the use of LEU cores would require new spent fuel shipment operations, and would have an effect on spent fuel disposal. In contrast to the failure of the Navy to provide updates in other areas, the 2014 Report does make a new specific statement about the increased environmental concerns for spent fuel. It indicates that LEU spent

¹⁹¹ 1995 Report, 13.

¹⁹² 1995 Report, 13.

¹⁹³ 1995 Report, 15.

¹⁹⁴ For example, U-238 content in a 93 percent weapons grade uranium fuel is 7 percent in comparison to its 80 percent, a ratio of 11.4. If 97 percent uranium fuel is used the ratio is 26.6.

¹⁹⁵ This fact is acknowledged in the 1995 Report, but is somewhat buried in the Navy's expression of concern about the impact of spent fuel storage in the state of Idaho. The Navy notes correctly that in 1995 spent naval fuel was approximately 0.1 percent of the total spent fuel created and stored in the United States. See 1995 Report, page 16. The reduction of the submarine force post-1995 will have reduced this percentage a bit further.

fuel would have “about 30 times the neutron radiation of the current HEU spent fuel” which might call for newly designed containers and shielding for spent fuel.¹⁹⁶ This statement is apparently added to the 2014 Report to reinforce the statements about increased costs associated with LEU fuel. Although it is not specifically stated in 2014, it is logical that increased neutron omissions from the spent fuel would require enhanced neutron shielding. Because neutron shielding requires lighter materials such as plastics or water, the Navy is correct that different (probably larger) shipping and storage containers would be required for spent LEU fuel.

The Navy did not consider how modification/improvement of the refueling process (such as the use of automation, refueling hatches, etc.) would potentially lessen individual exposures.

The spent fuel issue with LEU is important, but it needs to be further examined and put in a proper context where cost, risk, etc. are considered in order to properly compare LEU spent fuel issues with HEU spent fuel issues.

Effect on Occupational Radiation Exposure

The Navy is justifiably proud of its record of decreasing radiation exposure to shipyard workers.¹⁹⁷ However, the Navy’s treatment of this issue in its 1995 Report makes it seem inevitable that the use of LEU cores would lead to increased exposures. The Navy did not consider how modification/improvement of the refueling process (such as the use of automation, refueling hatches, etc.) would potentially lessen individual exposures.

The Navy, in its analysis of exposures related to LEU cores, appears to base radiation exposure on its past refueling practices. The Navy’s practices unfortunately are not at the same level of sophistication that appears to be practiced by the French Navy. French submarines are apparently designed for refueling, incorporating refueling hatches that give access to the reactor core without requiring cutting the pressure hull as has been U.S. practice. It appears highly likely that if LEU powered submarines could be designed in a manner that would allow for automation of the refueling system and greatly decrease radiation exposure to shipyard workers. Advances in refueling technology appear to have been totally ignored by the Navy in its reports to Congress.

Moreover, while the Navy might be correct that in the aggregate the use of LEU cores could potentially increase total exposure to the workforce, this does not mean that individual exposures to shipyard workers would increase. If there were an increase in aggregate exposure, keeping individual exposures at the same or even a lower level would be chiefly an economic issue because the obvious way to reduce individual exposures would be to assign more workers to complete the tasks so that the individual doses received would be less.

It is apparent that the Navy’s arguments on occupational exposure in the 1995 Report were overstated. As mentioned above, the clumsiness of the argument may have been a reason why the 2014 Report merely noted the NNPP’s history of reducing radiation exposure to shipyard workers and states that “increases in exposure associated with more frequent refueling would be inconsistent with the overall trend of reducing radiation exposure in the performance of nuclear work in the United States, and with the NNPP’s longstanding commitment to minimizing exposure to workers.”¹⁹⁸

¹⁹⁶ Ibid.

¹⁹⁷ The Navy released a report on occupational exposures, “Occupational Radiation Exposure from Naval Reactors’ Department of Energy Facilities,” Report NT-14-3, May 2014, available at <http://nnsa.energy.gov/sites/default/files/nnsa/09-14-inlinefiles/2014-09-10%20NT-14-3.pdf>. One conclusion of the report was that

According to the standard methods for estimating risk, the lifetime risk to the group of personnel occupationally exposed to radiation associated with the Naval Reactors Program is less than the risk these same personnel have from exposure to natural background radiation. This risk is small compared to the risks accepted in normal industrial activities and to the risks regularly accepted in daily life outside of work.

¹⁹⁸ 2014 Report, 4.

Economic Considerations

The 1995 Report contained a rather detailed analysis of the two options for use of LEU cores and the economic effects on the Navy's nuclear ship program as it was envisioned in 1995. In its study of economic factors the Navy considered the following areas:

- R&D costs, including test reactor operations,
- Reactor fuel and core manufacturing infrastructure,
- Ship lifetime maintenance costs,
- Ship availability,
- Ship construction costs,
- Shipyard infrastructure,
- Spent nuclear fuel shipping and disposal costs.¹⁹⁹

For the most part it appears that the Navy's economic analysis considered the appropriate variables and although the numbers cannot be accurately tracked in the 1995 Report because no background data were provided, it appears that the assumptions were relatively accurate for the 1995 timeframe.²⁰⁰

However, it is appropriate to point out that the lifetime maintenance costs estimated in the 1995 Report may be based on an unsubstantiated premise. The Navy estimated that for what they describe as the "baseline attack submarine with a life-of-the-ship" it will require two major non-refueling overhaul and modernization availabilities at approximately 10 and 20 years into the vessel's life.²⁰¹ Therefore the Navy in its analysis considers that the LEU option would add another overhaul outage to the vessel's life resulting in the need for more submarines to keep the same level of operational availability of submarines using HEU cores.

In addition to the facts that the economic costs are sensitive to lifetime of the LEU cores and the Navy's estimates in its 1995 Report are admittedly crude, the economic analysis has at least two other potential problems.²⁰²

First, it ignores the increasingly rapid change in technology that may in fact require more frequent overhauls for non-engineering reasons. If this were true then the use of LEU cores, even those with the 7.5-year lives described in the 1995 Report, might not add to time out of service. Second, by failing to account for potentially shortened refueling that might be the result of LEU cored submarine design to be integrated into an automated refueling system, the 1995 Report may significantly overestimate the costs and out of service time for LEU cores. Although it is somewhat unclear, it appears that in its 1995 Report the Navy based its estimates for refueling on its historic practices, which have involved a requirement to cut the pressure hull in order to get at the reactor core. Cutting and then re-welding the pressure hull is an expensive and time-consuming operation that requires extreme quality control. These considerations have a significant effect on the results shown in Table 1 above, which summarized the Navy's estimates of economic effect for each of the two options.²⁰³

¹⁹⁹ 1995 Report, 19–20.

²⁰⁰ See 1995 Report, 20.

²⁰¹ 1995 Report, 21.

²⁰² Some commentators challenge the Navy's estimates of the life of LEU cores, citing to the earlier 1990 study by Ippolito in his master's thesis. See Thomas Ippolito Jr., "Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design," (Master of Science thesis, MIT, 1990). In his thesis, Ippolito concluded that 20-year LEU core lives could be obtainable. However, Ippolito based his 20-year figure on an assumption that there would only be 60 days of full power operation on the reactor each year, a figure that arguably tends to underestimate reactor use. If the reactor actually sees more like 120 days of full power a year in operation (something like one-third power continuously every day), then Ippolito's figures for LEU core life are much closer to the 7.5-year figure the Navy used in its 1995 Report.

²⁰³ 1995 Report, 27.

Consideration of these factors might significantly affect, or possibly eliminate, the “effective reduction in baseline force/annualized replacement cost” for the LEU cores in existing design ships in Table 1. Reduction or elimination of the costs associated with extra outage time for refuelings might have a serious affect on the Navy’s expressed preference for life-of-the-ship LEU cores as what they seem to perceive as the lesser of two evils.

One of the chief failings of the 2014 Report was the failure to update the economic analysis section of the 1995 Report. When it provides an update, the Navy owes Congress more than a retrospective view of items, such as refueling costs. It needs to project reasonable assumptions for improvements in well-designed refueling options for LEU cores and to fold into its assessment the experiences of other navies in refueling.

In addition, the 1995 Report pointed out the limitations of shipyard infrastructure and the limitations of the infrastructure for nuclear work in conjunction with other required overhaul work, such as weapons upgrades. The Navy found that the LEU scenario “would place an unprecedented, sustained high refueling workload on every nuclear-capable yard, with no room for slippages and no reserve capacity for workload peaks in response to changes in mission requirements or emergent problems.”²⁰⁴ Clearly the Navy needs to provide Congress with an update of this assessment of shipyard infrastructure.

Proliferation Considerations

The section of the 1995 Report that discusses proliferation considerations is probably the most disappointing section of the report. It begins by considering the prospect for a FMCT addressed by the president in 1993. However, the 1995 Report only addresses the effect of an FMCT on stockpiles of HEU, claiming “use of HEU to fuel naval ships is not inconsistent with current U.S. nonproliferation policy since the HEU would be used as a propulsion fuel and not for nuclear explosive purposes.”²⁰⁵

Thus the Navy’s analysis is initially based on a self-serving statement of the problem. The Navy phrases the problem as to whether its use of HEU violates any existing agreements (it doesn’t) and whether any future agreement would limit the Navy’s use of HEU. This allows the Navy to conveniently ignore most of the arguments that are of concern about the very creation and existence of large stockpiles of HEU—that the HEU might ultimately be used for nuclear weapons rather than as reactor fuel either by states or non-state actors. In neither 1995 nor 2014 does the Navy ever directly address the fact that the HEU fuel used in its reactors could be directly, or with relatively simple metallurgical modifications, be used as a nuclear weapon either by a proliferating state or by a non-state actor.

When considering the Navy’s arguments about proliferation it is important to recognize that there are two types of HEU that have been used as naval propulsion fuel. Historically naval HEU fuel was a specific enrichment level reportedly at approximately 97 percent, a percentage higher than the enrichment used in nuclear weapons. With the drawdown of nuclear stockpiles at the end of the Cold War, a large amount of HEU that was removed from weapons was made available for the Navy’s use. Although this fuel might not have been as efficient as a special-purpose enrichment for naval fuel, it could be used, and has been used to power some naval propulsion reactors.

Potential Effects of Using LEU in Naval Ships on U.S. Nonproliferation Policies

The Navy stresses that its use of ex-weapons HEU as naval propulsion fuel does not violate any international agreements or the perspective FMCT given the Navy’s interpretation of what the FMCT would involve. The Navy’s understanding of the FMCT is consistent with U. S. policy statements about a tentative FMCT, all of which have been phrased as relating only to the cutoff of fissile materials for nuclear weapons. This view is probably not universally shared and most states, particularly the NNWS of the NPT appear to believe that an FMCT should be based on material rather than the use of material, thereby creating a complete ban on the production of any HEU or plutonium.

The Navy’s position is that its use of surplus weapons HEU is an economic benefit because it delays the need to invest in a new HEU production facility to support the Navy’s fuel requirements. Although the Navy’s statements are correct, they fail to address any proliferation or terrorist threat from the existence of the large stockpile of HEU set aside for naval fuel. The

²⁰⁴ 1995 Report, 26.

²⁰⁵ 1995 Report, 28.

emphasis on cost savings is misplaced. Cost savings are not nonproliferation benefits although the Navy would like to focus on cost-saving as if it were a nonproliferation benefit.

It is interesting also to note that the Navy makes no specific mention in either of its reports to Congress of the Megatons to Megawatts agreement between the United States and the Russian Federation. The purpose of the Megatons to Megawatts program was specifically to remove the proliferation hazards of large stockpiles of post-Soviet HEU by blending the HEU down to LEU enrichment levels, removing the proliferation hazard plus making the material available for civilian power reactors.

Keeping the focus on using the ex-weapons HEU for naval fuel, the Navy makes a purely economic argument and warns that “any use of this material for other purposes, such as blending down for commercial use, would accelerate the need for construction of a very expensive and politically sensitive HEU production facility.”²⁰⁶

While still ignoring the usefulness of HEU fuel for weapons purposes, the Navy’s 1995 Report takes a backhanded swipe at the LEU fuel cycle by noting that it produces a “significant amount of plutonium while and HEU fuel cycle does not.”²⁰⁷ It is statements like this that more or less defined the bias inherent in both of the Navy’s reports to Congress. Although the statement is true, it is misleading because it makes it appear that the LEU fuel cycle creates risks of nonproliferation and diversion while the HEU fuel cycle is free of such risks. An examination that intended to fairly compare LEU use to HEU use it would only be reasonable if it were to present both sides of the issue.

Affect on Security of Using an LEU versus HEU Fuel Cycle

The Navy correctly notes that the security of nuclear material depends on both being able to properly account for the material using MPC&A procedures and physical protection for the material.

Regarding the MPC&A requirements, the Navy observes that the LEU fuel cycle would involve more material than the HEU fuel cycle and therefore a greater MPC&A effort. Like many of the Navy’s arguments, this statement is true, but the implied conclusion lacks any consideration of the consequences of failure of the system—for HEU the potential of an MPC&A failure is a nuclear yield explosion whereas an MPC&A failure for LEU would perhaps result in a commercial loss. Finally, in the age of computers, bar code scanners, and upgrades in MPC&A practices, it is questionable how much greater an MPC&A effort would be needed for an LEU fuel cycle when compared to an HEU cycle.

The Navy describes three principal physical protection concerns:²⁰⁸

- Theft of nuclear material,
- Loss of a high-value component due to sabotage,
- Loss of U.S. military technology of significant interest to other nations.

The Navy correctly considers that the need for physical protection in the fuel cycle varies depending on the stage of the reprocessing in the fuel cycle. Although correctly noting that once enrichment has been completed HEU requires a higher security level, the Navy strangely then shifts the discussion of LEU cycle security to a discussion of protecting the material so as not to disclose classified information about fuel rods, and it therefore concludes that the costs of security at fuel and core manufacturing facilities are “only modestly higher for an HEU fuel cycle.”²⁰⁹

Astonishingly the Navy totally ignores the potential for theft of HEU to use in a weapon. It argues without substantiation that the finished naval core is “a very unattractive theft target regardless of whether LEU or HEU is used as fuel” and then shifts the physical protection analysis to a concern that the core would be damaged by sabotage.²¹⁰ Ignoring the risk that an

²⁰⁶ 1995 Report, 29.

²⁰⁷ 1995 Report, 29.

²⁰⁸ 1995 Report, 29.

²⁰⁹ 1995 Report, 30.

²¹⁰ 1995 Report, 30.

HEU core, or portions thereof, could be stolen for use as a weapon allows the Navy to argue that both LEU and HEU cores need the same protection. The Navy argues further that the LEU option using less than life-of-the-ship cores would require more cores than if a HEU life-of-the-ship core was used. The Navy then seems to assume that the risk of loss is equivalent and that the larger number of LEU cores each would require the same security as an HEU core and therefore LEU cores would have higher security costs. Eliminating the consequences of loss of material and thereby saying that the risk of loss is the same for LEU and HEU defies common sense and although the argument has more validity when spent fuel is considered, it may not be valid even for spent fuel because spent HEU fuel is still HEU and, depending on the amount of burnup, might still be a proliferation concern.

In summary, the Navy's arguments about physical security requirements do not withstand scrutiny and although the Navy doesn't state this in its 1995 Report; its arguments are only applicable to the option in which HEU life-of-the-ship cores are compared to LEU cores that require refueling.²¹¹ Even then, the Navy has made a tortured comparison in an apparent effort to support its preference for HEU by ignoring the risk that HEU can be directly diverted for weapons use.

The Risk of Theft or Diversion of Nuclear Material

In the final two paragraphs of its 1995 Report, the Navy makes a convoluted reference to the different levels of risk associated with the loss of HEU and LEU. Shockingly, rather than appraising Congress as to whether there would be less risk associated with the use of LEU material, the Navy seems to say that because it applies different levels of security requirements, the risk of loss of either LEU or HEU is the same.

The Navy states in its 1995 Report that “[s]ecurity measures are predicated on reducing the risk of theft or diversion to a low level for either HEU or LEU.”²¹² Therefore, because the Navy applies these requirements that the risks are the same shows either a deliberate attempt to mislead by ignoring or obfuscating the consequences of the loss, or incredibly sloppy analysis.

One might be tempted to believe that in part the Navy's failure to address at least the non-state actor concerns in its 1995 Report are excusable given that concerns for non-state actors were lower in the pre-9/11 period. However if that were the case, the Navy should have addressed the issue in its 2014 Report in response to Congress's request for a status update. The Navy chose not to provide an update, apparently allowing its desire to continue using HEU to override the Congressional mandate for an updated assessment of the relative merits of using LEU for naval propulsion reactors.

Without access to the Navy's R&D studies and data, it is impossible to directly refute many of the Navy's conclusions in its 1995 Report. Because the Navy chose for the most part not to update its 1995 Report in 2014, despite a Congressional directive to do so, it appears that the only option for obtaining a fair comparison of the merits or demerits of LEU use is for Congress to direct that there be an independent study with full access to Navy data to examine the question and report to Congress.

²¹¹ The Navy's argument obviously fails when a one-to-one comparison is made for LEU life-of-the-ship cores compared against HEU life-of-the-ship cores.

²¹² 1995 Report, 31.

Arguments the U.S. Navy Could Stress

In the previous section, the Navy's arguments against LEU use were examined. However, the arguments mentioned against LEU use may not include all the arguments that the Navy would make, if it appeared likely that Congress would direct the use of LEU.

In both its 1995 and 2014 Reports, the Navy mentioned the potential operational detriments that might be associated with LEU use. It did not pursue these issues in any detail, possibly because of classification concerns, but also because playing the "national security" trump card did not appear to be necessary. As mentioned by Rebecca Ward, citing an interview, "national security always trumps nonproliferation."²¹³ Ward's reference is particularly interesting because it mentions some details not brought out by other commentators, such as different thermal responses of HEU and LEU fuel that may require undesirable excessive control when power changes are made to an LEU core.²¹⁴ Other examples could be questions as to whether larger volume life-of-the-ship LEU reactors could "convective the cool" (an important noise minimization tactic) and whether the larger volume would require more pumping and hence more noise.

These arguments are precisely the type of detailed arguments against LEU use that the Navy might begin to stress when faced with the reality of losing its HEU-fueled reactors. Additionally, the Navy has hinted that problems that LEU cores might cause for vessel maneuverability, quietness, etc. These may be extremely valid and important arguments and might be dispositive in making a determination of whether to shift to LEU cores, particularly if other navies can continue to use HEU.

These arguments may have been discussed in classified fora, but to our knowledge they have never been discussed in any detail in an unclassified setting. To the extent an unclassified discussion is possible, opening the dialogue to a broader range of commentators would be desirable. Future considerations of LEU use should not be subject to being shrouded by a national security shield. As discussed in several places, in this study Congress should ensure that an independent analysis of these factors can be done, perhaps by properly cleared appointees from national scientific bodies.

²¹³ Ward, "USA and France," 184.

²¹⁴ Ward, "USA and France," 185.

Remaining Issues That Affect Naval HEU Use

For the U.S. government, eliminating HEU has both domestic and international components. Clearly Congress could force the Navy to unilaterally adopt LEU fuel for naval propulsion reactors. At least for the foreseeable future, that does not appear to be a likely option, particularly given the Navy's recommendations against LEU use.

On a purely domestic level the controlling factors against LEU use appear to be the economic costs coupled with the potential loss of advantage vis-à-vis nuclear-powered vessels (particularly submarines) of other nations. As addressed above, it appears perfectly feasible that either of the two options considered in the Navy's 1995 and 2014 Reports to Congress—LEU cores requiring refueling or LEU life-of-the-ship cores requiring redesigned vessels—are technically feasible. Sadly, the Navy's outdated 1995 cost estimates are the only measure of what LEU use might cost. Therefore, without even considering whether the conversion to LEU would be disadvantageous from an operational point of view, accurate cost estimates based on current state-of-the-art would be necessary for Congress to even begin to consider forcing the Navy to convert to LEU.

What appears to be needed at the international level for controlling the spread of nuclear propulsion technology is something akin to the Missile Technology Control Regime (MTCR).

Beyond the domestic arena, there are numerous issues that need to be addressed in terms of international instruments that currently exist, are in the proposal stages, or would be necessary to affect a significant reduction or elimination of HEU use. At a basic level the “loophole” in the NPT needs to be closed, ensuring that HEU cannot be removed from safeguards, even arguably temporarily, for naval propulsion uses.²¹⁵ Although such a provision without a conceptual change in the treatment of the status of NWS would not affect most of the nuclear naval programs that are in non-safeguarded NWS, it could tend to discourage use in NNWS such as Brazil from expansive nuclear propulsion programs.²¹⁶

How the international community can address the use of HEU for naval propulsion in non-NPT states such as India is also an issue that needs to be addressed. Leasing nuclear-powered submarines (or even the outright sale) should be prohibited under an international agreement. However, blocking sales and leasing would not address the indigenous Indian submarine program that uses

HEU. What appears to be needed at the international level for controlling the spread of nuclear propulsion technology is something akin to the Missile Technology Control Regime (MTCR). An international agreement analogous to the MTCR would at least have the potential of limiting the spread of nuclear propulsion technology and could potentially be limited to the spread of HEU fueled propulsion technology.²¹⁷

An overriding issue that needs to be resolved in future considerations of HEU use in naval propulsion is the issue of the scope of a potential FMCT. If the terms of an FMCT were to limit the agreement to the production of fissile material for only nuclear weapons, there would be probably little to no effect on HEU use for naval propulsion. A “true” FMCT that limited the production of fissile material to LEU levels or lower (i.e., one that would eliminate all HEU production and perhaps even high-end LEU production) would have a significant effect on the use of HEU in naval reactors. Most HEU using states appear to have sufficient HEU stocks to continue to operate well past the point where current nuclear-powered vessels would normally retire and their replacements could be developed using LEU cores long before HEU stocks were exhausted. Simply put, it is essential that the issue of defining the scope of a potential FMCT needs to be addressed.

²¹⁵ Beyond naval propulsion reactors any attempts to close the “loophole” should also address other potential uses.

²¹⁶ As indicated above, the Brazilian program appears to be following the French model and using LEU fuel; however, there is nothing that prevents them from using non-safeguarded HEU should they choose to do so.

²¹⁷ Recognizing that unless properly crafted any attempt to limit technology to LEU would to some extent be ineffective given that to a first approximation the only significant difference between LEU technology and HEU technology is the enrichment of the uranium.

Certainly a unilateral elimination of HEU use in naval propulsion by the United States would have a positive effect in reducing the amount of HEU available globally, perhaps affecting about 50 percent of the world's stock of HEU.²¹⁸ However, even if the United States were to unilaterally forgo using HEU, the issue would remain as to how to eliminate the other 50 percent of global HEU inventory.

One possibility is that a new international agreement might be reached wherein states would agree that all future vessels built after some agreed to date would be powered by LEU. An international verifiable agreement to use only LEU would eliminate any operational advantage arguments against LEU use since because all navies would be on an equal footing, limited only by the cleverness of their LEU designs. This would essentially be a naval arms control treaty. Such a treaty would, of course, need to be verifiable. Inspection and verification would arguably be less complex than the verification regimes of the various Strategic Arms Limitation Treaties (SALT) and could be performed with currently existing technology.

²¹⁸ The U.S. has by far the largest stock of HEU designated for naval fuel (see Figure 1). However, the exact allocation of the massive stock of HEU by the Russian Federation is not transparently designated for naval propulsion and could easily be as large, or larger than, that designated by the United States.

Conclusions and Recommendations

The conclusions and recommendations of this study focus on what can be done in the United States to minimize HEU use by using LEU fuel in future naval propulsion reactors.²¹⁹ It is apparent that LEU fueled reactors can be successfully used in both submarines and aircraft carriers. France apparently does this quite successfully. China also does this for submarines with at least some measure of success. Furthermore, the Navy's 1995 and 2014 Reports to Congress both admit this. It should also be recalled that the U.S. Navy essentially started out this way: the initial *Nautilus* core used 20 percent enrichment fuel.

However, the Navy's current position, as stated in its reports to Congress, is that LEU use is not advisable. It still appears that the Navy will need to be pulled or pushed into a shift of position by either domestic or international political pressures. Although such pressures may be mounting, they are insufficient at the present time to force any changes in the Navy's position despite the possible benefits of the reduction of proliferation and terrorism threats that would result from LEU use.

In its 2014 Report to Congress, the Navy failed to respond to Congress' direction in a number of aspects. The Navy apparently used a creative interpretation of Congress' directive to "update" its 1995 Report to avoid providing Congress with a transparent and thorough assessment of the state-of-the-art regarding the use of LEU fuel for its propulsion reactors. Perhaps that was not the Navy's intent, but it is certainly the perception given by the failure to address nearly two decades of progress by other navies in the use of LEU for propulsion reactors, failing to provide update budget projections, etc. Standing alone, the failure to mention why the French naval model could not be applied to U.S. submarines and aircraft carriers is inexplicable and enough to condemn the Navy's 2014 Report as nonresponsive and largely irrelevant.

However, the 2014 Report raises the possibility that although the Navy's overall conclusion that LEU use is inadvisable may still be the same, advances in fuel designs may significantly alter the cost estimates of the two basic LEU core options the Navy has previously considered: LEU cores in current designs require refueling, and LEU life-of-the-ship cores. Congress, the ultimate decision-maker on these issues, should demand that the Navy now explain its references to advanced fuel technology in its 2014 Report and provide Congress with a thorough current analysis of the merits, demerits, and costs of making the decision to replace HEU cores with LEU cores in future vessels.

The entire subject of naval reactor fuels is closely held confidential information globally. This makes specific recommendations difficult, if not impossible, to make. However, one troubling issue has surfaced in this study that does not appear to be addressed in the literature, or adequately addressed in the Navy's submissions to Congress. The question is whether the Navy's ability to create "life-of-the-ship" cores is technically sound.

In its 1995 Report, the Navy apparently did not consider that the life-of-the-ship fuel integrity problem, even for HEU cores, had been resolved. Long-life fuel integrity was a work in progress and the 1995 Report stated that for aircraft carrier cores "[t]he limiting technical consideration is corrosion of the cladding. Advanced cladding materials are in development and testing with the goal of realizing core lifetimes as long as 45 years."²²⁰ By failing to mention the issue in the 2014 Report it seems that the Navy felt that the fuel integrity issue, at least for HEU cores, was resolved by 2014.

The possibility exists that although the Navy is building life-of-the-ship cores for the *Virginia* class SSNs and the *Ford*-class aircraft carrier, the Navy's solution to the problem may not be adequate. Has the Navy made a non-conservative gamble on life-of-the-ship cores in order to gain an economic benefit? Given the economic pressures on the Navy's shipbuilding programs and the cost savings associated with life-of-the-ship reactor cores, the Navy would have been under considerable pressure to create an adequate life-of-the-ship fuel design.

²¹⁹ Although not explicitly stated at the outset, it should be apparent that conversion of current submarines and aircraft carriers, although theoretically feasible, is highly improbable. What is at issue is what can be done in terms of LEU use for future submarine and carrier designs. Whether there could be enough lead time to implement LEU cores for the *Ohio*-class replacement SSBN(X) is a question that should be addressed.

²²⁰ 1995 Report, 9–10.

How the Navy has resolved the long-term fuel cladding issue, a problem that results primarily from the evolution of gaseous fission products as the fissile/fissionable material burns in the core is not discussed in open literature. Because the Navy has not actually operated life-of-the-ship cores for the anticipated life of the current anticipated life of these vessels (33 years for SSNs, etc.; 45–50 years for aircraft carriers) the issue of whether the Navy has adequately resolved the issue must still be considered open. How did the Navy test its life-of-the-ship fuel design? The answer is that it probably used accelerated testing methodology. Such accelerated testing would surely have involved exposing fuel elements to at least the neutron influence that they would see in the life-of-the-ship setting, putting the fuel elements in a high flux test reactor running at high neutron levels for short periods of time (i.e., running for one year at 10 times the level normally seen in order to simulate 10 years of operation).

However, accelerated aging testing has often failed to be an accurate predictor of real-life performance in other fields, such as aircraft material testing. In part this appears to be due to the fact that metals in particular have age-related microchemical changes that do not appear in the shorter accelerated testing time frames. In addition, although the Navy's experience with reactor core and reactor pressure vessel operational wear is probably among the best in the world (but classified), it should be noted that the civilian power industry has from time to time found unanticipated serious material problems when cores and pressure vessels have been examined during refueling outages.²²¹

Therefore although the Navy claims to adhere to a conservative design philosophy in its nuclear propulsion program, it should be recognized that life-of-the-ship cores may be extending into a somewhat unknown, and perhaps unknowable, area of reactor fuel and fuel cladding performance—arguably the opposite of a conservative approach. This is not to imply that a fuel failure would create a serious public safety hazard, but the possibility that fuel damage such as cladding rupture might appear late in the lifecycle of the life-of-the-ship core would be a disastrous economic problem for the Navy, particularly if it were widespread.

Recommendations

The following are the initial recommendations of this study:

For the United States:

- Because the Navy's 2014 Report has proved to be deficient in a number of ways, Congress should request that the Navy prepare a new report that includes true updates, including cost revisions, on at least the subjects considered in the 1995 Report.
- Congress should request a complete set of briefings on the advanced fuel concept obliquely referred to by the Navy in its 2014 Report and its affect on use of LEU fueled reactors.
- Congress, perhaps working in conjunction with one of the national academies, should support a study by non-Navy, or Navy contractor, experts on the issue of LEU conversion. Such a study would have to have access to all Navy and Navy-contractor material on these issues.
- Congress and/or the Navy should consider how information could be exchanged with the French on their experiences with LEU use in submarines. It should be noted that there is some precedent for such an exchange given our early-program exchanges with the United Kingdom, which included the exchange of design information and access to facilities.
- It is quite possible that the Navy's 1995 and 2014 Reports to Congress do not disclose all of the concerns that the Navy would raise if it were to feel more threatened by the reality of an order to convert to LEU use. Congress would probably be reluctant to force LEU use if there is any argument that a shift to LEU would have a significant negative effect on the Navy's operational capability. Therefore Congress should ask for an expanded assessment of the tactical impacts vis-à-vis potential threats that would be anticipated if the Navy were to unilaterally shift to LEU use.

²²¹ For a discussion of some of these issues in U.S. civilian nuclear reactors, see the U. S. Nuclear Regulatory Commission's Fact Sheet on Reactor Pressure Vessel Issues, available at www.nrc.gov/reading-rm/doc-collections/fact-sheets/prv.html.

- The issue of whether the fuel elements for the Navy's life-of-the-ship cores, which are now only in the early portion of their service life, have been adequately tested should be addressed. This issue should be reanalyzed by the Navy and the results of the Navy's analysis should be reviewed by an independent panel of experts who have access to all the Navy's tests and studies.
- The issue of the long-term health of the Navy's nuclear propulsion program, including its R&D program, needs to be reviewed. Is the country heading into a "graying" area of decline like that experienced by the nuclear weapons complex? Are vital skills, methods, etc., such as refueling technologies, being lost? If so, what can or should be done to address these issues that should be considered at a national level?
- The nuclear propulsion infrastructure should similarly be examined to determine if funding is sufficient for future needs—particularly if LEU design and use were to be undertaken.
- The issue of using LEU fuel for the *Ohio*-class replacement SSBNs should be revisited. Although timing may be critical, the size of the hull of the SSBN should allow for LEU life-of-the-ship cores.

For the International Community:

- A study should be undertaken to fully explore the political ramifications of continued military HEU use on the prospects for a Fissile Material Cutoff Treaty and any potential feedback to the non-weapons military exemption of the Nuclear Nonproliferation Treaty from the continued use of HEU;
- A study should be undertaken to explore whether there could be an international agreement, perhaps reminiscent of the naval construction limitation treaties of the post-WWI period, to eliminate the use of HEU in naval propulsion reactors. Could an agreement be reached that would be verifiable?

Appendix A: Naval Propulsion Reactors of the Various Nations

Appendix A is a table describing the nuclear-powered vessels of the navies of the United States, the Russian Federation, the United Kingdom, France, China, India, Brazil and Argentina. When known, the NATO class and hull number are given. Additional columns include the reactor model, the number of reactors per vessel, the power level of the reactor, the number built, the number in operation in 2014, and the enrichment of the fuel used.

Table A-1. U.S. Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt) or Shaft Horsepower (shp)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Aircraft Carriers						
<i>Enterprise</i> Prototype (NA)	A1W	1	120	1	0	97.3%
<i>Enterprise</i> (CVN-65)	A2W	8	120	1	0	97.3%
<i>Nimitz</i> (CVN-68)	A4W	2	104	10	10	93%–97.3% ^a
<i>Gerald Ford</i> (CVN-78)	A1B	2	~300 ^b	1	1	93.0%
Cruisers						
<i>Long Beach</i> (CGN-9)	C1W	2	40,000 shp, 29.8	1	0	97.3%
<i>Bainbridge</i> Prototype	D1G ^c	2	30,000 shp, 110	1	0	97.3%
<i>Bainbridge</i> (DLGN-25/CGN-25)	D2G ^c	2	30,000 shp, 110	1	0	97.3%
<i>Truxtun</i> (CGN-35)	D2G ^c	2	30,000 shp, 110	1	0	97.3%
<i>California</i> (CGN-36)	D2G ^c	2	30,000 shp, 110	2	0	97.3%
<i>Virginia</i> (CGN-38)	D2G ^c	2	30,000 shp, 110	4	0	97.3%
Submarines						
Research Submarine (NR-1)	NR-1	1	unknown	1	0	97.3%
<i>Tullibee</i> Prototype	S1C	1	10	1	0	97.3%
<i>Tullibee</i> (SSN-597)	S2C	1	10	1	0	97.3%
<i>Nautilus</i> Prototype	S1W	1	13,400 shp, 50	1	0	20.0%
<i>Nautilus</i> (SSN-571)	S2W	1	13,400 shp, 50	1	0	20% ^d
<i>Skate</i> (SSN-578)	S3W	1	7300 shp, 26	4	0	97.3%
<i>Sargo</i> (SSN-583)	S3W	1	7300 shp, 26	1	0	97.3%
<i>Halibut</i> (SSN-587) ^e	S3W	1	7300 shp, 26	1	0	97.3%

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NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt) or Shaft Horsepower (shp)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
<i>Swordfish</i> (SSN-579)	S4W	1	7300 shp, 26	1	0	97.3%
<i>Seadragon</i> (SSN-584)	S4W	1	7300 shp, 26	1	0	97.3%
<i>Skipjack</i> (SSN-585)	S5W	1	78	5	0	97.3%
<i>George Washington</i> (SSBN-598)	S5W	1	78	1	0	97.3%
<i>Thresher/Permit</i> (SSN-593/SSN-594)	S5W	1	78	14	0	97.3%
<i>Ethan Allen</i> (SSBN-608)	S5W	1	78	5	0	97.3%
<i>Lafayette</i> (SSBN-616)	S5W	1	78	9	0	97.3%
<i>James Madison</i> (SSBN-627)	S5W	1	78	10	0	97.3%
<i>Benjamin Franklin</i> (SSBN-640)	S5W	1	78	31	0	97.3%
<i>Sturgeon</i> (SSN-637)	S5W	1	78	37	0	97.3%
<i>Parche</i> (SSN-683)	S5W	1	78	1	0	97.3%
<i>Glenard P. Lipscomb</i> (SSN-685)	S5W	1	78	1	0	97.3%
<i>Seawolf</i> (SSN-21)	S6W	1	220	3	3	93.0%
<i>Seawolf</i> Prototype	S1G	1	unknown	1	0	90.0%
<i>Seawolf</i> (SSN-575)	S2G	1	unknown	1	0	90.0%
<i>Triton</i> Prototype	S3G	1	34,000 shp, 130	1	0	97.3%
<i>Triton</i> (SSRN-586) ^f	S4G	2	34,000 shp, 130	1	0	97.3%
<i>Narwhal</i> (SSN-671)	S5G	1	90	1	0	93.0%
<i>Los Angeles</i> (SSN-688)	S6G	1	148-165 ^g	62	42	93%-97.3% ^a
<i>MARF</i> Prototype ^h	S7G	1	220	1	1	93.0%
SSBN-726 <i>Ohio</i> -class	S8G	1	220	18	18 ⁱ	93%-97.3% ^a
<i>Virginia</i> (SSN-774)	S9G	1	150	10	10	93.0%
<i>Ohio</i> Replacement (SSBN-X)	S1B	1	unknown	14 (Projected)	0	93.0%

Sources: *Jane's Fighting Ships*, (Series Publication); Norman Friedman, *U.S. Submarines Since 1945: An Illustrated Design History* (Annapolis, MD: Naval Institute Press, August 1994); Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *The Nonproliferation Ration Review* (Spring 2001); Norman Polmar and Kenneth J. Moore, *Cold War Submarines: The Design and Construction of U.S. and Soviet Submarines* (Washington, DC: Brassey's, 2004).

Note: Often specific reactor output was not available, in which case the output was calculated using 1 shaft horsepower = .746 watts or 0.000746 MW. The conversion to MWt was calculated using thermal efficiencies of known U.S. naval reactor designs and assuming others were similar.

^a Until the end of U.S. HEU production in 1992, HEU fuel enriched to 97.3% was produced specially for Naval reactors. Following the end of U.S. production, Naval reactor fuel was produced using material from dismantled weapons, enriched to approximately 93%. Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *The Nonproliferation Ration Review* (Spring 2001), available at <http://cns.miis.edu/npr/pdfs/81mahip.pdf>.

^b The out has still not been publicly released but it is believed to be approximately 300 Mwe. See www.world-nuclear.org/info/non-power-nuclear-applications/transport/nuclear-powered-ships/.

- ^c The D1G and D2G reactors were initially designed for Guided Missile Nuclear Destroyer Leaders (DLGs). The first vessel of this class, the *USS Bainbridge*, was redesignated as a Guided Missile Cruiser (CGN-25) in 1975. This is also true for the *USS Truxtun* (CGN-35).
- ^d Although the original *Nautilus* was fueled with 20% U-235, it was subsequently refueled with 40% U-235.
- ^e The *Halibut* was initially designated SSGN-587, as the U.S. Navy's first guided missile submarine. However, the decision to retire the Regulus cruise missile in 1964 made the SSGN platform obsolete at the time. There the *Halibut* was redesignated SSN-587 and it was reassigned to be one of the Navy's highly clandestine spy subs.
- ^f The *USS Triton* (SSRN-586) was the only vessel of her class, a nuclear-powered radar-picket submarine. However, the class was made obsolete in 1962, following development of an air-based radar picket platform and it was converted to an SSN class.
- ^g S6G submarines were initially fueled with D1G-2 cores (148MWt). However, upon refueling, they were replaced with 165 MWt D2W cores.
- ^h Modifications and additions to a reactor facility was an experimental prototype through which an experimental core was installed into a S5W reactor. The facility was sited at the Knoll's Atomic Power Laboratory Kesselring site in Ballston Spa, New York.
- ⁱ Four *Ohio*-class SSBNs were converted to SSGN following the START II Treaty. Conversion started first with the *USS Ohio* in 2002.

Table A-2. Soviet/Russian Naval Reactors

NATO Class/Project Number	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operational 2014	Enrichment (%Wt U-235)
First Generation (PWR)						
<i>November</i> (627, 627Ab)	VM-A	2	70	13	0	5–20% ^a
<i>Echo I</i> (659, 659T)	VM-A	2	70	5	0	5–20% ^a
<i>Hotel</i> (658, 658Mc, 658 Sd, 701e)	VM-A	2	70	8	0	5–20% ^a
<i>Echo II</i> (675, 675K f 675MK,675MKB)	VM-A	2	70	29	0	5–20% ^a
Second Generation (PWR)						
<i>Yankee</i> (667A, 667O, 667 AO, 667AN/09774, 667M, 667AT)	VM-2-4	2	180	34	0	~20%
<i>Delta I</i> (667B)	VM-2	2	155	18	0	~20%
<i>Delta II</i> (667BD)	VM-4 S	2	180	4	0	~20%
<i>Delta III</i> (667BDR)	VM-4 S	2	180	14	1	~20%
<i>Delta IV</i> (667BDRM)	VM-4 SG	2	180	7	6	~20%
<i>Charlie I</i> (670, 670A)	VM-4-1	1	65	11	0	~20%
<i>Charlie II</i> (670M)	VM-4-1	1	65	6	0	~20%
<i>Victor I</i> (671, 671V)	VM-4	2	150	16	0	~20%
<i>Victor II</i> (671RT)	VM-4 P 4T	2	150	7	0	~20%
<i>Victor III</i> (671RTM, 671RTMK)	VM-4A	2	150	26	4	~20%

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NATO Class/Project Number	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operational 2014	Enrichment (%Wt U-235)
Third Generation (PWR)						
<i>Oscar</i> (949)	VM-5 ^b	2	380	2	0	~40%
<i>Oscar II</i> (949A)	VM-5 ^b	2	380	11	6	~40%
<i>Typhoon</i> (941)	VM-5 ^b	2	380	6	3	~40%
<i>Sierra</i> (945)	VM-5 ^b	1	190	2	1	~40%
<i>Sierra II</i> (945)	VM-5 ^b	1	190	2	2	~40%
<i>Akula</i> (971)	VM-5 ^b	1	190	15	10	~40%
Fourth Generation (PWR)						
<i>Yasen</i> (885)m	^c	1	190	1	1	~40% ^c
<i>Borei</i> (955)n	VM-5	2	380	5	1	~40%
Research and Prototype Submarines (PWR)						
<i>Mike</i> (685)	OK-650 B	1	190	1	0	21–45% ^d
<i>Paltus</i> (1851)p, X-ray (10831)q	—	1	10	4	2	^e
<i>Uniform</i> (1910)r	—	1	15	3	3	^e
Metal-Cooled Reactors (all generations)						
(<i>November-class hull</i>)/ZhMT (645)	RM-1	2	73	1	0	90% ^f
<i>Papa</i> (661)	—	1	177	1	0	90% ^f
<i>Alfa</i> (705, 705K)	VM-40	2	155	7	0	90% ^f
Military Surface Nuclear Vessels						
<i>Kirov</i> (missile cruiser)/1144, 1144.2	KN-3	2	300	4	1	55–90% ^d
<i>Titan</i> /1941	VM-16/ KN-3 (OK-900 B)	2	171	1	0	55–90% ^d
Icebreakers and Floating Nuclear Power Plants (all generations)						
<i>Lenin-class</i> Icebreaker	OK-150	3	90	1	0	5%
Reconstructed <i>Lenin</i> Icebreaker	OK-900	2	159	1	0	55–90%
<i>Arktika</i>	OK-900 A	2	171	2	1	55–90%

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NATO Class/Project Number	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operational 2014	Enrichment (%Wt U-235)
<i>Rossiya</i>	OK-900 A	2	171	3	3	55–90%
<i>Taimyr & Vaigatch</i>	KLT-40	1	171	2	2	90% ^a
<i>Sevmorput</i>	KLT-40 M	1	135	1	1	90% ^a
Floating Nuclear Power Plant	KLT-40 S	2	150	Proposed	NA	18.6% ^h

Sources: IHS Jane's *Fighting Ships 2013–2014*, 116th ed., ed. Commodore Stephen Saunders (Englewood, CO: IHS Global Inc., 2013); Nils Bohmer, Alexander Nikitin, Igor Kurdik, Thomas Nilsen, Michael H. McGovern, and Andrey Zolotov, *The Arctic Nuclear Challenge* (Oslo, Norway: Bellona Foundation, 2001), known as the 2001 Bellona Report.

^a Ole Reistad, Morten Bremer Mærli, and Nils Bøhmer, "Russian Naval Nuclear Fuel and Reactors," *The Nonproliferation Review* 12, no.1 (2005), 173. This conclusion is substantiated by several publications addressing VM-A spent fuel in the context of proper storage, and, in one case, theft. Additional evidence exists that seems to indicate that while the maximum enrichment of First Generation reactors did not exceed 20%, various enrichment levels were used in First Generation designs.

^b There is a great deal of inconsistency regarding the nomenclature for Third Generation reactors systems. The general consensus is that the Third Generation Soviet reactors systems contained VM-5 reactors with OK-650 cores.

^c Reactor is reported to be of new design with a 25-year core-life.

^d Pavel Podvig, "History of Highly Enriched Uranium Production in Russia," *Science & Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives* 19, no.1 (2011), 46–67.

^e No information is known on the reactor type or enrichment used in Russia's very-small research submarines.

^f Based on an HEU obtained in Kazakhstan intended for the Alfa LMR program, it is suspected that all the LMR reactors were HEU.

^g The best information obtained regarding the KLT-40 Icebreaker reactor was provided to the Norwegian government in 1991 in preparation for a port visit of the NS Sevmorput to Norway. Although the *Taimyr* and *Vaigatch* are not expected to be identical to the Sevmorput, it provides the best place to start.

^h Christine Egnatuk, "Russia: Icebreaker Ships and Floating Reactors." In *Nuclear Terrorism and Global Security the Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013).

Table A-3. UK Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Submarines						
<i>Vanguard</i> SSBN	RR PWR 2	1	148	4	4	93%
<i>Trafalgar</i> SSN	RR PWR 1	1	78	7	5	93%
<i>Astute</i> SSN	RR PWR 2	1	148	5	2	93%
<i>Swiftsure</i> SSN	RR PWR 1	1	78	6	0	93%
<i>Resolution</i> SSBN	RR PWR 1	1	78	4	0	93%
<i>Valiant</i> SSN	RR PWR 1	1	78	2	0	93%
<i>Churchill</i>	RR PWR 1	1	78	3	0	93%
<i>Dreadnought</i> SSN	S5W	1	78	1	0	93%

Table A-4. French Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Aircraft Carriers						
<i>Charles De Gaulle</i> CVN	K15	2	150 MW	1	1	7.5%
Submarines						
<i>Suffren</i> SSN (<i>Barracuda</i>)	DCNS/ AREVA	1	50 MW	0 ^a	0	5% ^b
<i>Rubis Amethyst</i> SSN	CAS	1	48 MW	6	6	7.5%
<i>Le Triomphant</i> SSBN	K-15	1	150 MW	4	4	7.5%
<i>Le Inflexible (Redoubtable)</i> SSBN	unknown	1	unknown	6 ^c	0	3–90% ^d
Prototype <i>a Terre</i> (PAT)	PAT	1	unknown	1	0	3–5% ^e
<i>Q.244</i>	Q.244	^f	^f	0	0	0.7% Natural Uranium ^g

^a None of the *Barracuda*-class SSNs have been built yet. However, six are planned for construction to replace the *Rubis*-class.

^b Rebecca Ward, “USA and France: Naval Propulsion.” In *Nuclear Terrorism and Global Security the Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013), 189.

^c The *Le Inflexible*-class was renamed from the *Le Redoubtable*-class following the retiring of the flagship class.

^d Based on the timeline of French submarine construction and the timeline of HEU production at the Pierrelatte enrichment, it is likely the first few vessels of the *Redoubtable*-class were powered by LEU, but were subsequently replaced with HEU cores once it was available.

^e Given the uranium supply agreement with the United States, which limited use of the fuel for non-naval uses, it is likely that the original fuel provided by the United States was 3–5% enriched, as would be used in normal commercial reactors.

^f The first attempt to construct a naval reactor using natural uranium was unsuccessful. The *Q.244* was eventually commissioned at a conventionally powered ballistic missile experimental platform.

^g The first French attempt at a naval reactor used natural uranium given that France did not possess enrichment technology at the time.

Table A-5. Chinese Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Submarines						
Unnamed SSN (Type 095)	PWR	UNK	UNK	2	0 ^a	3–5%
<i>Jin</i> SSBN (Type 094)	PWR	2	150 MW	4	4	3–5%
<i>Xia</i> SSBN (Type 092)	PWR	1	90 MW	1	1 ^b	3–5%
<i>Shang</i> SSN (Type 093)	PWR	2	150 MW	3	2 ^c	3–5%
<i>Han</i> SSN (Type 091/091G)	PWR	1	90 MW	5	3	3–5%

^a Sea trials commenced in 2011.

^b According to *Jane's Fighting Ships 2013–2014*, the status of the *Xia*-class SSBN is uncertain following its refit in 1998.

^c Although the third of its class was reported launched in 2012, it is not yet known to be operational.

Table A-6. Indian Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Submarines						
<i>Arihant</i> SSBN	unknown	1	82.5 MW	1 ^a	0	40% ^b
<i>Schuka-B</i> SSN (Project 971 <i>Akula</i>)	VM-5 ^c	1	190 MW	1	1	40% ^d

^a A second vessel of the class is reported to be in progress.

^b “India” in *Jane's Fighting Ships 2013–2014*, 116th ed., ed. Commodore Stephen Saunders (Englewood, CO: IHS Global Inc., 2013).

^c The first Indian SSN was leased to the Indian Navy from Russia. The weapons and operations areas of the ship are controlled by Indian crew.

^d See specifications for the VM-5 reactor in the Soviet/Russian Naval reactors section of this appendix.

Table A-7. Brazilian Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
Naval Reactor Prototype	2131-R	1	Unknown (50 Mwe)	1	In Design	18–19% ^a

^a Togzhan Kassenova, *Brazil's Nuclear Kaleidoscope: An Evolving Identity* (Washington DC: Carnegie Endowment for International Peace, 2014), 29.

Table A-8. Argentinian Naval Reactors

NATO Class (Class Hull Number)	Reactor Model	Number of Reactors	Power (MWt)	Number Built	Number Operation 2014	Enrichment (%Wt U-235)
TBD ^a	CAREM	1 (Under Construction)	100	0	0	3.40%

^a The CAREM reactor, which is projected to be a prototype for an Argentinian naval reactor, is in construction.

Appendix B: Submarine Power Requirements

In this appendix publicly known information about submarines of the world has been collected in order to get some indication of the power requirements for the various submarine types.

Publicly available information on the displacement of the various submarines and their hull lengths, beam, speeds, etc. was collected and stored in an Excel spreadsheet.²²² Various calculations were then made in the spreadsheet in order to ultimately obtain an idea of the power required to drive the submarine at its reported top speed.

Initially, using a realistic assumption for sea water density, the reported displacement was used to obtain an overall volume V for the submarine. It was then assumed that the submarine was a right circular cylinder of volume V and length l , and a cross-sectional area A in square meters was calculated by dividing the volume by the length l as shown below.

$$A = \frac{V}{l}$$

Using the assumed circular area an effective radius, circumference and diameter was obtained using simple circle geometry as follows:

$$r = \sqrt{(A/\pi)}$$

Where r = square root of the quantity A divided by π . The effective diameter ($2 \times r$) could then be compared to the reported beam and, as can be seen from the table, the comparison was generally good, indicating that the method, although idealized, was a good first approximation for an ideal submarine.

In order to determine the power required to push this cylinder (submarine) at reported speeds through seawater, a standard engineering relationship for drag force was used to calculate the force of drag on an object moving through a fluid. The drag force, F_D , was calculated using the following equation:

$$F_D = \frac{1}{2} \rho v^2 C_d A$$

Where F_D is the drag force in newtons, ρ is the density of the water (1020 kg per cubic meter), v is the velocity of the submarine, C_d is the coefficient of drag dependent on the shape of object moving through fluid (assumed to be 0.82 for the calculations—the normal assumption for the drag coefficient on a long cylinder), and A is the area of the plane perpendicular to the direction of motion (the circular frontal area of the cylindrical submarine).

Power required for the submarine to overcome the drag force of the water was then obtained by noting the relationship that power is the product of force and velocity.

The resulting calculations displayed in the table give a useful indication of the relative power requirements of the various types of submarines.

It is interesting to note that often the reported power of the nuclear submarines' propulsion plant(s) is far more than that calculated to be necessary for the reported maximum speed. This is to be expected for several reasons.

²²² Note that there may be minor variations in the numbers between Appendix A and this appendix. This is due typically to the use in some instances of different references. No attempt was made to determine which references are the most accurate because the purpose of this appendix is to provide a semi-qualitative assessment.

Even if the drag calculations were perfectly accurate, the power the reactor would need to produce would be much higher than the power required for maintaining a specific speed due to the fact that the system is far from 100% efficient. Also, for some submarines (particularly those of the Russian Federation) the reported power is the total of two redundant reactors and the propulsion power available to the drivetrain is less than the total power available. Variations would also be expected based on the type of drivetrain (steam turbine direct, turbo electric, propulsor, etc.), streamlining factor, etc. Finally, for other nuclear submarines this may be due to the fact that most nations probably underreport the maximum speed of their submarines. In those cases the fact that the calculated power is sometimes significantly lower than the power reported may indicate that the submarine is capable of significantly higher top speeds.

It should also be noted that the drag equation is very sensitive to the velocity of the submarine. The drag force increases as the square of the velocity assuming all other factors stay the same. What this means is that, for example, if the maximum speed reported was 25 knots, the drag equation would yield a power requirement that would be only approximately 51 percent of the power required to drive the submarine if its real maximum speed were 35 knots. Of course, as mentioned above, there are a number of other factors at play (e.g., hull shape, streamlining, etc.) that would also increase or decrease drag.

Table A-9. Comparison of Submarine Power Requirements

Country	Class	Type	Submerged Displacement (Tonnes)	Diameter (m)	Beam	Submerged Speed (knots)	Power (MW)	Length	Power Req. (MW)
Argentina	TR-1700	Diesel-Electric	2264	6.5	7.3	25.0	unknown	66	29.9
	Type 209/1200	Diesel-Electric	1285	5.4	5.5	21.5	3.7	55.9	12.8
Australia	Collins	Diesel-Electric	3353	7.3	7.8	20.0	19.0	77.8	19.2
Brazil	Tupi	Diesel-Electric	1550	5.6	6.2	21.5	10.6	61.2	14.1
China	Xia Type 092	Nuclear	7000	8.5	10	22.0	58.0	120	34.7
	Jin Type 094	Nuclear	11000	10.2	unknown	20.0	unknown	133	36.9
	Han Type 091	Nuclear	5550	8.4	10	25.0	90.0	98	49.4
	Shang Type 093	Nuclear	6000	8.4	11	30.0	unknown	107	84.5
	Yuan Type 041	Diesel-Electric	3600	7.7	unknown	20.0	unknown	75	21.4
	Song Type 039/039G	Diesel-Electric	2250	6.1	8.4	22.0	18.2	74.9	17.9
	Golf Type 031	Diesel-Electric	3553	6.7	8.2	12.0	16.1	98.4	3.5
	Ming Type 035	Diesel-Electric	2113	5.9	7.6	18.0	7.6	76	9.1
	Kilo	Diesel-Electric	3950	8.2	9.9	10.0	7.1	74	3.0
France	Agosta *D	Diesel-Electric	1760	5.7	6.8	20.5	7.6	67.6	12.5
	Redoutable	Nuclear	8940	9.3	10.6	25.0	12.0	128.7	60.6
	Rubis	Nuclear	2670	6.8	7.6	25.0	48.0	72.1	32.3
	Le Triomphant	Nuclear	14335	11.4	12.5	25.0	150.0	138	90.6
France/Spain	Scorprene	Diesel-Electric	1590	5.6	unknown	20.0	unknown	63.5	11.2

Replacing Highly Enriched Uranium in Naval Reactors

Country	Class	Type	Submerged Displacement (Tonnes)	Diameter (m)	Beam	Submerged Speed (knots)	Power (MW)	Length	Power Req. (MW)
Germany	U-206	Diesel-Electric	498	3.6	4.6	17.0	2.0	48.6	2.8
	U-209	Diesel-Electric	1290	5.4	6.2	21.5	10.1	56	12.8
	U-212A	Diesel-Electric	1830	6.4	7	20.0	6.1	55.9	14.6
	U-214	Diesel-Electric	1980	6.2	6.3	20.0	15.5	65	13.6
India	Shishumar	Diesel-Electric	1850	6.0	6.5	22.0	10.6	64.4	17.1
	Arihant	Nuclear	6600	8.9	15	34.0	83.0	104	139.2
	Akula I	Nuclear	12770	12.0	13.6	28.0	190.0	110.3	141.9
	Akula II & 3	Nuclear	13800	12.3	13.6	35.0	190.0	113.3	291.5
	Sindhughosh	Diesel-Electric	3076	7.3	9.9	17.0	10.2	72.6	11.6
Israel	Dolphin	Diesel-Electric	1900	6.4	6.8	20.0	12.4	57.3	14.8
Iran	Kilo	Diesel-Electric	3950	8.2	9.9	10.0	7.1	74	3.0
	Ghadir	Diesel-Electric	120	2.3	3	unknown	unknown	29	0.0
	Nahang	Diesel-Electric	400	Not calculated	unknown	unknown	unknown	unknown	unknown
Italy	Sauro	Diesel-Electric	1631	5.6	6.8	20.0	9.9	63.9	11.4
Japan	Soryu	Diesel-Electric	4200	7.9	9.1	20.0	6.0	84	22.3
	Oyashio	Diesel-Electric	3000	6.8	8.9	20.0	8.2	81.7	16.4
	Yuushio *D	Diesel-Electric	2730	6.7	9.9	20.0	5.1	76	16.0
Netherlands	Walrus	Diesel-Electric	2740	7.1	8.4	20.0	14.1	67.7	18.1
Norway	Ula	Diesel-Electric	1150	4.9	5.4	23.0	4.0	59	13.2
Russia	Lada	Diesel-Electric	2700	6.8	7	20.0	5.2	72	16.7
	Delta IV	Nuclear	18200	11.7	12.3	24.0	360.0	166	84.6
	Delta III	Nuclear	18200	12.1	11.7	24.0	178.0	155	90.6
	Typhoon	Nuclear	33800	15.8	23	25.0	380.0	170	173.4
	Borei	Nuclear	24000	13.7	13.5	26.0	190.0	160	147.2
	Yasen	Nuclear	13800	12.5	12	31.0	unknown	111	206.7
	Sierra I	Nuclear	8100	9.7	11.5	34.0	190.0	107	166.1
	Sierra II	Nuclear	9100	10.1	11.5	32.0	190.0	111	150.0
	Akula	Nuclear	9100	10.1	13.5	35.0	190.0	111.7	195.0
	Alfa	Nuclear	3680	7.5	9.5	42.0	155.0	81	187.9
	Victor III	Nuclear	7000	9.0	10.8	30.0	144.0	107.2	98.4

Replacing Highly Enriched Uranium in Naval Reactors

Country	Class	Type	Submerged Displacement (Tonnes)	Diameter (m)	Beam	Submerged Speed (knots)	Power (MW)	Length	Power Req. (MW)
Russia (<i>con't</i>)	Victor II *D	Nuclear	7190	9.4	10.8	31.7	144.0	101.8	125.6
	Victor I *D	Nuclear	6085	9.1	11.7	32.0	144.0	92.5	120.3
	Oscar II	Nuclear	18300	12.2	18.2	28.0	380.0	154	145.6
	Oscar I *D	Nuclear	16500	11.9	18.2	28.0	380	145	139.4
	Kilo	Diesel-Electric	3076	7.2	9.9	17.0	5.4	73.8	11.4
South Korea	Chang Bogo	Diesel-Electric	1285	5.4	6.2	22.0	11.4	56	13.6
Sweden	Sjoormen	Diesel-Electric	1400	5.9	6.1	20.0	6.3	51	12.3
	Nacken	Diesel-Electric	1085	4.9	5.7	20.0	1.3	57.5	8.4
	Vastergotland	Diesel-Electric	1143	5.4	6.06	20.0	3.3	48.5	10.5
	Gotland	Diesel-Electric	1494	5.6	6.2	20.0	9.7	60.4	11.0
United Kingdom	Upholder	Diesel-Electric	2455	6.6	7.2	20.0	3.0	70.26	15.6
	Swiftsure *D	Nuclear	4900	8.6	9.8	30.0	78	82.9	89.1
	Vanguard	Nuclear	15900	11.5	12.8	25.0	41.0	149.9	92.5
	Trafalgar	Nuclear	5300	8.8	9.8	29.0	78	85.4	84.5
	Astute	Nuclear	7200	9.6	10.7	29.0	148	97	101.1
United States	Virginia	Nuclear	7300	0.0	10.3	32.0	150	114.9	114.9
	Seawolf	Nuclear	9142	10.3	12.9	35.0	220	107.6	203.3
	Los Angeles	Nuclear	6297	8.4	10.06	32.0	148.0	110.34	104.4
	Ohio	Nuclear	18750	11.7	12.8	25.0	220.0	170.69	95.8



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