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The Feasibility of Ending HEU Fuel Use in the U.S. Navy

Since September 11, 2001, the U.S. government has sought to remove weapons-useable highly enriched uranium (HEU) containing 20 percent or more uranium-235 from as many locations as possible because of concerns about the possibility of nuclear terrorism.

President Barack Obama worked to make this effort a global priority with biennial nuclear security summits between 2010 and 2016.

The primary focus of this HEU cleanout strategy has been on replacing HEU civilian research reactor fuel and uranium "targets" used in the production of medical radioisotopes with non-weapons-usable low-enriched uranium (LEU) fuel and targets. Eliminating the use of HEU in naval fuel was not on the agenda. Yet, naval reactors account for more than half of global HEU use and most of the global stockpile of HEU for nonweapons use.[1] As the phase-out of other uses continues, naval reactors will become increasingly dominant among nonweapon users of HEU unless actions are taken to convert them as well.

Given the focus after the September 11 attacks on reducing the possibility of nuclear terrorism, prioritizing the elimination of civilian uses of HEU was understandable. The security at most civilian sites is typically much lower than at sites where naval fuel is fabricated and stored, but the continued use of HEU for nonweapons purposes has implications for nuclear weapons proliferation.

The proliferation implications of the acquisition of nuclear-powered military vessels by non-nuclear-weapon states has been a cause of concern for almost 30 years.[2] Yet, the nuclear Nonproliferation Treaty (NPT) allows non-nuclear-weapon states to produce HEU for naval reactor fuel. Furthermore, the International Atomic Energy Agency (IAEA) safeguards agreement permits them to remove HEU from safeguards for "non-peaceful activities" other than nuclear explosives.[3]

Nonintrusive safeguards for the military naval nuclear fuel cycle have been proposed to address this loophole.[4] Whether non-nuclear-weapon states would accept such additional "discriminatory" safeguards is uncertain. Fortunately, nuclear submarines are so costly that, although some non-nuclear-weapon states have signaled their intention to build or acquire them, none has done so—yet. The example of HEU use established by the U.S. Navy and the three other navies that use HEU fuel (India, Russia, and the United Kingdom) could be used by any non-nuclear-weapon state-party to the NPT, however, to legitimize acquisition of HEU – mostly likely through indigenous domestic production – and thereby a nuclear weapons option. In fact, the head of the Atomic Energy

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Organization of Iran played that card at the height of the confrontation over Iran's uranium-enrichment program, just before Iran's 2013 election brought to power a leadership more interested in making a deal.[5]

Thus, although the primary rationale for eliminating HEU in civilian use has been the danger of nuclear terrorism, the primary rationale for eliminating HEU as a naval reactor fuel is to strengthen the nonproliferation regime. Furthermore, the inability to divert HEU from naval fuel cycles would greatly simplify the verification of a fissile material cutoff treaty.[6]

Thus far, discussion of shifting U.S. naval reactors to use LEU fuel has been driven by the interest of a few members of Congress.

Conceptual Plan

The U.S. Navy accounts for about 60 percent of global naval HEU use today, or about 2.5 tons, enough for 100 nuclear weapons, each year. A July 2016 report to Congress by the Office of Naval Reactors within the National Nuclear Security Administration (NNSA), a semiautonomous unit of the Department of Energy, raised the possibility of converting at least U.S. aircraft carriers to using LEU fuel. The report sketched out a $1 billion, 15-year plan to do irradiation and production tests on a new LEU fuel design.[7] The office believes that this fuel could replace the weapons-grade HEU fuel currently used by U.S. aircraft carriers. According to the report, a minimum of an additional 10 years would be required to build a land-based prototype reactor and a fuel production line. The whole program therefore would take at least 25 years before the first LEU core could be loaded into an aircraft carrier.

The report argues that the new LEU fuel is not suitable for submarines because it could not be used to build lifetime submarine cores without a costly increase in submarine size. This conclusion is not obvious. Also, the priority that the U.S. Navy has placed on achieving lifetime cores can be questioned. Among the six countries that deploy nuclear submarines, only the United States and the UK, which is dependent on the United States for naval reactor technology, have made it a priority to develop lifetime cores.

LEU fuel is already used in Chinese and French naval reactors. Little is known about China's technology, but France has been relatively open about the conversion of its navy from HEU fuel to LEU fuel starting more than 30 years ago.

The depth of U.S. nuclear naval expertise accumulated over the past seven decades is unsurpassed, including more than 30 different reactor designs, an excellent safety record, and a steady increase in the uranium density of naval fuel. Given this expertise, it should be possible for the Office of Naval Reactors to begin to produce LEU cores for all existing U.S. aircraft carriers and for newly designed U.S. submarines within about 20 years.

In any case, Congress, the White House, and the leaderships of the departments of Defense and Energy need more input before taking the decision on whether to support the proposed program or a more ambitious program that would be aimed at ending completely the production of naval HEU fuel in about two decades. During the summer of 2016, JASON, an independent group of technical defense consultants, conducted a classified review of the Office of Naval Reactors proposal. Hopefully, an unclassified summary of the JASON report will be made available. In the meantime, this article is an attempt to provide a critical, unclassified analysis based on publicly available information.

Congressional Prodding

Thus far, discussion of shifting U.S. naval reactors to use LEU fuel has been driven by the interest of a few members of Congress. The first expression of interest appeared in the National Defense Authorization Act for fiscal year 1995 as a request for a report on the use of LEU fuel instead of HEU fuel for naval nuclear reactors.

The response from the Office of Naval Reactors was negative: "[T]he use of LEU in U.S. naval reactor plants is technically feasible, but uneconomic and impractical."[8]

Two decades later, however, a request in the fiscal year 2013 National Defense Authorization Act for an update elicited a more positive response from the office. "[R]ecent 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." The report added that "[d]evelopment of an advanced fuel system would help maintain the unique naval nuclear technology base.... Once ongoing new ship design work is complete, it will not be practical to sustain all of the [Office of Naval Reactors] unique technology capabilities or develop an advanced fuel system without other sources of funding."[9]

The office therefore was proposing a deal: It would examine the option of developing LEU fuel to convert ships using HEU fuel in exchange for funding that would sustain its fuel development team and infrastructure until it is time to develop the next new naval propulsion reactor.

Congress responded in the fiscal year 2016 National Defense Authorization and energy and water appropriations acts with $5 million and a request for a research and development plan. In its 2016 report, the NNSA responded with a plan to develop and test the advanced LEU fuel and build a laboratory-scale production

Chris Oxley/Huntington Ingalls Industries

The $12.9 billion USS *Gerald R. Ford* is the lead ship in a new class of aircraft carriers powered by two nuclear reactors using highly enriched uranium fuel. Already about two years behind schedule, the U.S. Navy's costliest warship was scheduled for delivery earlier this year but is facing further delays amid Pentagon questions about the performance of key systems.

line. The LEU fuel would be enriched to 19.75 percent uranium-235 (U-235), just below the 20 percent threshold where enriched uranium is defined to be HEU and weapons usable.[10] The HEU currently used in U.S. naval fuel is enriched to 93 percent and was originally produced for use in Cold War nuclear warheads.

If funded by Congress, the R&D program would be launched in fiscal year 2018 with a 15-year budget that would average about 4 percent of the Office of Naval Reactors' fiscal year 2016 budget level.[11]

Proposed Program

In the preface to the 2016 report, the current director of the Office of Naval Reactors, Admiral James Caldwell, observes that the plan has "the potential to deliver a fuel that might enable an aircraft carrier reactor fueled with LEU in the 2040s [but that] the fuel is unlikely to enable converting current life-of-ship submarine reactors to LEU."

The U.S. Navy currently has 10 nuclear-powered Nimitz-class aircraft carriers in operation. The USS *Gerald R. Ford*, the lead ship of a new class of aircraft carriers, is in precommissioning status. The nuclear submarine fleet currently numbers 75. Five new Virginia-class attack submarines are under construction, and a new class of ballistic-missile submarines, the Columbia class, is being designed for production beginning in fiscal year 2021.[12] Each of the aircraft carriers has two propulsion reactors that are much more powerful than the single reactors that power the submarines. The aircraft carriers are refueled once in the middle of their 50-year design lives.

The latest generation of U.S. attack submarines, the Virginia-class, however, is equipped with cores designed to propel them for their entire 33-year design lives. The cores of the Columbia-class ballistic missile submarines also are being designed to propel them for their full (42-year) design lives. The basis for the Office of Naval Reactors' conclusion that U.S. nuclear submarines could not be converted to LEU use was that LEU cores of the same size as the current HEU cores would not provide enough energy to last a submarine's lifetime.

Advantages and Disadvantages

The pursuit of lifetime cores is a U.S. design choice justified by the fact that, in the past, the lengthy process of refueling has reduced U.S. submarine availability. The UK, whose submarines are based on U.S. technology and fueled by U.S. HEU, has made the same choice.

The first U.S. nuclear submarines had reactor compartment hatches to facilitate refueling operations,[13] but the United States and UK abandoned refueling hatches in later designs. It therefore became necessary to cut open the submarine hulls to access the reactors and then carefully weld the hulls shut again after refueling. This was a difficult process, requiring extreme quality control to maintain the strength of the hull structure. According to the 1995 report of the Office of Naval Reactors, refueling added eight to 10 extra months in dry dock to a long engineering overhaul.

Refueling French submarines, which are equipped with hatches above the reactor compartment, takes weeks at most.[14] The U.S. Navy has not explained publicly what operational advantages are achieved by removing refueling hatches from its nuclear submarines. Diving depth and quietness have been mentioned, but hatches can be designed so that they are no weaker than other parts of the hull. Indeed, the United States has installed large hatches for other purposes, most notably the three rapid-replenishment logistic hatches on Ohio-class submarines.[15] The submarine deck typically covers the seams associated with the hatches so that they do not create turbulence and noise. One of France's oldest Rubis-class nuclear attack submarines was quiet enough so that, in a war game in 2015, it reportedly "sank" a U.S. aircraft carrier and a number of its escort vessels.[16]

France and Russia and possibly China refuel their submarines regularly. France, which has been operating LEU-fueled naval reactors for more than 30 years, refuels every seven to 10 years during its submarines' general engineering overhauls. In its new Suffren-class submarines, average fuel enrichment has been reduced to less than 6 percent by increasing the volume of the core without increasing the mass or volume of the reactor.[17] Using LEU fuel of commercial-level enrichment avoids a cost that the United States will face when its current supply of excess Cold War HEU runs out and it has to build a special enrichment plant to produce either HEU or 19.75 percent-enriched LEU for its naval reactors.

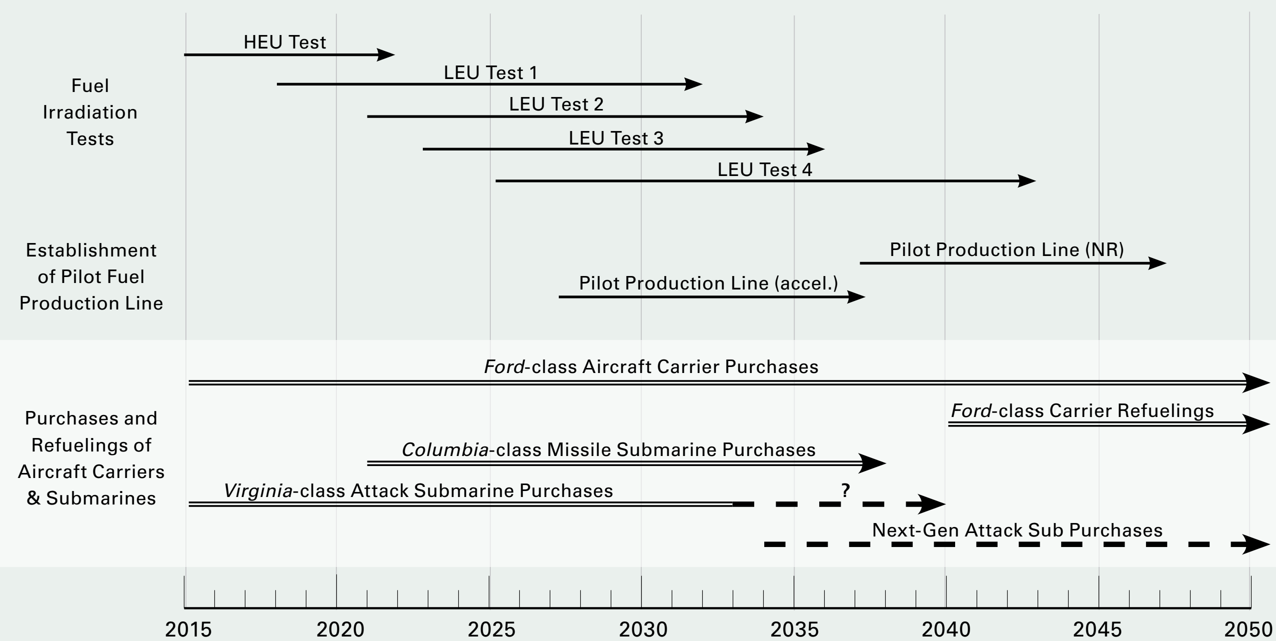
Although further optimization could lead to a Suffren-class submarine core life of 20 years, hardware upgrades and required maintenance require a long overhaul every 10 years in any case, and refueling does not significantly impact the duration of the overhauls. Visual and ultrasonic inspection of the reactor pressure vessels and their primary piping can take up to three months, but are done in parallel with other operations conducted at each long overhaul.[18] To isolate the reactor work from work on other parts of the submarine, a mobile workshop is hermetically sealed to the hull above the reactor compartment.[19]

When problems occur in the nuclear propulsion systems of U.S. and UK submarines, the absence of a refueling hatch can result in long outages. Repairing a faulty weld in piping near the reactor of a Virginia-class submarine has kept the submarine in dry dock for two years thus far, and three other submarines may have the same problem.[20] Discovery of a problem in the fuel used in UK ballistic missile submarines will require the replacement of the lifetime core of at least one and perhaps all of them.[21]

Finally, lifetime cores will only last the lifetime of a submarine if the submarine is kept on a strict energy budget. This issue came up in 2003 when the director of the Office of Naval Reactors informed Congress that the increased fraction of time at sea for U.S. attack submarines and the increased transit speeds to their stations that had been required since September 11, 2001, could substantially reduce the longevity

Figure 1: Timeline for Proposed Research, Development, and Production of LEU Fuel

Top. Timeline for research and development of LEU fuel as proposed by Department of Energy's Office of Naval Reactors (NR) and a 10-year "accelerated" timeline proposed by the authors for the final stage of establishing a fuel production line. **Bottom.** Timelines for the purchases (commencement of construction) and refuelings of Ford-class aircraft carriers and for the purchases of Virginia-class attack submarines, Columbia-class ballistic-missile submarine and of a follow-on class of attack submarines tentatively scheduled to be purchased starting in 2034. The Office of Naval Reactors proposes to use the new LEU fuel in Ford-class aircraft carriers. The authors propose that, in addition, the next attack submarine have a reactor designed to use LEU fuel.



Source: U.S. Energy Department Office of Naval Reactors of Virginia-class submarines.[22]

The LEU fuel design being considered by the Office of Naval Reactors would contain a higher density of uranium than current HEU fuel but a lower density of the chain-reacting isotope, U-235, because of its lower enrichment. The 2016 report states that "[a]n LEU-fueled submarine with this [new] fuel is expected to require at least one refueling, or the reactor (and hull) would need to be increased in size correspondingly."

The "at least one refueling" statement, i.e., at least two cores in the lifetime of the submarine, gives a measure of the increase in the uranium density of the proposed new LEU fuel because the report states that if LEU were substituted for HEU in the existing lifetime cores of Virginia-class submarines, they would have to be refueled "as many as three times," or up to four cores in the lifetime of a submarine. The 1995 report made the same statement and added that a lifetime LEU core would have three times the volume of an HEU core at the same level of technology. On the basis of these statements, the new higher-density fuel presumably would make possible an LEU lifetime core with a volume only twice that of the current HEU lifetime cores.

The Office of Naval Reactors judges that the reactor pressure vessels in Ford-class aircraft carriers could accommodate LEU cores with the new higher-density fuel large enough to keep their refueling frequency to one refueling at midlife but that current submarine reactors could not accommodate lifetime LEU cores. More controversially, however, the report argues that if U.S. submarines were designed with reactor pressure vessels large enough to accommodate lifetime LEU cores, the submarine hulls would have to be made larger, which would increase their costs significantly. The Office of Naval Reactors made a similar claim in its 1995 report, in which it asserted that an LEU lifetime core with triple the volume of the HEU core of a Virginia-class submarine would require an increase in the hull diameter and its displacement by about 3 feet and 12 percent, or 1,000 tons, respectively.

These assertions are questionable because the reactor cores are very small in comparison to the submarines that they power. The hull diameter of the smallest U.S. nuclear submarine currently in production, the Virginia-class, is about 10 meters, while the cavity in the M-140 cask that the Navy uses to ship spent submarine fuel is only 1.2 meters high, which makes that an upper bound on the height of the core.[23] Increasing each dimension by a factor of 1.26 would double the volume. If the height of the existing cores were 1.2 meters, doubling their volumes in such a way would increase their heights by 0.3 meters. It is possible that the reactor vessel might have to be increased in diameter, but it is difficult to believe that its internals and control rod system could not be reconfigured to allow a small increase in core height without forcing an increase in the submarine's hull diameter. Alternatively, the core volume could be doubled without increasing its height by simply enlarging its diameter by a factor of 1.41. The challenge of accommodating larger cores within the larger hulls of U.S. ballistic missile submarines would be less.

An important revelation in the 2016 Office of Naval Reactors report is that irradiation tests of the new fuel design with HEU had already begun in fiscal year 2015.[24] Indeed, it states that the decision on whether to do irradiation tests with LEU beginning in fiscal year 2022 would be based primarily on the evaluation of the HEU irradiation tests. Yet, because an LEU lifetime core is approximately two times larger, its fuel would only have to demonstrate that it performed well up to about half the irradiation level of the HEU core, measured in terms of fissions per cubic centimeter. Therefore, the new fuel design possibly could be useable for LEU fuel but not HEU fuel. On the other hand, if the tests were successful up to the irradiation level that would be required for an HEU core, the United States would have a choice of an LEU core or a more compact HEU core. In that case, the decision on whether to use the new fuel design with LEU fuel for nonproliferation reasons or the higher-performance HEU cores would depend on the priorities of future U.S. governments. The enacted fiscal year 2016 authorization and appropriation bills make clear, however, that congressional support for this program is based on the belief that the new fuel design should be used with LEU fuel.

[T]he decision on whether to use the new fuel design...would depend on the priorities of future U.S. governments.

Deployment Costs

The Office of Naval Reactors report estimates that production and testing of advanced cores would require at least an additional 10 years beyond the 15-year R&D program and cost several billion dollars. The projected costs include $600 million for a new fuel production line and "[s]everal billion dollars" for a new land-based reactor for testing a prototype core.

On average, this program would cost several times as much annually as the R&D program. The office also estimates that LEU cores will cost 25 to 35 percent more than HEU cores.

Congress might balk at these costs. A careful examination of the estimates to determine whether they are justified will be important.

Land-based prototype reactor. The Office of Naval Reactors once had a number of prototype reactors for training and fuel testing. It currently has only one, originally built as a prototype of the S8G reactor that powers the current generation of Ohio-class ballistic missile submarines. About $1.6 billion is currently being spent to overhaul and modernize the reactor and to manufacture a new core of the type that is to be used in the next-generation U.S. ballistic- missile submarine.[25] The refurbishment of the S8G, to be completed in fiscal year 2021, will allow it to operate for another 20 years, until fiscal year 2041.[26]

Given that the prototype will be 63 years old in 2041, the Navy may need a new training and prototype reactor in any case. It therefore may not be fair to charge its entire cost to the LEU fuel development program.

Furthermore, most naval cores are no longer tested in prototype. The director of the Office of Naval Reactors testified in 2013 with regard to the use of a new higher-density HEU fuel in the cores for the new ballistic missile submarines, saying that "[w]e did not have to build prototypes and do direct testing, but we could do that modeling in the high-performing computer."[27] The primary use of the S8G prototype today is for training naval reactor operators.

New fuel production line. The Office of Naval Reactors report asserts that if LEU fuel is used in U.S. aircraft carriers and HEU fuel is used in U.S. submarines, two production lines will be required. Yet, there are straightforward, nondestructive techniques to verify that LEU has not mistakenly been substituted for HEU in fuel or vice versa. Unless the new LEU fuel is very different in terms of the fabrication techniques involved, it is difficult to understand what would justify the cost of an entirely new production line. Currently, diverse HEU fuels are apparently manufactured on the same line. The fuel assemblies for the aircraft reactors are much longer than those for the submarine reactors, and the cladding of the fuel for the new Columbia-class ballistic missile submarines is of a different material than that for the Virginia-class cores.[28] Their production is most likely kept separate by processing the different fuels in separate batches during the different stages of production.

LEU fuel cost. The most important long-term issue will be whether LEU fuel will be much costlier than HEU fuel. If so, there will have to be a debate over whether the nonproliferation benefit is worth the cost. The Office of Nuclear Reactors indicates that the two HEU cores for the reactors on the *Gerald R. Ford* aircraft carrier cost about $1.5 billion and that LEU cores would cost 25 to 35 percent more. The reasons given for the cost increase are "[m]anufacturing and overhead costs [that] are expected to increase for the more complex fuel fabrication, LEU material costs, costs to down blend HEU to provide initial LEU fuel, and inefficiencies related to supporting separate LEU and HEU production lines."[29]

The fuel designs are secret, so it is not possible to comment on the relative complexity of the current HEU fuels and the proposed LEU fuel. With regard to the other arguments, however, there will be an extra cost in the near term for blending HEU down to 19.75 percent LEU; but in the long term, when the supplies of excess Cold War HEU are exhausted, it would be somewhat less costly to produce LEU for several reasons, including the lower security costs at the enrichment and fuel fabrication plants and for transport and storage of the LEU. In the 2016 Office of Naval Reactors report, it is estimated that security costs at the Navy's two nuclear fuel-fabrication facilities would be reduced by about $30 million per year if they no longer handled HEU. The issue of supporting two production lines has already been discussed.

Accelerated Timeline

According to the timeline in the Office of Naval Reactors 2016 report (see figure 1), the office would determine in fiscal year 2032, after the evaluation of the first irradiation tests of LEU fuel specimens, whether the LEU naval fuel is technically viable. Yet, the ongoing irradiation tests with HEU of the new fuel design that are to be completed at the end of fiscal year 2020 are of the same fuel design and therefore should provide the same


DCNS
A nuclear reactor vessel is lowered into a French ballistic missile submarine, *Le Terrible,* which runs on low-enriched uranium fuel.

information. Indeed, it should be possible to examine some of the HEU fuel samples after the halfway point of the irradiation tests in fiscal year 2018, when they will have reached irradiation levels beyond those required to qualify LEU fuel. If the conclusions from the HEU fuel irradiation and fabrication tests are positive, the program to test prototype LEU fuel and develop production capacity could be launched in the early 2020s, a decade earlier than in the proposed plan, and deliver LEU cores for aircraft carriers starting in the 2030s.

If decisions are made with Defense Department and congressional support to design the next-generation attack submarines, notated as SSN(X), to accommodate large lifetime LEU cores or with hatches that would allow quick midlife refuelings, they too could be equipped with LEU cores. If the SSN(X) is deferred in favor of continuing with Virginia-class attack submarines, a new larger reactor vessel might be included in the major redesigns that often occur between "blocks" of production of a submarine class. The Block V Virginia-class submarines that are to be purchased starting in fiscal year 2019, for example, will have a 70-foot "payload module" added immediately in front of the nuclear reactor compartment, with four large tubes that could store and launch up to seven Tomahawk cruise missiles each at a cost of about $300 million per submarine.[30] It would be too late to install LEU cores in the Columbia-class ballistic missile submarines that are already at an advanced design stage, but if and when they are replaced, their replacements too could be designed for LEU cores. In this scenario, therefore, no HEU cores would be installed after approximately 2040.

Other Countries

Nuclear-powered vessels are very costly. Virginia-class attack submarines cost about $2.7 billion each, Columbia-class ballistic missile submarines are projected to cost twice as much, and Ford-class aircraft carriers twice as much again.[31] This results in the club of countries with nuclear-powered ships being very small. For nuclear-powered aircraft carriers, it is almost a club of one, with the United States having 11 aircraft carriers and France one. Only six countries have nuclear-powered submarines: the United States, Russia, France, the UK, China, and India. Of these, four use HEU fuel, and two use LEU fuel.

Among the HEU fuel users, the UK is tied to the United States by technology and HEU supply. Therefore, if the United States switched to LEU fuel, the UK presumably would as well. The reactors that dominate Russia's current submarine fleet have zoned cores with enrichments much lower than those used by the United States and UK, ranging from 21 percent U-235 in the core interiors to 45 percent U-235 at their peripheries, and are designed to be refueled every 10 years or so with normal usage.[32] Technically, therefore, it would be much easier for Russia to switch its submarines to LEU fuel than for the United States. In fact, the reactors on Russia's next-generation, civilian nuclear-powered icebreakers are to be fueled with LEU.[33] India's submarines appear to be based on Russian designs. If the United States and UK switched to LEU fuel, it is possible that Russia and India would do so as well, thereby ending all global use of HEU for naval fuel and thereby potentially for all non-nuclear weapons uses.

The reactors on Russia's next-generation, civilian nuclear-powered icebreakers are to be fueled with LEU.

Conclusions

The Office of Naval Reactors has responded to congressional interest with a serious plan to develop a new higher-density fuel that could facilitate conversion of naval reactors to LEU fuel. It sees the LEU fuel of potential interest for aircraft carriers but not for submarines because lifetime LEU cores would not fit into current reactors and reactors designed for larger lifetime cores would not fit into submarines of the current size. The first point is more credible than the second. Furthermore, if the Navy were willing to design a refueling hatch into its submarines, the time penalty for refueling would not be significant.

The office believes that testing a core would require a new land-based prototype reactor costing several billion dollars. The government will have to decide in any case whether to build a new training and prototype reactor to replace the aging S8G reactor in West Milton, New York.

The office also estimates that LEU cores will cost 25 to 35 percent more than HEU cores. The effect on cost of the "more complex" fabrication of the LEU fuel is difficult to assess, but the other arguments for higher cost are not persuasive.

Finally, the office estimates that if the fuel development program is successful, it will be possible to begin building new LEU cores starting in fiscal year 2047. That schedule probably could be shortened by a decade.

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