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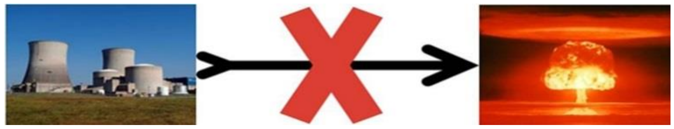

Working Paper # 3

Phasing Out Highly Enriched Uranium Fuel in Naval Propulsion: Why It's Necessary, and How to Achieve It

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International efforts to prevent the spread of nuclear weapons to additional states or terrorists are complicated by the routine use of nuclear weapons-usable, highly enriched uranium (HEU) as fuel for naval propulsion. Naval HEU fuel raises two major security risks: theft, by terrorists or criminals; and diversion, by states that would employ a naval program as deceptive cover to acquire fissile material. Accordingly, this paper explores the prospects and challenges of a global phase-out of naval HEU fuel, starting with a bilateral phase-out by the United States and Russia, the two countries that use the vast majority of naval HEU fuel. The following analysis proceeds through six steps. First, it elaborates the rationale behind such a phase-out. Second, it examines the potential timeline for a bilateral phase-out, based on a new analysis of the United States' and Russia's existing naval nuclear fleets and schedules for modernization (see Table 2). Third, it explores the technical feasibility of converting next-generation naval vessels from HEU to low-enriched uranium fuel (LEU) fuel. Fourth, it assesses the potential costs and savings of such conversion. Fifth, it assesses potential methods to verify a prospective ban on the use of HEU fuel for naval propulsion. Sixth, it explores options for diplomacy to achieve such a ban.

Why Phase Out Naval HEU?

The nuclear proliferation and terrorism risks of HEU fuel have been widely recognized for decades. In 1978, an international effort was initiated to phase out HEU fuel from nuclear research reactors by converting them to higher-density LEU fuel, to reduce such risks without significantly degrading reactor performance. Since then, around the world, 67 HEU-fueled research reactors have been converted to LEU fuel, and 20 have shut down.[1] Conversion to LEU fuel has been highly successful, according to a recent survey, which reported that "operators overwhelmingly perceived any negative

[1] Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing out Highly Enriched Uranium* (New York: Routledge, 2013). U.S. Department of Energy, National Nuclear Security Administration, "GTRI's Convert Program: Minimizing the Use of Highly Enriched Uranium," Fact Sheet, May 29, 2014, http://nnsa.energy.gov/mediaroom/factsheets/gtri-convert (accessed November 21, 2014).

impacts to be outweighed by positive ones."[2] In addition, pharmaceutical companies in three countries have successfully converted from HEU to LEU "targets" that are used to produce medical isotopes, and other countries are following suit. Due to these efforts, worldwide use of HEU fuel for research reactors and pharmaceutical production has been slashed by several hundred kilograms annually to less than one ton per year, and continues to decline.

Table 1
Estimated Annual Worldwide Use of Fresh HEU for Purposes other than Nuclear Weapons

Nuclear Activity	Kg/year
Research Reactors	750
Medical Isotope Targets	50
Icebreaker Ship Propulsion	150
Naval Propulsion	3,000

Source: Kuperman, *Nuclear Terrorism and Global Security.*

By contrast, naval reactors continue to require up to three tons of HEU fuel annually, representing three-fourths of global use of HEU for non-weapons purposes (see Table 1), mainly in the United States and Russia. Converting nuclear navies to LEU fuel would produce at least two major benefits for global security. First, it would eliminate the risk of HEU theft from the naval fuel cycle – which is greatest during fuel fabrication, transport, and storage, prior to loading. Second, it would provide moral leverage to demand that any country seeking to establish a nuclear navy should eschew HEU fuel too. This would reduce the risk that naval propulsion programs could be used as cover to acquire fissile material for nuclear weapons. For example, Iranian officials have claimed that they need

[2] Ferenc Dalnoki-Veress, "Primarily Positive Perceptions: A Survey of Research Reactor Operators on the Benefits and Pitfalls of Converting from HEU to LEU," presented at the European Research Reactor Conference (RRFM 2014), Ljubljana, Slovenia, April 1, 2014.

to produce HEU for a future nuclear navy.[3] Under the Nuclear Non-Proliferation Treaty, a country may remove from international inspection any fissile material it designates for naval propulsion. Thus, if a country claimed to need HEU fuel for naval propulsion, it could remove HEU from safeguards and divert it to nuclear weapons without any further enrichment. By contrast, if a country designated LEU for naval propulsion, it would need clandestinely to enrich that material further to make it suitable for nuclear weapons, which would significantly increase the probability of detection.

Potential Timelines for Conversion

Conversion of naval propulsion fuel from HEU to LEU would be easiest and most efficient if implemented in conjunction with the design of new naval vessels and the reactors to power them, rather than attempting to retrofit existing vessels and reactors. Accordingly, this section starts by reviewing timelines for development and deployment of future generations of naval vessels in the United States and Russia. One other country, the UK, uses significant amounts of naval HEU fuel, but it is very likely to follow the lead of the United States – which provides some of the HEU,[4] and may provide the fuel technology.[5]

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[3] "Senior Lawmaker: Iran Needs 60% Enriched Uranium for Submarines," December 26, 2013, *Fars News Agency*, http://english.farsnews.com/newstext.aspx?nn=13921005000419 (accessed November 22, 2014).

[4] The fuel is fabricated in the UK, at Rolls Royce's Derby facility, according to UK Ministry of Defence, "Historical Accounting for UK Defence Highly Enriched Uranium," March 2006, 3, http://fissilematerials.org/library/mod06.pdf (accessed November 21, 2014). The report says the HEU comes to the fabricator from the UK's Atomic Weapons Establishment, but the HEU could originate from a combination of U.S. supply and UK stocks including from retired nuclear weapons.

[5] Such technology transfer would be authorized by the "Amendment to the Agreement between the Government of the United Kingdom of Great Britain and Northern Ireland and the Government of the United States of America for Cooperation on the Uses of Atomic Energy for Mutual Defense Purposes," July 22, 2014, which entered into force on December 17, 2014, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/396347/TS_2.2015_Cm_8996_Web.pdf (accessed January 31, 2015).

The only other country that reportedly uses HEU naval fuel is India, which has one nuclear-propelled submarine leased from Russia,[6] is considering leasing a second from Russia,[7] and is testing its first nuclear submarine of indigenous design, while planning several more.[8] The enrichment level of India's naval fuel is reportedly 30 to 40 percent in both the leased and indigenous models.[9] If all three other countries that currently use HEU naval fuel – the United States, Russia, and the UK – agreed to convert to LEU, India would come under pressure to follow suit. India might even be able to convert its existing naval reactors to LEU fuel, given that its reactor cores reportedly use HEU fuel of relatively low enrichment and have short lifetimes that necessitate refueling in any case. The two other countries with nuclear navies, France and China, already use exclusively LEU naval fuel.

United States

Attack Submarines

In the United States, the most urgent potential conversion timeline would be for attack submarines (SSNs). The U.S. Navy currently has 72 SSNs of three types, but the latest model is the Virginia-class, the first of which started construction in 1999 and was commissioned in 2004.[10] The

[6] The first leased Russian vessel, the INS Chakra, a Charlie-class guided missile nuclear submarine, was commissioned by India in April 2012. Sudhi Ranjan Sen, "INS Chakra: Top 10 must-know facts," *NDTV*, April 06, 2012, http://www.ndtv.com/india-news/ins-chakra-top-10-must-know-facts-475108 (accessed March 14, 2015).

[7] Sam LaGrone, "India Interested in Leasing Second Russian Nuclear Attack Sub," *USNI News*, July 8, 2013, http://news.usni.org/2013/07/08/india-interested-in-leasing-second-russian-nuclear-attack-sub (accessed November 21, 2014).

[8] Pallava Bagla and Vishnu Som, "This is INS Arihant, First Made-in-India Nuclear Submarine," *NDTV*, August 20, 2014, http://www.ndtv.com/article/india/ndtv-exclusive-this-is-ins-arihant-first-made-in-india-nuclear-submarine-578949 (accessed November 21, 2014).

[9] Ahmad Khan, "Uranium fuel for INS Arihant (Indian Nuclear Submarine)," *Security Vault Insight Blog (SVIB)*, September 15, 2014, https://ahmadishaq.wordpress.com/2014/09/15/uranium-fuel-for-ins-arihant-indian-nuclear-submarine/ (accessed November 21, 2014). Pavel Podvig, "India activated its first nuclear submarine reactor," IPFM Blog, August 10, 2013, http://fissilematerials.org/blog/2013/08/india_activated_its_first.html (accessed November 21, 2014). *Australia by the Indian Ocean*, blog post, July 28, 2009, http://gentleseas.blogspot.com/2009/08/arihant-indias-first-homebuilt-nuclear.html (accessed November 21, 2014).

[10] "Attack Submarines – SSN," U.S. Navy Fact File, http://www.navy.mil/navydata/fact_display.asp?cid=4100&tid=100&ct=4 (accessed March 9, 2015).

Virginia-class has a 33-year service life, so the first one is scheduled to be retired and would need to be replaced in 2037. LEU fuel could be considered for the next generation, the "Virginia-replacement." Assuming a schedule similar to its predecessor, construction of an LEU-fueled SSN would need to start in 2032, for commissioning in 2037. Closely matching this estimated timeline, a U.S. Navy report recently projected that "RDT&E for the follow-on [attack] submarine is planned to support program initiation in FY 2034."[11] According to DOE's Office of Naval Reactors, research and development of an advanced LEU fuel system is estimated to require at least 10 to 15 years.[12] Therefore, such an LEU R&D program would need to be initiated as soon as possible to maximize the prospect of its reaching fruition in time to start construction of the first LEU-fueled SSN in the early 2030s (see Table 2).

Aircraft Carriers

The conversion timeline would be less urgent for U.S. aircraft carriers (CVNs). The U.S. Navy currently has 10 Nimitz-class CVNs, which are slated to be replaced by six to 10 of the Ford-class.[13] The first Ford-class CVN started construction in 2005 and is expected to be commissioned in 2016, shortly after the first retirement of a Nimitz-class CVN.[14] The Ford-class will have a 50-year service life, so that the first one would be retired and need to be replaced in 2066. LEU fuel could be considered for the next generation, the "Ford-replacement." Assuming a schedule similar to its predecessor, construction of an LEU-fueled CVN would need to start in 2055, for commissioning in 2066. (If an LEU advanced fuel

[11] Deputy Chief of Naval Operations (Integration of Capabilities and Resources) (N8), "Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for FY2015," June 2014, 15.

[12] U.S. Department of Energy, Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," Report to Congress, January 2014, 5.

[13] Six are planned to be purchased by 2042. Congressional Budget Office, "An Analysis of the Navy's Fiscal Year 2013 Shipbuilding Plan," July 2012, p. 13. Another four would be needed to maintain a fleet of ten. However, if the Navy were to proceed with plans to reduce the number of carriers on station to two, from the current three or four, it might require only six carriers total.

[14] "Navy Launches Massive Ford-Class Carrier Test," *Military.com*, February 20, 2014, http://www.military.com/daily-news/2014/02/20/navy-launches-massive-ford-class-carrier-test.html (accessed March 14, 2015). The vessel's first deployment is projected for late 2018 or early 2019.

system were developed successfully for SSNs well before then, a variant might be suitable for Ford-class CVNs, potentially enabling conversion to LEU fuel in the later ships of that class.)

Table 2
Conversion Timelines for U.S. and Russian Nuclear Navies

Country	Type	Latest HEU-fueled class built or under design	First commissioned	Service life (years)	Years from construction start to commissioning	Deadline to start construction of LEU-fueled replacement[‡]	Deadline to start 10 - 15 year design of LEU fuel/reactor
USA							
	SSN	Virginia	2004	33	5	2032	2017
	SSBN	Ohio-replacement	2031	40	10	2061	2046
	CVN	Ford	2016	50	11	2055	2040
Russia							
	SSN	Yasen	2014	25 - 30	21[ˠ]	2029[†]	Soon
	SSBN	Borei	2013	25 - 35	17[*]	2028[†]	Soon
	SSGN	Antey	1986	25	4	No known plans to replace this class	
	CGN	Kirov	1980	20-25	7	No known plans to replace this class	

[‡]Assumes that each replacement class requires the same time to construct as its predecessor class, except as noted.

[ˠ]Construction of the first Yasen SSBN was delayed by funding problems.

[*]Construction of the first Borei SSBN was delayed by missile problems.

[†]Based on estimates of the shortest service life of the current class, and 10 years from construction start to commissioning.

<u>Ballistic Missile Submarines</u>

The least urgent conversion timeline in the United States would be for ballistic missile submarines (SSBNs). The U.S. Navy currently has 14 Ohio-class SSBNs and is already designing an HEU-fueled successor, known as the “Ohio-replacement.” This new class will have a lifetime-core reactor, eliminating the need for refueling and thereby shortening the time required for mid-life maintenance, so that only 12 vessels will be needed. The first Ohio-replacement is slated to begin construction in 2021 for a planned delivery in 2027 – coinciding with the retirement of the first Ohio-class submarine –

followed by commissioning in 2031.[15] The Ohio-replacement is planned to have a 40-year service life, so that the first of this class would be retired and need to be replaced in 2071. LEU fuel could be considered for the follow-on generation, the "Ohio-replacement-replacement." Assuming a schedule similar to its predecessor, construction of such an LEU-fueled SSBN would need to start by 2061, for commissioning in 2071. (If an LEU advanced fuel system were developed successfully for SSNs well before then, a variant might be suitable for Ohio-replacement SSBNs, potentially enabling conversion to LEU fuel in the later submarines of that class.)

Russia

Ballistic Missile Submarines

Russia's eight older ballistic missile submarines (SSBNs) are being replaced by an expected 8 to 10 Borei-class SSBNs.[16] The first of this class started construction in 1996 and was originally scheduled for completion in 2001, but due to problems with the original missile design was not commissioned until 2013. The service life of the Borei-class will be 25 to 35 years,[17] so the first one could be retired and need to be replaced as early as 2038. LEU fuel could be considered for the next generation, the "Borei-replacement." Assuming 10 years from initiation to commissioning, construction of an LEU-fueled Russian SSBN might need to start as soon as 2028, for commissioning in 2038.

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[15] "SSBN-X Subs: America Going Nuclear to Replace Graying Boomers," *Defense Industry Daily*, June 12, 2014, http://www.defenseindustrydaily.com/ssbn-x-subs-america-going-nuclear-to-end-graying-boomers-024836/ (accessed September 10, 2014).

[16] Tom Spahn, "The Russian Submarine Fleet Reborn," *Proceedings Magazine*, 139, 6 (June 2013), http://www.usni.org/magazines/proceedings/2013-06/russian-submarine-fleet-reborn (accessed March 9, 2015). Nuclear Threat Initiative, "Russia Submarine Capabilities," June 10, 2014, http://www.nti.org/analysis/articles/russia-submarine-capabilities/ (accessed September 10, 2014).

[17] World Nuclear Association, "Nuclear-Powered Ships," http://www.world-nuclear.org/info/Non-Power-Nuclear-Applications/Transport/Nuclear-Powered-Ships/ (accessed November 7, 2014).

Attack Submarines

Russia's older attack submarines (SSNs) are to be replaced by seven Yasen-class SSNs. Construction of the first of this class started in 1993, but was suspended from 1996-2003 due to inadequate funding, delaying commissioning until 2014. The service life of the Yasen-class is estimated at 25 to 30 years,[18] so the first one could be retired and need to be replaced as early as 2039. LEU fuel could be considered for the next generation, the "Yasen-replacement." Assuming 10 years from initiation to commissioning, the construction of an LEU-fueled Russian SSN might need to start as soon as 2029, for commissioning in 2039.

Guided Missile Submarines

Russia has eight existing, HEU-fueled guided missile submarines (SSGNs) but no known plans to build a replacement class, as guided missile duties will be handled by the new Yasen-class attack submarines.[19]

Missile Cruisers

Russia has one remaining operational, HEU-fueled, Kirov-class missile cruiser (CGN), the *Pyotr Veliky*, commissioned in 1998. An older ship of the same class is being overhauled and may return to service. It is not known if Russia is planning a new generation of CGNs.[20]

[18] Military-Today.com, "Graney class," http://www.military-today.com/navy/graney_class.htm (accessed March 14, 2015). Its reactor is reported to have a lifetime core.

[19] NTI, "Russia Submarine Capabilities."

[20] Thomas Nilsen, "Pyotr Veliky's sisters to sail again," *Barents Observer*, September 22, 2011, http://barentsobserver.com/en/security/pyotr-velikys-sisters-sail-again (accessed March 9, 2015).

Technical Feasibility

Until recently, a debate persisted in the United States for nearly two decades about the technical feasibility of converting the Navy's nuclear propulsion reactors from HEU to LEU fuel. When the U.S. Congress initially mandated an inquiry into this question, the Office of Nuclear Naval Propulsion responded in 1995 with a report asserting that conversion would significantly increase costs and degrade performance by reducing the lifetime of reactor cores and/or increasing the size of naval vessels.[21] Several scholarly analyses before and after have disputed those claims, arguing that conversion would be feasible, especially in conjunction with designing a new naval vessel and reactor.[22]

This substantive debate appeared to subside in January 2014, when DOE's Office of Naval Reactors submitted a new report to Congress stating that it had determined conversion could be feasible with research and development of an advanced LEU fuel system.[23] However, some readers apparently were confused by the wording of the report, which repeated the earlier findings before presenting the new ones. The report reiterated that conversion to LEU would not be feasible using the current design of fuel in either existing,[24] or new,[25] reactors. It also stated, however, that conversion to LEU fuel could be feasible by designing an "advanced fuel system," which could "allow using LEU fuel with less impact on reactor lifetime, size, and ship costs."[26] The report was not explicit about whether a new reactor also would be required for the new fuel system, but this appears likely. (Table 3

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[21] Director, U.S. Office of Nuclear Naval Propulsion, *Report on Use of Low Enriched Uranium in Naval Nuclear Propulsion,* submitted to Congress, 1995, available at http://fissilematerials.org/library/onnp95.pdf (accessed January 26, 2015).

[22] Thomas D. Ippolito, "Effect of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design" (M.S. thesis, Massachusetts Institute of Technology, 1990). 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): 177-195. Cameron Liam McCord, "Examination of the Conversion of the U.S. Submarine Fleet from Highly Enriched Uranium to Low Enriched Uranium" (M.S. thesis, Massachusetts Institute of Technology, 2014).

[23] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores."

[24] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," 3.

[25] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," 4.

[26] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," 5.

summarizes these findings.) R&D would need to start soon to satisfy the timeline indicated above for converting the next generation of SSNs. As the report observes: "Advanced fuel system development would be a long-term effort that must start well in advance of a ship application. The investment to develop a fuel technology and determine its viability is estimated to be up to $2 billion over at least 10 to 15 years."[27]

Table 3
2014 Office of Naval Reactors Report: Is Conversion to LEU Potentially Feasible?

		Reactor Design	
		Current	*New*
Fuel	*Current*	No	No
Design	*New*	?	Yes

For Russia, converting naval propulsion to LEU fuel should be less of a technical challenge. In contrast to the U.S. nuclear navy, which uses 93- and 97-percent enriched HEU fuel, Russian submarines use fuel of approximately 21- to 45-percent enrichment, with a few zones possibly enriched to 70 percent.[28] Russia might even be able to convert its existing nuclear submarines to LEU fuel, for three reasons: they require routine refueling anyway, since their reactors do not have lifetime cores; refueling is relatively easy because Russia's submarines, unlike those in the U.S. Navy, have hatches for this purpose; and Russia's naval HEU fuel has much lower enrichment than that of the U.S. Navy, making it easier to convert to LEU fuel without shortening core life. However, considering the age of Russia's existing fleet, conversion of future classes of vessels might be more likely, since Moscow could be reluctant to expend substantial resources to convert the reactor fuel of vessels nearing retirement.

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[27] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," 5.

[28] Yaroslav Primachenko, "Russia: Naval Propulsion," in *Nuclear Terrorism and Global Security: The Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013): 196-207.

Russia's next generation of nuclear submarines is expected to be powered by the RITM-200 reactor, initially using 30- to 35%-enriched HEU fuel.[29] This means conversion to LEU fuel would require only a relatively modest reduction in enrichment. In fact, Russia already has developed an LEU-fueled variant of the RITM-200, which is expected to propel Russia's next generation of civilian, nuclear icebreaker ships. Russian officials say they chose LEU fuel for these civilian ships, and for forthcoming barge-mounted nuclear power plants, in hopes that – by complying with the global norm against HEU in civilian applications – they could sell both items abroad.[30] This suggests that Russia also could convert its next generation of naval reactors to LEU fuel. Instead, however, Russia's Navy currently plans to increase the enrichment of its HEU fuel, to lengthen reactor core life to match the maintenance cycle of its vessels.[31]

Potential Costs & Savings of Conversion

Conversion of naval propulsion to LEU fuel could incur costs or yield savings, but neither prospect should be exaggerated. As explained below, the impact of conversion on the overall cost of the U.S. naval nuclear enterprise could be relatively marginal. One ostensible cost of conversion would be the R&D for an advanced LEU fuel system, which the 2014 Office of Naval Reactors report estimates would require "up to $2 billion over at least 10 to 15 years." However, if the U.S. Navy did not develop an LEU fuel system, the Office of Naval Reactors likely would seek instead to conduct R&D on an HEU advanced fuel system, at similar cost. As the report states, "an advanced fuel system might enable either a higher energy core using HEU fuel, or allow using LEU fuel."[32] Thus, conversion to LEU could incur little to no net cost for R&D.

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[29] Primachenko, "Russia: Naval Propulsion."

[30] 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): 66-82.

[31] Primachenko, "Russia: Naval Propulsion."

[32] Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," 5.

The greatest potential cost would arise if conversion to LEU fuel shortened the lifetime of the reactor core, thereby necessitating refueling during the service life of each vessel. This would increase costs for fuel fabrication, ship maintenance, and spent fuel handling. Even more consequentially, by extending the vessel's maintenance time, it could necessitate purchasing one or more additional vessels to sustain the same operational presence. However, according to U.S. Congressional staff,[33] the Office of Naval Reactors recently expressed confidence that R&D would enable production of an LEU reactor core that could last the entire service life of U.S. nuclear submarines, thereby obviating such potential costs.

The only certain costs of conversion to LEU fuel would arise from the need for additional uranium-238, because a greater mass of LEU would be required to maintain sufficient U-235 to provide roughly the same neutron flux as HEU. The greater mass of uranium would also increase the weight, and possibly the volume, of spent fuel and/or waste streams, thereby raising costs on the back end of the fuel cycle, but this would depend on future technical and policy developments.[34] In any case, the costs arising from the fuel containing more U-238 should be relatively small compared to the overall costs of the naval nuclear enterprise.

Savings from conversion could arise at least two ways. First, conversion to LEU fuel could obviate the need for an expensive restart of production of HEU when existing stockpiles are exhausted –

[33] Personal communication, October 10, 2014.

[34] The RERTR program typically has converted reactors from HEU to LEU fuel while maintaining the same core volume. The Russian Navy probably could do likewise, given the relatively low enrichment of its HEU. It is unknown if the U.S. Navy could achieve this, due to secrecy about current reactors and uncertainty about future ones. Waste volumes likely would increase if naval spent fuel were reprocessed – a practice the United States halted in 1992 – but not necessarily if it were directly disposed, as the United States since 1992 has been planning to do.

which will occur in the United States sometime after 2064,[35] and much later in Russia.[36] However, if naval LEU fuel requires enrichment near 20 percent – the same level used to convert research reactors from HEU fuel – this too would necessitate restart of enrichment in the United States, which lacks a large stockpile of uranium enriched to that level. Currently, to produce such LEU for research reactors, the U.S. government blends down 93-percent enriched HEU originally produced for its nuclear weapons program. Thus, converting naval propulsion to LEU might not yield significant savings on uranium enrichment.

In the unlikely event that U.S. naval reactors could use LEU enriched to the lower level of approximately five percent typical of fuel in nuclear power plants – as the French Navy is moving towards – then the LEU could be purchased commercially, yielding substantial savings. However, it is unclear if "peaceful use" restrictions in multilateral agreements would prohibit the United States or other countries from fabricating naval fuel from commercial LEU enriched by the European consortium URENCO.[37] In any case, a steep reduction to five-percent enrichment in the fuel of U.S. naval reactors probably would curtail the lifetime of their cores, thereby sharply increasing costs for refueling and extra vessels, which would dwarf any savings on fuel.

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[35] U.S. Government Accountability Office, "Interagency Review Needed to Update U.S. Position on Enriched Uranium That Can Be Used for Tritium Production," GAO-15-123, October 2014, 3, states: "According to DOE, the department's current HEU inventory allocations are sufficient to meet national security demands through 2064." Morris E. Hassler, et al., "U.S. Department of Energy's Tritium and Enriched Uranium Management Plan Through 2060," presented at the 54th Annual Meeting of the Institute of Nuclear Materials Management," Palm Desert, CA, July 16, 2013, 6, states: "Naval Reactors (NR) HEU demand will be met through 2060 with HEU allocated from the 2005 Excess Declaration." 2060 is the end date of the planning document required by the U.S. Congress, so not necessarily the expected exhaustion date of HEU dedicated to naval fuel.

[36] Primachenko, "Russia: Naval Propulsion," 197, indicates that Russia has sufficient HEU dedicated to naval fuel for 150 years at estimated consumption rates.

[37] The two key agreements – with France, Germany, Netherlands, and the UK – state that nuclear material obligated under the agreements "shall only be used for peaceful, non-explosive purposes," but it is unclear if "peaceful" means non-nuclear-weapons or non-military. The U.S. government has interpreted this language to prohibit use of obligated material to produce "any nuclear weapons materials," but the possibility of use in naval fuel does not appear to have been addressed. A third agreement with Australia is explicit in banning use "for any military purpose," which appears to cover naval fuel. See U.S. GAO, "Interagency Review Needed to Update U.S. Position on Enriched Uranium," 20-21, 37.

Savings also could be realized due to the fact that LEU security requirements are far less stringent than those for HEU.[38] This could significantly reduce the cost of physical protection at a fuel fabrication plant or enrichment facility that avoided HEU entirely. However, in the United States, the plant that would likely fabricate LEU fuel for future naval reactors might also continue fabricating HEU fuel for older naval and research reactors for at least three decades.[39] If so, this could reduce or eliminate potential savings from lower security requirements, at least until the fabrication facility completely phased out HEU fuel. In light of the above uncertainties, it is impossible to predict if converting to LEU fuel would reduce or increase the costs of the naval nuclear enterprise, but in either case the budgetary impact would likely be relatively marginal.

Diplomacy

At least four diplomatic approaches could enable bilateral U.S.-Russia conversion to LEU naval fuel, and thereby pave the way for a global phase-out of HEU fuel for naval propulsion. The first option, a treaty, is the most obvious but also the most difficult. Several U.S.-Russia arms control treaties have been implemented, most recently the 2010 New START.[40] However, others have failed to be

[38] Under U.S. NRC regulations, which cover licensed nuclear facilities including the fabrication plant for naval fuel, HEU is Category I, requiring the highest level of security, except for small quantities containing less than 5 kg of U-235. By contrast, LEU is either Category II, if enriched to at least 10 percent, or Category III, which have lower security requirements. See U.S. NRC, "Safeguard Categories of SNM," November 5, 2013, http://www.nrc.gov/security/domestic/mca/snm.html (accessed November 21, 2014).

[39] Based on current procurement plans, the last Virginia-class SSN is due to be commissioned around 2050, requiring fabrication of an HEU fuel core in the 2040s. See Ronald O'Rourke, "Navy Virginia (SSN-774) Class Attack Submarine Procurement: Background and Issues for Congress," Congressional Research Service, July 31, 2014. The last Ford-class CVN and Ohio-replacement-class SSBN are scheduled to be commissioned around 2040, but additional procurement is possible. See Ronald O'Rourke, "Navy Ohio Replacement (SSBN[X]) Ballistic Missile Submarine Program: Background and Issues for Congress," Congressional Research Service, July 31, 2014; Ronald O'Rourke, "Navy Ford (CVN-78) Class Aircraft Carrier Program: Background and Issues for Congress," Congressional Research Service, September 16, 2014; Congressional Budget Office, "An Analysis of the Navy's Fiscal Year 2013 Shipbuilding Plan," July 2012.

[40] Others include the following: 1987 INF; 1991 START I; and 2002 SORT. The United States withdrew from the 1972 ABM Treaty after its implementation.

implemented, including the 1979 SALT II treaty and the 1993 START II treaty.[41] In light of the requirement for ratification by the U.S. Senate, and recent tensions with Russia over events in Ukraine, a treaty in this realm seems unlikely.

An alternative approach avoiding the requirement for ratification is an Executive Agreement, such as the 1972 SALT I Interim Agreement, which was implemented successfully.[42] However, the majority in the U.S. Senate might be resistant to an Executive Agreement that could be perceived as an attempt by the White House to evade the Constitutional requirement for Senate ratification of treaties.

A third variation would be conditional reciprocity. President George H.W. Bush attempted this in January 1992, by announcing that he was willing to eliminate the practice of deploying multiple warheads on U.S. land-based ballistic missiles – i.e., "de-MIRV" them – if Russian President Boris Yeltsin would reciprocate. Although other bilateral arms reductions were achieved at the time, Yeltsin declined to accept this offer, perhaps because it would have required Russia to eliminate more warheads than the United States.[43] To adapt this approach to the phase-out of naval HEU, either Russia or the United States would need to declare a willingness to convert its nuclear naval vessels to LEU fuel on condition that the other reciprocate. Considering that Russia's Navy already uses HEU fuel of considerably lower enrichment, which would facilitate conversion to LEU, Moscow might see a strategic advantage in issuing such a challenge to the United States. Alternatively, since the United States is expected to exhaust its reserve of HEU dedicated to naval propulsion well before Russia would, Washington might perceive an interest in challenging Moscow to reciprocate on conversion to LEU.

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[41] SALT II was not ratified by the U.S. Senate. START II was ratified by both countries, but Russia withdrew in response to U.S. withdrawal from the ABM Treaty. See Nuclear Threat Initiative, http://www.nti.org/treaties-and-regimes/strategic-arms-limitation-talks-salt-ii/, and http://www.nti.org/treaties-and-regimes/treaty-between-united-states-america-and-union-soviet-socialist-republics-strategic-offensive-reductions-start-ii/ (both accessed March 9, 2015).

[42] Usha Sahay and Kingston Reif, "Non-Treaty Cuts to the U.S. Nuclear Stockpile," *Center for Arms Control and Non-Proliferation*, November 2013.

[43] Susan J. Koch, *The Presidential Nuclear Initiatives of 1991-1992* (Washington, DC: National Defense University, 2012), 18-21.

A final diplomatic option is parallel unilateral action. An example occurred in September 1991, when U.S. President George H.W. Bush announced several unilateral nuclear arms control measures: elimination of ground-launched tactical nuclear weapons; removal of tactical nuclear weapons from naval vessels, and elimination of some of those weapons; acceleration of de-alerting for strategic nuclear weapons; and termination of previously proposed weapons systems. President Bush acted unilaterally but appealed to the Soviet Union to reciprocate. Just days later, Soviet President Mikhail Gorbachev announced parallel measures: elimination of all nuclear artillery, short-range missile warheads, and mines; removal of tactical nuclear weapons from naval vessels, and elimination of some of those weapons; de-alerting of some strategic nuclear weapons; and cancellation of several strategic nuclear weapons programs.[44]

This same approach, parallel unilateral action, has been successful in phasing out HEU fuel in research reactors. Starting in 1978, the United States developed higher-density LEU fuel, utilizing it to convert some domestic research reactors, and then called on foreign reactor operators likewise to eliminate HEU fuel.[45] Reciprocation has been forthcoming, most recently and significantly from Russia, which has now conducted conversion feasibility studies on six research reactors and is in the process of converting the first two of them to LEU fuel.[46] To expand this to the naval sector, either Russia or the United States would need to announce its intention to convert its nuclear navy to LEU fuel, and then challenge the other to follow suit. This final diplomatic option appears the most propitious, as it could enable symmetric action without necessitating a bilateral agreement.

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[44] Koch, *The Presidential Nuclear Initiatives of 1991-1992*, 10-17.

[45] For details on the Reduced Enrichment for Research and Test Reactors (RERTR) Program, see Alan J. Kuperman, "Nuclear Nonproliferation via Coercion and Consensus: The Success and Limits of the RERTR Program (1978-2004)," in *International Cooperation on WMD Nonproliferation*, ed. Jeffrey W. Knopf (University of Georgia Press, 2015, forthcoming).

[46] Braden Civins, "Russia: Research Reactors," in *Nuclear Terrorism and Global Security: The Challenge of Phasing out Highly Enriched Uranium*, ed. Alan J. Kuperman (New York: Routledge, 2013): 146-161.

Verification

Verification would not be necessary for some of the diplomatic options discussed above, but two possible strategies can be envisioned to verify conversion of naval propulsion to LEU fuel. The first would be simpler logistically, but harder politically and therefore technically. It would require only measuring the uranium enrichment of each core of fuel as it was loaded into a naval reactor. However, the United States (and other countries with nuclear navies) likely would balk at intrusive inspections that could reveal classified or proprietary information. Inspectors thus would need to use remote, non-destructive monitoring to try to measure the uranium enrichment of fuel in shipping containers. That challenge could prove difficult or impossible, especially in the face of national efforts to shield material or spoof monitors.

An alternative, and logistically more complicated, verification strategy could prove more feasible. Inspectors first would need to verify the enrichment of uranium being fed into a designated fuel fabrication plant. After fuel fabrication, inspectors would need to monitor fuel containers during storage and transport prior to loading of the reactors. Such a regime could verify that LEU fuel was being loaded into the reactors without revealing classified or proprietary information.[47] For either of these verification approaches, inspectors also would need to monitor vessels during extended port calls for maintenance, which is a relatively rare phenomenon, to ensure against potential clandestine refueling with HEU.[48]

[47] A similar regime is proposed by Sébastien Philippe, "Bringing Law to the Sea: Safeguarding the Naval Nuclear Fuel Cycle," *Bulletin of the Atomic Scientists*, September 4, 2014.

[48] Although the military advantage gained by clandestine refueling with HEU would be relatively minor, a verification regime to prevent such cheating would ensure a level playing field and thereby help to promote a global phase-out of HEU naval fuel.

Summary and Recommendations

The 2014 report to Congress from DOE's Office of Naval Reactors implies that phasing out HEU fuel from U.S. naval propulsion could be feasible after development of an LEU advanced fuel system at a cost of "up to $2 billion over at least 10 to 15 years." If successful, such conversion to LEU fuel would not significantly degrade performance or increase costs as previously feared, because the new fuel system would "allow using LEU fuel with less impact on reactor lifetime, size, and ship costs." Conversion to LEU fuel likely would affect only marginally the overall cost of the U.S. naval nuclear enterprise, and could even yield savings due to reduced costs for security and possibly uranium enrichment. If the United States took the steps necessary to convert its nuclear navy to LEU fuel, this could help persuade the other countries that currently use HEU naval fuel – the UK, Russia, and India – to do likewise, and deter other countries from pursuing HEU for naval propulsion.

A global phase-out of HEU fuel from naval propulsion could significantly reduce risks of nuclear proliferation and nuclear terrorism. It would end annual commerce of up to three tons of HEU – sufficient for over a hundred nuclear weapons each year – and thereby reduce worldwide use of fresh HEU by three-fourths. Converting existing nuclear navies to LEU fuel would also prevent Iran and other countries from credibly claiming that their future nuclear navies require them to produce HEU – which could be removed from safeguards and diverted to nuclear weapons. Ultimately, the switch to LEU naval fuel could enable a total global phase-out of HEU for non-weapons purposes, blocking a path to the bomb.

The most promising strategy to achieve these important objectives would be for the United States to pursue expeditious conversion of its next generation of nuclear naval vessels – starting with the attack submarines (SSNs) that will begin to replace the current Virginia-class in about 20 years – and challenge other countries to reciprocate. To accomplish this, the U.S. government must initiate R&D of an LEU advanced fuel system as soon as possible, to ensure it reaches fruition in time to start construction of the first LEU-fueled SSN in the early 2030s. The initial budget would be relatively small, but the program would need to start soon and be restricted to development of an LEU advanced fuel system, in order to contain costs and help persuade other countries to join a global phase-out of naval HEU fuel.