MARCH 2015

Naval Nuclear Propulsion: Assessing Benefits and Risks

The Report of an Independent Task Force

Convened by the Federation of American Scientists

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Design and layout by Suzanne Lewis.

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About the Task Force

In early 2014, the Federation of American Scientists (FAS) convened an independent, nonpartisan task force of about ten experts in the fields of national security, nuclear engineering, naval nuclear propulsion, nuclear security, and nonproliferation. The task force had the objectives to: (1) examine potential options for alternatives to highly enriched uranium (HEU), a nuclear weapons-usable material, for naval propulsion, and (2) identify possible effective ways to monitor and safeguard HEU as well as low enriched uranium (LEU) in the naval sector.

While the task force had research challenges of only having access to unclassified information and of working under a limited timeframe of just under one year, it was still able to bring fresh thinking to an issue that has been studied for more than twenty years in the nuclear security and nonproliferation community. An innovative approach was to explicitly include several professors and graduate students from major educational institutions and research universities that had not previously worked on this set of issues.

Selected members of the task force were assigned four different topical areas: (1) an analysis of how to achieve phase out of HEU in naval propulsion with particular attention to the United States and Russia (by Alan J. Kuperman of the Nuclear Proliferation Prevention Project at the University of Texas at Austin), (2) an examination of governance frameworks for safeguarding nuclear material in the naval sector (by Naomi Egel, Bethany L. Goldblum, and Erika Suzuki of the Nuclear Policy Working Group at the University of California, Berkeley), (3) an investigation into the unintended consequences of converting the U.S. nuclear fleet from HEU to LEU (by Jack Bell, Nathan Roskoff, and Alireza Haghighat of the Nuclear Science and Engineering Lab (NSEL) at Virginia Tech, and with advice from VADM (ret.) Charles "Joe" Leidig of the U.S. Naval Academy), and (4) an assessment of the United Kingdom's naval propulsion program and use of HEU (by Nick Ritchie of the University of York). These papers, conference calls, discussions, and an all-day face-to-face meeting of the task force further informed the writing of this final task force report.

The task force members thank the John D. and Catherine T. MacArthur Foundation for generous financial support. We are also grateful for organizational and editorial assistance from Pia Ulrich and Katie Colten of FAS. In addition, we are deeply appreciative of the information and advice provided by several officials in the executive and legislative branches of the U.S. government. An early stage outreach session at Oak Ridge National Laboratory in August 2014 helped in gathering insightful comments from several experts who are involved in uranium enrichment, naval reactors, and nuclear security. Moreover, we are thankful for comments and advice given by Richard L. Garwin, Marvin Miller, George Moore, Joseph Pilat, Christopher Preble, Michael Rosenthal, and Frank von Hippel. Furthermore, the February 2015 roundtable discussion in Washington, DC, which included about a dozen experts from inside and outside government, clarified some outstanding issues considered in the final preparation of this report.

Disclaimer: This report is a product of the task force and not of the Federation of American Scientists, which just convened the task force. The personal views of the task force members should not be read as reflecting the views of the private, public, and government organizations with which the task force members are presently or have been previously affiliated. Institutional affiliations are listed for identification purposes only. The report contains consensus Findings and Recommendations, followed by Additional Issues for Further Investigation. It is important to underscore that the task force as a whole was not asked to reach agreement on the section on Additional Issues. Individual members of the task force put forward ideas represented in that section.

Findings

1. The U.S. Navy and other nuclear navies have benefited from having nuclear-powered warships. The benefits include long-range military power projection via nuclear-powered aircraft carriers, cruisers, and submarines, capacity to remain at-sea for several months, and capability for nuclear-powered submarines to be submerged for a few months (the only limitation being storing enough food for the crew). To achieve these benefits, however, does not imply the continuing use of highly enriched uranium (HEU), a nuclear weapons-usable material, as naval fuel. HEU is presently used in four navies: the United States, the United Kingdom, Russia, and India. The United States and the United Kingdom use uranium enriched above 90 percent in the fissile isotope uranium-235. Based on projected demands and the U.S. government's declarations about the amount of HEU set aside for naval propulsion, the United States has at least 50 years of HEU stockpiled for naval purposes. Available open source information indicates that the United Kingdom probably has at least 80 years or more of supply. Russia and India have existing enrichment plants that can make HEU as needed.

2. Highly enriched uranium in naval nuclear propulsion poses proliferation and security risks. Non-state actors such as terrorist groups or criminal gangs could steal, buy, or be given HEU that they could then form into improvised nuclear devices, which are crude but powerful nuclear explosives. Also, a state could divert HEU from a naval nuclear propulsion program into a weapons program; such diversion could provide fissile material for this state or another allied or client state.

3. Low enriched uranium (LEU), a non-weapons usable material, fuels a number of naval reactors. The French government has publicly announced that it has shifted from HEU to LEU fuel for its nuclear-powered submarines. While the Chinese government has not provided confirmation about its naval nuclear fuels, available information indicates that China has used LEU fuels. Reportedly, Brazil is considering development of LEU-fueled nuclear-powered submarines. In its January 2014 report to Congress, the Office of Naval Reactors discusses the potential for future development of advanced, LEU-fueled naval reactors that might meet the rigorous performance requirements of the U.S. Navy. Success, however, is not guaranteed, and the Naval Nuclear Propulsion Program would require further significant financial resources for research and development.

4. Low enriched uranium poses implications for nonproliferation. First, LEU-fueled reactors can produce some quantities of weapons-usable plutonium, which could be separated from irradiated fuel by using reprocessing techniques. Second, producing LEU requires enrichment plants, which could provide the cover for a state to divert LEU into a covert plant for further enrichment to HEU or in the event of breakout from the Non-Proliferation Treaty (NPT) use a plant in an overt manner. If states want their own nuclear navies they will likely want or need to have their own enrichment plants, thus sowing the seeds for potential future nuclear proliferation or at least greatly challenging efforts to safeguard many more plants. Third, the fact that most of the work required to produce HEU is done when enriching to LEU means that LEU production itself raises the risk for future proliferation, such as via batch recycling of the LEU to produce quickly HEU in an enrichment plant.

5. Highly enriched uranium is still the greater danger because of the relative ease of use in an improvised nuclear device and its relative abundance in an HEU naval fuel cycle. While an LEU-fueled naval reactor will produce plutonium, an HEU naval fuel cycle will have much more available fresh fissile material during fabrication, transport, and storage. If a state does not already have existing stockpiles of this material or an enrichment plant, it would have to build an enrichment plant, which would raise the risk for future proliferation.

6. Comprehensive nuclear safeguards agreements contain a loophole that allows a non-nuclear weapon state to remove nuclear material from safeguards for "non-proscribed" military uses such as naval propulsion. The danger is that once the material is outside of safeguards, it could be diverted into a weapons program. While no non-nuclear weapon state party to the NPT has tested this provision, Brazil has expressed its intent to operate nuclear-powered submarines. Recently, some Iranian officials have openly discussed their interest in possibly enriching uranium up to HEU-levels (they mentioned 60 percent in the fissile isotope uranium-235) for naval propulsion purposes. It remains unclear how there can be confidence that such material will not be diverted for weapons purposes when the material is outside safeguards for an extended period of time.

7. The U.S. Navy and the Naval Nuclear Propulsion Program (NNPP) have favored

life-of-the-ship nuclear reactors to save costs. The two major cost savings are: (1) not having to pay for the replacement reactor cores and shipyard refueling operations and (2) not having to purchase additional nuclear-powered warships in order to meet the operational deployment requirements of the Navy. While HEU-fueled warships had initially required refueling every few years, continual innovations by the NNPP have resulted in lifetime cores of 33-years for the Virginia-class nuclear attack submarines (SSNs) and 40-plus years for the next-generation ballistic missile submarines (SSBNs) being developed to replace the current Ohio-class SSBNs. The Navy and the NNPP would strongly prefer that any follow-on generation of advanced LEU- or HEU-fueled warships would have lifetime cores.

8. Research and development for advanced LEU or HEU fuel for the next generation of U.S. SSNs would need to start no later than fiscal year 2017 to be ready in time for the replacement class of the Virginia-class SSNs to start construction in 2032. This is due to the long lead-time of at least 10 to 15 years to research and develop a new naval reactor and another five to 10 years to deploy the reactor. As to nuclear-powered aircraft carriers (CVNs), a potential long-lived LEU-fueled reactor would need to be designed by 2040 to serve as the replacement to the Ford-class CVNs.

9. Reviving nuclear arms control could allow for further reductions in the number of SSBNs and extend the U.S. stockpile of enriched uranium. As part of the assessment of whether New START, which was ratified by the Senate on December 22, 2010, was in the national interest, U.S. nuclear force planners determined that the United States would need at most 12 SSBNs to serve as the replacement to the present Ohio-class as compared to the present 14 SSBNs. If in the future the United States decides that 1,000 or fewer deployed strategic warheads are needed as compared to New START's 1,550 deployed strategic warheads, the SSBN fleet could be reduced to 10 or fewer boats. This would allow an extension of the U.S. stockpile of enriched uranium set aside for naval reactors and thus delay the time when a new enrichment plant would be needed. Development of life-of-the-ship LEU reactors could allow use of LEU-fueled SSBNs in the replacement generation beyond the recently designed SSBN(X), which is planned to start construction in 2021. Research and development of the next-next generation SSBN would have to begin by 2046.

Recommendations

1. The U.S. Naval Nuclear Propulsion Program should try to develop a lifetime core for an LEU-fueled reactor for the generation of SSN following the Virginia-class SSN, and the Obama administration and Congress should provide adequate funding no later than fiscal year 2017 to begin the research and development. The task force endorses this objective because of the downsides of refueling, in terms of operational and shipbuilding costs, and other issues such as minimizing radiation exposures to workers. This objective will be technically challenging and, if achieved, could have consequences for the performance and size of the reactor, nuclear plant, and the warship when compared to alternative HEU designs. The broader policy and capability costs versus benefits of these designs will need to be assessed before a final decision is made. Any shift from HEU to LEU naval fuel would have to meet rigorous performance requirements especially for sea warfare conditions.

2. The Obama administration and Congress should ensure that the Naval Nuclear Propulsion Program has adequate funding and resources to address current and projected needed investments in the overall naval nuclear enterprise. The needs include facilities, storage and transport casks for safe and secure handling of spent nuclear fuel, fuel fabrication facilities, reactor manufacturing facilities, reactor prototype and simulator training facilities, as well as upgrades in curricula for training naval nuclear propulsion crews on advanced nuclear propulsion plants. Considering the various needs of the enterprise, the NNPP should provide the administration and Congress projected potential costs and savings of an advanced LEU fuel system in comparison to an advanced HEU fuel system. A further assessment should factor in the impact of new LEU or HEU fuels on the federal government's 1995 agreement with the State of Idaho on limiting the amount of naval spent fuel shipments to that state. Specifically, the administration should ensure that adequate funding and other resources are kept on track to meet the 1995 commitment (and 2008 addendum) that Idaho will not become a de facto permanent repository of spent fuel and transuranic waste.

3. The United States should announce at the 2016 Nuclear Security Summit that the Naval Nuclear Propulsion Program will be initiating research and development no

later than fiscal year 2017 on an advanced LEU fuel system. On the basis of the case that an advanced LEU fuel system can be in the interests of other states that are presently using HEU, the Obama administration should invite the United Kingdom and Russia to make similar pledges. Given the close partnership historically between the United States and the United Kingdom on naval nuclear propulsion, a mutual pledge at the Nuclear Security Summit would send a stronger message especially considering that these two countries' nuclear navies use the highest enrichment levels in the world. Moreover, with the close political relations between President Barack Obama and Indian Prime Minister Narendra Modi, the United States should offer to work in partnership with India in assessing effective LEU-fueled reactors for India's nuclear-powered submarines. At a minimum, a commitment by India to consider LEU naval fuel could apply positive political pressure on Pakistan, which has expressed interest in nuclear-powered submarines, to follow suit. China should also be encouraged to declare its policy on naval fuels and continue using LEU-fueled submarines.

4. At the 2016 Nuclear Security Summit, the United States and United Kingdom should declare their intention to move forward with an investigation of the feasibility of a transparency and safeguards system for their naval nuclear fuel cycles. Such a system should not compromise naval operations and must protect proliferative and classified information. As nuclear weapon states, they can accept voluntary safeguards on declared nuclear material. If successful, this investigation could serve as a model for other nuclear-armed states' nuclear naval fuel cycles.

5. The United States should urgently work with the International Atomic Energy Agency (IAEA) and partner nations such as Argentina, Brazil, Australia, and the United Kingdom to develop effective means of monitoring and safeguarding nuclear material in the naval sector. The first application of these safeguards will most likely involve Brazil, which would probably become the first non-nuclear armed state with a nuclear-powered navy. However, due to Brazil's political sensitivities concerning additional safeguards, a non-nuclear weapon state without nuclear-powered warships but with submarines and a strong commitment to nonproliferation- such as Australia- should consider volunteering to test this new safeguards system. This state should consider making this pledge at the 2016 Nuclear Security Summit and then work with like-minded states and the IAEA to develop a potential safeguards system for naval nuclear fuels.

Additional Issues for Further Investigation[1]

Naval nuclear propulsion presents a complex set of policy and technical issues. In its deliberations and the time it had available, the task force was able to shine a spotlight on several major outstanding issues, as discussed above. Here, we present a few selected issues that some task force members believe require further investigation, but the task force did not seek to reach consensus on these particular issues.

1. Although the United States has a relatively large stockpile of HEU declared for naval propulsion purposes, this stockpile is estimated to last for about 50 years based on projected demands. Thus, this stockpile will near its end point by 2065. Ten years prior to that date, the United States will have to start construction of the first replacement CVN for the forthcoming Ford-class CVN. The deadline to start the design for an LEU-fueled reactor for this new CVN will have to begin no later than 2040. Whether the United States stays with HEU-fueled reactors or makes the conversion to LEU-fueled reactors, it will have to decide on the future source for the enriched uranium. Presently, the United States is not operating a nationally owned and controlled enrichment plant. Given the political sensitivities in building an enrichment plant, the United States will have to weigh the consequences of what type of plant to have. Thus, a further area of policy research is what would be the nonproliferation implications of the United States having an enrichment plant to produce HEU for naval purposes. One major consideration is the effect on a possible fissile material cutoff treaty. What inspection procedures, monitoring, and safeguards would the United States find acceptable? Additional research would examine whether an LEU enrichment plant would be better suited for possible future arms control and other commitments made by the United States.

2. An LEU-naval fuel cycle would generate a larger volume of radioactive waste and higher levels of radioactivity in the spent fuel than an HEU-fuel naval fuel cycle. The exact amounts for different reactor designs would have to be studied. Moreover, as mentioned in the

1 Please note that the task force as a whole was not asked to reach consensus on these issues, which came forth from individual task force members' research and companion working papers to the project.

recommendations section, the agreement the Department of Energy (DOE) has with the State of Idaho significantly limits the number of annual transfers of naval spent fuel to that state, and requires DOE to place spent fuel in dry cask storage within the next ten years and find a permanent repository by 2035 for the spent fuel. This issue is connected to the federal government's commitment to create and open a permanent repository for commercial spent fuel. Given the impasse over the site at Yucca Mountain, it is uncertain as to how these repository issues will be resolved. While a decision on an LEU-naval fuel cycle could have an impact on the larger set of issues surrounding the disposal of tens of thousands of tons of commercial spent fuel, the naval spent fuel is a small fraction (less than four percent) of the total accumulated amount of commercial and naval spent fuel. Nonetheless, considering the United States federal commitment to Idaho, a future investigation would calculate the amount of waste produced in an LEU-naval fuel cycle factoring in various sizes of the naval nuclear fleet and various potential designs for the LEU naval reactors.

3. The research team at the NSEL of Virginia Tech with consulting advice from VADM (ret.) Charles "Joe" Leidig identified several technical concerns that would benefit from further in-depth investigations. In order to maintain the current reactor core lifetime in an LEU-fueled submarine, the volume of the ship will increase. A further study would examine whether this increased volume would be too restrictive on the ability of the ship to carry out its missions. The option of having an LEU-fueled submarine with refueling one or more times would require accessing the reactor. One method is to install a refueling hatch, but this would likely limit the allowable diving depth due to decreasing the crushing depth—the depth that a submarine could reach without imploding due to water pressure. Limiting the allowable diving depth might affect the ship's capability to search for, evade or outmaneuver enemies. Thus, further study would examine the structural effects of adding a refueling hatch. Conversely, could a refueling hatch, or some other alternative means of refueling be designed, so that the maximum diving depth would not be adversely impacted?[2] Submarines need to withstand intense battle shock. Consequently, the Virginia Tech group also flagged the issue of further assessing fabrication of an LEU-fuel structure and material type that would satisfy the ruggedness criteria of the

2 Notably, one of the projects being investigated by Assistant Professor of Nuclear Science and Engineering R. Scott Kemp's research team at the Massachusetts Institute of Technology is "the possibility of modular reactor designs that would enable rapid refueling without the need for an access hatch, and without impacting naval operations or deployed forces." See: http://lnsp.mit.edu/naval-reactor-conversion/

U.S. Navy while increasing the uranium density for LEU fuels. Another concern is that LEU designs would require more shielding to protect against the higher energy radiation generated due to the increased production of plutonium; this is technically called neutron spectrum hardening. A further study would determine the amount of such hardening and the effects on crew radiation dose for different shielding designs. The increased production of plutonium in an LEU core could have significant effects in reactor control especially toward the end of core life. Further studies would (1) examine LEU fuel's effects on reactor control including change of power, restart, and end-of-life operation, (2) perform accident analysis for proposed LEU designs, and (3) determine the necessary changes in the training of reactor operators as well as the curriculum of the Naval Nuclear Power School. Furthermore, a LEU naval fuel cycle might increase the risk of refueling-related accidents if such LEU fuels would require refueling operations. Thus, further study would identify ways to reduce the risks associated with refueling operations.

Supporting Analysis for the Task Force's Findings and Recommendations

Why Does "Underway on Nuclear Power" Have Benefits?

On January 17, 1955, the U.S.S. Nautilus went on its maiden voyage and broadcast the message, "Underway on nuclear power," to announce the world's first use of nuclear power to propel a ship. The U.S. Naval Nuclear Propulsion Program is justifiably proud of its accomplishments for more than 60 years in designing safe and reliable nuclear reactors for submarines, cruisers, and aircraft carriers. While the U.S. Navy no longer operates nuclear-powered cruisers, its nuclear-powered warships consist of 10 aircraft carriers, 54 attack submarines, four guided missile submarines (SSGNs), and 14 ballistic missile submarines. This is the largest nuclear-powered fleet in the world, and more than 40 percent of the U.S. Navy's combat fleet uses nuclear power.

Because of nuclear power, these warships can project military and geopolitical power far from America's shores without the need for frequent refueling. In fact, the NNPP went from having to refuel the Nautilus every two years to now having a 40 plus year lifetime reactor core for the next generation SSBN(X) to replace the Ohio-class SSBNs. The Virginia-class SSNs also have lifetime cores that can operate for 33 years. The U.S. Navy has favored developing and deploying lifetime cores to save on refueling and operations and on not needing to procure more nuclear-powered warships to compensate for ships in refueling shipyards.[3]

Reportedly, U.S. naval reactors are fueled with weapons-grade uranium, which has more than 90 percent of its uranium as the fissile isotope uranium-235.[4] However, even lower proportions of uranium-235 can be used in nuclear explosives; notably the first generation nuclear bomb detonated over Hiroshima in 1945 had an average uranium-235 enrichment of 80 percent. Highly enriched uranium is defined as having 20 percent or greater proportion of uranium-235. While any enrichment-level of HEU is considered weapons-usable, higher

3 Stew Magnuson, "Nuclear Power Plants on New Submarines May Last 40-Plus Years," *National Defense*, February 2015.

4 Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *The Nonproliferation Review*, Spring 2001.

proportions of uranium-235 are more desirable for use in nuclear weapons. Weapons-grade uranium has allowed the U.S. and UK navies to develop very compact cores. Compactness permits the design of smaller reactor compartments and thus smaller size submarines. But depending on the missions of a submarine, it could still be relatively large in size even with a compact HEU-fueled core. For example, the Ohio-class SSBN has a displacement of 18,750 tons when submerged mainly due to the large volume taken up by 24 tubes for submarine launched ballistic missiles. The latest generation of SSN, the Virginia-class, has a displacement of almost 8,000 tons and carries dozens of torpedoes and cruise missiles. Thus, smaller reactor cores have not resulted in smaller nuclear-powered submarines but have helped minimize the amount of space used by the propulsion plant to allow for more volume for weapons and associated equipment.

Why Continue to Use HEU in Naval Reactors?

HEU is not required for nuclear-powered warships. While only the U.S. and UK nuclear navies reportedly use uranium enriched above 90 percent, India and Russia also use HEU fuel in their warships. The HEU in the Indian and Russian navies is still weapons-usable and can pose a security concern.

France has announced that its nuclear-powered submarines are fueled with low enriched uranium, which is not weapons-usable without undergoing further enrichment. The French navy has converted from HEU- to LEU-fueled naval reactors, which require refueling every ten years and use 7.5 percent enriched uranium. France is reportedly moving toward fuels that could make use of the 5 percent enriched uranium available from France's commercial enrichment plant. This decision was driven by France's closure of its facility for making HEU.[5]

China is believed to use LEU-fueled nuclear-powered submarines although Beijing has not confirmed whether this is the case. This lack of confirmation is in line with the Chinese government's longstanding policy to be opaque about details of its military nuclear programs. Nonetheless, open source information and a recent investigation, which interviewed several

5 Rebecca Ward, "USA and France: Naval Propulsion," Chapter 12 in Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (New York: Routledge, 2013).

Chinese experts, indicates that China started development of a program for LEU-fueled submarines in 1958. The recent analysis suggests that China's believed continued use of LEU naval fuels was likely a case of technological path dependency in which once a technology works it can become locked-in for further use.[6] This raises the interesting point that the United States and other nuclear navies that presently use HEU might find that technological inertia could pose resistance to a shift to LEU fuels, even when those newer fuels meet rigorous performance requirements.

Here are several considerations for the United States in deciding whether to convert from HEU to LEU naval reactors:[7]

1. As mentioned earlier, the latest generations of HEU-fueled naval reactors have lifetime cores, resulting in savings in refueling and shipbuilding costs.

2. Eliminating or reducing refueling activities will lower shipyard workers' radiation exposures. This consideration should not rule out conversion to LEU because lifetime cores are likely possible with LEU, according to Office of Naval Reactors staff.[8] In addition, technologies and procedures could be invented and implemented to keep exposures as low as reasonably achievable. For example, a refueling shipyard could be designed to use automation such as robotic tools as well as remote handling techniques as much as possible.[9]

3. To keep refueling minimized or eliminated, the NNPP would have to redesign the ships to make room for longer-lived LEU reactor cores that would require larger volume reactors. However, it is unclear, until further study, whether this would result in significantly bigger ships. Lower fissile content would require higher neutron flux to achieve same power, thus

6 Shing-yao (Sandra) Feng, "China: Reactors and Nuclear Propulsion," Chapter 7 in Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (New York: Routledge, 2013).

7 Many of these reasons are adapted from Office of Naval Reactors, "Report on Low Enriched Uranium for Naval Reactor Cores," Report to Congress, U.S. Department of Energy, January 2014.

8 Personal communications received separately by three task force members from congressional staff and Office of Naval Reactors at various dates in 2014.

9 Telephone communication with George Moore, Scientist-in-Residence, Center for Nonproliferation Studies, Middlebury Institute of International Studies at Monterey, February 20, 2015.

increasing challenges of structural materials and shielding. This would result in additional cost of potentially billions of dollars and time of 10 to 15 years to develop these new designs (the same as would be required to develop an HEU advanced fuel system), according to the January 2014 Office of Naval Reactors report to Congress.

4. Irradiated LEU-fueled reactor cores are much hotter radioactively than irradiated HEU-fueled cores, and moreover the LEU-fueled cores would result in larger volumes of radioactive waste to be stored, but the exact amounts will depend on the new fuel designs and thus will require further study. This waste would remain radioactive for longer period of time due to increased generation of transuranic isotopes. This could pose difficulties for the Department of Energy, which signed a 1995 agreement (and 2008 addendum) with the State of Idaho to commit to not having Idaho become a de facto permanent repository for such waste.

5. The United States has a large stockpile of HEU set aside for naval reactors that could last at least 50 years based on current and projected demands of about two tons annually and the declaration made by the U.S. Department of Energy about the size of the stockpile at 152 tons in 2004. (The United Kingdom has an estimated HEU stockpile of about 80 or more years based on projected demands and available information about its total HEU.)[10] Using this stockpiled material defers the time when the United States would have to build and operate an enrichment plant used for naval purposes. Presently, the United States does not even have an operational LEU enrichment plant that is nationally owned and thus potentially available for naval fuel purposes- although Urenco, a European consortium company, operates an enrichment plant in New Mexico. Nonetheless, if the United States decided to convert naval reactors to LEU fuels, it could have the stockpiled HEU down-blended to LEU. But such down-blending activity would only buy at most several decades of time before the United States would have to decide on a source for naval LEU fuels. On the other hand, indefinite use of naval HEU fuels would eventually lead to the United States' needing to build an HEU enrichment facility, which might also be useful for producing LEU for commercial purposes depending on the design of the facility. At this time it is too soon

10 Personal communication from Alexander Glaser and Frank von Hippel of Princeton University, March 5, 2015; see also the 2010 and 2013 Global Fissile Reports of the International Panel on Fissile Materials, available at: http://www.fissilematerials.org/

to decide among the options for such an enrichment facility. However, the United States would have to consider the possible effect such a facility could have on a future agreement on a cutoff on producing fissile material for weapons purposes. An inspection system for such an enrichment facility might be able to address concerns of other states.

Why Does HEU in the Naval Fuel Cycle Pose Security Risks?

The United States has been pushing for decades to phase out use of HEU in civilian reactors, which began in the late 1970s as a program to reduce the enrichment of research and test reactors. This program and related programs have been successful in converting or shutting down dozens of these reactors worldwide.[11] As a benchmark for how successful, the annual demand for HEU for research reactors and medical isotope production has been cut by several hundred kilograms- such that these facilities use less than one ton per year. This HEU demand will continue to fall as work proceeds on developing new fuels and converting facilities with proven non-HEU technologies. In contrast, naval nuclear propulsion globally requires about three tons per year with the U.S. Navy using on average two tons per year.[12]

Why should we be concerned about the security of naval fuels given the perception that militaries have rigorous protection measures? The military is not the sole custodian of naval fuels throughout the lifetime of the nuclear materials, and people who work at or have authorized access to naval fuel facilities, or personnel at shipyards that handle naval fuel could still plausibly present a threat for diversion of HEU. Fresh HEU fuel could also be vulnerable during transport and storage. Unfortunately, since the 1960s, there have been several incidents of alleged successful thefts and attempted thefts of HEU from the naval sector.

The incident of biggest concern allegedly took place in the 1960s at the naval fuel processing plant operated by the Nuclear Materials and Equipment Corporation (NUMEC) in Apollo, Pennsylvania. Five years ago, Victor Gilinsky and Roger J. Mattson, who had both served in the U.S. Nuclear Regulatory Commission, presented considerable circumstantial evidence

11 National Nuclear Security Administration, "GTRI's Convert Program: Minimizing the Use of Highly Enriched Uranium," Fact Sheet, U.S. Department of Energy, May 29, 2014.

12 Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing Out Highly Enriched Uranium* (New York: Routledge, 2013).

that appeared to point to a diversion of about 100 kilograms or possibly more of weapons-grade uranium from the NUMEC facility to Israel. They cited recent environmental sampling near Israel's Dimona nuclear weapons facility that indicated the presence of HEU bearing the signature of "ultra-HEU that was produced only" at the enrichment plant at Portsmouth, Ohio. It was unlikely that Israel had enriched the uranium, domestically. Also, they cited several statements by U.S. government officials during the late 1960s and into the 1970s that there were strong suspicions of diversion, that Israeli intelligence operatives had visited the NUMEC facility in 1968, and that there were other Israeli visitors who were suspected to have worked on Israel's nuclear weapons program.[13] After 1970, the United States tightened its security procedures on this type of material and these facilities.

But in more recent times, Russia has been a security concern. In particular, within a few years after the breakup of the Soviet Union, Russia had a huge backlog of decommissioned nuclear-powered submarines. Given the dire economic situation in the 1990s in Russia, it is not surprising that there were at least five known incidents of attempted theft or diversion of naval HEU from July 1993 to January 1996. Two serious incidents in 1993 prompted U.S. security experts to initiate discussions with their Russian counterparts in 1994 and 1995. In 1996, the U.S. Cooperative Threat Reduction Program began to implement in cooperation with Russian authorities improved security measures on naval fuel storage on land and on ships. There have been no reported incidents of Russian naval fuel theft since then. While security is not perfect, the extensive cooperative security work between Russia and the United States is an outstanding example of what the two countries can accomplish when facing a common threat.[14]

The insider threat was the common denominator for the Russian incidents as well as the alleged diversion from the NUMEC facility. In all cases, personnel who had worked at naval fuel facilities or had access to such facilities knew how to exploit or attempt to exploit vulnerabilities in security systems. This is why personnel reliability programs are needed to assess whether workers- including those at the highest leadership levels- can be trusted.

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13 Victor Gilinsky and Roger J. Mattson, "Revisiting the NUMEC Affair," *Bulletin of the Atomic Scientists,* March/April 2010.

14 Morten Bremer Maerli, "U.S.-Russian Naval Security Upgrades: Lessons Learned and the Way Ahead," *Naval War College Review*, Autumn 2003.

A forced break-in to an HEU storage facility is another plausible scenario. In fact, on July 28, 2012, three intruders broke through multiple layers of fencing to reach the Highly Enriched Uranium Material Facility (HEUMF) at Y-12 National Security Complex near Oak Ridge, Tennessee. The intruders did not intend to steal HEU; instead, they were anti-nuclear protesters belonging to the Plowshares movement. The group consisted of Megan Rice, a nun who belonged to the Society of the Holy Child Jesus and was 82 years old at the time of the break-in, Gregory Boertje-Obed, a Christian Pacifist in his late fifties, and Michael Walli, a Catholic layman in his early sixties. They had prepared for over a year, doing site surveillance and vulnerability assessments using open-source tools such as Google Earth and the Internet. Using simple bolt and fence cutting tools, they were able to easily breach security fences in the early morning hours of July 28, 2012. By 4:30 a.m. they had reached the HEUMF, where tens of tons of HEU are stored. They had several minutes available to use spray paint to write sayings, splatter blood and beat with sledgehammers on the walls of the facility as part of the rituals of the Plowshares movement. Eventually, a guard showed up; another several minutes went by before security back up arrived.[15]

The DOE Inspector General's report in August 2012 that described the findings of the investigation of the break-in identified several security lapses.[16] First, the Inspector General "found the response to the security breach at Y-12 was inadequate in several material respects" such as not having a Protective Force officer promptly dispatched despite the fact that a number of alarms [from the fences being cut] had been activated, not securing the scene soon after the first officer had arrived, not noticing the trespassers until they had "surrendered" to the responder, permitting the trespassers to continue to roam the area and pick up their belongings, and not providing adequate cover to the supervisor once he arrived on the scene, despite the supervisor ordering the first officer to provide cover. The Protective Force Supervisor did order a lockdown of the entire Protected Area at Y-12 putting into place a number of security measures including searches for other possible trespassers. However, the Inspector General's report documents several disturbing actions by the security force including

15 Eric Schlosser, "Break-In at Y-12: How a handful of pacifists and nuns exposed the vulnerability of America's nuclear weapons sites," *The New Yorker*, March 9, 2015.

16 Office of Inspector General, Office of Audits and Inspections, "Inquiry into the Security Breach at the National Nuclear Security Administration's Y-12 National Security Complex," Special Report, U.S. Department of Energy, DOE/IG-0868, August 2012.

an officer silencing a local alarm and not looking out of a gun port or available viewing glass to survey the situation. Moreover, the Inspector General uncovered that "security equipment repairs were not always treated as a priority at Y-12" and that there was "a substantial backlog of degraded and/or nonoperational security equipment." The National Nuclear Security Administration concurred with all recommended corrective actions by the Inspector General. The private security firm that had worked at Y-12 was fired and has since been replaced.

Today, the countries that could pose the greatest concern for security vulnerabilities are India and Pakistan because of the availability of HEU and the presence of terrorist groups, some of which appear motivated to acquire nuclear explosives. In recent years, India has developed and deployed an indigenous nuclear-powered submarine fueled with HEU. Reportedly, India wants to build at least four to five nuclear-powered submarines. This plan has prompted Pakistan to express interest in acquiring nuclear-powered submarines. Both India and Pakistan have enrichment plants that can produce HEU and are outside of IAEA safeguards. These two countries have safeguards on some specific civilian nuclear facilities but are not required to accept IAEA safeguards on all nuclear materials and facilities because they never signed and ratified the NPT.

Why Does the Naval Nuclear Fuel Cycle Pose Proliferation Risks?

Even if India and Pakistan were parties to the NPT and had then been required to accept comprehensive nuclear safeguards, they would still have the option of removing nuclear material from safeguards for naval propulsion purposes. In particular, the Comprehensive Safeguards Agreement, as required by the NPT for non-nuclear weapon state parties, has the provision in Paragraph 14 for "non-proscribed military uses" such as naval propulsion purposes to allow taking nuclear material outside of safeguards while used in this manner. Argentina and Brazil have a special Quadripartite Agreement with the IAEA and the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), which addresses the naval nuclear propulsion issue in Article 13. Both Paragraph 14 and Article 13 require a state party to inform the respective agency whether IAEA or ABACC that it intends to remove nuclear material from safeguards for a non-proscribed use and that the state pledges that during the period outside of safeguards that the material would not be used for nuclear explosives. Article 13 explicitly defines "non-proscribed use" as meaning naval propulsion. Once the material is removed from this activity, it shall be placed again under safeguards. The proliferation concern is that nuclear material could be diverted from this sector because safeguards would not be applied.[17]

Notably, in 2014 two non-governmental research groups outlined potential methods for transparency, monitoring, and safeguards on naval nuclear propulsion.[18] As part of the Task Force, the team at the Nuclear Policy Working Group at the University of California, Berkeley, created the concept of Naval-Use Safeguards Agreements (NUSA), which:

> builds on the precedent set by the Additional Protocol (AP), which expands traditional safeguards to better detect and provide greater confidence that states are not diverting nuclear material from permitted uses … Like the AP, signed between a state and the IAEA, NUSA are tailored to parties' specific needs and capabilities. Following the AP model, NUSA feature voluntary confidence building measures for NWS (both NPT states parties and India), but strongly encouraged and incentivized measures for NNWS. Once agreed upon, however, NUSA create legally binding obligations for NNWS with nuclear naval programs to carry out the framework provisions. As these agreements are personalized and tailored for specific issues, they are unlikely to encounter significant political challenges on a structural level. With this structure, NUSA are applicable to either LEU or HEU-based naval programs. The flexibility of this model makes it a viable option for enacting and strengthening safeguards on nuclear material in the naval sector, while taking into account state-specific factors, including choice of fuel and other civilian nuclear activities within a state.
>
> NUSA require that material in the naval nuclear fuel cycle be safeguarded through fuel fabrication, and that safeguards are reapplied upon removal of any spent fuel from the reactor core, including during refueling. Safeguards would also be applied throughout intermediary storage for spent fuel. States would further be required to inform the IAEA ahead of any submarine return to a refueling facility. NUSA would

17 For one of the earliest articles on this issue, see James Clay Moltz, "Closing the NPT Loophole on Exports of Naval Propulsion Reactors," *The Nonproliferation Review*, Fall 1998.

18 Sebastien Philippe, "Safeguarding the Military Naval Nuclear Fuel Cycle," *Journal of Nuclear Materials Management*, Vol. XLII. No.3, Spring 2014; N. Egel, B. L. Goldblum, and E. Suzuki, "Safeguarding Nuclear Material in the Naval Sector: An Examination of Governance Frameworks," Nuclear Policy Working Group, University of California, Berkeley, November 2014.

complement existing safeguards agreements rather than replace these in order to close the safeguards loophole in naval nuclear activities.[19]

19 Egel, Goldblum, and Suzuki, p. 5.

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