RERTR 2017 - 38th INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

NOVEMBER 12-15, 2017
EMBASSY SUITES CHICAGO DOWNTOWN MAGNIFICENT MILE HOTEL
CHICAGO, IL USA

Reduced Enrichment for Naval Propulsion Reactors

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ABSTRACT

The RERTR Program has reduced annual HEU commerce for non-weapons purposes – in research reactor fuel and medical isotope production targets – by several hundred kilograms annually, thereby significantly reducing risks of nuclear proliferation and nuclear terrorism. However, even larger amounts of HEU continue to be used for naval nuclear propulsion, which poses similar risks of proliferation and terrorism. Accordingly, in 2016, the U.S. government initiated research and development by its Office of Naval Reactors of an LEU advanced fuel system, which if successful could reduce or eliminate use of HEU fuel by the U.S. Navy and thereby encourage a global phase-out of HEU fuel for such propulsion. This paper examines the rationale of reduced enrichment for naval propulsion reactors, the steps taken to date by the U.S. government, the plans going forward, and the prospects and challenges of converting naval propulsion from HEU to LEU fuel.

1 Introduction

The Reduced Enrichment for Research and Test Reactors (RERTR) Program has reduced annual highly enriched uranium (HEU) commerce for non-weapons purposes – in research reactor fuel and medical isotope production targets – by several hundred kilograms annually, thereby significantly reducing risks of nuclear proliferation and nuclear terrorism. However, even larger amounts of HEU continue to be used for naval nuclear propulsion, which poses similar risks of proliferation and terrorism. Accordingly, in 2016, the U.S. government initiated research and development by its Office of Naval Reactors of a low enriched uranium (LEU) advanced fuel system, which if successful could reduce or eliminate use of HEU fuel by the U.S. Navy and thereby encourage a global phase-out of HEU fuel for such propulsion. This paper examines the rationale of reduced enrichment for naval propulsion reactors, the steps taken to date by the U.S. government, the plans going forward, and the prospects and challenges of converting naval propulsion from HEU to LEU fuel.

Preparation of this paper was assisted by a grant from the John D. and Catherine T. MacArthur Foundation to the Nuclear Proliferation Prevention Project (www.NPPP.org).

2 Why Naval Reactors?

The nuclear proliferation and terrorism risks of HEU fuel have been widely recognized for decades. In 1978, the international RERTR effort was initiated to phase out HEU fuel from nuclear research reactors by converting them to higher-density LEU fuel, to reduce risks of proliferation and terrorism without significantly degrading reactor performance. Since then, around the world, 96 civilian research reactors had been converted or shut down by October 2016 [1,2]. Conversion to LEU fuel has been highly successful, according to a recent survey, which reported that "operators overwhelmingly perceived any negative impacts to be outweighed by positive ones" [3]. In addition, since 1980, more than 20 large (>1 MW) new research reactors have been designed to use LEU fuel [21]. Moreover, by 2018, all major worldwide producers of Mo-99 for radio-pharmaceuticals, except in Russia, are expected to have successfully converted from HEU to LEU "targets" for their production processes. Due to these efforts, worldwide use of HEU for research reactors and pharmaceutical production has been slashed by several hundred kilograms annually to less than one ton per year, and the decline is expected to continue.

Table 1

Estimated Annual Worldwide Use, and Reduced Use, of Fresh HEU for Selected Purposes other than Nuclear Weapons

Selected Use of Fresh HEU (Globally)	Per Year (kg)
Research Reactors (RR)	750
Medical Isotope Targets	20
Naval Propulsion	**3,000**

Reduced Use of Fresh HEU (Globally)	Per Year (kg)
RR Conversion	280
RR Shutdown	450
Target Conversion	30
New RR Fueled with LEU	10's
Total Reduced by RERTR/GTRI	**> 760**

Sources: Alan J. Kuperman, ed., *Nuclear Terrorism and Global Security: The Challenge of Phasing out Highly Enriched Uranium* (New York: Routledge, 2013). DOE, "Tritium and Enriched Uranium Management Plan Through 2060," Report to Congress, October 2015. Frank von Hippel, personal communication, 2016.

By contrast, naval reactors – mainly in the United States and Russia – still require up to three tons of HEU fuel annually, about four times the amount used globally for research reactors and medical isotope production (Table 1). One percent of the annual HEU commerce for naval fuel, if stolen, would be more than enough for a nuclear weapon. France already has converted its nuclear navy from HEU to LEU fuel, and China's navy always has used LEU fuel [4], but the UK and India still use HEU fuel for naval propulsion. Converting nuclear navies to LEU fuel would yield at least two major benefits for global security. First, it would eliminate the risk of HEU theft from naval fuel cycles – which is greatest during fuel fabrication, transport, and storage, prior to loading.

Second, it would establish a precedent to demand that any new nuclear navies likewise avoid HEU fuel. This would reduce the danger that naval propulsion programs could be used as cover to acquire fissile material for nuclear weapons. In December 2016, for example, Iran's president ordered the development of naval propulsion reactors [5], which Iranian officials previously have said would require production of HEU [6]. Under IAEA safeguards agreements, a country may remove from international inspection any fissile material it designates for "a non-proscribed military activity" such as naval propulsion [7]. Thus, if a country claimed to need HEU fuel for naval propulsion, it could legally remove HEU from safeguards, then illegally divert it for nuclear weapons without any further enrichment, so timely detection would be unlikely. By contrast, if a country designated LEU for naval propulsion and then engaged in diversion, it would also need clandestinely to enrich further that material to make it suitable for nuclear weapons, thereby increasing substantially the probability of timely detection that could enable international preventive action.

An additional nonproliferation benefit of converting the U.S. nuclear navy to LEU fuel is that it could avert a potential resumption of U.S. HEU production [8]. The United States is gradually exhausting its stock of HEU designated for naval fuel, so unless a switch is made to LEU naval fuel in coming decades, the United States may have to resume production of weapons-grade uranium for the first time since 1992. This would undermine the U.S. nonproliferation goal of halting HEU production worldwide.

3 Actions to Date

In 1995, a study by the U.S. Office of Nuclear Naval Propulsion rejected the feasibility of converting the nuclear reactors in U.S. submarines and aircraft carriers to LEU fuel on grounds that it would lead to unacceptable costs including shorter core life, larger reactors, and/or larger vessels [9]. In 2014, however, this stance was revised when the U.S. Office of Naval Reactors submitted a report to Congress stating that development of a potential "advanced fuel system" could "allow using LEU fuel with less impact on reactor lifetime, size, and ship costs" [10]. Elaborating this new perspective, in July 2016, the U.S. Department of Energy's National Nuclear Security Administration (NNSA) submitted to Congress a conceptual plan for development of LEU naval fuel. It stated that "The required LEU fuel development program would span 15 years, and is projected to cost approximately $1 billion in FY 2016 dollars." The report highlighted the value for international security, stating that "Development of an advanced naval fuel that uses LEU would demonstrate United States leadership toward reducing HEU and achieving nuclear non-proliferation goals," and that "Having the option to use an LEU fuel system could have positive implications from a national security standpoint by creating a practical alternative to HEU reactors" [11].

In March 2016, President Barack Obama also expressed support for naval LEU fuel development, issuing a White House "Fact Sheet" that stated the following: "Consistent with its national security requirements and in recognition of the nonproliferation benefits to minimizing the use of highly enriched uranium globally, the United States values investigations into the viability of using low-enriched uranium in its naval reactors" [12].

The U.S. Congress, on a bipartisan basis, has authorized and appropriated funding for naval LEU fuel development since 2015. The FY 2016 National Defense Authorization Act, as enacted, provided that "$5,000,000 shall be made available to the Deputy Administrator for Naval Reactors for initial planning and early research and development of an advanced naval nuclear fuel system based on low-enriched uranium." The FY 2016 Consolidated Appropriations Act, as enacted, included "$5,000,000 to start a technical program to develop and qualify a low-enriched uranium (LEU) fuel system for naval reactor cores."

Again the following year, the FY 2017 National Defense Authorization Act, as enacted, provided that "$5,000,000 shall be made available to the Deputy Administrator for Naval Reactors of the NNSA for initial planning and early research and development of an advanced naval nuclear fuel system based on low-enriched uranium." The FY 2017 Further Continuing and Security Assistance Appropriations Act, and successor legislation, as enacted, extended the preceding year's funding levels, including for naval LEU fuel development, through most of FY 2017 until May 5, 2017.

The FY 2018 authorization and appropriation bills are pending. The FY 2018 National Defense Authorization Act conference report, issued on November 8, 2017, provides that "$5,000,000 shall be made available to the Deputy Administrator for Naval Reactors of the National Nuclear Security Administration for low-enriched uranium activities (including downblending of high-enriched uranium fuel into low-enriched uranium fuel, research and development using low-enriched uranium fuel, or the modification or procurement of equipment and infrastructure related to such activities) to develop an advanced naval nuclear fuel system based on low-enriched uranium."

The conference report further provides that "an additional $30,000,000 may be made available to the Deputy Administrator for such purpose . . . if the Secretary of Energy and the Secretary of the Navy determine under section 3118(c)(1) of the National Defense Authorization Act for Fiscal year 2016 (public Law 114-92; 129 Stat. 1196) that such low-enriched uranium activities and research and development should continue." This determination had been required to be submitted to Congress by September 2016, but it was postponed by the presidential election and the delay in confirming a new Secretary of the Navy until August 2017. The Secretaries of Energy and Navy are currently working on preparing that determination, according to U.S. officials.

4 Next Steps

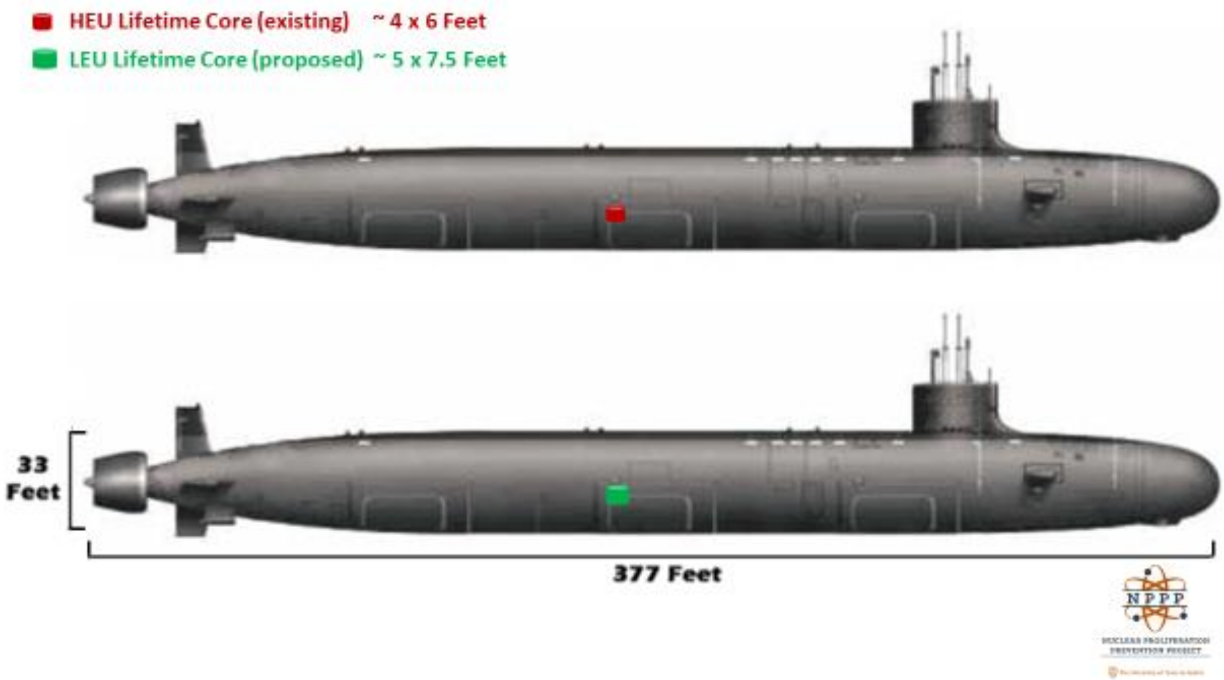
The July 2016 DOE report proposed a two-step plan to convert naval propulsion to LEU fuel. The first step, *developing* an LEU fuel system, was estimated to cost $1 billion over 15 years. The report explained that "Fuel system development produces a tested fuel system, a laboratory scale manufacturing approach, and test data needed to engineer a reactor core design. Development would be done with small fuel specimens to (1) establish basic manufacturing processes and (2) test irradiated fuel performance and properties." The second step, *deploying* an LEU fuel system, was estimated to cost several billion dollars over at least 10 more years. The report explains that "Fuel deployment includes: (1) new manufacturing facilities and production scale processes, (2) reactor prototyping to prove out large-scale fuel fabrication and performance, (3) designing a new reactor core and any associated propulsion system modifications, and (4) developing and procuring equipment for spent fuel transportation and disposal." Reactor modifications that could be necessitated by conversion from HEU to LEU fuel are explored in an independent study [13].

The schedule in the DOE report was projected to commence in FY 2018, meaning that LEU naval fuel could be developed by 2033 and deployed as early as 2043. The report implied that LEU fuel might be inserted in existing aircraft carriers starting in the 2040s, during scheduled mid-life refueling: "Preliminary design work has shown that an initial application of LEU fuel in an aircraft carrier reactor might meet ship performance requirements in the available size envelope, though at higher cost." By contrast, U.S. nuclear submarines have life-of-the-ship cores, so conversion to LEU fuel would likely be reserved for new submarines. The report states that "an LEU-fueled submarine reactor is a larger challenge which would not be addressed until experience could be gained during the development of an LEU-fueled aircraft carrier reactor."

Because LEU fuel has lower energy density, its use in submarines would require either a larger core or refueling during the life of the vessel. The required increase in core size to achieve a life-of-the-ship core with LEU fuel has been estimated by Sébastien Philippe and Frank von Hippel [14]. The height of the HEU core in U.S. submarine reactors is understood not to exceed four feet, which is the height of the internal cavity of the spent-fuel cask reported in unclassified licensing documents of the U.S. Nuclear Regulatory Commission [20]. The diameter of the core cannot be inferred directly from the diameter of the cask's cavity (six feet), because the spent fuel is divided into two casks [9] and may be packed less densely than in the core. The following calculations assume the current HEU core is four feet high by six feet wide (1.2m x 1.8m). The 2016 DOE report suggested that use of LEU fuel in an existing submarine reactor envelope might require only one refueling, so Philippe and von Hippel infer that future high-density LEU could have an energy density approximately one-half of existing HEU fuel. This implies that a life-of-the-ship core with future LEU fuel would require twice the current core volume, so the linear dimension would increase by the cube-root of two, or 1.26, enlarging the dimensions of a potential LEU life-of-the-ship core to approximately 5' x 7.5' (1.5m x 2.3m). Figure 1 illustrates the potential difference in size between current HEU and future LEU life-of-the-ship cores in relation to current U.S. Virginia-class attack submarines. A larger core would also require a larger reactor and greater volume of shielding, which would add weight and necessitate a marginally longer (or wider) vessel, which is not illustrated.

Figure 1

Estimated Size of HEU vs. LEU Life-of-the-Ship Core



5 Prospects and Challenges

The potential conversion of naval propulsion reactors from HEU to LEU fuel faces both technical and political challenges, analogous to those successfully overcome by the RERTR program to convert research reactors and medical-isotope production from HEU to LEU fuel and targets. The most immediate political challenge is that the U.S. Secretaries of Energy and Navy must submit to the U.S. Congress a joint determination, overdue by more than a year, regarding whether to continue the recently initiated development of naval LEU fuel. At least two political forces will exert pressure to terminate this LEU fuel development program. First, some U.S. naval reactor officials oppose switching from HEU, which they are familiar using, especially because LEU fuel would require redesigning the reactor and its surrounding module of the submarine. This is analogous to the resistance that RERTR initially faced from research reactor operators, who did not see any problem with continuing to use HEU fuel but did fear many problems from potential conversion to LEU fuel [15].

The second political obstacle is the expense of phasing out HEU fuel from U.S. naval propulsion, estimated at $1 billion to develop the LEU fuel and several billion dollars more to deploy it. Although such costs are substantial, they are relatively small compared to the enormous expense of constructing and operating U.S. nuclear naval vessels. For example, each new Virginia-class attack submarine is estimated to cost nearly $3 billion, and the U.S. Navy expects to sustain about 40 of them, for a total cost exceeding $100 billion in 2017 dollars [16]. Even more expensive per vessel are the 12 planned Columbia-class ballistic missile submarines, projected to cost a total of $70 billion (in 2010 and 2015 dollars) [17]. Most expensive per ship are the Ford-class aircraft carriers, at a price of about $13 billion each (in 2018 dollars), so the statutorily mandated fleet of 11 will cost about $140 billion [18]. In total, the U.S. naval nuclear fleet will cost more than $300 billion merely to construct, not including operating costs. In that light, a few billion dollars to develop and deploy LEU reactors would represent a marginal increase of perhaps two percent of naval nuclear construction costs – and an even smaller percentage of the amount including operating costs. Conversion to naval LEU fuel also could yield savings from reducing the security costs associated with fuel fabrication, transport, and storage. Nevertheless, opponents of conversion to LEU fuel likely will cite the program's estimated costs as grounds for cancelation.

Policymakers must keep in mind the compelling policy argument in favor of the naval LEU fuel development program: It could significantly reduce risks of nuclear proliferation and nuclear terrorism. If the US converted to LEU fuel, the UK likely would follow suit, considering that country's heavy reliance on U.S. naval reactor design and enriched uranium. That would reduce worldwide HEU use for naval fuel by perhaps 80 percent, sharply reducing risks that terrorists or criminals could steal a sufficient amount for a nuclear weapon. Conversion by the U.S. and UK also would apply pressure on the two other HEU naval fuel users, Russia and India, to likewise convert to LEU. New nuclear navies too would face intense international political pressure to eschew HEU fuel. In combination with RERTR's gradual elimination of HEU from research reactors and medical isotope production, and the feasibility of using LEU fuel for proposed space reactors [19], a phase-out of HEU fuel from naval propulsion could eventually enable a global halt of HEU commerce for non-weapons purposes. This would block perhaps the easiest path to nuclear weapons.

Lastly, there are technical challenges to converting naval reactors from HEU to LEU fuel. France has successfully overcome these, but the U.S. case is more challenging because of higher power demands and an institutional preference for life-of-the-ship cores. Nevertheless, the U.S. Office of Naval Reactors, which has the greatest expertise, expressed optimism in its January 2014 report to Congress that an "advanced fuel system" could "allow using LEU fuel with less impact on reactor lifetime, size, and ship costs." The U.S. DOE, in its July 2016 report to Congress, likewise expressed optimism that an "advanced fuel system could allow use of LEU fuel with minimized impact on reactor lifetime, size, and ship costs." The only way to assess this feasibility is to complete the recently initiated naval LEU fuel development program, estimated to require $1 billion over 15 years. In light of the enormous potential benefits for U.S. and international security from reducing risks of nuclear proliferation and nuclear terrorism, that would be time and money well spent.

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