Office of

NAVAL REACTORS

Report on Low Enriched Uranium for Naval Reactor Cores

Report to Congress

January 2014

United States Department of Energy
Washington, DC 20585

Message from the Director

US Naval nuclear reactors are fueled with highly-enriched uranium in order to meet the rigorous demands of a US Naval warship operating at sea.

Pursuant to the direction included in House Report 112-479, the attached report is being provided to the following Members of Congress:

- **The Honorable Mike Rogers**
  Chairman, Subcommittee on Strategic Forces
  House Committee on Armed Services

- **The Honorable Jim Cooper**
  Ranking Member, Subcommittee on Strategic Forces
  House Committee on Armed Services

- **The Honorable Mark Udall**
  Chairman, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

- **The Honorable Jeff Sessions**
  Vice Chair, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

If you have any questions or need additional information, please contact me or Nora Khalil, Director of External Affairs, at (202) 781-6061.

Sincerely,

ADM John Richardson

Executive Summary

This report examines the potential of using low-enriched uranium (LEU, 20% or lower ^{235}U) in place of highly-enriched uranium (HEU, 93% ^{235}U) in a naval nuclear fuel system. Two options exist: (1) substitute LEU fuel for HEU into the current naval fuel system and (2) develop a new fuel system that can increase uranium loading to offset some impacts of using LEU fuel.

US Navy warship requirements determine naval fuel system design features that require HEU fuel to deliver optimum performance. These Navy requirements include ruggedness, endurance, stealth, maneuverability and compactness that are necessary to deliver safe, effective operation of nuclear reactors onboard Navy warships. While LEU is used in commercial and most research reactors, naval requirements are far more demanding than those in land-based reactors.

Substituting LEU for HEU would fundamentally decrease reactor energy density, increase lifecycle and operating costs, increase occupational radiation exposure, and increase the volume of radioactive wastes. Thus, while it may be feasible to replace HEU fuel with LEU fuel in current US Naval reactor plants, it is not economical or practical to do so. For example, the OHIO-Class Replacement ballistic missile submarine is being designed for a 40+ year core life without the mid-life refueling needed in the current OHIO-Class. Eliminating the refueling allows the Navy to meet the strategic deterrent mission with two fewer SSBNs and saves about $40B in ship acquisition and life cycle costs. LEU fuel would eliminate these savings while adding substantial cost and occupational radiation exposure. LEU in current naval reactor fuels and core designs would reduce core life by a factor of 3 to 4. Today's ships would then require 2 to 3 refuelings instead of no refueling, or at most one refueling. Conceivably, a much larger LEU fueled core could be developed, which might preserve core life but would negatively impact ship performance.

With respect to developing an advanced fuel system, recent work has shown that the potential exists to develop an advanced fuel system that could increase uranium loading beyond what is practical today while meeting the rigorous performance requirements for naval reactors. Success is not assured, but an advanced fuel system might enable either a higher energy naval core using HEU fuel, or allow using LEU fuel with less impact on reactor lifetime, size, and ship costs. Advanced fuel system development would be a long-term effort that must start well in advance of a ship application.

The capability to develop advanced naval fuel resides within a small cadre of highly specialized, experienced, and qualified engineers and scientists. These experts, laboratory facilities, and Program funding are currently dedicated to supporting the existing Fleet and advancing technology to meet Navy requirements for new designs including the new Land-based Prototype reactor and the OHIO-Class Replacement submarine. It will not be practical to sustain these capabilities or work on an advanced fuel system without additional sources of funding. Consequently, until this funding can be secured advanced fuel is not being pursued beyond the early concept stage.

Low Enriched Uranium for Naval Reactors' Cores

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I. Legislative Language

This report responds to legislative language set forth in House Report 112-479, which accompanied the FY13 National Defense Authorization Act, on page 329, wherein it is stated:

> *"The Committee is aware of a study conducted by the Director, Naval Reactors in 1995 to assess the technical, environmental, economic, and proliferation implications of using low-enriched uranium (LEU) in place of highly-enriched uranium (HEU) in naval nuclear propulsion systems. The Committee notes that the report concluded that "the use of LEU in U.S. Naval reactor plants is technically feasible, but uneconomic and impractical.*
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> *The Committee directs the director, Naval Reactors to submit a report, to the congressional defense committees by March, 1 2013, that describes any updates to the findings and conclusions from the 1995 report, including any changes in the estimated costs for fabricating HEU and LEU life-of-ship cores, the ability to refuel nuclear-propelled submarines and ships without extending the duration or frequency of major overhauls, and the overall health of the technology base that may be required to utilize LEU in Naval nuclear propulsion systems."*

II. Background

The Naval Nuclear Propulsion Program (NNPP) started in 1948. Since that time, the NNPP has provided safe and effective propulsion systems to power submarines, surface combatants, and aircraft carriers. Today, nuclear propulsion enables virtually undetectable US Navy submarines, including the sea-based leg of the strategic triad, and provides essentially inexhaustible propulsion power independent of forward logistical support to both our submarines and aircraft carriers. Over forty percent of the Navy's major combatant ships are nuclear-powered, and because of their demonstrated safety and reliability, these ships have access to seaports throughout the world.

The NNPP has consistently sought the best way to affordably meet Navy requirements by evaluating, developing, and delivering a variety of reactor types, fuel systems, and structural materials. The Program has investigated many different fuel systems and reactor design features, and has designed, built, and operated over 30 different reactor designs in over 20 plant types to employ the most promising of these developments in practical applications. Improvements in naval reactor design have allowed increased power and energy to keep pace with the operational requirements of the modern nuclear fleet, while maintaining a conservative design approach that ensures reliability and safety to the crew, the public, and the environment. As just one example of the progress that has been made, the earliest reactor core designs in the NAUTILUS required refueling after about two years while modern reactor cores can last the life of a submarine, or over 30 years without refueling. These improvements have been the result of prudent, conservative engineering, backed by analysis, testing, and prototyping.

The NNPP was also a pioneer in developing basic technologies and transferring technology to the civilian nuclear electric power industry. For example, the Program demonstrated the feasibility of commercial nuclear power generation in this country by designing, constructing and operating the Shippingport Atomic Power Station in Pennsylvania and showing the feasibility of a thorium-based breeder reactor fuel cycle in a pressurized light-water environment by designing, fabricating and operating the world's only light-water-cooled breeder reactor. Many of the basic materials relied upon by commercial reactor plants today, including zirconium alloys and uranium oxide fuels, were initially developed by the Naval Reactors Program.

III. Requirements of Naval Nuclear Reactors

Naval reactors must meet unique design criteria applicable to US Navy submarines and aircraft carriers. They must have ruggedness, endurance, maneuverability, and compactness that are far greater than land-based reactors. These requirements directly drive the unique design requirements of naval fuel systems, and are important to ensuring submarines and aircraft carriers effectively carry out their missions while ensuring safety to the crew, the public, and the environment.

- Naval fuels must satisfy very high standards for fuel integrity. Naval fuel systems reliably retain the fission products under extremes of operating conditions, providing maximum flexibility to the propulsion plant to respond to possible casualties and still maintain electrical and propulsion power for the ship. This is particularly important for a submarine, where loss of propulsion may place the ship and crew in jeopardy.
- Naval fuel elements and modules are rigid and tough, able to withstand the extreme shock loads that might occur in a collision or an attack without losing integrity or compromising the ability to operate the reactor. The design shock loads for naval fuel are more than 10 times greater than seismic loading assumed for land-based reactors.
- Naval reactors are operated in closed environments in close proximity to the crew, who live onboard for months at a time. To minimize the exposure of the crew to radiation, the fuel must keep the highly radioactive fission products from getting into the coolant. Current naval fuel element design, materials, and fabrication techniques retain the fission product radioactivity inside the fuel element and prevent radioactivity from reaching the coolant. US Navy reactors are so effectively shielded and radioactivity is so controlled that a typical nuclear powered warship crew member receives significantly less radiation exposure than a person would receive from background radiation at home in the US in the same period. Features of naval fuel design that protect the crew apply equally to protection of the public and the environment, and demand a conservative engineering and operational approach. This is vital to maintaining national and international acceptance, as nuclear-powered warships make calls into sea ports throughout the world.
- Naval reactors must support rapid and frequent power changes to accommodate tactical ship maneuvering without excessive thermally-induced stresses on the fuel system.
- Naval reactor plants on submarines must be quiet. Flow-induced noise increases with flow rate and pump input power. Naval fuel systems allow high reactor power for relatively low flow rate and main coolant pumping power to reduce detectability for modern submarines.
- Naval cores operate for many years without refueling to minimize life-cycle costs, demand on support infrastructure, and occupational radiation exposure, while maximizing ship operational availability to Fleet commanders. Modern submarine cores are designed to last the life of the ship, and aircraft carriers are refueled only once during their 50 year service life.
- To be cost-effective, naval reactor plants must be compact. Ship design is highly integrated, since the size of the ship impacts the required power to propel the ship at a particular speed. The reactor must fit within the space and weight constraints of a warship, leaving

room for weapons and crew, but must still be powerful enough to drive the ship at tactical speeds for engagement or rapid transit to an operating area while carrying sufficient fuel to last for decades.

A pressurized water reactor, with HEU fuel in high integrity fuel elements has proven to be the optimum design to meet the essential functional requirements for nuclear propulsion for warships, as well as to provide very long core lifetimes for maximum affordability and ship readiness. The use of HEU maximizes the amount of fissile material in the small volume of the core, enabling very long lifetimes while maintaining compactness. Water coolant has good heat transfer properties, is not hazardous or aggressively corrosive, and does not have violent chemical reactions with air. Water does not have any significant long-lived radioactive states, so after-shutdown radiation levels are low and personnel can safely and rapidly enter the reactor compartment to do maintenance within minutes after the reactor is shut down. The thermal expansion properties of water also provide a natural feedback mechanism that assists in making naval reactors self-controlling and inherently stable during power changes.

IV. Impact of LEU Alternatives

Substituting LEU for HEU into the current naval fuel system would reduce the amount of fissionable fuel in current reactor cores. There are two feasible ways to substitute LEU fuel for HEU in current naval fuel systems:

- Ships could be designed of similar size to today's ships but would require multiple reactor refuelings over the life of the ship.
- Ships could be designed to be large enough to accommodate a larger LEU core with an equivalent amount of energy as modern HEU cores to provide equivalent lifetimes.

Either of these options would require billions of dollars of investment to develop and deploy. These options would also lead to sustained increases in lifecycle and operating costs.

Developing and testing an LEU-based variant of the current naval fuel system would take at least 10 to 15 years due to the need for long-term irradiation testing to show that the fuel meets all of the rigorous requirements for naval reactor applications. Building the first core would take at least an additional 5 to 10 years, assuming that core design, manufacturing qualification, and vendor facilitization could be aggressively started in parallel with fuel technology development.

The discussions below assume LEU at 20% enrichment, the highest level of enrichment within the internationally recognized definition of LEU. This was done to assess use of LEU at the enrichment level that would cause the least adverse impact on naval reactors. To assess the sensitivity of a lower enrichment level, a submarine core with an enrichment of 5% was studied, but determined to be infeasible and cost prohibitive, based on ship size and displacement.

If LEU is substituted for HEU in a current naval reactor core, the lower energy content of the LEU would translate into reduced core life. For example, a VIRGINIA-Class submarine reactor core, which today operates for the 33 year ship life without refueling, would have to be refueled three times if HEU fuel were replaced with LEU. A FORD-Class aircraft carrier would require two refuelings instead of one refueling. More frequent refueling would result in about a $1.0 billion per ship increase in life-cycle costs associated with greater reactor servicing workload and large increases in manufacturing costs to build refueling cores. The greater time spent in shipyards means that the ships would not be available for Navy missions. The Navy would need to procure more ships to provide the same operational availability with more frequent refueling.

Since 1966, the Naval Reactors Program has significantly reduced the total radiation exposure to shipyard workers, by constantly improving work procedures and tooling, personnel training and temporary shielding. The development of long-lived reactor cores requiring less frequent refueling also has been a significant factor in this reduction. More frequent refueling would lead to an increase in the occupational radiation exposure received by shipyard maintenance personnel and personnel involved in the defueling, shipping, storage, and disposal of spent naval fuel. The increases in exposure associated with more frequent refueling would be inconsistent with the overall trend of reducing radiation exposure in the performance of nuclear work in the United States, and with the NNPP's longstanding commitment to minimizing exposure to workers.

In addition, LEU spent fuel would have about 30 times the neutron radiation of the current HEU spent fuel. The effect of the increased neutron radiation was not evaluated in detail, however, it is expected that changes would be needed to shielding and container designs for spent fuel shipping and handling, potentially requiring expensive new spent fuel containers and infrastructure.

If an LEU core were not constrained to fit into an existing design ship, the core could be made bigger to put in more fissile uranium and increase its endurance. LEU fuel would roughly triple the size of a VIRGINIA-Class submarine reactor. The larger reactor would require extensive design of new equipment and structures due to the additional size and weight of the core, reactor, shielding, and other reactor plant components. The ship's volume would need to be increased to add buoyancy to compensate for the increase in reactor compartment and shielding size and weight. The larger reactor plant would increase the size of today's submarines and aircraft carriers and would adversely impact ship performance, increase ship acquisition cost, require substantial up-front ship design cost, and require modifications or additions to construction and maintenance infrastructure. For example, the larger reactor vessel required for an aircraft carrier core with LEU cannot be constructed with current US infrastructure.

Naval reactor cores have evolved in compactness to the point where the maximum amount of uranium is loaded into the smallest practical core volume using current naval fuel systems. The only way to make more volume available for uranium would be to remove cladding, structure or coolant. In other words, absent improvements in fuel technology, no more uranium could be loaded into a modern long-lived core without degrading the structural integrity or cooling of the fuel elements.

In summary, substituting LEU for HEU in a current naval fuel system offers no operational advantage, is impractical, and is not cost-effective.

Use of HEU in naval propulsion reactors supports US Government policy on nonproliferation. The current source of naval fuel is excess weapons-HEU from dismantled warheads. This provides a safe, economical way of removing this material from the threat of diversion, and postpones the need to obtain a new, costly enrichment facility for HEU.

An alternative to substituting LEU fuel for HEU would be to develop a new, advanced fuel system. An advanced fuel system has been conceived that could increase uranium loading beyond what is practical today while meeting the rigorous performance requirements for naval reactors. Success is not assured, but an advanced fuel system might enable either a higher energy naval core using HEU fuel, or allow using LEU fuel with less impact on reactor lifetime, size, and ship costs. 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. At least another ten years beyond that would be needed to deploy a nuclear reactor with this fuel.

V. Technology Base Health

Naval nuclear propulsion uses unique technologies that are not used in the commercial nuclear industry or academia. Long-term research and development in these unique technologies has advanced the state of the art while maintaining technical competencies that are essential to nuclear propulsion operations, and which can only be maintained by doing relevant work. Historically, Naval Reactors has maintained a healthy technology base through research and development on long-term technology improvements. For example, the technologies that will enable a 40+ year core life in the OHIO-Class Replacement ballistic missile submarine were developed over several decades.

Current and projected funding is not sufficient to execute robust, long-term research and development programs. Since 2003, the Naval Reactors Program has redirected several hundred million dollars away from traditional technology, design, and testing to accommodate emergent requirements including packaging spent fuel for dry storage and the need to safely maintain aging facilities, including a prototype reactor site that is almost 60 years old. At present, research and development resources are almost entirely committed to near term support of the existing Fleet and near-term technology advancements to meet Navy requirements for new designs including the Land-based Prototype reactor and the OHIO-Class Replacement submarine.

Development of an advanced fuel system would help maintain the unique naval nuclear technology base and may enable either greater energy in a HEU core or a naval core using LEU fuel. Essential staff and facilities needed to develop an advanced fuel system are in place and include unique resources such as the Advanced Test Reactor and other facilities within the Knolls Atomic Power Laboratory and the Bettis Atomic Power Laboratory. These capabilities are currently being sustained by ongoing new design work and design project funding. Once ongoing new ship design work is complete, it will not be practical to sustain all of the Program's unique technology capabilities or develop and advanced fuel system without other sources of funding. If these essential capabilities are lost, then development of an advanced fuel system will become impractical.

VI. Conclusion

Substituting LEU for HEU would fundamentally decrease reactor energy density, increase lifecycle and operating costs, increase occupational radiation exposure, and increase the volume of radioactive wastes. Thus, while it may be feasible to replace HEU fuel with LEU fuel in current US Naval reactor plants, it is not economical or practical to do so.

Recent work has shown that the potential exists to develop an advanced fuel system that could increase uranium loading beyond what is practical today while meeting the rigorous performance requirements for naval reactors. Success is not assured, but an advanced fuel system might enable either a higher energy naval core using HEU fuel, or allow using LEU fuel with less impact on reactor lifetime, size, and ship costs.

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