Conceptual Research and Development Plan for Low-Enriched Uranium Naval Fuel

Report to Congress
July 2016

National Nuclear Security Administration
United States Department of Energy
Washington, DC 20585

Message from the Director, Naval Reactors

U.S. Naval nuclear reactors are fueled with highly-enriched uranium (HEU) to meet the rigorous demands of a U.S. Naval warship operating at sea. In a January 2014 report to Congress, Naval Reactors identified that the use of low-enriched uranium (LEU) in place of HEU would negatively impact reactor endurance, reactor size, and ship costs. However, a recently conceptualized advanced fuel system might mitigate these negative impacts enabling future use of low-enriched uranium.

Fuel research and development is expected to span at least 15 years. Funding requirements for fuel development through 15 years are about $1 billion, and the work could be carried out if additional funding is provided. While success is not assured, this development has the potential to deliver a fuel that might enable an aircraft carrier reactor fueled with LEU in the 2040's, aligned to FORD class procurement. The fuel is unlikely to enable converting current life-of-ship submarine reactors to LEU. If successful, engineering and manufacturing costs to deploy the new fuel in a future aircraft carrier would be several billion dollars, in addition to the cost of fuel development.

Pursuant to the direction included in Section 3118 of the FY 2016 National Defense Authorization Act and the Division D Explanatory Statement accompanying the Consolidated Appropriations Act for 2016, the attached report is being provided to the following Members of Congress:

- **The Honorable Mike Simpson**
  Chairman, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Marcy Kaptur**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Lamar Alexander**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **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 Jeff Sessions**
  Chairman, Subcommittee on Strategic Forces
  Senate Committee on Armed Services
- **The Honorable Joe Donnelly**
  Ranking Member, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

If you have any questions or need additional information, please contact me or Neil Lapointe, Deputy Director of Governmental Affairs, at (202) 781-5805.

Sincerely,

Admiral James F. Caldwell, Jr.

Executive Summary

The U.S. Navy's need for warships with safe and effective nuclear propulsion necessitates durable, maneuverable, compact, quiet, and long-lasting reactors. Historically, these unique requirements result in a naval fuel system which uses highly-enriched uranium (HEU) fuel to deliver optimum performance. This report provides a conceptual development plan for an advanced naval nuclear fuel system that could increase uranium loading beyond what is achievable today while meeting the rigorous performance requirements for naval reactors. This advanced fuel system has been considered for a more compact and long-lived reactor using HEU fuel; however, it also has potential to use low-enriched uranium (LEU) fuel, with reduced impact on reactor lifetime, size, and ship costs.

This report provides a plan that is intended to determine the technical and economic viability of an advanced fuel system which might enable use of LEU fuel in an aircraft carrier reactor. The fuel is unlikely to enable/allow conversion of current life-of-ship submarine reactors to LEU, but might be sufficient for use in an aircraft carrier reactor. The conceptual plan includes manufacturing and testing demonstrations which span at least 15 years and requires at least $1 billion in fiscal year (FY) 2016 dollars. Follow on funding would be needed to mature this conceptual plan and bring it to reality. Success is not assured; significant resources could be expended in the pursuit of this fuel system without delivering a satisfactory LEU-fueled naval reactor design. Therefore, the plan provides milestones for assessing progress and determining whether a practical LEU fuel system is achievable and if work should continue. These milestones involve test infrastructure assessments, fuel testing, and manufacturing trials. The schedule assumes that existing Naval Reactors Program facilities and equipment to test, transport, and examine highly radioactive irradiated fuel specimens can be quickly adapted, refurbished, or reactivated. This schedule also assumes that the Advanced Test Reactor is separately funded to replace aging infrastructure and increase its operational reliability from an average of 175 irradiation test days per year to 210 test days per year on a consistent basis. Early work to define and execute these facility and equipment upgrades would be essential and could control the overall schedule.

Separate from and beyond the fuel system qualification and development plan described above, full LEU fuel deployment in an aircraft carrier would involve: (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 since the spent fuel would be more radioactive than HEU. A transition to LEU would be more costly than just developing a new HEU fuel using existing naval fuel systems. The engineering and manufacturing costs to deploy the new fuel in a future aircraft carrier would be several billion dollars and are summarized within the report.

The conceptual plan provided in this report is based on nearly 70 years of experience in the Naval Reactors Program investigating different fuels and deploying reactor design improvements that have allowed increased power, energy, and lifetime 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. For example, the reactor core in the *USS Nautilus*, the first nuclear powered submarine, required refueling after two years of operations. Thirty years later, in the 1970s and 1980s, reactors only required refueling once or twice throughout the life of the ship. Today, *Virginia Class* submarines, the Navy's newest fast attack submarines, are designed around a life-of-ship reactor core. A conversion to LEU fuel is similarly expected to involve at least a 20-30 year commitment.

The operational needs of U.S. Navy submarines and aircraft carriers place a high importance on the reactor core energy density. The replacement of HEU with LEU would result in a reactor design that is inherently less capable and more expensive and cannot be completed within current outyear budget funding constraints.

Finally, while the transition from HEU to LEU would not directly produce a more militarily desirable reactor design, an advanced naval fuel development program would provide the Navy with a path to use LEU in the future. 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. Fuel development work would also advance fuel technology and sustain the cadre of highly specialized naval fuel experts and unique test infrastructure that are vital to naval nuclear propulsion operations. These resources are currently dedicated to supporting the existing Fleet and new design projects. Existing projects must continue without compromise or delay from any developmental work on LEU fuel. Existing staff and facilities would need to be augmented to execute the development of an advanced naval fuel system technology to support LEU fuel.

Conceptual Research and Development Plan for Low-Enriched Uranium Naval Fuel

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I. Legislative Language

This report responds to legislative language set forth in Section 3118 of the FY 2016 National Defense Authorization Act, wherein it is stated:

> *"CONCEPTUAL PROGRAM PLAN - Not later than 90 days after the date of the enactment of this Act, the Deputy Administrator shall submit to the congressional defense committees a conceptual plan for a program for research and development of an advanced naval nuclear fuel system based on low-enriched uranium to meet military requirements. Such plan shall include the following:*
>
> *(1) Timelines.*
> *(2) Costs (including an analysis of the cost of such research and development as compared to the cost of maintaining current naval nuclear reactor technology).*
> *(3) Milestones, including an identification of decision points in which the Deputy Administrator shall determine whether further research and development of a low-enriched uranium naval nuclear fuel system is warranted.*
> *(4) Identification of any benefits or risks for nuclear nonproliferation of such research and development and eventual deployment.*
> *(5) Identification of any military benefits or risks of such research and development and eventual deployment.*
> *(6) A discussion of potential security cost savings from using low-enriched uranium in future naval nuclear fuels, including for transporting and using low-enriched uranium fuel, and how such cost savings relate to the cost of fuel fabrication.*
> *(7) The distinguishment between requirements for aircraft carriers from submarines.*
> *(8) Any other matters the Deputy Administrator determines appropriate."*

This report also responds to legislative language set forth in the Division D Explanatory Statement accompanying the Consolidated Appropriations Act for 2016 wherein it is stated:

> *"In lieu of direction in the House and Senate reports, Naval Reactors is directed to provide to the Committees on Appropriations of both Houses of Congress, not later than March 31, 2016, a report that describes the key goals and milestones, timeline, and annual budget requirements to develop a LEU fuel system for naval reactor cores."*

II. Background

The Naval Reactors Program started in 1948. Since that time, Naval Reactors has provided safe and effective nuclear propulsion systems to power submarines, surface combatants, and aircraft carriers. Today, nuclear propulsion enables virtually undetectable U.S. 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 40 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 Naval Reactors Program 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. Naval Reactors 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, and employs the most promising of these developments in practical applications. Improvements in naval reactor design have allowed increased power, energy, and lifetime 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 approximately 2 years while modern reactors last the life of a submarine, over 30 years, without refueling. The reactor being designed for the OHIO Class Replacement ballistic missile submarine is targeting a life of over 40 years. These improvements have been the result of prudent and conservative engineering based on decades of rigorous analysis, testing, and prototyping.

The Naval Reactors Program was also a pioneer in developing basic technologies and transferring these technologies to the civilian nuclear electric power industry. For example, the Naval Reactors Program demonstrated the feasibility of commercial nuclear power generation by designing, constructing and operating the Shippingport Atomic Power Station in Pennsylvania. The Naval Reactors Program also showed 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 U.S. Navy submarines and aircraft carriers. Naval reactors must be far more durable, maneuverable, compact, quiet, and long-lasting than land-based reactors. Naval fuel systems must meet these needs to make certain that submarines and aircraft carriers effectively carry out their missions while ensuring safety to the crew, the public, and the environment. These requirements are summarized below:

- 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, fuel must keep the fission products from getting into the reactor coolant. This is made possible by highly specialized naval fuel element design, materials, and fabrication techniques. U.S. Navy reactors are so effectively shielded and radioactivity is so closely controlled that a typical nuclear powered warship crew member receives significantly less radiation exposure than an average U.S. citizen does from natural background and medical radiation exposure. For example, the occupational exposure received by the average nuclear-trained sailor living onboard one of the Navy's nuclear-powered ships in 2014 was less than a twentieth of the radiation received by the average U.S. citizen from natural background sources that year. 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 must make calls to ports throughout the world.

- Naval fuel elements and modules are rigid and tough, able to withstand the extreme shock loads that might occur in an attack without losing integrity or compromising the ability to operate the reactor. The design shock loads for naval fuel are significantly more than the seismic loading assumed for land-based reactors.
- Naval fuels must satisfy very high standards for fuel integrity. Naval fuel systems reliably retain the highly radioactive fission products under extremes of operating conditions, providing maximum flexibility to the propulsion plant to safely respond to possible casualties and still maintain electrical and propulsion power for the ship.
- Naval reactors must support rapid and frequent power changes to accommodate tactical ship maneuvering without fuel failures from thermally-induced stresses on the fuel system. This is different than the commercial reactors used for power generation which typically aim to operate at a constant high power.
- Naval reactor plants must be compact to be cost-effective. Ship size impacts the power required to propel the ship. 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.
- 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 pumping power to reduce detectability.
- Naval reactors must 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. Recent submarine reactors are designed to last the life of the ship; aircraft carriers are refueled only once during their 50 year life.

A pressurized water reactor with HEU fuel in high integrity fuel elements has proven to be the optimum design to meet these essential functional requirements for nuclear propulsion for warships. The use of HEU maximizes the amount of fissile material in the small volume of the reactor core, enabling long lifetimes while allowing for a compact reactor plant.

IV. Impact to the Navy of Replacing HEU with LEU

This report assumes LEU at 19.75 percent 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.

If LEU is directly substituted for HEU in a current naval reactor core, the lower energy content of the LEU would translate into reduced reactor life and/or increased reactor size. For example, a VIRGINIA-Class submarine reactor, which today operates for the 33 year ship life without refueling, would have to be refueled as many as three times. A FORD Class aircraft carrier would require two refuelings instead of one. The additional refuelings would increase Navy fleet operating costs by several billion dollars per year due to the consequent greater reactor servicing workload, reduced ship mission availability, increased disposal costs, increased occupational radiation exposure, and large increases in manufacturing and procurement costs to build refueling cores.

To mitigate the impact of LEU on reactor core lifetime or core size, an advanced fuel system would be required to increase the loading of fuel in the same volume. Such a fuel system would increase uranium loading beyond what is possible today while meeting the rigorous performance requirements for naval reactors. The details of this fuel system are classified and are not described in this unclassified report. However, the development and deployment of this fuel system involves technical and programmatic risks that are inherent in a major change to the naval fuel technology that has been established over the last 70 years. Success is not assured, but this advanced fuel system could allow use of LEU fuel with minimized 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. Previous Naval fuel system development work has, depending on complexity, started up to 15 years before initial deployment.

This report provides a conceptual plan and resource estimate to develop an advanced naval reactor fuel that uses LEU. The conceptual research and development plan is similar to previous successful efforts by the Naval Reactors Program. The scope accounts for the complexity and aggressive characteristics of the fuel to accommodate a large change in enrichment, as well as the state of current infrastructure and facilities. The program has been separated into two phases: (1) fuel system development and (2) fuel system deployment.

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 fuel deployment phase incorporates the new fuel system into a reactor core design and establishes production scale manufacturing capability. 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.

The conceptual implementation of the above for LEU fuel is described in detail within Section V for the initial fuel system development and Section VI for the long-term fuel system deployment. The fuel system development phase would extend through at least 15 years. Annual budget requirements for 15 years of the fuel system development phase are provided in Section V and total $1 billion in FY 2016 dollars. These costs include work to define and execute the needed facility upgrades which are expected to be the critical path and likely to control the overall schedule.

Initial fuel system deployment is described based on initial deployment in a future FORD Class aircraft carrier. This deployment phase will likely require at least 10 more years and cost several billion dollars.

V. Fuel System Development

The Naval Reactors Program has developed and deployed several new fuel systems over the 70 year history of the nuclear Navy. For example, the fuel system being deployed in the OHIO Replacement ballistic missile submarine is different from the fuel system deployed in the OHIO Class ballistic missile submarine. The evolution of Naval fuel designs has enabled long reactor lifetimes and progressive extension of the interval between refueling from about 2 years in 1953 to a single refueling in the life of a FORD Class aircraft carrier and submarine reactors that last the life of the ship without refueling. Naval Reactors has created a conceptual research and development plan for LEU fuel based on this long experience in developing new nuclear fuels at the Bettis and Knolls Atomic Power Laboratories. The fuel development process is described in Section V.A while the LEU-specific plan is discussed in Section V.B.

V.A Overall Fuel System Development Process

Fuel is manufactured and tested in small specimens that evaluate different aspects of fuel performance. Irradiation testing is essential. Nuclear fuel can fail in ways that can only be found through irradiation testing. The process of performing these irradiation tests is outlined below:

- Fuel test specimens are fabricated, usually iterating on several processing steps to achieve the desired properties and create manufacturing techniques that can be scaled up to factory production. Once the desired characteristics can be manufactured, small fuel specimens are fabricated for testing. This typically requires two to three years when new, developmental manufacturing methods are involved.
- Fuel performance is demonstrated through accelerated testing of these small fueled specimens in a test reactor. The Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) is the only domestic test reactor available that can perform these fuel tests. Specimens are irradiated for up to ten years to simulate the effects of aging through the life of the ship.

- Specimens are periodically removed from the ATR and transported to the Expended Core Facility at the Naval Reactors Facility at INL, where they undergo interim examinations before being returned to the ATR for additional testing. The interim examinations verify fuel performance and provide data used to develop performance limitations for the fuel system.
- Near the end of their irradiation time, some specimens undergo a series of severe tests which simulate rapid power changes to provide assurance the fuel system can perform under worst-case operating conditions.
- When the specimens have been fully irradiated, they are shipped to the Knolls Atomic Power Laboratory for examination in hot cell facilities that can remotely examine highly radioactive materials. The examination process typically requires approximately two years to complete.

The above process is typically repeated in multiple overlapping phases within a 10-15 year period. Interim examination results from the first specimens, supplemented by fuel analysis models, provide confidence to proceed with subsequent test iterations. Initial test results are also used to improve fuel system design and construction of subsequent test iterations. These initial specimens are built with small scale laboratory equipment, usually not representative of factory equipment. Factory fabrication methods are developed in parallel and can be used to make specimens for follow-on fuel tests. The result of this stepwise development is a fuel system that the Program has high confidence can be successfully deployed in a reactor.

V.B LEU Fuel System Development

A schedule for LEU naval fuel system development irradiation testing is shown in Figure V.B.1 and an annual breakdown of funds required to execute this schedule through 2032 is provided in Table V.B.1. This schedule includes five irradiation testing programs and three milestones which will be used to determine whether to continue further research and development. The capacity of test infrastructure is likely to control the schedule. LEU fuel development schedule and funding are assumed to start in FY 2018.

Figure V.B.1 – LEU Fuel System Development Timeline

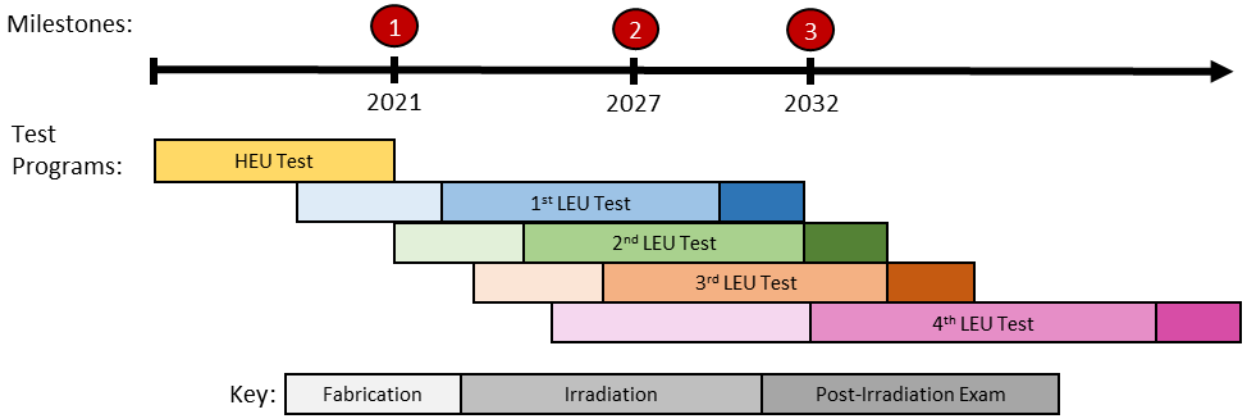

Table V.B.1 – Funding Requirements for LEU Fuel System Development

Fiscal Year	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26
$M (FY16)	35	65	85	80	80	75	65	65	70
Fiscal Year	**FY27**	**FY28**	**FY29**	**FY30**	**FY31**	**FY32**	**Total**		
$M (FY16)	70	60	60	60	60	60	990		

The five irradiation and testing programs will progressively improve the fuel system design and demonstrate fuel performance consistent with the discussion in Section V.A above. The first testing program could be done with HEU fuel using available fuel, facilities, and support infrastructure. Follow testing programs would use LEU fuel once a test infrastructure has been put in place to handle the more radioactive LEU specimens. Information obtained during the HEU test will be generally applicable to the LEU fuel system development, and therefore is an adequate surrogate for LEU testing while test support infrastructure is put in place. Conceptual design engineering studies would be performed in parallel with fuel testing. Design engineering studies would be done to ensure test specimens are representative of a practical core design, assess the effects of test results on reactor plant design and performance, balance design and manufacturing constraints, and evaluate options for a prototype reactor core as described in Section VI.B. Figure V.B.1 also provides three milestone decision points to assess progress. These milestones are described in the following list, including the key information available to determine whether further research and development of the LEU fuel system is warranted:

- **2021 – Milestone 1:** Assess fuel system performance using HEU fuel and identify if further pursuit is warranted with LEU fuel. Work to support this milestone would also include identifying the laboratory test infrastructure (e.g. specimen transportation casks design and procurement and hot cell refurbishment) modifications necessary to support LEU testing.
- **2027 – Milestone 2:** Assess final HEU and initial LEU irradiation test results for further indication of fuel system feasibility. Laboratory scale fabrication trials would also have been completed for the first and second LEU test specimens including work attempting to fabricate a full-sized fuel element. These fabrication trials would provide insight on major obstacles in manufacturing full-scale fuel elements.
- **2032 – Milestone 3:** Assess final results from the first LEU test and subsets of data from the second and third LEU tests. Initial assessments of pilot scale manufacturing assessments will also be available to inform the feasibility and costs associated with producing the fuel system in enough quantity to produce a reactor core to power an aircraft carrier.

The funding line in Table V.B.1 extends through Milestone 3 in 2032 and totals $990 million in FY 2016 dollars. The scope in Table V.B.1 covers laboratory scale manufacturing, irradiations testing and the infrastructure work (discussed below) necessary to meet the above milestones. The expenditures through each milestone are about $265 million through Milestone 1, $690 million through Milestone 2, and $990 million through Milestone 3. The schedule and funds required are dependent upon the success of the irradiation tests.

The plan encompassed in Figure V.B.1 and Table V.B.1 assumes that supporting fuel specimen manufacturing and examination infrastructure needs can be refurbished in the near term, consistent with the goals of the first milestone. These infrastructure needs are discussed below; all costs are included in the funding requirements provided in Table V.B.1:

- Irradiated LEU fuel is significantly more radioactive than irradiated HEU fuel due to the increased buildup of transuranic isotopes. The effect of the increased radioactivity would be evaluated to determine the extent of design modifications needed for the containers used in shipping and handling of irradiated test specimens. The impact of increased radioactivity on fuel test specimen transport and examination may require a re-design of the containers used to transport specimens from the ATR to the Expended Core Facility and Knolls Atomic Power Laboratory. These two containers would each cost up to $25 million, with the first expected to finish in FY 2021 and the second in FY 2026. To ensure specimens can be safely handled following irradiation, these containers would have to be designed and procured in parallel with building LEU fuel specimens, prior to inserting specimens into the ATR.
- An LEU fuel development program would require expanding the ATR test space currently allocated for Naval Reactors testing. To support this fuel system development, one of the ATR's large operating test loops needs to be reassigned and reactivated for naval fuel testing at an initial cost of about $70 million and recurring operating costs of $3 million per year. Reactivating this loop for pressurized water testing may displace other users. Work to reactivate an ATR loop would need to begin in approximately FY 2018 to support the first LEU test shown in the Figure V.1.B plan.
- Hot cell laboratories are used to examine the highly radioactive irradiated fuel specimens. Substantial investment will be needed in the near future to recapitalize the Program's more than 50-year old examinations and irradiation testing infrastructure. The addition of LEU development work would require approximately $20 million per year for added hot cell facility maintenance, refurbishment, and staffing to support an LEU fuel system development program.

This plan also assumes that the ATR will separately receive funding to appropriately maintain the reactor and complete the corrective and preventive maintenance necessary to reverse the declining trend and increase operational reliability from the current average of less than 175 irradiation days up to 210 irradiation days per year. This action is being addressed separately by the Department of Energy and is required whether or not the Naval Reactors Program pursues LEU fuel.

VI. New Fuel Deployment

The fuel system development program would complete the testing necessary to determine whether an LEU naval fuel is technically viable by 2032. If successful, then the fuel system could potentially be deployed in a reactor. Deployment would involve: (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. Some of the specific costs associated with full fuel deployment are discussed in Sections VI.A through VI.D, and are in addition to the $990 million fuel development described in Section V.

The advanced LEU fuel system concept has the potential to satisfy the energy requirements of an aircraft carrier without affecting the number of refuelings (current NIMITZ and FORD class carriers require one 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. The advanced LEU fuel system is unlikely to meet requirements for current life-of-ship submarine reactors. An LEU-fueled submarine with this fuel is expected to require at least one refueling, or the reactor (and hull) would need to be increased in size correspondingly. Both of these options increase lifecycle and operating costs, occupational radiation exposure, and the volume of spent nuclear fuel produced. For these reasons, 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. Therefore the deployment plan and costs discussed in the remainder of this report are focused on delivering an LEU-fueled aircraft carrier.

VI.A Manufacturing Process and Infrastructure

An advanced fuel design involves different methods and equipment for manufacturing fuel elements. New manufacturing and inspection processes and new types of manufacturing equipment and facilities will need to be developed. Factory construction is envisioned to occur in two stages. First, a pilot line would develop production processes which could be used to produce fuel elements for a prototype reactor. The cost of this effort is expected to be approximately $300 million (FY 2016 dollars) distributed over a seven year period. Second, the process established via the pilot line would be expanded to the capacity needed to meet the demand of the initial fleet application. The cost of this pilot line expansion effort is expected to be approximately $300 million (FY 2016 dollars) distributed over an eight year period. Production facility planning would be accomplished in parallel with fuel development.

Naval fuel and reactor vendor facilities are licensed by the Nuclear Regulatory Commission to meet security requirements associated with HEU handling and storage. The total security cost at the two sites is about $60 million per year (FY 2016 dollars). Current security measures will be necessary as long as these facilities handle and store HEU. Since the plan described in this report only focuses on delivering an aircraft carrier core, the Program will still require HEU fuel for submarine applications and therefore vendor facilities will be required to meet security requirements for both HEU and LEU fuel. For illustrative purposes, if all HEU were no longer required, the savings associated with reductions in security requirements are estimated to be about $30 million per year (FY 2016 dollars).

HEU is transported via special shipments managed by the National Nuclear Security Administration's (NNSA) Office of Secure Transport. There will still be costs associated with transporting LEU fuel. While exact estimates are not available, the impact of enrichment on naval fuel shipment costs is judged to be relatively small.

VI.B Prototype Reactor

The fuel development plan is based on experience gained with small fuel specimens tested in the ATR. Given the critical role of fuel reliability in supporting Navy missions, Naval Reactors has always demonstrated major new fuel technologies in a prototype reactor core before deploying these technologies in a warship. The prototype test proves that the fuel works in an actual naval core and demonstrates the real world fuel performance and core lifetime. Prototype development and operation would cost several billion dollars. The scope of any required prototype reactor would need to be defined before the 2027 Milestone 2 from Section V.B).

VI.C LEU Aircraft Carrier Reactor Core Design and Procurement

Based on previous Program experience, the design and procurement of a new LEU-fueled reactor core for the FORD Class is estimated to require about ten years and cost $1.5-$2.4 billion (FY 2016 dollars) through delivery of the initial fueling of a FORD Class carrier. This cost includes reactor core design engineering and procurement of two first article cores and is in addition to the costs for fuel system development, a land-based prototype, and other costs discussed in this report.

VI.D Spent Fuel Transportation and Disposal

As discussed elsewhere in this report, spent LEU fuel is more radioactive than spent HEU fuel. Therefore, equipment associated with the transportation, handling, and packaging of spent LEU fuel will need to be designed and procured. This equipment includes new spent fuel transport containers with additional shielding, equipment to load and unload the new transport container, and water pool handling and processing equipment. The total costs of this fuel transportation and disposal work are estimated to be up to $1 billion (FY 2016 dollars).

VI.E Manufacturing Costs for LEU Fuel and Cores

The effect on core manufacturing and overhead costs was estimated based on the expected impacts on the cost of a set of two FORD Class reactor cores. Manufacturing and overhead costs are expected to increase for the more complex fuel fabrication, LEU material costs, costs to down blend HEU to provide initial LEU fuel, and inefficiencies related to supporting separate LEU and HEU production lines. While Naval Reactors would work to minimize the impact, the additional manufacturing cost is estimated to be a 25 percent to 35 percent premium on per-reactor manufacturing costs, or up to $265 million (FY 2016 dollars) per FORD Class reactor core.

Finally, since the plan described in this report only focuses on delivering an aircraft carrier reactor core, vendors will be required to maintain two separate lines of work, one for HEU-fueled submarines, and another for LEU-fueled aircraft carriers. This will require additional overhead costs associated with running HEU and LEU production lines in parallel, which are difficult to quantify at this time.

VII. Uranium Enrichment

Naval reactors are constructed using HEU recovered from excess nuclear weapons and other HEU stores. This section briefly presents the expected impact to uranium production and enrichment due to a transition from HEU to LEU fuel.

Given current policy choices, and assuming weapons stockpile reductions occur as planned, the HEU inventory allocated for naval reactors will be sufficient for forecasted Navy needs until 2064. There is currently no domestic uranium enrichment facility free of peaceful use restrictions that can provide new fuel to the Navy once the current stockpile is exhausted. Initial LEU development and reactor core production work would use a relatively small amount of HEU down-blended with natural or depleted uranium to achieve an enrichment of 19.75 percent.

The costs for developing and operating an enrichment facility for naval requirements are expected to be of comparable magnitude whether LEU or HEU is used for future cores. Projected requirements of LEU fuel for aircraft carrier needs are expected to be similar to the amount estimated by the NNSA to support tritium production in an October 2015 report entitled *TRITIUM AND ENRICHED URANIUM MANAGEMENT PLAN THROUGH 2060*.

VIII. Benefits and Risks

The benefits of pursuing the LEU fuel system development work detailed in this report are as follows:

- Development of an advanced naval fuel that uses LEU would demonstrate United States leadership toward reducing HEU and achieving nuclear non-proliferation goals.
- The Navy requires a unique cadre of reactor fuel technical expertise to address emergent issues in manufacturing and support of the Fleet. A fuel development effort, such as this LEU work, is what builds, hones, and sustains this expertise.
- Fuel system advancements made in this effort would extend the state of the art in naval fuel and could yield a higher performing naval reactor fuel system and an option for the Navy to transition to LEU fuel.

The risks of pursuing this work are as follows:

- The success of this LEU fuel system development and deployment is not assured. Use of LEU is a major departure from more than six decades of experience with HEU fueled naval reactors; design, manufacturing, operating behavior, shielding and radiological controls, fuel handling, and fuel disposal are affected in significant ways. Significant resources could be expended in the pursuit of this fuel system without delivering a satisfactory LEU-fueled naval reactor design.

- The LEU fuel development program represents a risk to other naval efforts such as potential new core design for future submarines if resources are not provided commensurate with the requirements.
- The operational needs of U.S. Navy submarines and aircraft carriers place a high importance on the reactor core energy density. The replacement of HEU with LEU will result in a reactor design that is inherently less capable and more expensive. Navy and Department of Energy funding would need to be appropriately augmented if the U.S. Government decides to pursue LEU for naval reactors.

IX. Conclusion

The Naval Reactors Program has identified an advanced naval nuclear fuel system technology which may enable use of an LEU reactor in an aircraft carrier reactor plant. The required LEU fuel development program would span 15 years, and is projected to cost approximately $1 billion in FY 2016 dollars. The advanced fuel would not meet the lifetime requirements of a modern submarine. If this fuel development program is successful, several billion dollars would be required to deploy the advanced fuel system in a new nuclear reactor fueled with LEU.

Success is not assured, and the plan provides milestones for assessing progress and determining whether work should continue. These milestones are related to test infrastructure assessments, test data evaluations, and manufacturing trials. The schedule assumes that existing facilities and equipment to test, transport, and examine LEU fuel specimens can be quickly adapted, refurbished, or reactivated for LEU fuel testing. This schedule also assumes that the ATR is funded sufficiently to replace aging infrastructure and increase its operational reliability to from an average of 175 irradiation days per year to 210 irradiation test days per year on a consistent basis. Early work to define and execute these facility and equipment upgrades would be essential and could control the overall schedule.

The LEU fuel deployment in an aircraft carrier would involve: (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. The engineering and manufacturing costs to deploy the new fuel in a future aircraft carrier would be several billion dollars.

The operational needs of U.S. Navy submarines and aircraft carriers place a high importance on the reactor core energy density. The replacement of HEU with LEU will result in a reactor design that is inherently less capable and more expensive. Navy and Department of Energy funding would need to be appropriately augmented if the U.S. Government decides to pursue LEU for naval reactors.

Finally, while the transition from HEU to LEU would not directly produce a more militarily desirable reactor design, an advanced naval fuel development program would provide the Navy with a path to use LEU in the future. 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. Fuel development work would also advance fuel technology and sustain the cadre of highly specialized naval fuel experts and unique test infrastructure that are vital to naval nuclear propulsion operations. These resources are currently dedicated to supporting the existing Fleet and new design projects. These existing projects must continue without compromise or delay from any developmental work on LEU fuel. Existing staff and facilities cannot execute this advanced naval fuel development without additional sources of funding.