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Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications

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1 INTRODUCTION

Every U.S. Navy reactor deployed during more than 60 years of nuclear-powered ship operations has been fueled by highly enriched uranium (HEU). Relative to lower enrichments, HEU offers militarily significant advantages in compactness and longevity of nuclear reactor cores. Nevertheless, there are reasons to investigate changing to low-enriched uranium (LEU), as summarized in a recent statement from the White House:

> "United States Navy submarines and aircraft carriers are powered by reactors that use highly enriched uranium in order to meet demanding performance requirements. However, consistent with its national security requirements and in recognition of the nonproliferation benefits to minimizing the use of highly enriched uranium globally, the U.S. values investigations into the viability of using low-enriched uranium in its naval reactors." —White House Fact Sheet, Feasibility of Low Enriched Uranium Fuel in Naval Reactor Plants, March 31, 2016

In uranium, "enrichment" level refers to the concentration of the ^{235}U isotope: ^{235}U mass divided by total uranium mass.[1] Internationally accepted definitions of HEU and LEU are shown in Table 1, which also gives enrichment levels of natural uranium and the uranium loaded into today's U.S. naval propulsion reactors.

The U.S. Congress directed[2] the U.S. Naval Nuclear Propulsion Program (NNPP) to deliver during FY16 a report on its *Conceptual Research and Development Plan for Low-Enriched Uranium Naval Fuel.* NNPP is instructed to report on several specific topics, including differences in reactor requirements for aircraft carriers and submarines. The legislation also directs the Secretary of Energy and the Secretary of the Navy to provide—within 60 days of

[1] Every atom of a given element has the same number of protons, but "isotopes" of an element differ in the number of neutrons per atom. Every uranium atom contains 92 protons. The ^{235}U isotope, which contains 143 neutrons ($92 + 143 = 235$), is of special interest because it can be made to fission relatively easily compared with ^{238}U, the most abundant uranium isotope.

[2] Division D Explanatory Statement accompanying the Consolidated Appropriations Act for 2016.

Table 1: Enrichment Definitions and Values

Description	^{235}U / [total U]
Natural Uranium	$\sim 0.72\%$
HEU	$\geq 20\%$
LEU	$< 20\%$
Today's naval-reactor HEU	93-97%

the report's delivery—the "... determination of the Secretaries as to whether the U.S. should continue to pursue research and development of an advanced naval nuclear fuel system based on LEU." The requested report was submitted in August of 2016 [1]. At the time of this writing, the Secretaries had not yet submitted their joint recommendation.

JASON was asked by NNPP to conduct a technical assessment of NNPP's proposed new LEU fuel concept and the conceptual plan to develop and qualify this fuel. This report contains the requested JASON assessments, findings, and recommendations. An unclassified naval nuclear propulsion informatin (UNNPI) Executive Summary, Section 2 of this report, details the study charge and summarizes JASON's unclassified findings and recommendations. Additional assessments, findings, and recommendations are included in a limited-distribution appendix to this report, Appendix A, about challenges posed by the proposed fuel concept.

1.1 Background

1.1.1 The U.S. nuclear-powered fleet

Nuclear power offers the U.S. Navy capabilities that no other power source can achieve, stemming from a remarkably high energy density that allows safe extraction of power at finely controlled rates for long durations from a compact source. Not only does a nuclear power plant meet the electrical needs of the 5500 sailors on a NIMITZ-class aircraft carrier while propelling the ship at more than 30 knots, launching and recovering aircraft and powering a complex weapons system, the power plant does this for more than two decades without refueling. The nuclear power plant is compact, enabling the ship to carry supplies and spare equipment for itself and the rest of the battle group. Naval nuclear propulsion plants can withstand battleshocks while continuing to operate and can be throttled rapidly over wide ranges of power. Nuclear propulsion enables the U.S. Navy to project power around the world in an economical fashion not possible with any other power source. Table 2 gives a comparison with earlier ships in the naval history.

Table 2: Summary of characteristics of naval vessels

Ship (era)	Length (m)	Power (MW)	Range (km)	Stored Energy (GJ)	Max. Speed (km/h)	Comment
Galley (ancient)	30	0.06	500	16	13	Trireme
Sailing ship (1800)	93	0.7	3,000	None	24	USS Constitution
Oil fired battleship (1945)	200	97	10,000	97,000	50	USS Massachusetts
NIMITZ Carrier (1980)	300	[redacted]			61	USS Carl Vinson

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The U.S. Navy currently deploys nuclear reactors only on aircraft carriers and submarines—all other ship types are powered by fossil fuel. Descriptions of the nuclear-powered ships are provided in Table 3.

Each U.S. nuclear-powered warship remains in the fleet for decades. The time from launching the first ship in a given nuclear-powered ship class (i.e., a particular ship design) to launching the last one is also measured in decades. A particular ship design typically has a presence in the deployed fleet for well over half a century. The first FORD-class carrier will be commissioned in 2017, the final one in the 2050s, and each is designed for a 50-year life, so FORD-class carriers will be at sea for approximately 90 years. Many design decisions—including the size of the reactor compartment and size of the reactor pressure vessel—must

Table 3: Description of nuclear-powered warships in the U.S. Navy

Shorthand	description	comments	
CVN	aircraft carrier	10 deployed today (NIMITZ class) FORD class begins 2017 ~ 1100 ft. long; ~ 90,000 tons [redacted]	(b)(3)
SSBN	ballistic-missile submarine	14 deployed today (OHIO) OHIO-replacement begins late 2020s ~ 550 ft. long; 18,750 tons (OHIO) [redacted]	(b)(3)
SSGN	Cruise missile submarine	re-purposed SSBN 4 deployed today (OHIO)	
SSN	fast attack submarine	~ 55 today (LOS ANGELES + SEAWOLF) + VIRGINIA) [redacted] VIRGINIA-replacement could begin 2040s ~ 300 ft. long; 7,900 tons (VIRGINIA)	(b)(3)

be solidified well in advance of the first launch. Figure 1 shows the time line for FORD-class carrier, showing that reactor-design decisions were made ~ 15 years prior to first launch. Thus, the time from initial reactor design to final ship retirement can be as much as a century for a given ship class. It is possible to create and deploy modified designs between the launching of the first and last ships in the class, and/or at the mid-life overhaul for a given ship. However, changes in one system on a ship usually have a ripple effect that cause changes in other systems and thus may be more difficult to implement than if they had been made in the initial design.

The long time scales associated with the naval nuclear fleet and the timings of particular ship-class launches have implications for decisions about LEU fuel. Figure 2 sketches the composition of the naval nuclear fleet out to the year 2100, under the assumption that the overall CVN/SSBN/SSN deployment numbers will not change much. Geopolitical and technical changes will probably induce fleet-composition changes over this time scale, but this sketch of one possible future serves our purpose as a reference for discussion. In this

[redacted] (b)(3)

Figure 1: Example reactor-design timeline: FORD-class carrier HEU core (A1B), from design to delivery. The delivery will now take place in 2017. (Adapted from slide in presentation to JASON by John Barry, June, 2016).

sketch the number of aircraft carriers declines slightly from 11 to 10 over the 90-year time frame, with the FORD class gradually replacing the NIMITZ class and then giving way to a FORD-replacement class. The SSBN fleet in this sketch also maintains 10 or more deployed ships, with the OHIO class giving way to the OHIO-replacement class and eventually its replacement. The sketch shows the LOS ANGELES SSNs gradually aging out of the fleet and being replaced by VIRGINIA-class ships, which will give way to their replacements beginning in the 2040s.

Perhaps the most important point to be taken from Fig. 2 is that design decisions made for the VIRGINIA replacement, perhaps as early as $\tilde{2}030$, could determine whether it is practical to stop making HEU cores—an important milestone in any HEU-to-LEU transition scenario—by $\tilde{2}060$. As we discuss later in this report, we find that it would be impractical to deploy LEU reactors in already-designed submarines (the VIRGINIA-class SSNs currently being built and deployed and the OHIO-replacement SSBNs that will begin deployment in

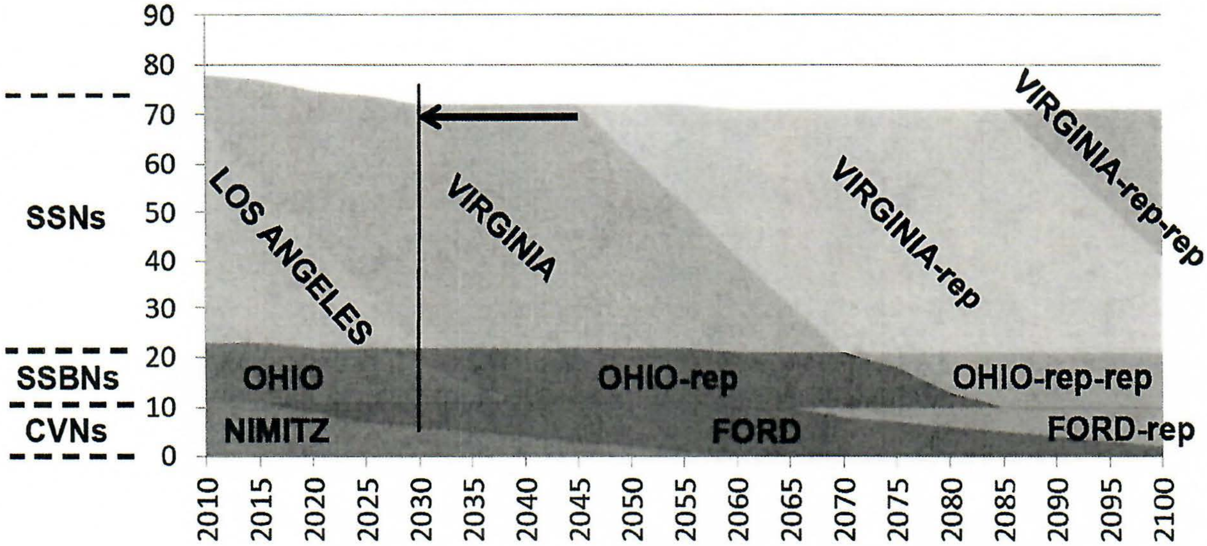

Figure 2: Schematic depicting nuclear-fleet evolution, roughly consistent with build plans but not perfect in detail. The vertical axis is number of ships; the horizontal axis is calendar year. The purpose of this rough sketch is to illustrate several key points: 1) A given class of nuclear-powered ship (such as the FORD carrier) is present in the fleet for many, many decades. 2) Ship and reactor design decisions affect the fleet for many decades. For example, many design decisions for the VIRGINIA-replacement nuclear power plants could be made as early as 2030 (see arrow and line on figure), and reactors for this class will be manufactured through the 2060 time frame. If the U.S. wishes to cease making HEU cores by 2060, VIRGINIA-replacement design parameters should be chosen (perhaps as soon as 2030) to allow for the possibility of an LEU core.

the 2020s), because the reactor pressure vessels and reactor compartments are sized for HEU cores and the ships are not designed for refueling. This means the first practical opportunity to deploy an LEU reactor in a submarine is in the VIRGINIA-replacement class, for which key features of the propulsion-plant design could be determined as early as 2030 under current schedules. If the reactor compartment is not designed to accommodate a life-of-ship LEU core, and if later re-design to accommodate such an LEU core is impractical, then HEU cores will be required for all VIRGINIA-replacement SSNs, the last of which will launch in the 2060s. On the other hand, if design parameters and fuel development allow an LEU reactor to be deployed in the VIRGINIA-replacement SSN, then it is possible that the Navy's final HEU core will be built in the 2040s, for the final OHIO-replacement SSBN or one of the early VIRGINIA-replacement SSNs.

1.1.2 Requirements for U.S. naval propulsion reactors

Nuclear reactors that power U.S. Navy warships must meet stringent requirements, some of which are listed below.

- Naval reactors must be compact and have long lives, implying high burnup (fissions per unit volume or mass) and high energy density (total energy delivered over the reactor life, per unit volume). The OHIO-replacement core is designed to meet military requirements for the entire 42-year life of the ship with no refueling. In comparison, commercial reactor fuel is replaced after 3-6 years in a reactor. [redacted] (b)(3)

- [redacted] (b)(3)

- Naval reactors must have high reliability and availability, especially the ability to restart quickly after a shutdown. A warship without power is vulnerable to many potential hazards, especially during hostilities.

- Naval reactor fuel must not allow fission products to leak into coolant. Meeting this requirement has many advantages: it protects crew members from radiation exposure; permits efficient design of shielding; protects the public and environment; and fosters national and international acceptance of U.S. nuclear-powered vessels, whose missions are facilitated by being welcomed at many international ports.

- Naval reactor components must function as designed for many decades in extreme radiation and temperature environments, without replacement, resisting nature's ever-present corrosion mechanisms in a hot aqueous environment.

- Power plants on submarines must be quiet, which imposes constraints on the design of pumps, in-core components including fuel modules, flow rates, etc.

- Power plants on warships must be able to withstand battle shocks and continue to function, meeting requirements that are far more stringent than seismic requirements for land-based plants. This places significant limitations on fuel design, reducing the amount of uranium that can be loaded into a given core volume and thus affecting the viability of LEU cores.

Fielding life-of-submarine cores that meet all of these requirements is a notable achievement for which NNPP deserves recognition. Repeating this achievement with LEU fuel is a significant challenge.

1.1.3 U.S. Navy nuclear propulsion plants

U.S. Naval reactors are Pressurized Water Reactors (PWRs). Figure 3 illustrates the key components of a naval PWR.

Naval propulsion plants are designed with other systems of the ship so that everything fits into the allowed spaces and meets all requirements outlined in the previous section. Figure 4 illustrates the location of the aft reactor on the FORD-class carrier, the layout of equipment in the reactor compartment, and the layout of the reactor core and other internal components in the reactor pressure vessel.

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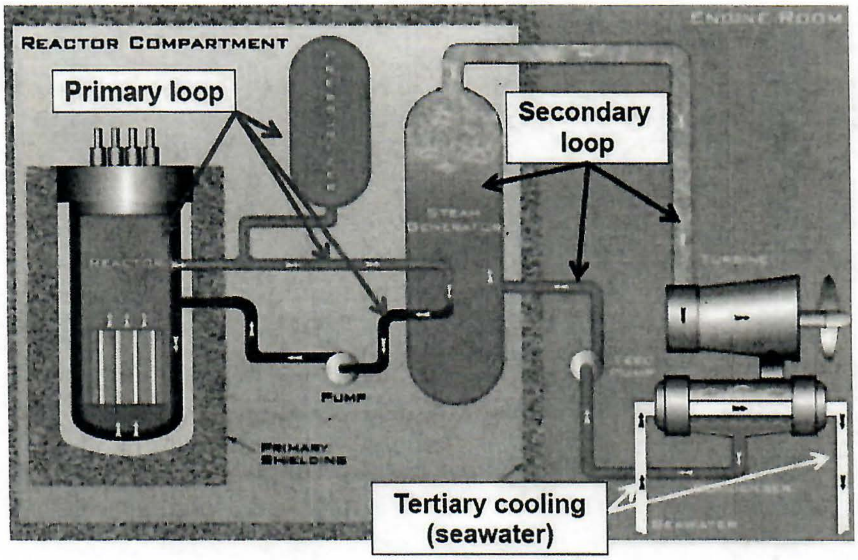

Figure 3: Schematic of naval pressurized water reactor propulsion plant. The "primary" cooling water, which is pumped through the reactor and through a heat exchanger called the "steam generator." The steam generator transfers primary-coolant heat to the "secondary" water, which boils. The resulting steam drives a turbine, which in turn drives a load that could include an electrical generator, a propeller shaft, etc. The secondary water gives up its waste heat to seawater through a heat exchanger in the condenser. As long as heat exchangers do not leak, the primary coolant is isolated from the secondary, which is isolated from the seawater. (Adapted from John Barry presentation, June 2016.)

1.1.4 LEU, HEU, and nonproliferation

We mentioned above that a motivating factor for exploring the use of LEU in naval reactors is "recognition of the nonproliferation benefits to minimizing the use of highly enriched uranium globally." Here we explore this further to establish important context for our technical evaluations and recommendations.

There are many international structures and controls aimed at preventing the proliferation of nuclear weapons. The international "nonproliferation regime" attempts to monitor and safeguard material that could be diverted for weapons use, along with equipment and processes that could produce such material. The International Atomic Energy Agency (IAEA) plays key roles in the nonproliferation regime, and the Non-Proliferation Treaty (NPT) is an

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important foundational element.

IAEA Information Circular (INFCIRC)/153 [3] contains Section 14, "Non-Application of Safeguards to Nuclear Material to be used in Non-peaceful Activities," which exempts HEU for naval nuclear propulsion from IAEA safeguards. The upshot of this section is that if

[redacted] (b)(3)

a nation asserts that its HEU will be used to power a military vessel, then the HEU will remain outside of the IAEA safeguards structure. This "loophole" has led to calls to end the U.S. Navy's use of HEU, both to reduce the perceived risk of proliferation and to show leadership in the global nonproliferation arena.

Nuclear weapons require materials and configurations that permit exponential growth of a fission chain reaction with a short time constant. Without a short time constant even a highly supercritical configuration would disassemble itself and become sub-critical before a nuclear-weapons-scale number of fissions could take place[4]. ^{235}U works well for this, as does plutonium, but ^{238}U has properties that degrade weapon performance: 1) ^{238}U inelastically scatters neutrons that emerge from fission, making them move more slowly, and 2) ^{238}U captures those slower neutrons without fissioning, thereby acting as a neutron poison. Uranium therefore becomes more valuable for weapons use as its enrichment in ^{235}U grows and its ^{238}U content correspondingly decreases.

The international community, notably including the IAEA, has agreed on 20% enrichment

[redacted]

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as the boundary between highly enriched uranium (HEU) and low-enriched uranium (LEU). This boundary has important implications, for LEU is considered not directly usable for weapons, whereas HEU is treated as weapons-usable. The IAEA defines a "significant quantity" (SQ) of HEU to be the mass that contains 25 kg of ^{235}U:

$$1 \text{ SQ of U} \equiv \frac{25\text{kg}}{\varepsilon} \quad \text{if } \varepsilon \geq 20\% \,,$$

where ε is the enrichment. One SQ is roughly interpreted as the amount that a proliferant needs to collect to make a nuclear weapon. According to IAEA definitions, LEU *cannot* be used to make a weapon, no matter the design or amount of available LEU.

However, even an infinite mass of LEU would not constitute an SQ in nonproliferation parlance.

The choice of 20% enrichment to define LEU comes from tests and calculations carried out in the early 1950s, which indicated that a nuclear weapon could not be built using uranium enriched to less than 20%.[3] Uranium at 20.1% enrichment is *not* significantly more weapons-usable than at 19.9%—there is no sharp physics threshold. Many metrics have been proposed for quantifying the attractiveness of materials for weapons. For our purposes it is sufficient to consider the critical mass of an isolated sphere of U as a function of enrichment, which is shown in Fig. 7. The figure illustrates that there are no thresholds near the 20% enrichment level that would affect design or construction of a nuclear weapon. We needn't worry about someone making a weapon with 19.99%-enriched uranium and the same is true for enrichments of 21% or 22%. This topic has received serious consideration in studies and discussions related to converting research reactors from HEU fuel to LEU fuel. For example, see the recent National Academies study on converting test reactors to LEU [2].

In summary,

- There is a nonproliferation-based motivation to stop employing weapons-usable material for naval propulsion;
- The international community agrees that uranium enriched below 20% is not directly weapons-usable;
- The 20% level is conservative and somewhat arbitrary—from a technical point of view, an few-percent increase in enrichment above this conservative bound does not appreciably change the material's weapons usability.

[3]See footnote 1 in Ref.[9].

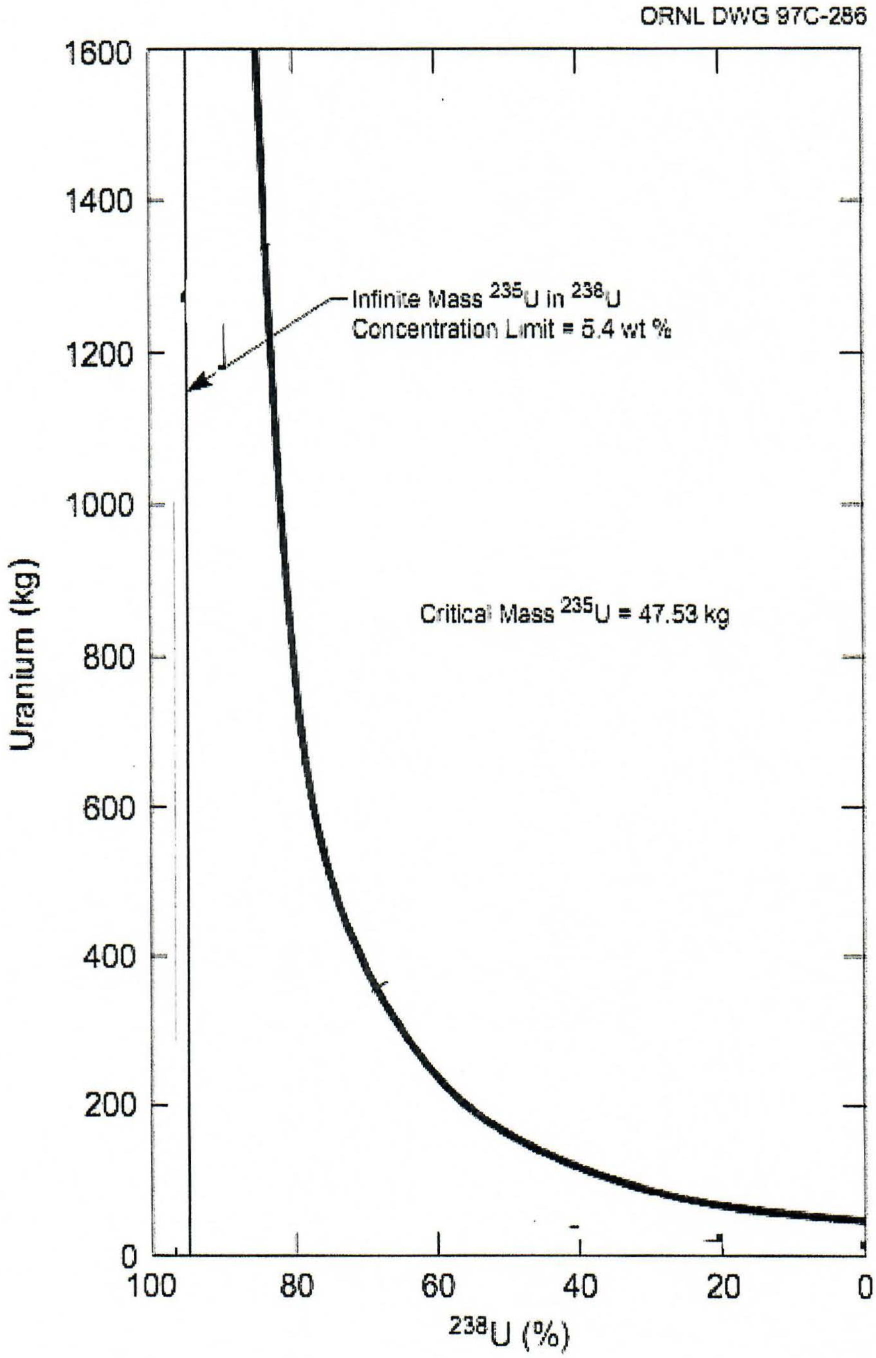

Figure 7: Mass of a bare metal sphere needed to reach criticality at nominal density, as a function of ^{238}U fraction (which is $\sim 1-$ enrichment) [10].

1.2 Boundary Conditions for the Study

The charge for this JASON study is summarized in Section 2. Here we provide more detail about the study's scope.

The study does not consider a redesign of the naval propulsion plant or a change from PWR technology. [redacted] (b)(3)

If successful, the new fuel concept, called "Enhanced Lifetime Element using LEU" (ELE-LEU) fuel could allow NNPP to fuel some naval propulsion reactors with low-enriched uranium (LEU) fuel. The FORD-class aircraft carriers, currently at the beginning of a multi-decade duty schedule, are the chosen candidates for deployment of the first LEU reactors if such reactors prove feasible and a decision is made to deploy them. The energy-density requirements are lower for aircraft-carrier reactors than for submarine reactors, which leads to a greater likelihood that an LEU-fueled reactor can meet the requirements for a FORD class aircraft carrier without extensive changes to other systems. JASON is charged with evaluating the plan for developing fuel to meet this FORD-class target. Discussions with NNPP clarified that JASON was encouraged to also provide comments and suggestions that might help NNPP further develop LEU fuel for use in more challenging applications, such as submarines.

1.3 Conduct of the Study

The study began with discussions among JASONs, the JASON Program Office, and NNPP leadership during the JASON fall meeting in November, 2015. The tasking statement was drafted and revised during the subsequent months. In January, 2016, NNPP provided introductory briefings to a subset of the JASON study team in La Jolla, CA, as part of the

JASON winter study. Further discussions were held during the JASON spring meeting in April, 2016. NNPP arranged two informative field excursions in early May, 2016—one to Naval Reactors headquarters in Washington, DC, and one to the BWXT core-manufacturing facility in Lynchburg, VA. The study began in earnest in June, 2016, when the full JASON study team received briefings for two full days early in the 2016 summer study. Another informative field excursion was arranged in July, during which JASONs were shown propulsion plants on an aircraft carrier (the USS Carl Vinson) and an attack submarine (the USS Pasadena). During the course of the summer study in June, July, and August, NNPP provided written answers to numerous questions submitted by the study team. NNPP also participated in discussions with the study team, many via secure telephone and one in person in La Jolla.

JASON presented preliminary findings and recommendations in late July. This included one presentation of a preliminary version of the material in the main body of this report, a second presentation of a preliminary version of the technical details found in Appendix A, and lengthy discussions with NNPP attendees. The final product of the study—this report—has benefited from NNPP input and feedback before, during, and after the presentation of preliminary findings and recommendations, and from the study team's efforts between late July and late September.

1.4 Remainder of Report

The remainder of this report is organized as follows. The Executive Summary describes the study charge and presents the key unclassified findings and recommendations of the study. Section 3 discusses high-level issues associated with establishing feasibility of developing, qualifying, and implementing a naval-reactor fuel using LEU. These high-level issues present challenges to deploying LEU in the fleet, independent of the details of the fuel technology. The principal issue is that relative to an HEU design, roughly 4.5 times as much LEU must be placed into the reactor to achieve comparable performance. Section 3 briefly describes the history of naval fuel development, summarizes the current state of naval fuels and reactors, and outlines the HEU/LEU options for the future. Section 4 describes the new Enhanced Life Element (ELE) fuel concept, which could substantially increase the U density in the core relative to the fuel system that has been the mainstay in naval reactors for many decades; outlines the current draft ELE-LEU reactor design for the Ford-class carrier; and presents JASON observations on ELE and the ELE-LEU core. Section 5 outlines the currently defined Naval Nuclear Propulsion Program LEU manufacturing development and qualification program. This section presents JASON's evaluation of whether the program is sufficiently comprehensive to address known and conceivable engineering challenges and offers JASON suggestions for improvements, including approaches that might shorten timelines and/or reduce costs. Section 6 addresses high-level policy considerations and decisions necessary for a properly informed decision concerning pursuit of an LEU-fueled core for naval reactors, via discussion of several possible future scenarios. The limited-distribution Appendix A adds discussion, observations, and suggestions at a level of detail that was not permitted in the main report.

2 EXECUTIVE SUMMARY

JASON was asked by the Naval Nuclear Propulsion Program (NNPP) to conduct a technical assessment of a new fuel concept proposed for use in nuclear reactors on U.S. Navy warships. This new "Enhanced Lifetime Element" (ELE) concept could increase uranium loading in naval reactors well beyond that of today's fuel systems. Realizing this potential could enable replacement of highly enriched uranium (HEU) in naval propulsion reactors with low-enriched uranium (LEU), with less impact on reactor size and lifetime than would be the case with today's fuel systems. JASON was asked to provide

1. A technical assessment of the high-level issues associated with establishing feasibility of developing, qualifying, and implementing a naval-reactor fuel using LEU;
2. An assessment of the currently defined Naval Nuclear Propulsion Program LEU manufacturing development and qualification program approach, evaluating whether it is sufficiently comprehensive to address known and conceivable engineering challenges toward a practical course of action that satisfies U.S. Navy military requirements;
3. An evaluation of other key high-level policy considerations and decisions that would need to be made to make a properly informed decision concerning pursuit of an LEU-fueled core for naval reactors.

The first and third charge elements concern high-level issues and considerations that are independent of fuel-technology details. The second charge element directs JASON to study a particular proposed fuel technology, ELE, and NNPP's current plan[4] for developing and qualifying ELE-LEU fuel. Successful ELE development could substantially reduce the enrichment needed to meet performance requirements with a reactor of a given size.

There are five options for the future of U.S. naval nuclear propulsion: 1) continue an all-HEU fleet; 2) deploy LEU on some ships (e.g., aircraft carriers) but not others; 3) deploy LEU

[4]Admiral J. F. Caldwell, "Conceptual Research and Development Plan for Low-Enriched Uranium Naval Fuel," HQ-#561535, July, 2016.

on all ships, with life-of-ship reactors (no refueling) on submarines; 4) deploy LEU on all ships, with refueling of some or all submarines; 5) deploy either LEU or "LEU+" (uranium enriched marginally beyond 20%) on every nuclear-powered ship, with life-of-ship reactors on submarines. Some options require development of new fuel concepts, such as ELE.

Each option has unique costs and benefits. Defining those costs and benefits would require further study, including in-reactor testing of any new fuel concept.

The NNPP conceptual plan calls for testing the new ELE-LEU fuel in the Department of Energy's Advanced Test Reactor (ATR) at the Idaho National Laboratory. The test scenarios are chosen—guided by computation, experience, and judgment—to stress the fuel in such a way that if it performs well, NNPP can qualify the fuel for use in propulsion cores. If ATR testing yields positive results for ELE-LEU fuel and a decision is made to move toward deployment, NNPP's conceptual plan includes using the fuel in a prototype reactor prior to fleet deployment. Prototype fueling and operation would be designed to prove out engineering and manufacturing and to provide high confidence that the new fuel could be successfully deployed in the fleet.

ELE-LEU fuel requires manufacturing processes that differ from those of current fuel. If testing yields positive results and a decision is made to move toward deployment, NNPP would have to develop the necessary new processes, and the facilities in which these processes could be implemented, to create ELE-LEU cores.

Charge element 3 seeks JASON input on considerations that should influence a decision concerning pursuit of LEU-fueled naval reactors. JASON finds that

- An important consideration is what combinations of design parameters (such as reactor size, propulsion plant size and arrangement, required shipyard facilities, etc.) could allow LEU reactors to be deployed in submarines, and how these design features might affect submarine mission capability.
- Deploying LEU-fueled naval reactors would require development of manufacturing,

maintenance, training, and disposal infrastructures for LEU that differ from today's HEU infrastructures. Some dual LEU and HEU infrastructures might need to operate in parallel for decades.

- Key reactor-compartment design decisions for the VIRGINIA-replacement SSN could be made before 2030. Unless the reactor compartment is designed such that it can ultimately accommodate an LEU reactor, it will be difficult to deploy an LEU reactor in the SSN fleet before the last VIRGINIA-replacement is launched in the 2060s.

Charge element 1 refers to high-level issues associated with developing, qualifying, and implementing LEU fuel for naval reactors. JASON finds that

- Deploying LEU reactors in submarines might require larger reactor-core volumes and/or reduced total energy compared to today's HEU reactors, which could make it difficult to achieve life-of-submarine cores.
- The U.S. Navy no longer has the needed capacity in physical resources, equipment, or personnel at shipyards to execute mid-life refueling of all submarines. Because there are more attack submarines (SSNs) than ballistic-missile submarines (SSBNs), the capacity required to refuel SSNs would be greater than for ongoing SSBN refueling.

Charge element 2 asks for an assessment of the currently defined NNPP development and qualification approach for LEU fuel. JASON finds that

- The NNPP conceptual plan for developing and qualifying ELE-LEU fuel, including several phases of in-reactor testing following by prototype testing, is sufficiently comprehensive to address known and conceivable engineering challenges. The test schedule is reasonably rapid in light of the strict requirements for naval fuel, the lessons learned from 60 years of fuel development, the unknowns introduced by the ELE concept, and the realities of ATR availability.

- The proposed ELE-LEU fuel differs significantly from previously tested fuel types, which makes it impossible to confidently predict ELE-LEU fuel performance without testing the new fuel in a test reactor (such as the ATR).

- The currently planned combination of testing in the Advanced Test Reactor and a prototype reactor is likely to provide sufficient information for NNPP to accurately and confidently project the new fuel's performance in fleet-deployed reactors.

- "Scaled" fuel tests with smaller test elements could provide more data (more simultaneous test specimens and shorter test times), which might help NNPP reduce uncertainties in performance of the new fuel.

JASON recommends that NNPP:

- Estimate the propulsion-plant design parameters that could enable life-of-ship ELE-LEU reactors in the submarines that will follow the VIRGINIA and OHIO-replacement classes. Assess the impact of these design parameters on mission capability and cost.

- Use computational tools and engineering judgment to search for fuel-testing scenarios that differ from those currently assumed to be "worst-case" but that have the potential to cause failure in the new ELE-LEU fuel.

- Explore the use of reduced-scale fuel tests to enable coverage of a wider fuel-test parameter space without increasing the time or volume needed for in-reactor testing.

The full report explains the bases for these findings and recommendations at the C/RD level. The report includes a limited-distribution appendix with additional findings and recommendations. All findings and recommendations in the classified report and appendix are consistent with the unclassified statements in this summary.

3 HIGH-LEVEL ISSUES AFFECTING LEU DEPLOYMENT

The first element of the study charge asks JASON to assess high-level issues associated with the use of LEU fuel in U.S. Navy propulsion reactors. Here we discuss four such issues: total energy deliverable by the core, volume of the reactor, enrichment level of the fuel, and refueling.

3.1 Total Deliverable Energy

A reactor's total deliverable energy is distinct from its maximum power level, which is limited not by uranium enrichment but by considerations concerning temperature and coolant-flow. Maximum power level is not an issue for this study. Enrichment sets the total deliverable energy of a reactor core and determines how long a given core can power a given ship. Total deliverable energy constitutes a key high-level characteristic of a naval reactor core.

Total deliverable energy (E_{tot}) satisfies several simple mathematical relations:

$$
\begin{aligned}
E_{\mathrm{tot}} &= P_{\mathrm{avg}} \times L \\
&= \int_{t_0}^{t_0+L} P(t)dt \\
&= P_{\mathrm{max}} \times \mathrm{EFPH} \\
&= [\text{total number of fissions}] \times [\text{energy deposited per fission}] \ , \qquad (1)
\end{aligned}
$$

where

$$
\begin{aligned}
L &\equiv \text{core lifetime} \\
P_{\text{avg}} &\equiv \text{average reactor power over the core lifetime} \\
t_0 &\equiv \text{time of initial criticality} \\
P_{\text{max}} &\equiv \text{maximum rated reactor power} \\
P(t) &\equiv \text{reactor power at time } t \\
\text{EFPH} &\equiv \text{Effective Full-Power Hours} \\
&\approx \text{number of hours the core could operate at full power, } P_{\text{max}} \qquad (2)
\end{aligned}
$$

Total deliverable energy in a reactor core can be limited by either of two principal factors:

1. Material degradation of core components (fuel elements, in particular), and/or
2. Inability to achieve criticality under required conditions, due to the accumulated effects of nuclide depletion and production (which are triggered by neutron absorption and radioactive decay).

Through decades of effort informed by decades of experience, the NNPP has "solved" the materials-degradation issue to the point that cores in the fleet have demonstrated multi-decade lifetimes, and the OHIO-replacement core is expected to achieve a 42-year service life. With the possible exceptions that we discuss in Appendix A, and under the current plan to make only minor changes to the overall design of the cores, NNPP's success with long-lived core materials increases the chance of such success in cores fueled by LEU. We therefore focus on the lifetime limitation that stems from nuclide depletion and production in LEU cores.

From Eq. (1) we see that total deliverable energy is constrained by the total number of fissions the core can yield before it can no longer achieve criticality under required conditions. The total number of fissions in a uranium-fueled PWR is largely limited by the number of ^{235}U atoms loaded into the core:

$$
\begin{aligned}
N_{\text{fissions}}^{\text{tot}} \doteq\ & N_{235} \times \left[\text{fraction of } {}^{235}\text{U atoms fissioned}\right] \\
& + N_{\text{Pu-239}}^{\text{produced}} \times \left[\text{fraction of } {}^{239}\text{Pu atoms fissioned}\right] \\
& + \text{ smaller terms,} \qquad (3)
\end{aligned}
$$

where

$$
\begin{aligned}
N_{235} &\equiv \text{total number of } {}^{235}\text{U atoms loaded,} \\
N_{\text{Pu-239}}^{\text{produced}} &\equiv \text{total number of } {}^{239}\text{Pu atoms produced during reactor operations,} \\
& \quad \text{mainly via neutron capture in } {}^{239}\text{U followed by two } \beta \text{ decays.} \qquad (4)
\end{aligned}
$$

In a PWR fueled by HEU enriched beyond 90%, little ^{239}Pu is produced, and almost all of the fissions are of ^{235}U. [redacted] (b)(3) In an LEU-fueled U.S. naval propulsion reactor, the number of ^{235}U fissions will dominate the number of ^{239}Pu fissions, and it will be difficult to design a naval LEU core whose fraction of ^{235}U atoms fissioned is as high as in a naval HEU core.

It follows that in a U.S. Navy PWR core, the total deliverable energy is roughly proportional to the number of ^{235}U atoms loaded into the fuel. This is a significant constraint: one ton of 93%-enriched uranium has as many ^{235}U atoms as 4.7 tons of 19.75%-enriched uranium. It is easy to understand why the U.S. Navy has used HEU for every nuclear-powered ship it has ever built.

In summary, to achieve the same total deliverable energy or core lifetime with an LEU core as is provided by an HEU core, the NNPP must figure out how to load more than 4.5 times as much uranium into the LEU core.

3.2 Reactor Volume

Loading 4.5 times as much uranium into a core with 4.5 times the volume is conceptually simple. However, reactor core volume on a naval warship is a fundamental design parameter that is tightly coupled to, and constrained by, many other ship design parameters. Given a base reactor and ship design, it is possible that a modest increase in core volume could be accommodated by redesigning only a modest portion of the propulsion plant. However, some level of core-volume increase would have a "ripple effect" that would force a substantial redesign of the ship.

Independent of LEU considerations, there has been pressure for more than six decades to increase the uranium density in naval nuclear propulsion cores, because an increase in total deliverable energy from a smaller core volume has significant military value. As a result of decades of high-priority development and testing, today's HEU cores for the VIRGINIA-class SSN have a relatively high uranium-loading density (mass of uranium in the core divided by the core volume, usually expressed as grams of U/cc-core, where cc is cubic centimeters). [redacted] (b)(3)

[5]Each U.S. Navy reactor core has a unique three-part identifier of the form XnY, where X=A for aircraft carriers or S for submarines, Y identifies the company managing the lab that designed the reactor (G for General Electric, W for Westinghouse, B for Bechtel Marine Propulson Corporation (BMPC), etc.), and n denotes the n-th reactor designed for X under Y's management.

[redacted] (b)(3)

[redacted] However, reactor volume is a design parameter that couples to many other ship design parameters, and significant increases in reactor volume would spawn a cascade of significant ship-design changes.

3.3 Enrichment

The mass of uranium that contains a given number of ^{235}U atoms is proportional to 1/enrichment. 4.7 tons of 19.75%-enriched uranium has the same number of ^{235}U atoms as 1.0 ton of 93%-enriched uranium. As later sections of this report discuss, even if the NNPP research and development program succeeds in developing and qualifying its proposed new ELE-LEU fuel, the resulting uranium loading density will not reach 4.7 times that of today's VIRGINIA cores. If LEU is to be deployed and there is a need for more ^{235}U/cc-core than the proposed technology can provide with 20%-enriched LEU, considering enrichments that are modestly greater than 20% may be valuable. The 20% value that defines the LEU/HEU boundary does not arise from a physical threshold; rather, the weapons usability of enriched uranium is a smooth function of enrichment in the range around 20%. For example, 25%-enriched uranium is not much more attractive for weapons use than is 20%-enriched uranium. A recent National Academies study on the conversion of research and test reactors from HEU to LEU recommends an intermediate step of converting to 30-45% enriched commercially available U_3Si_2 fuel [2]. Based on this precedent and the technical arguments regarding the absence of a sharp threshold, we suggest that reducing naval reactor fuel enrichment to a value modestly greater than 20% would be seen within the nonproliferation community as a significant step and might provide almost as much nonproliferation value as going all the way to 20%.

3.4 Refueling

The only reactor refuelings that the Navy currently performs are for the NIMITZ-class carriers, at the rate of about one per five years, and the OHIO-class SSBNs, at the rate of about one per year.

Many LOS ANGELES-class SSNs were refueled at mid-life, but all planned refuelings of this class have been completed. The VIRGINIA-class SSNs, some of which have been deployed and some of which remain to be built, have life-of-ship reactor cores and will not require refueling. One SEAWOLF Class ship, USS JIMMY CARTER, is likely to be refueled.

Naval reactor refueling requirements will continue to decrease as the fleet evolves during the coming decades. The FORD-class carriers, which will be built and launched over the course of the next four decades, will be refueled at mid-life, at an average rate of about one per five years, the same refueling rate as for today's NIMITZ-class carriers. The OHIO-replacement SSBNs, which will be launched from the late 2020s into the 2040s, are designed with life-of-ship reactor cores, with no refueling planned. The VIRGINIA-class SSNs will continue to be launched for more than another decade, and their first replacement SSN is still a quarter of a century away from its launch. One SEAWOLF Class submarine, the USS Jimmy Carter, is likely to be refueled. After the last OHIO-class SSBN is refueled, the Navy has no foreseeable need for submarine-refueling capabilities. This has led to a substantial reduction of shipyard capabilities (notably refueling-capable drydocks), which during the cold war could execute 8 refuelings per year but will soon be asked to execute only one per five years.[6]

The costs and benefits of refueling differ by ship type. For the FORD-class carrier, the Navy has opted for mid-life refueling. This decision was influenced by many factors, including:

[6] Currently, NIMITZ-class refuelings take place at Newport News, OHIO refueling is done at Puget Sound and Norfolk, and Portsmouth defuels but does not refuel. Pearl Harbor and Electric Boat no longer have refueling capabilities. The Charleston and Mare Island facilities are closed.

- With a 50-year ship life, a life-of-ship core would have been a challenge.
- Carriers need a substantial mid-life overhaul anyway.
- With only 10 or 11 carriers and a 50-year ship life, only one refueling is needed approximately every five years and thus only one refueling-capable drydock is needed.

In contrast, the Navy has opted for a life-of-ship core for the VIRGINIA-class SSN, influenced by factors that include the following.

- A 33-year core was achievable.
- With approximately 50 SSNs and a 33-year ship life, refuelings would have been needed at a rate of approximately 3 per year, which would require significant drydock infrastructure and would likely reduce the number of SSNs available for deployment at any given time.

Many observers have noted that the U.S. Navy refueled its submarines in the past, that other countries refuel their submarines now, that other countries use LEU fuel in their submarines, and that therefore the U.S. Navy could deploy LEU-fueled reactors that require refueling. These observations are true but can be misleading, for they do not convey the substantial advantages—mostly in reduced costs to deploy today's and tomorrow's capabilities—that the U.S. has derived from its long-lived submarine reactor cores, the need for fewer submarines of each class, and the reduction in refueling-capable shipyard infrastructure.

3.5 Implications of High-Level Issues

Relative to an HEU-fueled naval reactor, deploying an LEU-fueled reactor would require some combination of

- Increased reactor core volume,

- Decreased total deliverable energy (core lifetime),
- Increased uranium loading per unit core volume.

Increasing core volume by more than a modest fraction could have a significant negative effect on ship design, especially for submarines. Decreasing total deliverable energy could require refueling, which for attack submarines would require substantial drydock capabilities. [redacted] (b)(3)

In Section 4 we discuss a new fuel concept proposed by NNPP, known as the Enhanced Lifetime Element (ELE), which has the potential to increase U/cc-core substantially relative to today's fuel technology. We also discuss the prospects that U/cc-core could be increased to the point that LEU reactors could be deployed with the same volume and total deliverable energy as the HEU cores now in the VIRGINIA-class SSNs and planned for the OHIO-replacement SSBNs.

4 PROPOSED ELE-LEU FUEL FOR NAVAL REACTORS

This section describes the proposed ELE-LEU fuel concept at a level of detail appropriate for the intended distribution of the main body of this report. More detail is provided in Appendix A, which is intended for more limited distribution. We begin with a brief description of the progress that NNPP has made in nuclear reactor fuel technology during six decades of deploying reactors on warships. The main point is that today's technology is advanced and mature, with a high level of uranium loading per unit volume of core and with high levels of burnup achieved without fuel failures. The U.S. Navy has derived significant military benefit from the combination of this mature fuel technology and uranium that is enriched to 93-97%.

Simply replacing 93%-enriched uranium with 20%-enriched uranium in the same mature fuel technology, thereby *diluting* the fuel by a factor of 4.7, would reduce total deliverable energy per unit volume by approximately the same factor. This would dramatically shorten core lifetimes (total energy) unless reactor volumes were comparably increased. Reduction of total energy density by a factor of more than 4 would significantly disrupt the Navy's submarine operations.

The introduction of LEU-fueled reactors into U.S. naval warships would be greatly facilitated by a new fuel technology with the potential for significantly higher loadings of uranium per cc of core. NNPP has proposed such a technology, namely the Enhanced Lifetime Element (ELE) fuel concept, which is the centerpiece of the proposed plan to develop and qualify LEU fuel. This report focuses on the development and qualification of ELE.

4.1 Brief History of Naval Fuels and Reactors

The nuclear navy began with the launch USS Nautilus in 1955, whose reactor needed refueling approximately once per 18 months. The Nautilus demonstrated the valuable capabilities of a nuclear-powered submarine, including its ability to remain stealthily submerged for much longer than diesel-powered submarines, and paved the way for the U.S. to develop a large nuclear-powered fleet with capabilities that exceed those of any fleet in history.

[redacted] (b)(3)

Behind this progress lies decades of research, development, and testing that allowed NNPP to push more and more HEU per unit volume into its reactors while meeting safety and performance requirements.

The basic fuel technology used today was first deployed by the U.S. Navy in the 1960s and has undergone steady incremental improvement in uranium loading density (U/cc-core) since that time. There has never been a confirmed leak of fission products from this type of fuel on any U.S. naval propulsion reactor since its first deployment in the 1960s. This is a remarkable record. It is also the standard that any new fuel technology must meet if it is to be considered for deployment in a U.S. warship.

4.2 Enhanced Lifetime Element

A 1995 DOE report [6] on the use of LEU in the Navy concluded, "The use of LEU for cores in U.S. nuclear powered warships offers no technical advantage to the Navy, provides no significant nonproliferation advantage, and is detrimental from environmental and cost perspectives."

Congress requested a second report that was delivered in 2014 [7]. This report offered a more positive perspective, stating that "...recent work has shown that the potential exists to develop an advanced fuel system that could increase uranium loading beyond what is practiced today while meeting the rigorous performance requirements for naval reactors."

The striking difference between the two reports is due partly to the invention of a new fuel technology, which NNPP calls the Enhanced Lifetime Element (ELE) (often pronounced "Ellie"), during the intervening years. The ELE fuel concept was conceived as a way to increase the uranium density in HEU-fueled cores beyond the limit of what today's deployed technology could ever achieve. NNPP recognized that a large uranium density increase might also enable LEU fuel to get much closer to the ^{235}U density of HEU cores that use today's fuel technology, potentially enabling the introduction of LEU cores into the U.S. fleet without the "significant negative consequences" mentioned in the 1995 report.

[redacted] (b)(3)

The ELE concept does not require changes to this picture or description, but changes only the details of the fuel "meat"– how the uranium is loaded inside the fuel element. [redacted] (b)(3)

Figure 8 compares the ELE fuel element to the FORD class A1B HEU fuel element. The figure shows three important changes:

- ELE technology places more U/cc into the fuel meat;
- [redacted] (b)(3)
- [redacted] (b)(3)

The result of these changes is that slightly more ^{235}U is loaded into the ELE-LEU core than is presently loaded into the A1B core. [redacted] (b)(3)

[redacted]

(b)(3)

[redacted]

(b)(3)

The ELE-LEU reactor for the FORD-class aircraft carrier exists only as a calculation at this time. Calculations suggest that if the ELE-LEU fuel technology can be successfully developed and qualified, it might be possible for an LEU-fueled nuclear reactor to meet requirements for modern U.S. aircraft carriers without changing the core volume.

While these are promising results, it would be premature to declare that an LEU core can meet A1B requirements without changing the core volume. In the report to Congress on "Conceptual Research and Development Plan for Low-Enriched Uranium Naval Fuel" [1], Admiral James Caldwell notes that if the program attempts to develop and qualify the new LEU fuel, "success is not assured." This cautionary statement has a solid technical foundation, as we discuss in the next two subsections.

4.3 Performance of New Fuel

Figure 6 shows the fuel element—the basic unit of reactor core construction and central object of this discussion. The fuel element contains the uranium fuel and must contain the resulting fission products throughout core life. Nuclear reactor fuel is subjected to an extreme environment, especially if it undergoes high burnup, where burnup could be measured in energy per unit mass of originally loaded uranium or in fissions per unit volume of fuel, for example. The following processes occur simultaneously in a fuel element of a naval reactor core:

- [redacted] (b)(3)
- radiation-induced embrittlement
- thermal annealing
- thermal creep
- radiation-induced creep
- thermal gradients ⇒ stresses ⇒ cracking of the fuel meat and surrounding zircalloy

JASON offers the following observations regarding ELE-LEU fuel performance.

1. Given the knowledge and simulation tools available today, nuclear reactor fuel performance at high burnup levels is not predictable without a foundation of relevant experimental data.

2. ELE fuel technology differs enough from previous technologies that at this time there is not sufficient experimental data from which to confidently predict performance.

3. Naval reactor fuel must not leak fission products into the primary coolant. This is a difficult requirement for any new fuel to meet, especially given other performance requirements.

4.3.1 Failure modes and causes

Figure 9 illustrates a leaking fuel element. If the element's cladding (zircaloy in the present discussion) remains intact, fission gases will remain in the fuel meat. This is a more difficult challenge than it may at first appear. The fuel, including the cladding, is subjected to the conditions and processes described above for more than two decades in a carrier reactor and even longer in submarine reactors. Designing a fuel system that can maintain its integrity for this long under these conditions presents a major technical challenge.

[redacted] (b)(3)

These considerations show that surprises are possible with ELE-LEU—the new fuel may not perform as hoped. These considerations also explain why it is necessary to subject any new fuel concept to rigorous in-reactor testing. NNPP's plans for this are discussed in Section 5, along with JASON's assessments of their sufficiency and suggestions for improvements.

[redacted] (b)(3)

4.4 LEU Reactor Operations

Before deploying an LEU reactor, NNPP must understand how LEU reactor operations will differ from those of an HEU reactor. Here we discuss some differences that should be considered.

Throttles and control rod positions constitute the main controls for regulating reactor power during military operation. The throttles control the amount of power taken out of the reactor by regulating the steam demand. As more steam is sent from the steam generator to the turbines during an up-power maneuver, the primary coolant temperature exiting the steam generator (and entering the reactor core) is lowered. The negative coolant-temperature coefficient of reactivity makes the reactor supercritical, which increases the fission rate and ultimately raises the coolant temperature enough that the reactor returns to a critical state at the higher core power level. Control rod motion is used to regulate reactor temperature (e.g. as core cenon levels change) with reactor power following steam demand.

In an LEU reactor, Doppler broadening of resonances in the fuel from increased core power provides an additional negative feedback mechanism. This adds to the negative feedback from coolant temperature. The microscopic cross section, σ, in the vicinity of the energy resonances shown in Fig. 10 has large values, σ_o, in a narrow range, δ, around each resonance energy, E_o. As material temperature increases, thermal motion broadens the resonance width δ and the absorption rate increases. The effect in an LEU core is that at higher temperatures, resonance absorption in ^{238}U removes neutrons that would otherwise scatter to lower thermal energies, some of which would cause ^{235}U fissions. This explains the negative reactivity effect of increased fuel temperature.

Overcoming the negative feedback from Doppler broadening after a power increase will require either a lower coolant temperature or movement of control rods, compared to the coolant temperature and control-rod locations in an equivalent HEU reactor. That is, operating an LEU-fueled naval-propulsion reactor may require more frequent changes of control-rod positions compared to the HEU case. It is possible that the design of the control-rod

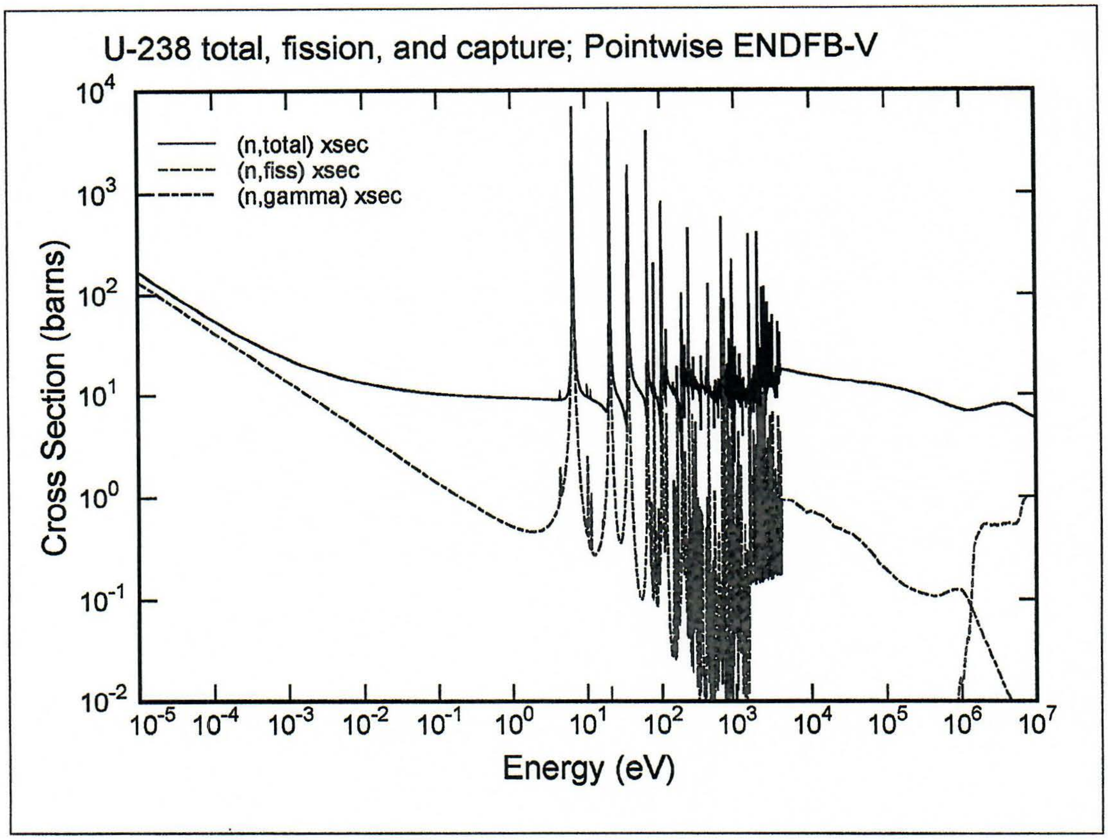

Figure 10: Cross sections for neutron interactions with ^{238}U: total, fission, and capture. The vertical axis spans a factor of 10^6.

drive mechanisms would have to be modified to accommodate this higher duty cycle.

An LEU reactor will have different dynamic behavior than an HEU reactor, especially late in core life, due to the buildup of ^{239}Pu, which has a smaller delayed-neutron fraction than that of ^{235}U. To a good approximation, a reactor's dynamic response to a change in multiplication factor (call it Δk) depends on $\Delta k/\beta$, where β is the delayed-neutron fraction.[7] Approximately 0.65% of the neutrons from ^{235}U are delayed, but only $\approx$ 0.21% of those from ^{239}Pu are delayed.

[7]Delayed neutrons are emitted by daughters of fission products at some time after the parent fission event, with delay times ranging from sub-second to a few minutes.

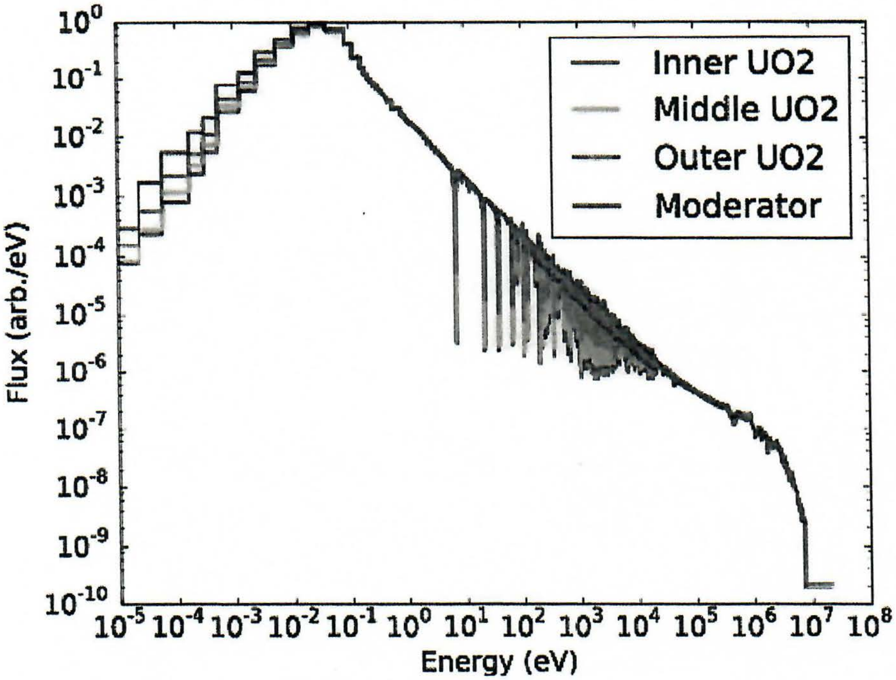

Figure 11: Neutron energy spectrum computed at different positions inside the UO_2 fuel and the moderator. This shows the position sensitivity of the neutron flux at resonance energies.

NNPP estimates approximately 20% of fissions will come from ^{239}Pu near the end of the ELE-LEU-fueled A1B-replacement core's life. The effective delayed-neutron fraction in the core at end of life will therefore be roughly $0.2 \times 0.21\% + 0.7 \times 0.65\% \approx 0.56\%$, which is smaller than at beginning of life and smaller that of an HEU core. The LEU core will therefore have faster dynamics than an HEU core once significant Pu has built in. NNPP will need to evaluate whether this change warrants changes to training or operational procedures.

4.5 LEU Reactor Calculations

NNPP has designed an LEU core that is calculated to meet reactor requirements for the FORD-class carriers—the same requirements met by the A1B HEU core, in the same core footprint and volume—if ELE-LEU fuel is successfully developed. NNPP has used its well-tested computational capabilities to guide and assess this preliminary design.

The new LEU fuel presents challenges that the program's computational capabilities have not had to meet in the past, given that they have needed to perform well only for reactors fueled with HEU using today's fuel technology. The calculations may have larger errors for ELE-LEU fuel than for the current HEU fuel, and these errors may cause the computational results to be overly optimistic.

The following subsections discuss important physics processes in LEU fuel that may not be modeled adequately without improving computational models.

4.5.1 Resonances

A fundamental quantity that must be calculated is the rate at which the fuel absorbs neutrons per unit volume (absorption rate density, or ARD), as a function time t and position $\vec{r}$ in the fuel-bearing material:

$$\mathrm{ARD}(\vec{r},t) = \sum_{i=1}^{\#\text{ of nuclides}} N_i(\vec{r},t) \int_0^\infty \phi(\vec{r},E,t)\sigma_a^i(E,T(\vec{r},t))dE \ , \tag{7}$$

where N_i is the number density of the i^{th} isotope, ϕ is the neutron flux, σ_a^i is the microscopic absorption cross section for nuclide i, E is the neutron energy, and T is the material temperature.

Difficulties arise from resonances, which cause $\sigma_a^i(E,T)$ to change by orders of magnitude when E changes by fractions of a percent. Figure 10 illustrates this for ^{238}U. Figure 11, which comes from a detailed calculation of a simplified commercial PWR, illustrates the effects that resonances can have on ϕ at different positions. In the interior of the fuel, $\phi(E)$ is strongly depressed by the high cross sections associated with each resonance. The effect is smaller in the fuel near the fuel/coolant interface, and smaller still in the coolant. Note that if one used any $\varphi(E)$ function averaged over a spatial region (for example, the entire fuel pin) to calculate the absorption rate density everywhere in that region, the calculation would err significantly in its spatial variation.

Figure 12 shows η, the number of neutrons produced for each neutron absorbed, as a function of the energy of the absorbed neutrons. For ^{235}U, η varies across the energy range around the resonance region, at places reaching as low as $\eta = 1.6$ from an average of about 2.0. This means that in HEU fuel, the multiplication factor is not terribly sensitive to miscalculation of the absorption rate in resonances vs. the thermal-neutron absorption rate.

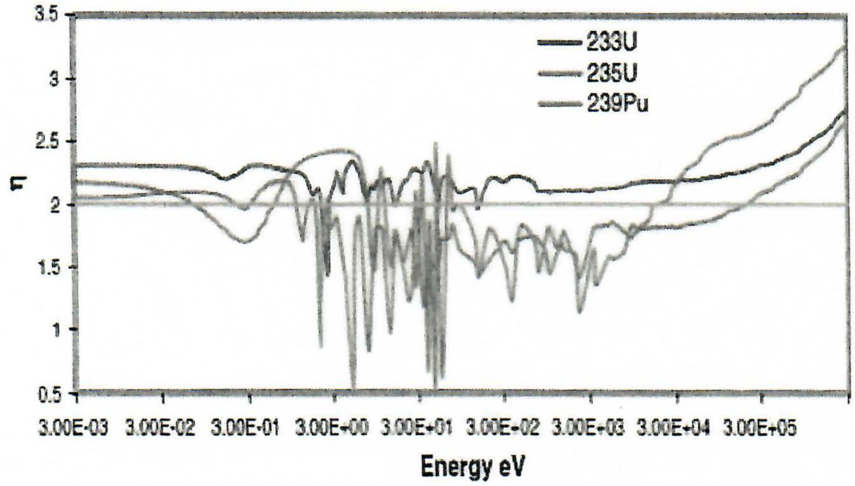

Figure 12: Number of neutrons emitted per absorption as a function of the kinetic energy of the absorbed neutron.

With LEU fuel, ^{238}U strongly captures neutrons in the sharp resonances shown in Fig. 10 with very little chance for a fission to result (i.e. for ^{238}U, $\eta \sim 0$ in the resonance region.) There is a dramatic difference between the outcomes of absorption in resonances vs. absorption after thermalization. This places more stress on the calculation: resonance absorptions must be calculated more accurately with LEU than with HEU to produce a given overall accuracy of the calculated multiplication factor.

Neutron capture in ^{238}U ultimately produces ^{239}Pu. In the proposed LEU design for the FORD-class carriers, approximately 20% of late-time fissions are in ^{239}Pu. Correctly predicting late-time reactor behavior and core lifetime depends on correctly predicting the amount and spatial distribution of ^{239}Pu. NNPP reactor-analysis codes will need additional testing (e.g. verification and validation) before they can be trusted to be accurate for LEU cores, and they might need modifications in their treatments of nuclide production and depletion for reactions that involve capture in resonances.

4.5.2 Doppler feedback

Temperature feedback is an important factor in reactor operations, as was briefly discussed earlier. With HEU-fueled naval PWRs, temperature feedback is due mostly to the coolant, and mostly to temperature-driven changes in the density of the primary coolant water. An LEU-fueled naval PWR would have an additional strong feedback mechanism from Doppler broadening of ^{238}U resonances in the fuel, as discussed in the previous section on LEU reactor operations. We repeat this here to emphasize that the feedback effect will not be properly calculated for LEU reactors unless analysis codes accurately calculate resonance absorption.

4.5.3 Delayed-neutron fraction

As we mentioned in a previous section, the delayed-neutron fraction in an LEU reactor will decrease as ^{239}Pu builds up, and it will vary spatially to the extent that ^{239}Pu concentration varies spatially. With HEU cores, computations of transient behavior can be accurate using a delayed-neutron fraction that is constant in space and time. With LEU cores it is probably necessary to use position- and time-dependent delayed-neutron fraction to achieve the desired accuracy. This may require code modifications along with some amount of code verification and validation.

4.6 LEU Reactor Design

The breeding of ^{239}Pu increases the energy density of an LEU-fueled naval PWR beyond that obtained from ^{235}U alone. This could help obtain a given energy density without having to load quite as many ^{235}U atoms as one might first estimate. An interesting question is how large the second term in the following equation could become:

$$N_{\text{fissions}}^{\text{tot}} = N_{235} \times \left[\text{fraction of } ^{235}\text{U atoms fissioned}\right] + N_{\text{Pu-239}}^{\text{produced}} \times \left[\text{fraction of } ^{239}\text{Pu atoms fissioned}\right] + \text{much smaller terms,}$$

There are limits to this that stem from fundamental neutron accounting. Fig. 12 shows that the fission of ^{235}U produces somewhat less than two neutrons per absorption. One of these is needed to continue the chain reaction. Leakage and capture in non-fuel materials remove some fraction of another neutron, on average. Less than one neutron remains to convert a ^{238}U atom to a ^{239}Pu atom. [redacted] (b)(3) The bottom line is that in a core that begins with $\approx$ 20% enriched uranium, it will not be possible to replaced a large fraction of consumed ^{235}U atoms with in-core-created ^{239}Pu atoms.

The same argument shows that only a small fraction of the original ^{238}U atoms will be destroyed by neutron absorption in a core that begins with $\approx$ 20% enriched fuel. That is, the ^{238}U "poison" will not be significantly depleted. This adds to the difficulty of designing a long-lived LEU-fueled core.

5 ELE-LEU FUEL DEVELOPMENT, QUALIFICATION, AND MANUFACTURING

Reactor fuel performance at high burnup levels is not predictable without a foundation of relevant experimental data. NNPP will not deploy a new reactor fuel in the fleet unless it has performed well in high-burnup tests in a reactor. This is prudent. NNPP recognizes that fuel testing in available test reactors cannot exactly match the conditions in a fleet-deployed reactor. Because of this, NNPP often requires that a new fuel be deployed in a prototype reactor in advance of fleet deployment—especially if the new fuel technology is a significant change from past technologies—so that any problems with the fuel are likely to occur in the prototype before they arise in the field. The NNPP view is that if ELE-LEU fuel is developed to the point of satisfactory performance in test reactors, the new technology is sufficiently different from past experience that the prototype-reactor would be required to provide enough confidence to deploy an ELE-LEU reactor in the fleet.

In this section we discuss the NNPP conceptual plan for ELE-LEU fuel testing, development, qualification, and manufacturing. We provide technical assessments where warranted and offer suggestions that could improve the planned program.

5.1 Fuel Testing

Fuel failures (e.g., fission and fuel leaks into coolant) usually stem from the interaction of a large number of complicated phenomena (Section 4), including multiple collisional displacements of each atom in the fuel, buildup of pressure from solid fission products and fission gases, chemical interactions among the large array of elements generated by fission, radiation-induced embrittlement, radiation-induced creep, thermal effects such as annealing, creep, stresses, cracking, etc. [redacted] (b)(3)

[redacted] (b)(3)

[redacted] (b)(3)

5.1.1 ELE-LEU test plans

Figure 13 shows the time-line for the development of the ELE-LEU fuel of the FORD-class carriers. The irradiation test program continues for 20–25 years in four overlapping phases, each test taking of order five years of in-reactor irradiation with years before and after irradiation for specimen design, manufacturing, testing, and destructive evaluations, as illustrated in the figure. NNPP requires testing of fuel at its end of life conditions, reached after 25 years of use in the carrier core. For example, to test the fuel's ability to contain fission gases during a transient event, the integrated fission density must be brought to the end of life level. [redacted] (b)(3)

NNPP fuel testing is performed in the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL). The ATR is depicted in Fig. 14, showing the five loops available for tests and the "serpentine" fuel geometry designed to deliver neutron fluxes approaching $10^{15}/\text{cm}^2$-s. Each test loop has its own coolant loop, allowing independent temperature control. Availability of ATR test loops is a key constraint on the development of new fuels.

In devising a test program for a new fuel, key questions include:

- What are the best tests to perform, given the constraints on time and space in the test reactor?

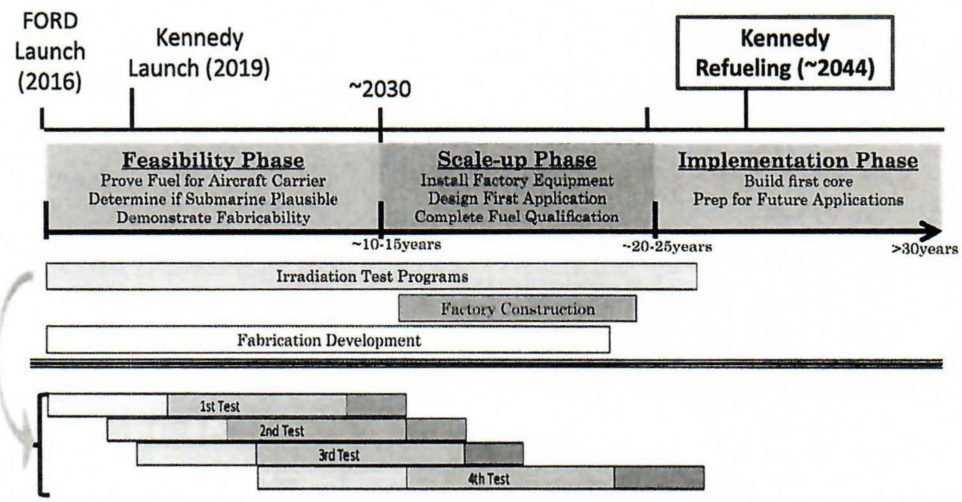

Figure 13: Approximate planned timeline for ELE-LEU in-reactor testing (four phases), development and construction of fabrication facilities, and deployment of first LEU-fueled reactor on a FORD-class carrier, shown here as the second ship (USS John F Kennedy) built in this class.

- Will successful fuel performance in the tests imply success in the field, or are there in-field scenarios that are more stressful than the test scenarios?
- Does failure in a test indicate high likelihood of failure in the field, or are the test scenarios more stressful than field scenarios can reasonably be expected to be?

As we understand it, the NNPP deterministic testing philosophy is to choose test scenarios that are judged to over test fuel relative to predicted core conditions, and use the data to establish conservative engineering limits that prevent conditions that could cause the conservative limits to be exceeded during operation. This judgment is guided by several key ingredients:

- scientific understanding of key phenomena,
- computations that embody as much of this understanding as is practical (which is not the complete body of understanding),

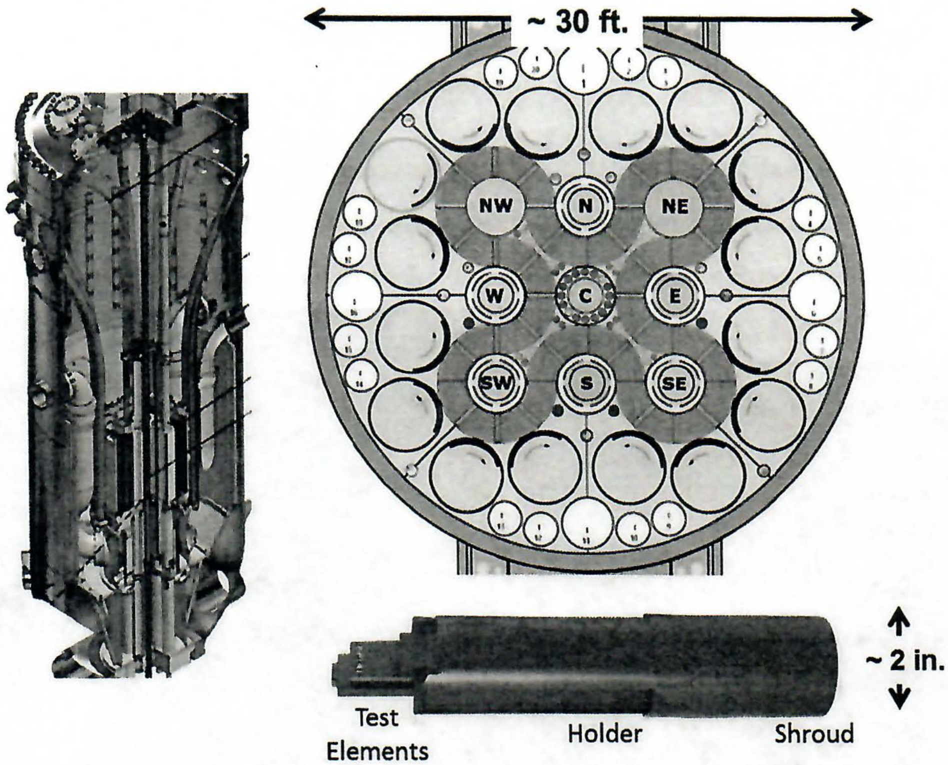

Figure 14: Schematic of the Advanced Test Reactor, highlighting (in light green) the five "loops" that are used by NNPP. Each loop has its own independent pressurized coolant system—independent of the reactor's cooling system and of the other loops. The northwest (NW) loop houses two parallel test locations, so there are six test locations in all. The figure at the bottom shows a test holder.

- experience with past fuel technologies, including how closely modern computations can match previous observations.

If ELE-LEU fuel performs in its testing approximately as well as or better than NNPP predicts that it will, then NNPP will have moderate confidence that it will perform at least as well as conservatively predicted under the conditions of fleet deployment. NNPP is likely to requires observation of ELE-LEU fuel operating in a prototype reactor to move from "moderate" confidence to the "high" confidence that would be necessary for fleet deployment of such a new technology. Fleet deployment would not have to wait until end of life of a prototype core, but the prototype would stay "ahead" of any fleet reactor in its burnup state.

This would increase the chance that any unforeseen problem would arise in the prototype before in the fleet, giving NNPP time to address it before it affected missions.

Figure 15 illustrates that the ELE test plan includes collecting data points at dozens of points in test-parameter space, from more than one hundred individual fuel specimens. Figure 16 illustrates the power profile over time that is typical of the kind of "bounding" test that NNPP plans for ELE-LEU fuel. [redacted]

(b)(3)

5.1.2 JASON assessments and suggestions for testing

JASON's study of the NNPP test plan revealed several complications we list here and consider in the rest of the section.

[redacted] (b)(3)

[redacted]

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- We suggest running suites of simulations with varying materials parameters, mesh resolution, failure models, etc.

[redacted]

(b)(3)

Scaled Fuel Tests A larger number of test data points in the relevant parameter space could help constrain the models used to characterize LEU fuel. The use of scaled experiments could mitigate the shortage of ATR test loops and long duration of the tests. Achieving the target burnup sooner enables more data collection in the same time interval, and changing the burnup rate means changing the power density, which changes the temperature profile, calling into question the relevance of the test.

The JASON study team suggests that NNPP consider employing sub-scale fuel tests—tests that reduce the spatial and temporal scales of a given test while maintaining to a large extent the same local conditions (temperature, burnup density, fission-gas density, stresses) as in a full-scale test. We find that this idea has the potential to greatly increase the rate at which relevant data could be collected from the available ATR test time. Scaled tests not only decrease the time to completion of a test, they also may allow conducting more tests simultaneously in a given flow loop.

We do not view scaled tests as a replacement for full-scale tests or a short-cut to qualification. Rather, we view this as a path to larger quantities of relevant data that would reduce uncertainties, increase confidence in predictions, and reduce the risk of deploying the new fuel.

The basic idea is illustrated in Fig. 17, which uses a scale factor of $1/2$ as an easy-to-understand example. Consider the test article of thickness b shown on the left side of Fig. 17. In cross section, the article contains fuel of areal density σ and thickness h in cladding of total thickness b; $b/2$ on each side. Providing a neutron flux ϕ to the article will generate heat through fission with areal density proportional to $\phi\sigma$ that must be transported across the cladding to the surrounding coolant with a temperature gradient, such that $\Delta T \propto \phi\sigma/b$.

The same conditions are obtained in a test article half the size and thickness, shown to the right in the figure, if it is subjected to four times the neutron flux and provided with sufficient cooling to have the same surface temperature (which is obtained to a good approximation by doubling the coolant flow). The energy production per unit area will be twice as high (half the fuel, four times the flux), but the resulting temperature profile will be the same because the element is only half as thick. Doubling the coolant flow compensates for doubling the heat production. Coolant inlet temperature can be modestly adjusted to achieve the desired element-surface temperature. The scaled test reaches the same burnup as the full sized article in a quarter the time, and four times as many articles can be tested in the same volume.

The scaling by a factor of two in the above example is notional: the optimal scaling factor will depend on the attainable water flow in the ATR, the number of samples in the test train, and other factors.

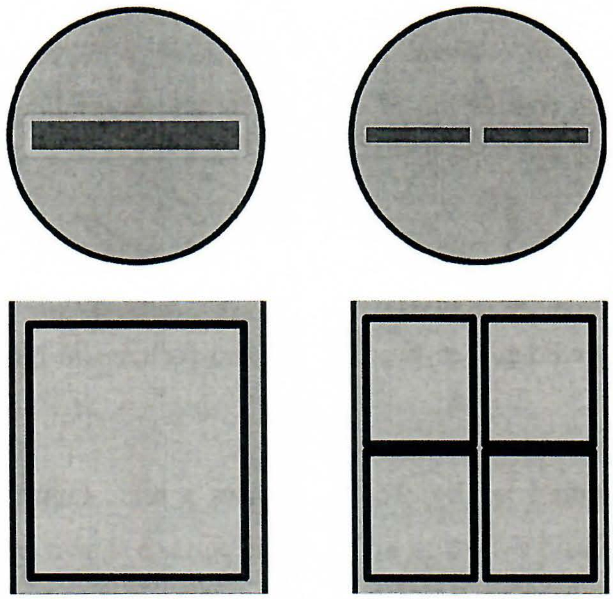

Figure 17: Illustration of scaled test, shown with a scale factor of 1/2. The upper left figure is a cross-sectional sketch of a full-sized test element in its flow loop (with many details omitted). In the lower left is an axial view showing one face of the test element. The right-hand figures show the corresponding half-scale test objects. All four of the half-scale test objects would reach the same burnup as the single full-scale object in one/fourth the time, provided that the cooling rate in the loop could be doubled (mostly by doubling the flow speed) and the driving flux could be quadrupled. This would increase the data return rate by a factor of 16.

5.2 Manufacturing ELE-LEU Fuel

The new ELE fuel technology would require manufacturing techniques and equipment that are different from those used for today's fuel. Before deploying an ELE-fueled reactor, fabrication processes would have to be developed and manufacturing facilities constructed. The quality assurance processes and procedures for the new fuel type would need to be developed along with the fabrication processes.

We cannot discuss details in this main report and address more details in the limited-distribution appendix, Appendix A.

6 OPTIONS FOR THE FUTURE

The future of uranium enrichment levels in the U.S. Naval fleet will be determined by the progress in development of new fuel concepts, such as the ELE concept described above, and decisions made by the U.S. In this section we separate the possible futures into several categories to facilitate discussion of high-level considerations that should help inform decisions.

If there is a decision to substantially reduce today's enrichment levels, designers and decision-makers will need to make trade studies balancing core lifetime, size of propulsion plant, cost, uranium enrichment level, shipyard capabilities, and many other variables, all within the constraint of meeting military requirements. JASON has deliberated on many of these trades. One key message is that if there is a decision to try to eliminate the use of HEU in the fleet, then we recommend that the 20%-enrichment boundary between HEU and LEU be considered flexible. That is, the use of enrichments modestly higher than 20%—which we shall call "LEU+"—should be considered if this has substantial advantages over 20% enrichment. For example, if LEU+ enabled life-of-ship cores for submarines while 20% enrichment required refueling, this would constitute a "substantial advantage."

Use of LEU+, properly called HEU in today's terminology but only modestly beyond 20%, could go a long way toward meeting nonproliferation goals and setting a positive example. The U.S. would not be able to make the unqualified claim of an all-LEU fleet, but the country could justifiably claim that the replacement of > 90%-enriched material with "LEU+" material accomplishes essentially the same goal.

The next five sections consider the technical consequences of different uses of LEU in the fleet in the coming century. We have assumed the current force structure and level of operations for illustration, recognizing that things will undoubtedly change to some extent on the many-decade time scale being considered.

6.1 All HEU Fleet

An all HEU fleet would look like today's fleet with the same level of manufacturing and maintenance infrastructure, except that today's SSBN-refueling infrastructure would no longer be needed after the last OHIO SSBN is refueled. All the submarines will have life-of-ship cores once the OHIO-class SSBNs leave the fleet, enabling the Navy to stop refueling submarines and retain only those facilities at Norfolk and Puget Sound that are needed for defueling. Additional HEU beyond that currently allocated to NNPP would be needed starting in the 2060s.

Obviously, this scenario does not advance the non-proliferation goal of eliminating the use of HEU.

6.2 LEU in Aircraft Carriers Only

Should the new fuel concept prove viable for LEU-fueled aircraft carriers but unable to achieve life-of-ship LEU cores for submarines, there could be a decision to convert the carrier fleet to LEU beginning in the 2040s while continuing to operate submarines with HEU enrichments > 90%. This would be accomplished by using LEU for every new aircraft-carrier core beginning in the 2040s, both for refueling older ships and for fueling new ships.

This scenario would require different infrastructures for manufacturing fuel and cores, one for HEU and one for LEU. As the LEU and HEU reactors operate somewhat differently, the Navy would need additional kinds training, possibly resulting in Navy personnel not being inter-operable between carriers and submarines. Owing to the higher radioactivity of an LEU core at the end of its life, NNPP would need to either design and operate a single defueling infrastructure that accommodates both HEU and LEU cores or design a defueling capability for LEU cores and operate dual infrastructures.

Converting the carrier fleet to LEU offers a step toward an all-LEU fleet, leaving the door open for later conversion of submarines to LEU if more advanced fuel became available or submarine requirements became less demanding. However, this partial-LEU scenario might not be viewed favorably by the nonproliferation community, for it would leave the Navy indefinitely dependent on HEU at > 90% enrichment.

6.3 All-LEU Fleet with Submarine Refueling

Should the new fuel concept prove viable for LEU-fueled aircraft carriers but unable to achieve life-of-ship LEU cores for submarines, an all-LEU fleet could still be fielded if submarines were refueled. Some duplicate LEU and HEU infrastructure would be needed during a transition phase, which might last more than a decade, but ultimately the fleet would be supported by an all-LEU infrastructure.

Refueling-capable shipyards and dry-docks would be needed for refueling submarines, with a much higher capacity needed for SSNs than for SSBNs because of the higher numbers and shorter lifetimes of SSNs. Refueling capacity does not exist today to support one or more refueling(s) of every submarine.

Submarine availability would be reduced because refueling would take each submarine out of service for some time period. Perhaps clever engineering could reduce this refueling-outage time below the values that were attained during previous refueling eras, but it is likely that on average at least one and probably a few SSNs would be out of service for refueling. The cost for this option, relative to options that have life-of-ship submarine cores, includes the cost of the shipyard infrastructure, the cost of any additional submarines that would be built to make up for the out-of-service number, and the cost of ship-design trades that would be made to allow refueling.

In this scenario, it is likely that LEU cores could enter the SSN fleet shortly after they enter the aircraft-carrier fleet in the 2040s, *if* the VIRGINIA-replacement SSNs were designed to permit refueling. If this were the case, it is conceivable that the Navy's final HEU core would be made in the 2040 time frame.

This scenario achieves the non-proliferation goal of eliminating use of HEU, and it could do so in the 2040 time frame, but it may have significantly higher cost than other options.

6.4 All-LEU Fleet With Life-of-Ship Cores on Submarines

An all-LEU fleet without the need for refueling becomes possible if the new ELE-LEU fuel concept is successfully developed and submarine propulsion plants can be designed with reactor cores that have lower energy density than today's VIRGINIA Class cores. A somewhat larger reactor, if practical and cost effective, could provide a way to shift to lower fuel enrichment in the future. If the VIRGINIA-replacement propulsion plant is designed to accommodate these somewhat larger cores, then the transition to an all-LEU fleet could begin in the 2040s for both the aircraft carriers (as described previously) and the SSNs, with VIRGINIA-replacement ships built from the mid-2040s onward receiving LEU reactors. SSBNs after the OHIO-replacement would also be designed to receive larger LEU cores.

A key element of this scenario is a sufficiently large reactor to accommodate an LEU core that meets military requirements and provides an affordable and practical ship. The key challenge is the required total deliverable energy. In Fig. 18 we illustrate the magnitude of the challenge by plotting total uranium (blue bars) and ^{235}U core-averaged density for several different reactors (some hypothetical). The key parameter is the height of the red bar (^{235}U density), to a good approximation the total deliverable energy is proportional to this number times the core volume. The first set of bars describes today's FORD-class HEU reactor. The second set assumes that ELE-LEU is successfully developed and represents NNPP's preliminary design of a replacement for the FORD HEU reactor that uses ELE-LEU fuel. Note that the red bars are about the same height.

The third set of bars represents a "maxed-out" ELE-LEU core, in which we have made optimistic assumptions about the ELE-LEU fuel loading that might be achievable. The fourth

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Figure 18: Blue bars show uranium level loading needed to achieve the ^{235}U loading show by the red bars for each of four different situations. The leftmost pair of bars show the loading for the A1B FORD class core, the next set of bars are the loading for the ELE-LEU concept for the FORD class refueling proposed by NNPP. The third pair shows what JASON believes may be possible if certain loading economies can be achieved and the rightmost shows what is needed for a life-of-ship VIRGINIA class SSN core. The gap is the shortage in ^{235}U loading between what ELE-HEU is likely to provide and what is needed for a VIRGINIA class core.

set of bars represents the LEU uranium loading that would be required to equal the ^{235}U loading of today's VIRGINA-class and OHIO-replacement HEU cores. [redacted] (b)(3)

[redacted] (b)(3)

[redacted] (b)(3)

In this scenario, some duplicate LEU and HEU infrastructure would be needed during a transition phase, which might last more than a decade, but ultimately the fleet would be supported by an all-LEU infrastructure. As is the case in the business-as-usual all-HEU scenario, submarine refueling would end when the last OHIO-class SSBN is refueled.

This scenario achieves the non-proliferation goal of eliminating use of HEU, and it could do so in the 2040 time frame.

6.5 LEU and LEU+

Should the new fuel concept prove viable for LEU-fueled aircraft carriers but unable to achieve life-of-ship LEU cores for submarines, the U.S. may wish to consider enrichment slightly beyond LEU's formal 20% level. We refer to this as LEU+. LEU+ could be $\sim 25\%$ enrichment, for example, or even 30%. By the analysis of the previous section, this could permit the use of LEU on submarines with no increase in core size, provided energy-density requirements do not grow more than 15-20% beyond today's requirements. The idea is that LEU+ could be high enough to make life-of-ship cores possible but low enough to present essentially the same negligible proliferation risk as LEU at 19.99%.

One variant of this scenario would use LEU for aircraft carriers and LEU+ for submarines. Another variant, which might have simpler infrastructure characteristics, would use LEU+ for all reactors.

Infrastructure requirements would be the same as in the all-LEU life-of-ship scenario, but this scenario is simpler in that it does not require larger cores. If somewhat larger cores prove easy to accommodate, then the required LEU+ enrichment would be lower—closer to the definition of LEU.

LEU+ would formally be called HEU in today's terminology, but no one would dispute that 25%-enriched uranium is much less attractive for weapons use than is 93%-enriched uranium. A strong technical case could be made that a proliferator would not bother with 25%-enriched uranium any more than 19.99%-enriched material.

This scenario would not strictly satisfy the nonproliferation goal of eliminating "HEU" from the fleet. It would lower the maximum enrichment used from its current $> 90\%$ level to a much lower value that is only modestly above 20%. This might be a satisfactory compromise among nonproliferation goals, military requirements, and costs.

6.6 Summary

The feasibility, costs, and benefits of the options above depend on how well the ELE-LEU concept works. If a decision is made soon to proceed with ELE-LEU development, then by the time the design of the VIRGINIA-replacement propulsion plant is being solidified in the 2030 time frame, NNPP will have a good idea of whether ELE-LEU will succeed. As we have repeatedly indicated, the design of the VIRGINIA-replacement propulsion plant is a key milestone in any scenario involving transition to LEU or LEU+ cores for submarines. If the design accommodates LEU or LEU+ cores, then the Navy's final HEU core might be built as early as 2040. If not, HEU cores will be built at least until the final VIRGINIA-replacement SSN receives its core in the 2060s.

NNPP has developed a conceptual plan for developing and qualifying ELE-LEU fuel. In our view this plan addresses the known and conceivable challenges. The phenomena involved are complex enough that only high-burnup testing can determine whether the proposed fuel will meet requirements, but preliminary results and analyses are promising.

The ELE concept, if successfully developed, increases the density of uranium loading to the point that LEU cores for aircraft carriers would be achievable with mid-life refueling, which is already the practice with HEU cores for aircraft carriers. [redacted] (b)(3)

The Executive Summary, Section 2, give JASON's findings and recommendations.

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A CHALLENGES POSED BY ELE-LEU (LIMITED DISTRIBUTION)

In this appendix we discuss the Enhanced Lifetime Element Low-Enriched Uranium (ELE-LEU) fuel concept and the challenges it poses to the Naval Nuclear Propulsion Program (NNPP) at a level of detail that is restricted to a more limited distribution than the information in the main report.

Section A.1 describes the fuel system that has been successfully deployed in naval reactors since the 1960s, discusses ideas for increasing the uranium loading density of that fuel system, outlines the basics of the ELE concept, and introduces the preliminary ELE-LEU reactor design for the FORD-class aircraft carrier. Section A.2 discusses potential performance differences between ELE-LEU fuel and the fuel with which NNPP has experience. Section A.3 addresses new reactor-analysis challenges posed by ELE-LEU fuel, relative to the challenges of existing fuel. Section A.4 discusses testing and qualification of ELE-LEU fuel, and Section A.5 addresses manufacturing challenges.

A.1 Introduction

A.1.1 Existing naval propulsion fuel

Today's naval propulsion reactors are pressurized-water reactors (PWRs) with the following characteristics:

- They use HEU with ~ 93-97% enrichment.

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DEPARTMENT OF ENERGY
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NRLFO:OC:19-014
5 June 2019

Steven Aftergood
Federation of American Scientists
1112 16th Street, NW, Suite 400
Washington, DC 20036

Dear Mr. Aftergood:

This constitutes a final response to the request for information that you submitted electronically to the United States Department of Energy (DOE) under the Freedom of Information Act (FOIA), 5 U.S.C. §552. Your request was filed with the DOE Headquarters FOIA Office and assigned tracking number HQ-2018-01262-F. It was then transferred to this office for response and assigned tracking number NRLFO-2018-01344-F.

You requested "a copy of a 2016 report entitled "Low-Enriched Uranium (LEU) for Potential Naval Nuclear Propulsion Application.""

You further noted that "[t]his report was prepared for DOE (sponsors: James Mosquera/Steve Bell by the JASON science advisory panel. It has the report number JSR-16-Task-013. I believe that DOE Naval Reactors must approve any distribution of the report. If this report is classified, we request that reasonably segregable unclassified portions be released. If an unclassified summary is available, that would be particularly helpful."

The Naval Reactors Laboratory Field Office (NRLFO) conducted a search for responsive information based upon your request. NRLFO also requested that its management and operating contractor (currently, Fluor Marine Propulsion, LLC) as custodian of certain NRLFO records, conduct a search. These searches located the document you requested, which in its unredacted form is classified Confidential.

In accordance with your request, the Naval Reactors Program has conducted a declassification review and/or segregability analysis on this document. A final response to your request is enclosed. The requested document has been reduced to the unclassified level through application of redactions in accordance with Exemptions 1 and/or 3 of the FOIA, as appropriate.

Exemption 1 of the FOIA provides that information authorized to be kept secret in the interest of national defense or foreign policy pursuant to criteria established by an

Executive Order and properly classified in accordance with such Executive Order is exempt from release under the FOIA. Any information in the enclosed documents that has been determined by an authorized classification official to constitute information requiring protection against unauthorized disclosure pursuant to an Executive Order is withheld from release.

Exemption 3 of the FOIA provides for withholding from release information "specifically exempted from disclosure by statute...provided that such statute (A) requires that the matters be withheld from the public in such a matter as to leave no discretion on the issue, or (B) establishes particular criteria for withholding or refers to particular types of matters to be withheld." Both the Atomic Energy Act of 1954, as amended (AEA), and Section 130 of 10 U.S.C. are Exemption 3 statutes. Sections 141-146 of the AEA, 42 U.S.C. §§ 2161-2166, prohibit the disclosure of information concerning atomic energy defense programs that is classified as Restricted Data.

In addition to containing classified information, this document in its unredacted form contains information related to Naval nuclear propulsion technology that is properly and currently identified as sensitive unclassified technical data called Naval Nuclear Propulsion Information (NNPI). Under 10 U.S.C. § 130 resides a prohibition against public disclosure of unclassified technical data with military application if such data may not lawfully be exported outside of the United States without approval, authorization, or license under Export Administration regulations. This requirement applies to NNPI since it is protected under regulations of the Bureau of Export Administration of the Department of Commerce (15 C.F.R. 744 et seq.) and the International Traffic in Arms Regulations of the Department of State (22 C.F.R. 120 et seq.). Information protected from release under exemption b(3) of the FOIA pursuant to the foregoing statutes is being withheld accordingly.

You have been categorized as representing a non-commercial scientific institution under the U.S. Department of Energy regulation implementing the FOIA, based upon the definition at 10 CFR 1004.2(k). Any fees applicable to the foregoing effort were to be addressed in accordance with 10 CFR 1004.9; responding to your request for information did not result in the application of fees.

The Deputy Director, Naval Nuclear Propulsion Program (Naval Reactors) is the denying official for Naval Nuclear Propulsion Information. This response may be appealed within 90 calendar days from your receipt of this letter pursuant to 10 C.F.R. § 1004.8. Appeals should be addressed to Director, Office of Hearings and Appeals, HG-1, L'Enfant Plaza, U.S. Department of Energy, 1000 Independence Avenue, S.W., Washington, D.C. 20585-1615. The written appeal, including the envelope, must clearly indicate that a FOIA appeal is being made. You may also submit your appeal to OHA.filings@hq.doe.gov, including the phrase "Freedom of Information Appeal" in the subject line. The appeal must contain all of the elements required by 10 C.F.R. § 1004.8, including a copy of the determination letter. Thereafter, judicial review will be available to you in the Federal District Court either:

1) in the district where you reside; 2) where you have your principal place of business; 3) where DOE's records are situated; or 4) in the District of Columbia.

You may contact DOE's FOIA Public Liaison, Alexander Morris, Acting Director, Office of Information Resources, at 202-586-5955, or by mail at MA-90/Forrestal Building 1000 Independence Avenue, S.W. Washington, D.C. 20585 for any further assistance and to discuss any aspect of your request. Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer. The contact information for OGIS is as follows: Office of Government Information Services, National Archives and Records Administration, 8601 Adelphi Road-OGIS, College Park, Maryland 20740-6001, e-mail at ogis@nara.gov; telephone at 202-741-5770; toll free at 1-877-684-6448; or facsimile at 202-741-5769.

I appreciate the opportunity to assist you with this matter. If you have any questions about this correspondence, please contact me at (412) 476-7202.

Sincerely,

C. P. Nunn

C. P. Nunn
FOIA Coordinator