Nonproliferation Fuels Development Activities Summary

Report to Congress
June 2022

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

Message from the Administrator

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) has responsibility for many of the Nation's nonproliferation missions worldwide and additionally for providing safe, long-lived and reliable naval nuclear propulsion systems to the U.S. Navy. To meet rigorous military operational requirements, U.S. naval nuclear reactors are fueled with High Enriched Uranium (HEU). In the interest of lowering proliferation risks, since 2018, a team of subject matter experts in civilian nuclear reactors operation, fuel fabrication, and modeling and simulation have conducted research and development exploring the feasibility of advanced Low Enriched Uranium (LEU) fuel systems to determine the likelihood of meeting the stringent requirements for the power output, compact size, and long-life the U.S. Navy requires.

I am pleased with the progress DOE/NNSA has made in this technically challenging effort. In fiscal year 2021, we reached a critical milestone of fuel specimen insertion into several irradiation platforms across the complex. These experiments will produce the first information evaluating novel fuel fabrication techniques as well as fuel performance characteristics.

Meeting U.S. Navy safety and operational requirements with LEU is a daunting task and success is far from certain. A 2016 report from the Director of Naval Reactors stated that it could take over $1 billion and 15 years for fuel development R&D. The same report suggests that even if successful, the propulsion system would be less capable, only applicable to aircraft carriers and require several billion dollars, in addition to fuel development costs, to deploy the supporting engineering, manufacturing and testing infrastructure. NNSA staff continue to assess the technical challenges, cognizant of previous analyses that showed that the use of LEU would negatively impact reactor endurance, reactor size, ship costs, and operational effectiveness.

Pursuant to congressional direction, this report is being provided to:

- **The Honorable Rosa L. DeLauro**
  Chair, House Committee on Appropriations
- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations
- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Adam Smith**
  Chairman, House Committee on Armed Services
- **The Honorable Mike Rogers**
  Ranking Member, House Committee on Armed Services

- **The Honorable Jim Cooper**
  Chairman, Subcommittee on Strategic Forces
  House Committee on Armed Services
- **The Honorable Doug Lamborn**
  Ranking Member, Subcommittee on Strategic Forces
  House Committee on Armed Services
- **The Honorable Patrick Leahy**
  Chairman, Senate Committee on Appropriations
- **The Honorable Richard Shelby**
  Vice Chairman, Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
  Chair, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable Jack Reed**
  Chairman, Senate Committee on Armed Services
- **The Honorable Jim Inhofe**
  Ranking Member, Senate Committee on Armed Services
- **The Honorable Angus King**
  Chairman, Subcommittee on Strategic Forces
  Senate Committee on Armed Services
- **The Honorable Deb Fischer**
  Ranking Member, Subcommittee on Strategic Forces
  Senate Committee on Armed Services

If you have any questions or need additional information, please contact Dr. Benn Tannenbaum, Associate Administrator for Congressional and Intergovernmental Affairs, at (202) 586-7332, or Ms. Katie Donley, Deputy Director for External Coordination, Office of the Chief Financial Officer, at (202) 586-0176.

Sincerely,

Jill Hruby
Under Secretary for Nuclear Security
Administrator, NNSA

Executive Summary

The Nonproliferation Fuels Development effort within the Department of Energy's National Nuclear Security Administration (DOE/NNSA) aims to develop an advanced nuclear fuel system that uses high-assay low-enriched uranium (HALEU)[1]. A high-density HALEU fuel could result in long-life, load-following compact power reactors with potential applications in marine propulsion, off-grid energy supply, and transportable power systems. Sponsoring research and development (R&D) of HALEU fuels for such applications could reduce the use of weapons grade high-enriched uranium (HEU)[2] and further U.S. Government nonproliferation goals. However, the funding to conduct such R&D would likely come at the cost of other nonproliferation efforts that would have greater effects on threat reduction and advancement of U.S. Government nonproliferation goals.

The technical approach for this assessment involves an integrated combination of fuel fabrication studies, irradiation testing, and computational modeling and simulation (M&S). A joint National Laboratory team composed of staff from Idaho National Laboratory, Oak Ridge National Laboratory, and Argonne National Laboratory executed R&D in the three aforementioned areas in fiscal year (FY) 2021. The FY 2021 R&D highlights include:

- Completion of six experimental campaigns exploring the feasibility of ultrasonic additive manufacturing technology for high density fuel fabrication.
- High-fidelity examination of fabricated fuel specimens for structural and chemical characterization.
- Final design, risk assessment, and insertion of four irradiations campaigns in research reactors across DOE/NNSA.
- M&S assessments to enable fuel screening, fuel performance assessments, and designs of future experimental campaigns.

The effort also executed a R&D independent review in FY 2021 in collaboration with the Office of Naval Reactors. The independent review technical feedback highlighted the positive experimental attributes of the project and motivated a new series of targeted modeling and simulation approaches and experiments, to be executed in FY 2022, that could expedite the screening of candidate fuel concepts.

[1] Uranium enriched to 19.75 percent or less in fissile uranium-235 (^{235}U)
[2] Uranium enriched to greater than 90 percent in fissile ^{235}U

Nonproliferation Fuels Development Research and Development Summary

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I. Legislative Language

This report responds to a congressional request set forth in the Joint Explanatory Statement to accompany the *National Defense Authorization Act for Fiscal Year 2022* (P.L. 117-81) (FY 2022 NDAA):

> *We direct the Administrator for Nuclear Security, not later than 60 days after the date of enactment of this Act, to submit to the congressional defense committees a report on activities conducted using amounts made available for fiscal year 2021 for development of an advanced naval nuclear fuel system based on low-enriched uranium, including a description of any progress made toward technological or nonproliferation goals as a result of such activities.*

II. Introduction

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) initiated a congressionally-mandated effort in 2018 to assess the feasibility of using high assay low enriched uranium (HALEU) fuel for long-life, load-following[3] compact reactors. The ultimate objective of this effort is to identify high-density nuclear fuel systems that could be used in naval propulsion, off-grid energy supply, and transportable power systems; thus, providing an alternative to the use of weapons grade highly enriched uranium (HEU) in naval nuclear propulsion and helping address U.S. Government nonproliferation goals. Three national laboratories comprise the team: Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and Idaho National Laboratory (INL), which is designated as the lead laboratory.

In collaboration with the DOE's Office of Nuclear Energy and DOE/NNSA's Office of Naval Reactors, the participating laboratories selected a set of power and performance criteria to guide an aggressive experimental campaign. Compact, high-burnup (high fuel utilization) systems operating with HALEU are technologically challenging as they require very high uranium density to deliver reliable power outputs and must have precise fuel integrity properties to retain fission products and limit radiation exposure risks.[4]

Accepted fuel development and qualification practices normally require decades of extensive irradiation testing and post-irradiation examination (PIE) to ensure safe reactor operations. DNN R&D's research and development effort is pursuing approaches to accelerate the

[3] Load following describes a change in power level based on changing power demands. For example, a navy ship could be cruising at low speed and transition to combat speeds in little time when the situation requires it.
[4] Precise fuel integrity properties refer to the integrity of the fuel element, meaning that zero percent of the highly lethal fission products can migrate out of the fuel system and interact with the reactor coolant.

feasibility assessments of candidate fuel systems, including use of modeling and simulation (M&S), to advance the technology readiness maturation more quickly. In FY 2021, research and development (R&D) activities centered on irradiation experiments and fuel fabrication and characterization campaigns to investigate the structural integrity of plausible fuel concepts and assess performance characteristics.

III. Research and Development Fiscal Year 2021 Objectives

In previous years, the Nonproliferation Fuels Development (NFD) effort (1) performed a technical survey to identify candidate fuel systems for investigation; (2) prepared an experiment plan to investigate feasibility of candidate fuel systems based on demanding performance criteria; and (3) initiated R&D activities pursuant to the experiment plan. In FY 2021, the effort sponsored the following activities:

- Candidate fuels sample fabrication using ultrasonic additive manufacturing (UAM) and other novel fuel fabrication techniques;
- Preliminary characterization of the structural integrity and chemical properties of fabricated fuel samples;
- Completion of experimental designs, safety analysis and campaign plans prior to reactor insertion activities;
- Insertion of test capsules into irradiation platforms: the High-Flux Isotope Reactor (HFIR), the Advanced Test Reactor (ATR), and the Transient Reactor Test Facility (TREAT); and
- Investigation of novel R&D approaches that could accelerate a theoretical reactor development timeline, currently estimated to be a 20-to-25-year effort, or remove uncertainties.

These FY 2021 objectives enabled systematic examination, testing, and analysis of select fuel materials that can lead to one or more fuel systems achieving Technical Readiness Level 3 (TRL3) sooner than projected.

IV. Description of DNN R&D Executed Activities

Fuel Fabrication and Material Characterization

To address the desired performance requirements, the candidate fuel systems must have a higher density of uranium fuel than a typical light water reactor (LWR) fuel system. Fabrication studies on fuel systems that might enable very high uranium densities are essential to explore and understand how the properties of the final fuel form are influenced by the fabrication process.

In FY 2021, the effort executed six fuel fabrication campaigns. Work centered on synthesis of high-density fuel forms, optimization of fabrication parameters and improved fuel performance properties (e.g., fission product retention), and exploring fuel packing techniques that could result in higher burnups. A total of 80 specimens[5] were produced for characterization. Specimens of UAM-fabricated materials were subjected to mechanical property testing and used to complete broad investigations into corrosion behavior and performance under high-temperature steam conditions. Fabricated samples were also characterized using the X-ray capabilities of the Advanced Photon Source (APS) at ANL to better understand the role of texture and potential fabrication defects on fuel deformation. Figure 1 illustrates a UAM specimen geometry that was used for pre-irradiation characterization.

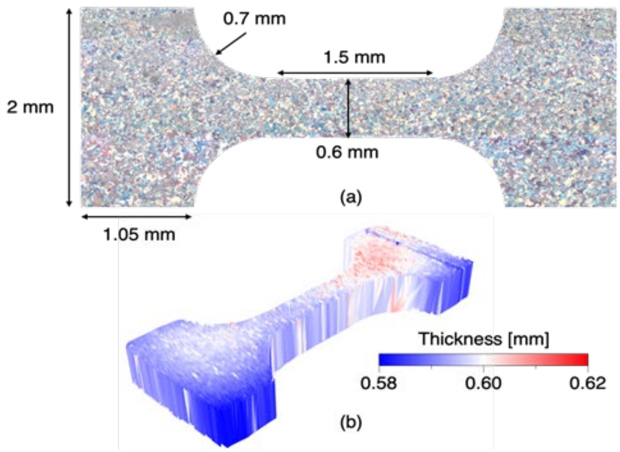

Figure 1: Representative specimen (left) produced with the Ultrasonic Additive Manufacturing equipment shown on the right.

High temperature steam oxidation tests performed on UAM-fabricated specimens showed a higher accumulation of oxygen than observed with traditional fabrication methods, a sign of inadequate material bonding that may lead to fuel failure during reactor operations. The degradation mode likely responsible for the inferior performance is selective interlayer oxidation in the UAM specimen as observed via a scanning electron microscope image.

Significant quantities of high purity uranium-bearing fuels of various types and sizes were also fabricated. These fabrication campaigns provided consistent samples for experimental activities to evaluate fuel performance during irradiation. There was some preliminary success in producing high uranium density specimens that exhibited desired pre-irradiation characteristics; however, more experimental data is needed to develop statistical confidence.

[5] A specimen is composed of multiple experiments collocated in a single vessel. Sometimes the specimen has fuel forms, when assessing fuel characteristics, or materials, when assessing structural integrity.

Irradiation Experiments

Irradiation of test specimens and the subsequent PIE is the most difficult step in the development of a new reactor fuel system. The effort achieved a significant milestone in FY 2021 with the insertion of four neutron irradiation experiment campaigns into research reactors at ORNL (HFIR) and INL (ATR and TREAT). The four irradiation experiments include a variety of materials that will provide over 160 experiments for PIE. The ATR and HFIR experiments are independent, but both are specifically designed to accelerate irradiation effects and gather data for temperature ranges of 300-500°C, a temperature range with minimal test and evaluation data and essential to load following scenarios.

The first irradiation campaign in the ATR was completed in April 2021 and the test capsules were shipped to the Hot Fuel Examination Laboratory at INL where disassembly and initial PIE was completed. These irradiation experiments were designed and executed using a novel approach that enabled the fuel specimens to achieve desired burnups (uranium fuel utilization) with less time in the reactor than typically needed. The complete PIE results – planned for FY 2022 – will provide information on fuel behavior (e.g., fuel swelling and fission gas retention). These PIE results will also provide the opportunity for comparing the veracity of the novel approach for accelerated burnup with traditional irradiation test approaches. Other fuel system specimens were inserted in the HFIR to allow PIE for a range of fuels at different operational parameters. The specimens with the lowest burnup were retrieved from HFIR in September 2021 and the remaining specimens were removed in April 2022. The PIE performed on this series of specimens will provide fuel performance characteristics as a function of increasing burnup exposure. These first experiments of UAM-fabricated specimens will serve as an initial screening on whether UAM plate material will retain acceptable mechanical properties during irradiation.

A series of increasingly aggressive transient tests (abnormal operational conditions) in TREAT, that were completed in July 2021, enabled a preliminary comparison of fuel deformation results between multiple uranium-bearing fuels under rapid transient conditions. Ion irradiation experiments were performed with the Argonne Tandem Linac Accelerator System to provide structural integrity characterization data for various fuel system materials as well as initial data on fuel performance (fission product retention[6]) for comparison to neutron irradiation conditions. In this experimental campaign, high-energy ions replicate fission fragment damage to gain insights into structural displacements at material interfaces, isolate separate effects, and measure gas accumulation and morphology at prototypic temperature and high dose. Ion irradiations also offer an expedient technique for experiment-based screening of fuel material concepts.

[6] Fission product retention prevents the lighter atomic nuclei, formed by the splitting of heavier atomic nuclei during nuclear reactions, from interacting with the reactor coolant.

The testing of candidate fuel systems and materials across the initial range of temperature and irradiation conditions explored in FY 2021 will provide fundamental data that could be used to guide further experiments.

Computational Modeling and Simulation

The M&S work included both fuel specific as well as comparative studies, which provided insights into how various candidate fuel systems might perform relative to one another. Examples of M&S activities include:

1) The TREAT fuel transient experiment discussed above was initially investigated with a simulation to evaluate specific aspects of transient behavior for multiple fuel system designs. These predictions, while applicable for a narrow set, will be compared to the conditions and configuration results of specimens from the TREAT experiments.
2) Screening analyses were performed to provide preliminary comparative results on fuel performance and potential benefits that might be realized from various fuel system concepts.
3) A fuel performance code methodology was developed for evaluation of failure mechanisms given a fuel system design. The M&S results provided preliminary insights into how a HALEU fuel geometry (e.g., arrangement and configuration) can impact behavior during irradiation.
4) Preliminary M&S of theoretical reactor systems were performed to investigate how fuel concepts compare in meeting the demanding performance requirements. These studies can serve as a screening tool to help identify potential deficiencies in a concept.

V. Preliminary Lessons Learned

The experimental and computational work performed in FY 2021 provided early insights into specific challenges that would have to be addressed for several candidate fuels. Novel approaches and processes for improved execution of the multi-faceted R&D activities have also been developed. Examples of these preliminary lessons-learned are:

1) Select fabrication approaches have shown potential for achieving the high uranium densities anticipated for the HALEU fuel concepts.
2) UAM can reduce fabrication uncertainty in the fuel fabrication process; however, process parameter adjustments are needed to reduce the high oxidation rates observed in the product material.
3) Ion irradiation may provide an expedient avenue for initial evaluation and screening of fuel material relative to select phenomena that occurs during neutron irradiation.
4) The design and fabrication methodology of millimeter sized portions of fuel systems in a small capsule enclosure allows PIE investigations on the underlying micro-scale phenomena that might impact macro-scale performance of the fuel system.

VI. Budget Execution

The COVID-19 pandemic initially limited fabrication and experimental campaigns execution through 2020, but the participating laboratories were successful in reaching the critical sample insertion experimental milestone in FY 2021, and the FY 2021 costing rate increased to be nearly consistent with the appropriation. The table shows that of the $50 million appropriated for the Nonproliferation Fuels Development program since 2018, the program had costed $18.8 million by the end of FY 2020 ($11.2 million in carryover) and increased this to $37.1 million by the end of FY 2021 ($12.9 million in carryover).

	Prior Years Enacted	2021 Carryover	2021 Enacted	2021 Costed	2022 Carryover
Nonproliferation Fuels Development	$30,000,000	$11,210,110	$20,000,000	$18,301,301	$12,908,809

The FY 2022 carryover will support the post-irradiation examination of active experiments in addition to the execution of delayed fabrication and experimental campaigns.

VII. Conclusion

In FY 2021, the effort transitioned from a planning phase into an iterative experimental campaign phase; the preliminary findings represent early progress towards what is estimated to be a 20-to-25-year reactor fuel system design effort that would cost over $1 billion and detract from higher-priority nonproliferation and naval propulsion R&D activities. The lessons learned suggest that the planned activities could lead to a HALEU fuel feasibility assessment. However, extensive test and evaluation would be necessary at additional cost before any feasible fuel could be selected for long-term fuel qualification studies. In addition, completed experimental and computational studies could help answer technical questions related to development of HALEU fuel systems for the demanding performance requirements of long-life, load-following compact power reactors.

The R&D roadmap for this effort is technically challenging and, despite efforts to accelerate the feasibility assessments, it will take significant time and fiscal resources to identify a HALEU candidate fuel capable of long-life and load following operations in a compact reactor. A 2016 report from the Director of Naval Reactors stated that it could take over $1 billion and 15 years for fuel development R&D. The same report suggests that even if successful, the propulsion system would be less capable, only applicable to aircraft carriers and require several billion dollars, in addition to fuel development costs, to deploy the supporting engineering, manufacturing and testing infrastructure. The analysis showed that the use of LEU would negatively impact reactor endurance, reactor size, ship costs and operational effectiveness. The 2021 DNN R&D activities represent a significant milestone in the effort’s progress. However, these initial activities are the first steps on a long, costly path to fuel development and success is not assured.

SEWD Response
Current FY 2023 Summary
LEU for Naval Reactors R&D

Execution Summary

DNN R&D received $90 million in total appropriations (FY 2018 – FY 2023) for research and development (R&D) on low-enriched uranium (LEU) fuels for naval applications.

The table below shows DNN R&D funding and costing by appropriation year, as of 28 February 2023, which have occurred under DNN R&D's Nonproliferation Fuels Development (NFD) control point. It shows that 81 percent of prior-year funding has been costed and that none of the current-year appropriation has yet been costed. The joint NFD national laboratory team (Oak Ridge, Argonne, and Idaho) received full FY 2023 funding within the last month and should begin showing FY 2023 costs in the next reporting cycle.

Nonproliferation Fuels Development	**Enacted**	**Costed to Date**	**Uncosted to Date**
FY 2018	5,000,000	5,000,000	0
FY 2019	10,000,000	9,999,830	170
FY 2020	15,000,000	15,000,000	0
FY 2021	20,000,000	20,000,000	0
FY 2022	20,000,000	6,582,735	13,417,265
FY 2023	20,000,000	0	20,000,000
Total	**90,000,000**	**56,582,565**	**33,417,435**

The NFD effort includes performing hundreds of (relatively inexpensive) irradiation experiments on a wide range of candidate fuel samples (including varying material types, geometries, and enrichment levels) to understand and compare characteristics and performance before narrowing this field to the most promising materials for more in-depth (and more expensive) analysis. Performing these experiments has required capital improvements and equipment purchases in each fiscal year. The technical approach involves an integrated combination of fuel fabrication studies, irradiation testing, and computational modeling and simulation (M&S). Delays in costing have been driven by the inability to conduct in-person irradiation experiments during COVID restrictions and long-lead procurements. To date, DNN has conducted over 250 irradiation experiments, and another 350 experiments are in process or planned.

Due to the nature of the required expertise, nearly all the NFD laboratory staff at ANL, INL, and ORNL would be otherwise supported by DOE/Nuclear Energy. There are a small number of NFD laboratory staff who had historically received funding for reactor conversion efforts from within DNN's Material Management and Minimization program.

Activity Summary

FY 2020

- Capital procurements to build dedicated capabilities needed for iterative experimentation on fuel concepts with novel features that could enable required performance in LEU fuels
  - Uranium Atomizer at INL: Enable variable uranium concentrations within plate fuels

  - ATLAS Material Irradiation Station (AMIS) at ANL: Dedicated station to irradiate fuel samples
  - Ultrasonic Additive Manufacture (UAM) at ORNL: First-ever application to reactor fuels for building novel fuel designs (world's first use of Zirconium with additive manufacturing)
  - Various other equipment procurements
- M&S to determine performance of known fuel core geometries in smaller reactors
- Preliminary studies to understand how changes in reactor size and operating conditions would affect neutron flux and thermal conductivity, and therefore, safety and performance of fuel cores.

FY 2021

- Completion of six experimental campaigns exploring the feasibility of UAM for high-density fuel fabrication.
- High-fidelity examination of fabricated fuel specimens for structural and chemical characterization.
- Final design, risk assessment, and insertion of four irradiations campaigns in research reactors across DOE/NNSA.
- M&S assessments to enable fuel screening, fuel performance assessments, and designs of future experimental campaigns.
- Iterative experiments and M&S using variety of fuel types, geometries (e.g. monolithic vs. plate), and enrichment levels to determine candidate types and designs for further research
- Other experiments:
  - Initiated coated fuel characterization at ATLAS;
  - Completed installation of uranium atomizer at INL to support advanced manufacturing of high-density fuels with high purity, consistent coatings, and consistent particle size distribution — attributes that could enable higher energy outputs per unit volume
  - Conducted HFIR irradiations to impart neutron damage on structural materials
  - Conducted TREAT reactor transient-conditions test
  - Performed ATR irradiations for U-10Mo, U-7Mo, and U-Nb-Zr alloys
  - Conducted APS characterization experiments of both fresh and irradiated materials
  - Assessed gas accumulation and fuel swelling and expand experimental throughput at the ATLAS.

FY 2022

- Equipment procurements and upgrades at INL, ANL, and ORNL to build dedicated experimental capabilities focused on fuel fabrication, testing, and characterization
- Following an independent review at the end of FY21, replanned the experiment campaign for obtaining basic fuel-performance data for advanced ceramics that were identified as strong potential candidates for high assay, low-enriched, uranium-based fuel replacements.
  - Designed new irradiation experiments for UC and UN fuels, and to measure in-core thermal conductivity of UN, UC, and U-10Mo fuels.
  - Completed fabrication studies of uranium monocarbide (UC) and uranium mononitride (UN) fuel particles
  - Determined how to reduce surface roughness and decrease the porosity in UCN kernel fabrication processing

  - Conducted ATLAS irradiations on a UCN compact and initial U-xMo fuel sample
  - Completed HFIR irradiations for UMo fuel systems over a range of burn-ups
  - Completed a test irradiation and analyzed specimen for fuel cracking stability in layered UO2
  - Developed an Ultrasonic Additive Manufacturing (UAM) processes for fabrication of Zirconium (Zr) plate fuel concepts
  - Performed a second round of Advanced Photon Source (APS) testing on UAM-fabricated Zr
  - New experiment fabrications were completed in FY22 for measuring fuel to melt phenomena and onset phase change, which will be irradiated in FY23.

FY 2023

- Continue with another 300-plus iterative experiments and M&S using a variety of fuel types, geometries, and enrichment levels, especially focused on advanced uranium ceramic fuels, such as Uranium Nitride and Uranium Carbide, and continue to refine candidate technologies for further research.
- Perform realistic modeling of potential fuels and reactor performance using newly procured and approved (for operations) classified computer cluster at ANL.