DEVELOPMENT, QUALIFICATION, AND LICENSING OF ADVANCED NUCLEAR FUEL CONCEPTS

A Report for the
U.S. Senate Committee on Environment and Public Works and the
U.S. House of Representatives Committee on Energy and Commerce

U.S. Nuclear Regulatory Commission
July 2026

Enclosure

Table of Contents

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) developed this report as required by Section 404 of the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024 (ADVANCE Act) (Ref. 1). Specifically, Section 404(c) of the ADVANCE Act requires the NRC to "submit to the appropriate committees of Congress a report describing the efforts of the Commission under subsection (a)." Section 404(a) provides direction to "establish an initiative to enhance preparedness and coordination with respect to the qualification and licensing of advanced nuclear fuel."

Implementing the ADVANCE Act is a key priority for the agency, and the NRC is continuing to work to enhance efficiency in all processes, including its licensing and environmental reviews. In developing this report, the NRC considered actions it has taken to address the topics specified in Section 404. The report highlights the NRC's completed or ongoing actions, as well as potential future actions to implement Section 404.

The NRC values public input and feedback on its implementation of the ADVANCE Act. As part of its efforts to respond to Section 404 of the ADVANCE Act, the NRC engaged with the Department of Energy (DOE), national laboratories, the nuclear energy industry, technology developers, nongovernmental organizations, and other public stakeholders.

NRC INITIATIVES TO ENHANCE PREPAREDNESS AND COORDINATION WITH RESPECT TO THE QUALIFICATION AND LICENSING OF ADVANCED NUCLEAR FUEL

The NRC is prepared to review and qualify advanced nuclear fuel for use, including both advanced fuel concepts for light-water reactors (LWRs), such as accident tolerant fuel, and fuel for advanced non-light water reactors (non-LWRs). This is a result of the agency's ongoing commitment to regulatory modernization, technical readiness, and effective stakeholder engagement. As the nuclear industry continues to develop and propose novel fuel types, the NRC is ensuring that its regulatory framework and licensing approaches can efficiently accommodate a variety of advanced fuel concepts, and that its independent technical review of advanced fuels is grounded in sound science.

The NRC's Accident Tolerant Fuels (ATF) program exemplifies the agency's ability to adapt its independent regulatory oversight to evolving industry initiatives. Since its inception, the ATF program has progressed from evaluating novel fuel and cladding for light-water reactors—developed collaboratively by industry and the DOE—to addressing broader issues such as increased enrichment and higher burnup. This experience demonstrates that effective coordination with federal partners can enhance technical readiness and regulatory efficiency, while the NRC's safety and licensing decisions remain independent and aligned with its public health and safety mission. This balanced approach enables the NRC to uphold its independent safety mission while fostering the timely and effective qualification of advanced fuel technologies, consistent with the goals of the ADVANCE Act.

Historically, the NRC's regulatory framework focused on LWRs using low-enriched uranium (LEU) fuel. The NRC's recent issuance of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 53, "Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," represents a major milestone in enabling the timely deployment of advanced nuclear fuels. Part 53's technology-neutral structure avoids fuel-specific constraints embedded in older regulations, such as provisions tied to particular cladding materials or effective limits on enrichment, thereby removing historical barriers for advanced fuel designs.

To support applicants in demonstrating conformance with NRC regulations and to provide NRC staff with a robust and safety-focused review approach, the NRC developed a fuel qualification assessment framework documented in NUREG-2246, "Fuel Qualification for Advanced Reactors - Final" (Agencywide Documents Access and Management System Accession No. ML22063A131). Licensees and applicants have successfully used NUREG-2246 for both established and advanced fuel concepts.

To further improve efficiency and responsiveness, the NRC has revised and streamlined its licensing processes for advanced fuels for both new and operating reactors. This includes compressing review schedules to align with updated performance metrics, increasing the use of integrated review approaches such as core teams, modernizing internal procedures to reduce redundancy, and integrating artificial intelligence tools to support document analysis, knowledge management, and workload prioritization. These improvements have enabled the agency to manage a growing and increasingly diverse set of advanced fuel-related activities while maintaining its focus on safety and regulatory rigor. Table 1, attached to this report, highlights several actions of particular relevance to the agency's readiness efforts.

The NRC has also strengthened its technical capabilities to support the review of advanced fuel concepts. The ATF project plan outlined NRC's strategy to ensure preparedness for the licensing and regulation of new fuel technologies and provided the framework for the agency to coordinate inter-office efforts, supported by a formal working group and steering committee. These groups are comprised of staff and management with expertise in advanced nuclear fuels and draw on experience across program offices to ensure comprehensive technical coverage. As the NRC also considers long term plans for organizational change to become more efficient and effective, the core membership of these groups will be maintained to provide continuity of its mission.

To further bolster the NRC's technical expertise for emerging fuel designs, the agency has participated in research collaborations and technical exchanges with DOE, national laboratories, international organizations (including non-governmental organizations and other countries' nuclear regulatory organizations), and other stakeholders. These efforts have informed updates to internal guidance and review methodologies, ensuring that the NRC is prepared to evaluate diverse advanced fuel types, including High-Assay Low-Enriched Uranium (HALEU), Tri-structural Isotropic (TRISO) particle fuel, and ceramic cladding materials.

In addition, the NRC continues to coordinate closely with external partners to support early engagement and knowledge sharing. The agency has ongoing consultations and standing meetings with DOE, the national laboratories, and industry to maintain awareness of emerging technical needs and regulatory challenges. The NRC meets quarterly with DOE and industry through the ATF Working Group, where participants share updates on priorities, exchange progress on key initiatives, and identify areas requiring additional regulatory clarity. The agency also holds biweekly consultations with industry, through the Nuclear Energy Institute (NEI), to discuss licensing related activities and coordinate workshops and other public meetings. Collectively, these consultations continue to be instrumental in supporting the safe and timely development of advanced nuclear fuel technologies.

Finally, the NRC is actively engaging in lessons-learned activities from completed and ongoing licensing and certification efforts related to advanced fuel concepts. This includes work on ATF, the development and qualification of HALEU feedstock, and the broader category of advanced fuels beyond HALEU. The NRC has completed significant licensing actions with respect to increased enrichment (IE) of feed material in the HALEU range (greater than 5 weight-percent [wt%] but less than 20 wt% U-235), transportation licensing of uranium hexafluoride (UF6) in the HALEU range, transportation of ATF concepts with enhanced cladding and HALEU fuel, transportation of TRISO fuel, and licensing of TRISO fuel fabrication for fuel in the HALEU range. This experience will directly translate to licensing capabilities including increased efficiency for the medium- to long-term fuel concepts that have not yet been qualified for use.

Together, these efforts demonstrate the NRC's readiness to support the evolving needs of the nuclear industry. By focusing on modernization, technical depth, and strategic coordination, the agency is well-positioned to evaluate and license a wide range of advanced fuel concepts in alignment with the goals of the ADVANCE Act.

ASSESSMENT OF PREPAREDNESS FOR ADVANCED NUCLEAR FUEL

NRC's preparedness to review and qualify advanced nuclear fuel for use is demonstrated through numerous successful licensing and qualification efforts. While technology-specific illustrative examples are provided below, collectively, the NRC staff has reviewed and approved 15 topical reports (TRs) supporting qualification of ATF and advanced fuels and is tracking 8 more TRs for completion in the near term. TRs are industry-submitted technical documents that address specific safety-related subjects for NRC review. Through the Topical Report Program, NRC staff conduct an independent, upfront evaluation of TRs and develop a Safety Evaluation for reference in future licensing actions. This approach also increases licensing efficiencies by minimizing repeated reviews of the same technical topic for both applicants and NRC staff.

Since the passage of the ADVANCE Act, staff have provided feedback to advanced reactor applicants and pre-applicants through six white papers related to fuel qualification. White papers contain information submitted to the NRC on a technical, programmatic, regulatory, or administrative topic and, unlike TRs, do not require a safety evaluation review. The staff continue to engage with pre-applicants and applicants to provide clarity on how the NRC's technology-inclusive and performance-based fuel qualification assessment framework can be applied to proposed novel fuel concepts.

(i) Accident Tolerant Fuel

ATFs are designed to enhance the safety and performance of nuclear fuel under both normal operating conditions and accident scenarios and include technology concepts like IE and Higher Burnup (HBU). These fuel concepts typically incorporate advanced cladding materials and modified fuel compositions like coated zirconium alloy cladding or doped uranium dioxide, respectively. The NRC has been actively engaged in the evaluation and regulatory consideration of ATF since the early stages of its development, recognizing its potential to improve fuel integrity and reduce the likelihood of core damage during beyond-design-basis events.

Since the development of the ATF Project Plan in 2018, the NRC has reviewed and approved 15 TRs related to ATF and advanced fuels in operating reactors. The agency has conducted extensive pre-application engagement with fuel vendors and utilities to support the safe and timely deployment of ATF technologies.

In parallel, the NRC participated in collaborative research efforts with the DOE, national laboratories, and international regulatory bodies to evaluate ATF performance characteristics and ensure that regulatory considerations are addressed. In addition, to streamline environmental reviews for ATF licensing and minimize the need for complex site-specific evaluations for each license amendment request, NUREG-2266, "Environmental Evaluation of Accident Tolerant Fuels with Increased Enrichment and Higher Burnup Levels" (ML24207A210), assessed the reasonably foreseeable environmental impacts of near-term ATF technologies—specifically those involving IE and HBU—on the uranium fuel cycle, transportation of fuel and waste, and decommissioning for LWRs. These and other efforts have informed the development of interim staff guidance (ISG) and updates to existing review frameworks to accommodate the unique attributes of ATF designs. For example, the NRC issued an ISG for chromium-coated cladding in ATF-ISG-2020-01, “Supplemental Guidance Regarding the Chromium-Coated Zirconium Alloy Fuel Cladding Accident Tolerant Fuel Concept” (ML19343A121), which helped expedite and form the safety basis for multiple pertinent TRs and license amendment requests submitted by the industry.

The NRC sponsored Pacific Northwest National Laboratory (PNNL) to conduct a phenomena identification and ranking table (PIRT) exercise to assess ATF concepts for spent fuel storage and transportation. PIRTs are structured processes used to systematically identify and rank physical phenomena affecting fuel safety, performance, and integrity. It helps prioritize areas for further investigation or mitigation. As part of this effort, PNNL completed a state-of-knowledge literature review in October 2024 (ML24292A170), focusing on ATF designs including high burnup and high enrichment fuels. Following the literature review, PNNL conducted the formal PIRT exercise, and the NRC published the final technical report (NUREG/CR-7310) in June 2025 (ML25174A009). The report evaluated ATF concepts such as Cr-coated zirconium alloy cladding, iron-chromium-aluminum (FeCrAl) cladding, and high burnup/enrichment fuels. The overall conclusion of the report indicates that the NRC framework is applicable to ATF concepts. In addition, the data provided by applicants in alignment with the frameworks established in existing ISGs and standard review plans reduces the need for expanded independent evaluations and increases licensing efficiency.

In accordance with the ATF project plan developed in collaboration with the nuclear industry, the NRC has already licensed the transportation and utilization of lead test assemblies (LTAs) at individual plants for the purpose of obtaining incore data for analysis by the nuclear industry and national laboratories. The data gathered from LTA programs have been leveraged in industry’s safety case made in ATF TR submittals. The NRC has approved TRs for doped fuel pellet technologies for each of the major LWR fuel vendors and has subsequently approved batch loading of doped pellets. As of June 2026, the NRC is reviewing the first TR for a Cr-coated cladding design on an accelerated schedule using the previously mentioned ISG.

Regarding HBU, the NRC sponsored a PIRT panel public meeting in 2024 to examine HBU uranium dioxide fuel fragmentation, relocation, and dispersal (FFRD) during design-basis accident conditions, as well as the potential consequences of fuel dispersal. The resulting PIRT enhanced the agency’s knowledge base on the behavior of HBU fuel and the associated safety considerations. The final PIRT results were published in 2024 in NUREG/CR-7307, “Phenomena Identification and Ranking Tables on High Burnup Fuel Fragmentation, Relocation, Dispersal, and Its Consequences for Design-Basis Accidents in Pressurized- and Boiling-Water Reactors” (ML24155A058). In addition, the PIRT rankings have since supported targeted research to address open questions related to FFRD and its impacts. For example, the PIRT findings informed the development of Draft Regulatory Guide (DG) 1434, "Addressing the Consequences of Fuel Dispersal in Light-Water Reactor Loss-of-Coolant Accidents" (ML24320A013) providing guidance for evaluating consequences of FFRD during loss of coolant accident events. The PIRT results have also enabled more efficient NRC reviews of industry topical reports.

Separately, the NRC has approved several TRs that facilitate operation to HBU in support of extended fuel cycles, including Framatome’s HBU TR, Electric Power Research Institute’s (EPRI’s) Alternate Licensing Strategy TR, and Westinghouse’s Incremental Burnup TR. These approvals reflect, in part, the NRC’s broader and evolving understanding of HBU fuel behavior, as informed by research and related activities such as the FFRD PIRT described above.

The NRC has demonstrated the ability to efficiently review ATF, HBU, and IE fuels and is prepared to make final safety determinations regarding license applications and amendment requests for ATF, HBU, and IE to support longer fuel cycles and power uprates. Industry timelines indicate these submittals will continue to be made throughout the latter 2020s and into the 2030s.

Additionally, with respect to increased enrichment, fuel fabrication and transportation, the NRC has demonstrated licensing readiness by approval of four transportation packages with ATF payloads and issuance of license amendments for two separate fuel facilities to fabricate fuels up to 6.5 wt% enrichment and 8 wt% enrichment, respectively.

(ii) Ceramic Cladding Materials

Ceramic cladding materials, particularly silicon carbide (SiC) composites, are being developed as advanced alternatives to traditional zirconium-based cladding in nuclear fuel assemblies. These materials offer several advantages, including high-temperature strength, excellent corrosion resistance, and low neutron absorption, making them attractive for both ATF applications in LWRs and for use in advanced reactor designs. Ceramic cladding exhibits fundamentally different mechanical and thermal behaviors from conventional metallic cladding, which present unique regulatory considerations.

The NRC has engaged in pre-application discussions with fuel vendors and reactor developers exploring SiC-based systems (e.g., ML23032A477 and ML25182A364) and maintains awareness of experimental data from applicable DOE-supported test programs. These activities, coupled with NRC staff foundational expertise in materials science and fuel performance modeling, contribute to the agency's readiness to assess SiC-specific key safety and performance issues (e.g., fracture mechanics, irradiation effects, and thermal conductivity under both steady-state and transient conditions) using NRC's established technology-inclusive fuel qualification framework.

The NRC is prepared to make final safety determinations for applications using ceramic-cladded fuels, and ongoing research and development activities continue to enhance the technical basis supporting their use. Key areas of focus include clarifying brittle failure modes, evaluating the impacts of complex fabrication processes, and refining analytical tools and testing protocols. The NRC continues to monitor ongoing development efforts to maintain its expertise on the distinct behaviors and safety implications of ceramic cladding technologies and to engage with programs generating data needed to reduce key uncertainties.

(iii) Fuels Containing Silicon Carbide (TRISO Fuels)

Outside of ceramic-clad fuel, other fuel forms containing a SiC layer are most notably represented by TRISO particle fuel, a robust fuel form designed for use in high-temperature gas-cooled reactors (HTGRs) and other advanced reactor concepts. Each TRISO particle consists of a uranium-based fuel kernel surrounded by multiple protective layers, including a dense SiC layer that serves as a miniature containment barrier. This SiC layer plays a critical role in retaining fission products and maintaining structural integrity under extreme conditions, including high temperatures and irradiation.

The NRC actively engaged in the evaluation of TRISO fuel through pre-application activities and technical exchanges with developers of advanced non-LWRs, including HTGRs and microreactors. The agency has reviewed experimental data from DOE-supported irradiation and post-irradiation examination campaigns and has participated in collaborative efforts with national laboratories to understand TRISO fuel behavior under both normal and accident conditions. These efforts have informed the development of analytical tools and safety evaluation methods tailored to particle fuel systems.

The NRC considers itself well-prepared to review and qualify TRISO fuel as demonstrated through several successful reviews and approvals. For example, the staff reviewed and approved, with conditions and limitations, a TR by EPRI, EPRI-AR-1(NP)-A, "Uranium Oxycarbide (UCO) TRISO-Coated Particle Fuel Performance," which documents a performance demonstration of UCO TRISO-coated fuel particles that are anticipated for use in both helium-cooled and molten salt-cooled high temperature reactors (ML20336A052). A related joint report by the NRC and Canadian Nuclear Safety Commission on TRISO fuel qualification was published in June 2023 (ML23172A242). These activities were leveraged in the review of Kairos Power LLC (Kairos) TRISO-based fuel qualification methodology (ML23048A326) and fuel performance methodology (ML21256A221) TRs. Kairos successfully referenced these, and other related TRs, in its construction permit application for the Hermes and Hermes 2 test reactors. The construction permits were issued by the NRC in 2023 and 2024 (ML23338A258; ML24324A021 and ML24324A022, respectively). The NRC also approved an X-Energy TRISO fuel qualification TR in 2023 (ML23160A294) and related mechanistic source term TR in 2025 (ML25262A107). The NRC's review of the latter TR, with further comments from the Advisory Committee on Reactor Safeguards (ML25204A121), highlighted areas where additional data could provide a more mechanistic understanding of fuel performance and reduce uncertainties, as discussed in Section 5 of this report.

The NRC continues to expand its understanding of TRISO fuel performance through ongoing interactions with DOE, national laboratories, and advanced reactor stakeholders. These engagements provide opportunities to incorporate emerging operational insights and updated performance information into the agency's regulatory approach. Through this coordination, the NRC helps ensure the regulatory framework remains fully capable of enabling the safe and effective deployment of TRISO-based fuel systems.

The NRC is prepared to license TRISO fabrication and transportation and is currently reviewing a license amendment for a facility seeking authorization to produce TRISO fuels enriched up to 10 wt% U-235. The NRC has recently approved another fuel facility to produce TRISO fuel enriched to less than 20 wt%. In addition, the NRC has approved TRISO contents in two transportation packages.

(iv) High-assay, Low-enriched Uranium Fuels

High-assay, low-enriched uranium fuels are enriched to levels above the traditional commercial range of 3–5 wt% U-235, but below the 20 wt% threshold of highly enriched uranium. HALEU is a critical enabling fuel for many advanced reactor designs, offering benefits such as longer core lifetimes, improved neutron economy, and more compact reactor geometries. Several near-term advanced reactor developers have identified HALEU as essential to their deployment strategies. The LWR industry has identified HALEU as essential to achieve higher fuel burnups and extended cycle lengths. The NRC has taken proactive steps and is prepared for the licensing and regulation of HALEU fuels. This includes ongoing pre-application engagement with developers proposing HALEU-fueled designs, as well as coordination with the DOE and fuel cycle stakeholders. In support of this effort, the NRC initiated a rulemaking titled, "Modernizing Reactor Licensing, Safety Oversight, and Siting Practices" that, among other things, would revise NRC regulations to facilitate the commercial use of uranium enriched above 5 wt% U-235, which provides guidance, enhances clarity, and reduces the need for exemptions. This rulemaking is intended to modernize the regulatory framework and remove barriers to the safe and secure use of HALEU in civilian applications. More information on the scope of this rulemaking and the estimated publication schedule can be found at the NRC's public website for Planned Rulemaking Activities. In parallel, the agency is developing Regulatory Guide 1.183, Revision 2 (currently DG-1425), which updates guidance for alternate source term analysis and supports the use of higher enriched fuel.

HALEU is used in all the advanced non-LWRs for which the NRC has issued construction permits, including Kairos Hermes 1 and Hermes 2, Abilene Christian University's Molten Salt Research Reactor (ML24243A040), and Kemmerer Unit 1 (ML26034B247). Additionally, the NRC has approved lead test assemblies for HALEU fuel in LWRs and has reviewed and approved at least one TR from each of the major LWR fuel vendors related to HALEU fuel, demonstrating the capability of the NRC to license HALEU fuel.

The NRC has approved amendments to the licenses of two enrichment facilities allowing them to produce HALEU enriched to 10 wt% and 20 wt% U-235; in addition, the NRC has approved a new transportation package for UF6 up to 20 wt% enrichment. The rulemaking referred to above adds flexibility to the regulatory framework for transport of HALEU.

(v) Molten Salt Based Liquid Fuels

Molten salt based liquid fuels are a fundamentally different class of nuclear fuel in which fissile material is dissolved directly into a circulating molten salt mixture, rather than being fabricated into solid fuel rods or pellets. These fuels are typically associated with molten salt reactors (MSRs), which may operate at high temperatures and low pressures, and offer potential advantages in terms of passive safety, fuel utilization, and waste minimization. Because the fuel is in liquid form, it also serves as the reactor's coolant, creating a tightly coupled relationship between fuel behavior and thermal-hydraulic performance.

Early NRC experience with molten salt fuels dates back to experimental programs such as the Molten Salt Reactor Experiment at Oak Ridge National Laboratory (ORNL). In recent years, the NRC has gained experience with this technology through pre-application discussions with advanced reactor developers and participation in DOE-led research initiatives. These engagements inform vendor strategies and research and development efforts to ensure the unique technical attributes of liquid fuel systems (e.g., real-time fuel chemistry monitoring, online reprocessing, and the dynamic nature of fission product transport within the reactor system) support NRC licensing.

The NRC staff are applying their expertise in reactor physics, materials behavior, and radiological safety to address the unique considerations introduced by molten-salt-based fuel systems. This work includes evaluating how fuel-salt properties, corrosion and containment performance, and safeguards approaches for systems with online processing are reflected within the agency's fuel qualification framework. Technical considerations associated with molten-salt fuels, along with the supporting analytical basis, are described in NUREG/CR-7299, "Fuel Qualification for Molten Salt Reactors" (ML22339A161).

(vi) Fuels Derived from Spent Nuclear Fuel or Depleted Uranium

Fuels derived from spent nuclear fuel or depleted uranium represent a class of advanced fuel concepts aimed at improving resource utilization and reducing the long-term radiotoxicity of nuclear waste. These fuels may involve the chemical reprocessing of used fuel to recover fissile materials, or the use of depleted uranium as material in fast-spectrum reactors. Such approaches are often associated with closed fuel cycles, fast reactors, or advanced recycling technologies.

The NRC has limited direct licensing experience with these fuel types in the context of commercial power reactors, as the U.S. has historically pursued an open fuel cycle (spent nuclear fuel is not reprocessed, but rather treated as waste directly after being used in a reactor). However, the agency has regulatory expertise in the oversight of spent fuel storage, transportation, and reprocessing activities, providing a strong foundation for effectively reviewing and qualifying for use, fuels from spent fuel or depleted uranium. In recent years, the NRC has engaged in early discussions with developers of fast reactors and fuel cycle facilities that may utilize recycled or reprocessed fuel forms, including metallic fuels, mixed-oxide (MOX) fuels, and uranium-transuranic composites.

Leveraging its foundational knowledge in fuel behavior and radiological safety, the NRC is poised to address unique aspects of fuels derived from spent nuclear fuel or depleted uranium, such as fuel fabrication, isotopic composition, safeguards, and waste management. The NRC continues to monitor domestic and international developments in advanced fuel cycles and is evaluating the regulatory implications of potential future applications involving recycled or reprocessed fuels.

(vii) Other Related Fuel Concepts, as Determined by the Commission

The NRC has seen significant interest in metallic fuels, particularly for sodium-cooled fast reactors (SFRs). In SFR applications, metallic fuel concepts typically use a uranium-zirconium or uranium-plutonium-zirconium alloy in steel cladding. Metallic fuel provides several beneficial characteristics for SFRs, including high thermal conductivity (and corresponding low fuel temperature), high chemical compatibility with sodium, and ability to achieve very high burnup. Advanced metallic fuel concepts for SFRs include unalloyed uranium fuel and actinide-bearing fuel, which may provide further advantages in fuel performance and improve fast reactors' capability to disposition nuclear waste, respectively. Another important metallic fuel application is the monolithic uranium-molybdenum alloy fuel with aluminum cladding under development by the DOE and National Nuclear Security Administration (NNSA) for the U.S. High Performance Research Reactor (USHPRR) project, which is needed to support research reactor conversion to LEU fuel.

The NRC is well-prepared to license metallic fuels and has successfully completed several activities involving this technology over the last several years. Through these efforts, the NRC has drawn on the substantial body of research and operating experience with metallic fuels, developed primarily through fuel operated by the DOE and the National Laboratories at the Experimental Breeder Reactor II (EBR-II) and Fast Flux Test Facility (FFTF).

The NRC contracted with Idaho National Laboratory (INL) to use this operating experience data to develop an example metallic fuel qualification report, resulting in NUREG/CR-7305, "Metal Fuel Qualification: Fuel Assessment Using NRC NUREG-2246, 'Fuel Qualification for Advanced Reactors'" (ML23214A065), which was released in August 2023. Similar to NUREG/CR-7299 for MSRs, NUREG/CR-7305 addresses metal fuel-specific technology aspects that help focus the applicant and reviewer on technology attributes most important to safety and was leveraged by the NRC staff in its review of TerraPower's TR NAT-2806-A, "Fuel and Control Assembly Qualification" (ML25083A296), which was referenced in the Kemmerer Unit 1 construction permit application. The NRC continues to engage on fuel qualification TRs and white papers with other SFR pre-applicants.

ACTIVITIES UNDERTAKEN RELATED TO THE MEMORANDUM OF UNDERSTANDING WITH THE DEPARTMENT OF ENERGY

(i) Knowledge Sharing

The NRC staff regularly attend meetings sponsored by DOE's Advanced Fuels Campaign (AFC), including the AFC Annual Review Meetings held in November/December and the AFC Metal Fuel Workshops held in May. These meetings offer an opportunity for NRC staff to obtain the latest technical information on advanced nuclear fuel behavior under normal operating conditions and accident conditions. The meetings also allow NRC staff to build contacts among technical experts at the national laboratories that can be leveraged when conducting new fuel reviews. Under the memorandum of understanding (MOU), interagency database sharing has expanded to formally include advanced reactor data in addition to the previous ATF-related data. Several staff have also been assigned temporary duties at DOE programs to assist with high priority projects and facilitate direct knowledge sharing.

The MOU serves to enhance the partnership between the NRC and DOE and shorten the timeline from conceptual models to approved technologies.

(ii) Facility Sharing

Both the NRC and the DOE are participants in the Organization for Economic Co-operation and Development Nuclear Energy Agency's Second Framework for Irradiation Experiments (FIDES-II), which includes several joint experimental projects related to advanced nuclear fuel behavior. INL acts as the operating agent for three of these projects related to advanced fuels. Under the terms of the NRC-DOE MOU, NRC participates as a core group member of these joint projects, which allows the NRC to influence the work performed as part of the program in order to address outstanding questions related to advanced nuclear fuel safety. These projects are providing data on advanced fuel behavior under new conditions (e.g., HBU, different power levels, different TRISO fuel kernel composition), which will reduce uncertainties and allow the NRC to license these fuel types more efficiently.

The NRC has also benefited from new capabilities developed at the Severe Accident Test Station facility at ORNL. ORNL has performed experiments to better understand the behavior of ATFs under simulated loss-of-coolant accident conditions and has shared those findings with the NRC staff. These experiments provide data to reduce uncertainties and more efficiently license ATF.

AREAS OF NEEDED RESEARCH RELATED TO ADVANCED NUCLEAR FUEL

Significant progress has been made in updating and evaluating the NRC's safety computer codes used for licensing across the nuclear fuel cycle. In fiscal year (FY) 2021, the NRC outlined its readiness strategy for licensing non-LWRs. From FY 2021 through FY 2025, the NRC hosted a series of public demonstration workshops highlighting enhancements to these safety codes and their application to various non-LWR technologies, including SFRs, HTGRs, fluoride-salt-cooled high-temperature reactors, MSRs, heat pipe reactors, and microreactors. These safety code development and demonstration activities allowed NRC staff to gain experience with relevant non-LWR phenomena, which in turn accelerated licensing activities like the Hermes-1 and Natrium construction permit reviews. The results of this research are publicly available on the NRC's Nuclear Power Reactor Source Term website and have helped to identify areas where additional data would facilitate more efficient licensing reviews. In addition, NRC frequently discusses knowledge gaps and data needs with DOE, national laboratories, and industry through venues like AFC and EPRI's Collaborative Research for Advanced Fuel Technologies (CRAFT) program. Addressing these research needs will allow for more efficient licensing activities and removal of limitations and conditions that may be applied to account for large uncertainties.

(i) Accident Tolerant Fuel

Additional research is needed to expand the data available for near-term ATF concepts, including doped fuel, coated cladding, and high burnup fuel under accident conditions. While existing data may be adequate for licensing, additional information would reduce uncertainties, which could otherwise lead to limitations and conditions in regulatory approvals. These needs are being addressed through INL-led FIDES-II projects, in which the NRC is a core group member. Ongoing research to understand ceramic cladding behavior under both normal and accident conditions is aligned with the expected licensing timelines for these materials. In addition, the AFC is supporting the vendors developing ceramic cladding systems, ensuring that the necessary technical challenges are addressed so vendors can ultimately build a robust safety case.

Key issues include cladding hermiticity, cladding wastage during normal operations, and establishing failure limits under various operating and accident scenarios. These efforts are being pursued through the AFC.

(ii) TRISO Fuel

Extensive data is available on TRISO fuel with UCO kernels from DOE's Advanced Gas Reactor program. Nevertheless, further data would support use of this fuel type under variations in kernel or particle layer dimensions, kernel composition, or operating conditions and enhance the understanding of the underlying mechanisms. These needs are being addressed through the Accelerated Testing of Materials in Capsules (ATOMIC) project under FIDES-II and the AFC program. Because existing tests have focused on TRISO particles embedded in a graphitic matrix; additional research would also be beneficial to evaluate the behavior of alternative matrix materials, such as SiC. The ATOMIC project includes several irradiation campaigns that provide valuable data on new fuel designs, helping improve understanding of fuel performance and associated phenomena, which in turn supports staff readiness to assess safety performance, review applicant fuel qualification information, and evaluate analytical models and source-term assumptions for advanced reactor licensing.

(iii) HALEU Fuel

Research needs for HALEU-based fuel cycles include nuclear data and criticality benchmarking data. While numerous thermal, intermediate, mixed, and fast experiments are available for validation, data gaps remain for systems with different fuel forms, such as TRISO particle compacts, uranium metal, and uranium salts. Additionally, no critical experiments exist for irradiated HALEU fuel, which is essential for validating spent fuel storage and transportation applications. The DOE/NRC Criticality Safety for Commercial-scale High Assay Low-Enriched Uranium for Fuel Cycle and Transportation (DNCSH) program aims to address these gaps. Initiated in FY 2023 and scheduled for completion by FY 2028, DNCSH aims to produce high-quality, publicly available benchmark experiments, nuclear data, and evaluations tailored to HALEU systems where current data is insufficient. This effort leverages NRC/DOE collaboration under a MOU, enabling shared access to technical expertise and infrastructure at U.S. national laboratories.

Additional research is currently underway to produce high quality radiochemical assay (RCA) data for high burnup pressurized water reactor and boiling water reactor fuels, as well as advanced fuel concepts such as ATF and HALEU-based fuels supporting advanced nuclear technologies. Generating this data will reduce key uncertainties in burnup credit evaluations and in decay heat and shielding analyses. These improvements will directly enhance the efficiency and robustness of regulatory reviews under 10 CFR Parts 71 and 72 for the back end of the fuel cycle, enabling more predictable and well-supported licensing decisions.

(iv) Molten Salt Fuel

The foundational data on molten salt fuels is based on experience at ORNL. Additional opportunities for research on the thermophysical and corrosion properties of irradiated fluoride-based and chloride-based fuel salts during normal operations and accident conditions over the operating range of interest to the vendors would support the development of evaluation methodologies.

(v) Fuels Derived from Spent Nuclear Fuel

While there is data on uranium-plutonium-zirconium alloy fuel from EBR-II and FFTF that would support development of fuels derived from spent nuclear fuel, areas of research that will enhance the safety case include fuel swelling, fuel-cladding chemical interactions, and transient performance. Significant work was conducted more than a decade ago on MOX fuel for LWRs; revisiting and supplementing this research will be essential given renewed interest in MOX utilization for LWR applications. While most fast reactor pre-applicants interacting with the NRC have expressed interest in metallic fuel, there is extensive operating experience with MOX fuel in fast reactors from France and Japan, with some domestic experience, that may be leveraged to support future applications.

(vi) Other Related Fuel Concepts, as Determined by the Commission

Significant data exists on sodium-bonded uranium-zirconium alloy fuel in steel cladding under normal operating conditions, primarily from the EBR-II and the FFTF. This data was used to develop empirical relationships that are used to model metallic fuel performance in NRC, National Laboratory, and industry codes. While data supports a strong safety basis for fuel performance within a specified parameter and operating envelope (e.g., fuel or cladding dimensions, geometry, composition, operating conditions), additional data would enhance the safety basis when conditions significantly deviate from this envelope. Research and development that improves the understanding of the underlying mechanisms of certain fuel behaviors would also further reduce uncertainties and enhance the safety basis. These data and research needs are being addressed through the ATOMIC project under FIDES-II and the AFC program. Additional research to characterize fuel behavior under transient conditions, and substantially more data would be needed for other metal fuel concepts, such as uranium-molybdenum alloys, to categorize fuel performance or determine safe operating envelopes.

OTHER CHALLENGES OR CONSIDERATIONS

As discussed above, the NRC is well-positioned to make final safety determinations on a variety of advanced fuel applications and has demonstrated this through the development and use of a robust technology-inclusive and performance-based fuel qualification assessment framework. Additional test data, research, and development would improve mechanistic understanding of phenomena, expand existing performance envelopes, reduce uncertainties, and enhance the safety basis for advanced fuels, enabling more efficient fuel qualification reviews and preparation for reviewing the next generation of advanced fuels.

As highlighted by the ADVANCE Act, NRC's access to DOE facilities and its experts in modeling and simulation are critical to ensure the NRC effectively engages with research, development, demonstration, and commercial application of advanced nuclear fuels by the civilian nuclear industry. As many advanced fuel concepts require specialized facilities for irradiation, analysis, and validation, cooperation between DOE, the national labs, international peers, industry fuel vendors and reactor developers are essential to enabling access to the data and expertise needed to safely deploy advanced fuels. NRC's continued coordination with DOE and other advanced fuels stakeholders will not only enhance in-house technical expertise, but provide enhanced visibility and understanding of available data sets and initiatives.

While there are areas of active research for the back end of the fuel cycle, available data on the characterization of waste forms may be a limiting factor in the near term with respect to understanding potential technical issues. NRC has identified the RCAs and criticality benchmarks as areas needing continued attention with respect to preparedness for efficient technical reviews. Further, other technical considerations such as decay heat profiles considering both short- and long-term time scales, short-term and long-term material degradation, gas generation, sodium bonded fuel interactions, etc. may benefit from additional research to assist with licensing storage casks and certifying transportation packages containing irradiated fuel and other contents.

Some advanced fuel types introduce novel safeguards and security considerations, particularly those involving higher enrichment levels or on-site fuel reprocessing. These may require updated regulatory approaches or coordination with other federal agencies and international bodies to ensure compliance with nonproliferation obligations.

The NRC will continue to monitor these and other emerging issues as part of its ongoing efforts to support the safe and timely deployment of advanced nuclear fuel technologies.

CONCLUSION

The NRC is prepared to license, and qualify for use, a wide range of advanced nuclear fuel concepts and has taken meaningful steps to enhance this preparedness, consistent with Section 404 of the ADVANCE Act. Through a combination of technical engagement, regulatory and process modernization, and strategic coordination with the DOE and other stakeholders, the agency has positioned itself to support the safe and timely deployment of innovative fuel technologies.

The assessments presented in this report reflect the NRC's current understanding of its capabilities and challenges across ATF and several advanced fuel types, including ceramic cladding materials, TRISO particle fuel, HALEU, molten salt based liquid fuels, and fuels derived from spent nuclear fuel or depleted uranium. Continued progress will depend on access to high quality data, sustained interagency collaboration, and the ability to adapt regulatory frameworks to address novel fuel behaviors and associated safety considerations.

The NRC remains committed to ensuring that its licensing processes are safety-focused, efficient, transparent, and grounded in sound science. As the nuclear industry continues to evolve, the agency will continue to engage with stakeholders and refine its regulatory approach to support the safe use of advanced nuclear fuels in the public interest.

ACRONYMS

10 CFR	Title 10 of the *Code of Federal Regulations*
ADVANCE Act	Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024
AFC	Advanced Fuels Campaign
AI	Artificial Intelligence
ATF	accident tolerant fuel
ATOMIC	Accelerated Testing of Materials in Capsules
DNCSH	DOE/NRC Criticality Safety for Commercial-scale High Assay Low-Enriched Uranium for Fuel Cycle and Transportation
DOE	Department of Energy
EBR-II	Experimental Breeder Reactor II
EPRI	Electric Power Research Institute
FFRD	fuel fragmentation, relocation, and dispersal
FFTF	Fast Flux Test Facility
FIDES-II	Second Framework for Irradiation Experiments
FY	fiscal year
FQTR	fuel qualification topical report
HALEU	high assay low enrichment uranium
HBU	higher burnup
HTGR	high-temperature gas-cooled reactor
IE	increased enrichment
INL	Idaho National Laboratory
ISG	interim staff guidance
JEEP	Joint Experimental Project
LTA	lead test assembly
LWR	light water reactor
MOU	memorandum of understanding
MOX	mixed oxide
MSR	molten salt reactor
NEI	Nuclear Energy Institute
Non-LWR	non-light water reactor
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PIRT	phenomena identification and ranking table
PNNL	Pacific Northwest National Laboratory
RCA	radiochemical assay
SFR	sodium-cooled fast reactors
SiC	silicon carbide
TR	Topical report
TRISO	tri-structural isotropic
UCO	uranium oxycarbide
UF6	uranium hexafluoride
wt%	weight-percent

REFERENCE

1. Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024, Pub. L. No. 118-67, div. B, § 506, 138 Stat. 1447, 2024.

ATTACHMENT

SUMMARY OF ACTIONS RELATED TO THE ACCELERATING DEPLOYMENT OF VERSATILE, ADVANCED NUCLEAR FOR CLEAN ENERGY ACT OF 2024 (ADVANCE ACT) SECTION 404(c)

Actions described in this attachment include implemented, ongoing, and potential new actions related to Section 404(c) of the ADVANCE Act and Executive Order 14300, “Ordering the Reform of the Nuclear Regulatory Commission” (90 FR 22587; May 29, 2025). This table is not exhaustive but highlights actions of particular relevance to this report.

The table provides the status and timeframes for each of the actions. Actions noted as “completed” have been fully implemented by the U.S. Nuclear Regulatory Commission (NRC) and the benefits are being realized for ongoing licensing reviews. Actions listed as “In progress” or “Ongoing” are in the process of being implemented by the NRC or are continuous respectively, with any periodicities noted.

Table 1 – NRC Program Actions Related to ADVANCE Act Section 404

Action	Impact	Status
Enter a MOU with the Secretary of Energy to share technical expertise and knowledge.	Expands NRC and DOE collaborative research activities to include advanced fuels, building on the established ATF framework, and previous MOU.	Completed
Establish an internal Advanced Fuels working group and steering committee.	Provides centralized resource management and guidance to implement directives specified in the ADVANCE Act and Executive Order 14300.	Completed
Revise advanced fuel qualification and licensing review schedules and resource allocation.	Review timelines reduced by up to half in certain cases with more accurate resource estimates.	Completed
Hold a series of public demonstration workshops highlighting enhancements to safety codes and applications to advanced reactors.	Demonstrated improved modeling capabilities and safety analysis tools, increasing stakeholder confidence in NRC's readiness to review advanced reactor designs.	Completed
Hold a series of workshops to discuss topics related to FFRD associated with advanced fuel types.	Discussed technical topics of mutual interest to the NRC and industry that will inform future guidance for advanced fuel employment.	Completed
Develop a rulemaking to clarify and regulate the use of IE and HBU fuels.	Streamlines the regulatory process for employing certain advanced fuels in commercial reactors.	In progress
Hold a series of tabletop exercises to discuss the licensing pathway for future power uprates for commercial reactors.	Simulated the complete license amendment submittal and review for two pilot commercial reactors to identify any obstacles prior to real world application in the near future.	Ongoing
Hold periodic engagements with industry stakeholders.	Regular engagements with vendors, utilities, and trade groups ensure that the NRC remains appraised of industry needs to best allocate agency resources.	Ongoing, weekly
Hold periodic engagements with the DOE.	Maintains mutual interagency awareness of NRC and DOE activities, allowing for improved allocation of resources and support as necessary.	Ongoing, quarterly
Continue participation in the AFC program review meetings.	Supports coordinated research and testing activities that accelerate qualification of advanced fuel concepts, reducing duplication of effort and improving technical basis for licensing decisions.	Ongoing, annually