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Advanced Fuels Campaign Execution Plan

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Idaho National Laboratory

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EXECUTIVE SUMMARY

The Advanced Fuels Campaign (AFC) Execution Plan outlines the strategy, mission, scope, near-term and long-term goals, structure, and organization associated with nuclear fuels and materials research, development, and demonstration activities within the Department of Energy's (DOE) Nuclear Fuel Cycle and Supply Chain (NFCSC) program. NFCSC has been given responsibility to identify and mature advanced fuel technologies for the DOE using a science-based approach, focused on developing a fundamental understanding of nuclear fuels and materials to drive development of integrated nuclear fuel and materials technology. This science-based approach combines theory, experiments, and multiscale modeling and simulation to achieve a predictive understanding of relevant behaviors ranging from fuel fabrication processes (and their resulting fuel microstructures) through fuel/cladding performance under irradiation (in contrast to more empirical, observation-based approaches frequently used in fuel performance modeling and fuel qualification).

The traditional scope of AFC includes the evaluation and development of multiple fuel forms to support two fuel cycle options: once-through and full recycle. The word "fuel" is used generically to include conventional fuels, transmutation targets, and any associated cladding or duct materials. The once-through fuel cycle addresses advanced light water reactor fuels with enhanced performance, extended burnup, and reduced waste generation. In fiscal year (FY) 2012, AFC's scope expanded to include research, development, and demonstration (RD&D) for light water reactor (LWR) fuels with enhanced accident tolerance.

Fuel fabrication activities include the development of innovative methods to enhance process efficiencies, reduce waste, and improve control over as-fabricated fuel microstructural properties to achieve desired in-reactor performance. Using modern modeling and simulation approaches, the objective is to predict fresh fuel properties given the feedstock characteristics and fabrication process parameters. The performance-related activities include small-scale, in-reactor, and out-of-reactor phenomenological testing (distinct from, but synergistic with, integral prototypic testing) and extensive, quantitative characterization (focusing on characterization of fuel and cladding materials at the scale of microstructure) both before and after testing. Larger-scale, prototypic experiments are conducted in concert with phenomenological testing to drive a Fuel Development and Qualification program, incorporating a fundamental understanding of fuel behavior performance characteristics. Then, using the tools developed under the productive science-based approach, fuels will be optimized to meet specific performance requirements, thereby minimizing the need to repeatedly perform large-scale, integral experiments over a wide parametric range as a means of experimental exploration.

Two significant initiatives are underway within AFC. First, a gap analysis completed in early FY 2019 identified critical irradiation testing needs that are lacking within the national light water reactor (LWR) fuels testbed since the shutdown of the Halden Reactor in 2018. The identified gaps are for instrumented, prototypic testing of LWR fuels, especially under boiling water reactor conditions, ramp conditions, and conditions leading to fuel failure; these needs exist for supporting current LWR fuels and their possible extension to higher burnups, but are especially urgent relative to near-term development and qualification of accident-tolerant fuels. Recommendations that resulted from the Halden Gap Analysis focused on enhancements at Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT) to fill gaps in testing capabilities relative to these needs. Second, a concerted effort to develop and demonstrate a systematic approach to accelerating the development, testing, and qualification of new fuel systems has been initiated. This is highlighted by a test strategy that combines the considerable advances in multiscale, mechanistic fuel modeling of recent years with a MiniFuel separate effects test program in the High Flux Isotope Reactor (HFIR) and a Fission Accelerated Steady-state Testing (FAST) semi-integral accelerated test program in ATR. This approach is being tested/demonstrated using the metallic fuel system, but if successful it is expected to be extensible to multiple fuel types and diverse applications.

This document includes an overview of the NFCSC program, a definition of science-based development of nuclear fuels, near-term goals for Advanced LWR fuels (ALFs), and longer-term goals for Advanced Reactor Fuels (ARFs) RD&D. This includes the activities that will be conducted to achieve success toward the grand challenge, as well as the goals and milestones to be achieved over the next few decades of research and development.

The grand challenge for AFC is to develop and demonstrate transformational technologies in support of the U.S. nuclear industry in the form of high-performance, high-reliability nuclear fuel systems for both current and future reactors.

Long-term goals are based on the DOE Office of Nuclear Energy (DOE-NE) Roadmap[1]. This document spans multiple decades to achieve demonstration and qualification of advanced fuel forms to support the different fuel-cycle options. The near-term goals for enhanced accident-tolerant fuels (ATFs) for LWRs are included in this execution plan. A major challenge is to achieve the near-term goals associated with ATF while maintaining steady progress toward longer-term goals associated with the advanced reactor mission. Another major challenge is to identify opportunities to accelerate the traditional fuel qualification process to meet ATF objectives. A detailed set of 5-year goals was developed, which are consistent with the overall science-based fuel development approach. The 5-year scope is summarized as follows:

- Support the near-term development of Advanced LWR fuels technologies with improved performance, enhanced accident tolerance, and extension to higher burnups, with implementation of batch reloads of one or more ATF concepts in commercial reactor(s) as early as the mid-2020s. This will include enabling burnup extension to >75 GWd/MTU.

- Perform innovative research and development on longer-term advanced reactor technologies, having applications to both once-through and recycle scenarios, with a view to maturing the technology readiness level (TRL) of new fuel concepts of interest to industry to the point of entering a formal fuel qualification program.

- Continue the development and demonstration of the “science-based” approach, with state-of-the-art research and development infrastructure, needed to accelerate the development and qualification of new fuel concepts.

- Collaborate on the development of predictive, multiscale, multiphysics fuel performance models, and codes as well as development of advanced instrumentation needed to collect in-situ data to assess and validate those tests.

The 5-year milestones in the AFC Execution Plan are based on an assumed budget. This execution plan will be updated annually, and the milestones adjusted to reflect actual funding profiles as budget guidance is made available.

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ACRONYMS

AFC	Advanced Fuels Campaign
AFDQ	accelerated fuel development and qualification
AFQ	accelerated fuel qualification
ALF	advanced LWR fuel
ARDP	Advanced Reactor Demonstration Program
ARF	advanced reactor fuel
ARES	Advanced Reactor Experiments for Sodium
ART	Advanced Reactor Technologies
ASI	Advanced Sensors and Instrumentation
ATF	accident-tolerant fuel
ATR	Advanced Test Reactor
BU	Burn up
BWR	Boiling Water Reactor
CDE	Critical decision equivalent
CRADA	Cooperative research and development agreement
CRAFT	Collaborative Research on Advanced Fuel Technology
DOE	Department of Energy
EBR	Experimental Breeder Reactor
EPRI	Electric Power Research Institute
FAST	Fission Accelerated Steady-state Testing
FCCI	fuel-cladding chemical interaction
FCMI	fuel-cladding mechanical interaction
FCRD	Fuel Cycle Research and Development
FFRD	Fuel fragmentation, relocation, and dispersal
FFTF	Fast Flux Test Facility
FGR	fission gas release
FIDES	Framework for Irradiation Experiments
FOA	funding opportunity announcement
FPT TEG	Fuel Performance and Testing Experts Group
FY	fiscal year
GAIN	Gateway for Accelerated Innovation in Nuclear
GFR	gas-cooled fast reactor
HBu	High burnup
HBWR	Halden Boiling Water Reactor
HERA	High-burnup Experiments in Reactivity-initiated Accidents
HFEF	Hot Fuel Examination Facility
HFIR	High Flux Isotope Reactor
IMCL	Irradiated Materials Characterization Laboratory
INL	Idaho National Laboratory
ITEG	Irradiation Testing Expert Group
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Center
LFA	lead fuel assembly
LFR	lead-cooled fast reactor
LIFT	Leading Innovation for Fuel Technologies
LOCA	loss-of-coolant accident
LTA	Lead Test Assembly
LTR	Lead Test Rod
LWR	light water reactor

LWRS	Light Water Reactor Sustainability (program)
MARCH	Minimal Activation Retrievable Capsule Holder
M&S	modeling and simulation
MITR	Massachusetts Institute of Technology Reactor
MOU	Memorandum of Understanding
MOX	mixed oxide fuels
NDE	nondestructive examination
NE	Office of Nuclear Energy
NEA	Nuclear Energy Agency
NEAMS	Nuclear Energy Advanced Modeling and Simulation (program)
NEET	Nuclear Energy Enabling Technology
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NFCSC	Nuclear Fuel Cycle and Supply Chain
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NSRR	Nuclear Safety Research Reactor
NTD	national technical director
NTRD	Nuclear Technology Research and Development (program)
ODS	oxide dispersion strengthened
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PMC	Power Cooling Mismatch
PWR	Pressurized Water Reactor
QPIRT	Quantitative Phenomena Identification and Ranking Table
R&D	research and development
RD&D	research, development, and demonstration
RIA	reactivity-insertion accident
SAFDL	Specified and Accepted Fuel Design Limits
SATS	Severe Accident Testing Station
SCWR	super-critical water-cooled reactor
SERTTA	Static Environment Rodlet Transient Test Apparatus
SFR	sodium fast reactor
SMR	small modular reactor
SPP	strategic partnership project
TESB	TREAT Experiment Support Building
TREAT	Transient Reactor Test Facility
TRISO	tri-structural isotropic
TRL	Technology Readiness Level
TSRA	Technology and System Readiness Assessment
UC	uranium carbide
UN	uranium nitride
VHTR	very high temperature reactor
VTR	Versatile Test Reactor

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Advanced Fuels Campaign Execution Plan

1. INTRODUCTION

The Advanced Fuels Campaign (AFC) Execution Plan provides a summary level description of how the Advanced Fuels Research, Development, and Demonstration (RD&D) program supports achievement of the overarching Department of Energy (DOE) Office of Nuclear Energy (NE) mission and program objectives. This execution plan is guided by the Nuclear Energy Research and Development Roadmap[1] and the implementation plans for the research and development (R&D) Objectives[2,3,4] defined within the roadmap. It is a living document that is updated annually.

1.1 Nuclear Energy RD&D Roadmap

To achieve energy security and greenhouse-gas emission-reduction objectives, the United States (U.S.) must develop and deploy clean and affordable domestic energy sources as quickly as possible. Nuclear power will continue to be a key component of a portfolio of technologies that meets our energy goals. Therefore, DOE-NE developed a roadmap of its RD&D activities that will ensure nuclear energy remains a compelling and viable energy option for the United States.[1]

DOE-NE organized RD&D activities according to four objectives to address the challenges of expanding the use of nuclear power (Figure 1):

1. Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
2. Develop improvements in the affordability of the new reactors to enable nuclear energy to help meet the Administration's energy-security and climate-change goals.
3. Develop sustainable nuclear fuel cycles.
4. Understand and minimize the risks of nuclear proliferation and terrorism.

Advanced Fuel RD&D crosscuts all R&D objectives, as discussed below:

Objective 1: Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors. Extending the lifetime of the existing reactor fleet does not require the development of advanced fuels. However, increasing the efficiency of the existing fleet in the future will require advanced fuels that can sustain higher power densities and achieve higher burnups. Accident-tolerant fuel (ATF) scope supports this objective.

Objective 2: Develop improvements in the affordability of the new reactors to enable nuclear energy to help meet the Administration's energy-security and climate-change goals. High- burnup (HBu), high-performance fuels will be required to support the full economic benefit of next- generation nuclear plants. These new fuels will maximize the use of natural resources and minimize nuclear waste. FAST reactors, with emphasis on the sodium-cooled FAST reactor and high- temperature reactors aimed at process-heat applications, require special types of fuels. For small modular reactors, special fuel development needs will be identified in the future; however, no specific fuel development activities currently exist under the small modular reactors R&D program. All DOE nuclear fuel RD&D is within the AFC scope.

Objective 3: Develop sustainable nuclear fuel cycles. A variety of advanced fuels are being considered in support of the two fuel-cycle options. This will be covered in more detail in Section 3.

Objective 4: Understand and minimize the risks of nuclear proliferation and terrorism.

Technologies that reduce the risk of proliferation may impact advanced fuel development; for instance, (a) the fuel composition may be affected by the type of separations or fuel-treatment technologies used in various fuel cycles, and (b) materials accounting restrictions and implementation of advanced safeguards technologies may affect the fabrication process and plant designs.

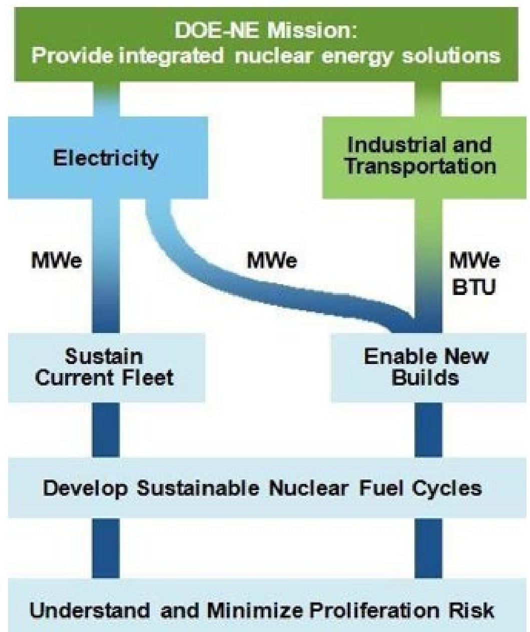

Figure 1. Four objectives for nuclear energy research, development, and demonstration.

1.2 Science-based Approach

Fuel development and qualification is a lengthy and expensive process. The traditional empirical approach to fuel development is not amenable to conducting research on multiple fuel forms and types with very aggressive performance objectives. (Refer to Appendix A for additional information on fuel qualification.) In addition, limited resources in budgets, human resources, and facilities further complicate the situation. Fortunately, the advances made in the fundamental understanding of materials, instrumentation and measurement techniques, and development and growth of high-performance computing provide a means to overcome these barriers and implement a new approach to research and development. Termed the "science-based" approach, this process involves small-scale experiments, coupled with theory development and advanced modeling and simulation, to optimize the number, cost, and objectives of engineering-scale tests (Figure 2).

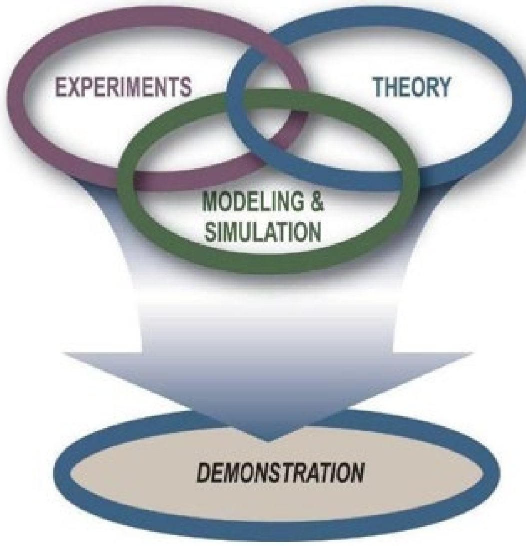

Figure 2. Goal-oriented, science-based approach.

1.2.1 Experiments

As opposed to large-scale, integrated experiments typical of demonstration-based programs, the focus on experiments for a science-based approach shifts to smaller-scale, phenomenological, fundamental mechanisms, and integral effects testing aimed at the measurement of fundamental properties. This approach provides a fundamental understanding of targeted phenomena and the data needed for model development. New and innovative experimental design and novel measurement techniques will be incorporated into experimental programs. In some cases, targeted integral experiments will also be needed. However, small-scale integral testing combined with scientifically developed scaling laws may alleviate the need for some full-scale experiments. Novel measurement techniques with high-spatial resolution (micron- to submicron-scale characterization) are needed for science-based fuel development. Finally, in- situ instrumentation for in-pile experiments will be needed to understand the evolution of behavior with exposure as well as the transient in-pile behavior of the fuels and materials.

1.2.2 Theory

Essential elements of the science-based approach are to build upon existing theories and to develop new theories that explain the various phenomena of interest, based on either first principles or observations made during phenomenological testing or uncovered through analysis of modeling results. In the long-term, theory must span from quantum mechanics to continuum mechanics in explaining the behavior of physical systems. A well-integrated, science-based approach is needed between experiments and theory development. For advanced fuels, the near-term theory development will be a mesoscale (microstructural) understanding of fuels and materials under irradiation conditions.

1.2.3 Modeling and Simulation

The knowledge and data gained under experimental and theoretical elements of the science-based approach will be incorporated into advanced modeling and simulation (M&S) tools that take advantage of state-of-the-art computing capabilities. Due to the very complex nature of the licensing process for nuclear fuels, a formal science-based approach must be developed and implemented to demonstrate the validity of newly developed simulation tools to address the behavior of fuels and materials in realistic situations and qualify these tools for use in informing the licensing process. The technical objective of the M&S effort is to provide insight into highly non-linear, coupled, multiphysics processes that occur during fuel fabrication and fuel performance. The practical objectives are listed below:

- Minimize the number of empirical iterations required during fabrication and high-dose irradiation testing of fuels by designing the performance into the fuel in the early scoping phases of development
- Reduce the number of prototypes and large-scale experiments needed before demonstration and deployment
- Quantify uncertainties associated with design and operational parameters.

1.2.4 Demonstrations

Nuclear energy systems are large-scale, complex facilities characterized by phenomena that can span ten orders of magnitude in space and time. Financing these systems requires the synthesis of complex business considerations and long-term financial commitments. Plant construction requires the use of large amounts of basic commodities such as concrete and steel. Facility operation requires adherence to a plethora of regulations at the local, state, and federal levels. At the same time, the U.S. regulatory process still relies heavily on experiments to confirm the ultimate safety of nuclear power systems (including fuels). Ultimately, the amelioration of these risks requires that new nuclear energy systems must be thoroughly demonstrated before commercial deployment. Therefore, new technologies, regulatory frameworks, and business models must be integrated into first-of-a-kind system demonstrations and prototypes. Construction and operation will then provide sufficient top-level validation of system technical and financial performance to enable deployment. For fuels, demonstration means fabrication of test assemblies, typically referred to as lead use assemblies (LUA), using prototypic processes and tested in a prototypic environment. At the end of testing, it must be demonstrated that the behavior of the LUAs is within the bounds of established safety and operational envelopes. Historically, the safety-acceptability of advanced fuels in LUAs requires prior transient testing of those fuels.

1.2.5 Idealized Fuel Testing Paradigm

As previously mentioned, fuel development and qualification are typically a lengthy and expensive process largely due to the challenge of evaluating irradiation effects on fuel performance.

Therefore, a concerted effort to develop, demonstrate, and implement a systematic approach to accelerating the development, testing, and qualification of new fuel systems has been initiated in the past several years (see Figure 3). This approach relies on seamless integration of advanced modeling and experimental tools while breaking down the integral performance to subcomponent/condition evaluations, sometimes called separate effects. This relationship is illustrated in Figure 3.

Ultimately, an accelerated approach to fuel qualification is selecting the best available tools to arrive at answers that support defining and predicting fuel design/safety criteria in the most efficient manner possible, where efficiency is measured in terms of cost and time. Improving the fuel development toolset has become a focus for AFC in recent years. Examples include:

1. **Innovative MiniFuel and FAST irradiation test designs** to accelerate the fuel burnup process and provide separation or isolation of certain fuel design parameters and conditions. These experimental approaches are currently in different phases of evaluation under AFC.
2. **Modular and flexible irradiation test platforms**, such as the Minimal Activation Retrievable Capsule Holder (MARCH) system at the TREAT facility that enables efficient transient testing of fuels in a variety of environments, specifically targeting separate effects to integral performance evaluations.
3. **Advanced in-situ instrumentation** for irradiation testing, recently implemented at the TREAT facility and a focus of capability development for Advanced Test Reactor (ATR). This effort includes strategic development of refabrication and instrumenting of previously irradiated fuel rods and installation of an upgraded ATR closure plate to facilitate lead-out instrumentation accessibility. The Nuclear Energy Enabling Technology (NEET) Advanced Sensors and Instrumentation (ASI) program is working with AFC to establish these capabilities.
4. **Advanced Post-Irradiation Examination and Experiment capabilities**, notably installed in the Irradiated Materials Characterization Laboratory (IMCL), that include a focus to obtain data that support development of lower length scale models as well as transient performance evaluations, such as the Severe Accident Testing Station (SATS).
5. **Mechanistic, multiphysics models and simulation tools** developed primarily under the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. AFC has and will continue to provide support in providing data and models to be implemented in the BISON fuel performance code, working closely with the NEAMS program. Development and qualification of a relevant experiment database of post-irradiation data from relevant fuel experiments is necessary to validate these models.

The fuel qualification programs outlined in later sections are increasingly implementing these techniques. The Leading Innovation for Fuel Technologies (LIFT) initiative, focusing on qualification of metallic fuels, notably includes a world- leading demonstration of these tools used in an integrated process through the development and qualification of a sodium-free metallic fuel design in 5 years.

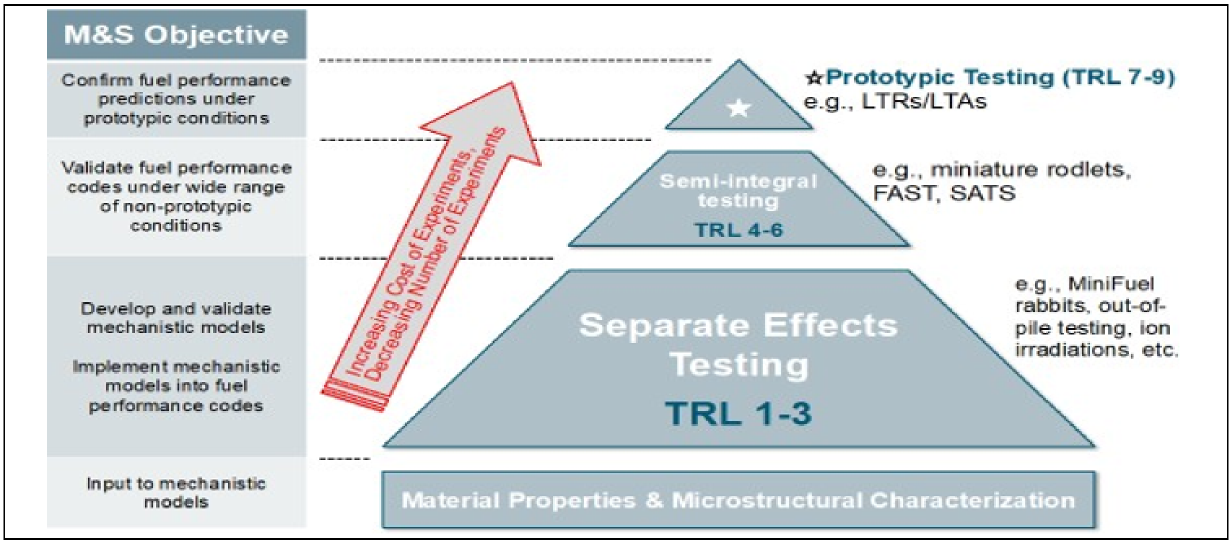

Figure 3. Idealized fuel testing paradigm.

2. ADVANCED FUELS CAMPAIGN MISSION, SCOPE, AND OBJECTIVES

As discussed in the previous section, development of advanced fuels crosscuts all four objectives and the three broad fuel-cycle categories under Objective 3 in the DOE-NE Roadmap, as well as the objectives outlined in the ATF program.

2.1 Mission and Objectives

AFC's goal is to develop and demonstrate approaches to accelerated testing and qualification of new fuels by applying materials science and engineering to design, develop, optimize, and test prototypical advanced nuclear fuels, thus providing compelling options for current and future reactors.

AFC's mission is to (1) support the development/qualification of Accident-Tolerant and High-Burnup Fuel (LWR) technologies, and (2) perform R&D on fuel technologies for future advanced reactors.

Objectives:

1. **Major Increase in fuel burnup and performance over current technologies**. An increase in fuel burnup is desired for all fuel-cycle options. However, the quantitative goals for burnup depend on the reactor type and, more importantly, the selected fuel-cycle option. In some cases, practical and economic concerns limit burnup beyond fuel-cycle efficiency and technology limitations. Burnup in once-through cycles is limited by the initial enrichment constraints and cladding material properties. Burnup for fuels used in a full-recycle scenario may be limited by reactor physics, storage, and disposal constraints after the discharge of spent fuel. Another important consideration in increasing burnup is to ensure near-zero failure, a standard that industry is striving for at current burnup levels. Quantitative limits for the burnup grand challenge

under various fuel-cycle scenarios will be developed as the program progresses and fuel-cycle scenarios are defined.

2. **LWR Fuels with enhanced accident tolerance**. Improvements will be measured by increased margin to fuel failure, increased time for response during an accident to prevent severe damage to the core, and reduced hydrogen generation when the core is uncovered, and the fuels and cladding are in contact with steam.
3. **Fuel development and qualification candidates**. Integrate the identification, prioritization, and performance of DOE-led strategic needs for nuclear fuels R&D. Establish and maintain strategic partnerships with complementary DOE programs, nuclear industry, and the Nuclear Regulatory Commission (NRC). Metallic fuel is the first candidate for accelerated qualification. Develop proposals for other strategic fuel concepts with potential to impact future advanced reactor systems (e.g. UN, UL, advanced high temperature/dose claddings). The program will accomplish this in two phases: 1) qualification of the reference fuel form historically used at EBR-II and FFTF and 2) development of a next generation metal fuel.
4. **Qualified Metallic Fuel**. Metallic fuel is the leading fuel technology for a number of advanced reactor designers due to its unique performance attributes. Although metallic fuel designs are very mature for some applications, metallic fuel technology has not yet been deployed at a commercial scale. Therefore, the necessary regulatory framework has not been fully developed to facilitate deployment. This foundational resource for advanced reactor design can be established via submission of Topical Report(s) to the NRC for their review/approval, markedly reducing the time and burden of licensing for any industrial user.

2.2 Scope

AFC is organized into three primary functions that are designed to enable the underlying goal to accelerate the development and qualification of new fuels and conduct advanced laboratory-led science and technology research.

Crosscutting capability development is currently integrated into the Fuel Development and Qualification function; however, it may become a standalone function in the future. Additionally, AFC is tightly coupled to fuels M&S in the NEAMS program and in-situ-instrumentation with the Advanced Sensors and Instrumentation (ASI) program, as shown in Figure 4.

The three primary AFC functions are listed below.

1. Fuel Development and Qualification

Implementation of qualification methodologies for specific fuel technologies. Managing partnership frameworks with external mission drivers/sponsors (e.g., industry, regulators).

2. Technical Areas

Direct execution of project scope developed in collaboration with Qualification Program Leads and Strategic Leads to support external sponsors.

3. Advanced Fuels Science and Technology

Advanced Fuels Science and Technology is the strategic, think tank function in the campaign. This group of experts maintain partnerships with complementary DOE programs, nuclear industry, and the NRC for the purpose of advancing compelling fuel options that will meet the future needs of the nuclear industry. Responsibilities include integrating the identification, prioritization, and performance of DOE-led, long-term R&D.

Advanced Fuel Performance Modeling and Simulation is a primary need for the development of advanced fuel systems. AFC maintains a close connection with the development of a multiscale, multiphysics fuel performance code infrastructure under the NEAMS program (see Figure 4). On-going AFC/NEAMS interactions closely demonstrate the value of in-situ data strains that are used in assessment and development of complex systems. The time dependent behavior simulated using advanced M&S often require invention, development, and deployment of advanced sensors and instruments. The AFC program is increasingly posturing with the ASI program to accomplish this.

For any given fuel type, the mission of AFC ends when fuel qualification is completed via an engineering-scale demonstration of fabrication processes and irradiation of LFAs to demonstrate in-pile performance.

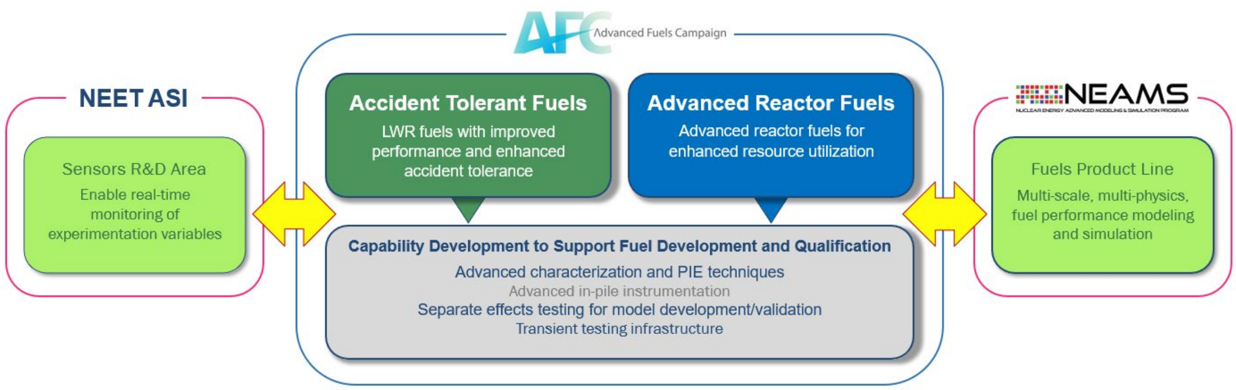

Figure 4. AFC RD&D functional areas.

2.3 Funding Opportunity Announcement Projects

A key component of the AFC is engagement with industry, especially for Advanced Light Water Reactor Fuels (ALF). In FY 2012, DOE-NE designated funds for funding opportunity announcement (FOA) competitive awards to identify, develop, and test advanced LWR fuel concepts with the potential for improved performance under hypothetical accident scenarios (i.e., ATFs). Three industry-led teams were selected: Westinghouse Electric Company, LLC, General Electric Global Research, and Framatome. Each team is a separately funded effort to develop team-specific ATF designs. Phase I of these efforts lasted from 2012–2016 and focused on concept selection. Each team chose to focus near-term ATF efforts on the development of various forms of coated Zircaloy cladding with or without a doped (high-density) UO2 fuel pellet.

DOE signed agreement extensions in the fall of 2016 to initiate Phase II, which would focus on the development and qualification of the chosen ATF concepts. The development and qualification phase was originally intended to last through 2022 and conclude with the introduction of lead use assemblies in commercial reactors. However, due to industry demand the program was accelerated and lead use assemblies were inserted into commercial reactors in 2018. It was decided then to extend the development and qualification phase to 2025–2026 with the new goal of introducing batch-scale reload quantities into at least one commercial reactor.

2.4 Integrated Research Projects

The initial integrated research projects and their teams have concluded their awards; none are active at this time.

2.5 Interfaces

Advanced fuel development cannot be implemented in isolation from the other DOE RD&D programs. Likewise, successful development strategy requires interfacing with national and international institutions outside DOE.

2.5.1 Interfaces with Other Programs and Program Elements

Under R&D Objective 3, Sustainable Nuclear Fuel Cycles, AFC interfaces with the other R&D Objectives within the NE R&D Roadmap,[1] with all the RD&D pathways defined in the Sustainable Nuclear Fuel Cycle Implementation Plan,[3] and with the goals outlined in the ATF Roadmap.[5]

- **Light Water Reactor Sustainability (LWRS) Program**. ATF requires a strong technical interface with LWRS. Limited work has been performed for ALFs under the LWRS program, previously including silicon-carbide cladding development, and currently initial analysis of system impacts of accident scenarios in reactors with ATF. The LWRS cladding-development work has transitioned to AFC; analysis activities are conducted under the LWRS Risk Informed Safety Margin Characterization Pathway.
- **Nuclear Energy Advanced Modeling and Simulation (NEAMS)**. Advanced M&S is managed and executed as a crosscutting program within DOE-NE and includes advanced fuels M&S activities. These activities must be closely coordinated with theory development and experimental activities within AFC. The interface with NEAMS is essential since M&S is a critical element of the science-based fuel development strategy.
- **Advanced Sensors and Instrumentation (ASI).** The ASI program includes R&D scope focused on the development of in-pile instrumentation and capabilities to enable integration with irradiated nuclear fuels and materials. Development and qualification of these capabilities should be closely coordinated with AFC to leverage state-of-the-art instrumentation but to also develop and implement next generation devices into representative reactor core environments via in-pile experiments. These tools are crucial to reducing uncertainties in material performance under irradiation and to strategies that accelerate development and qualification efforts.
- **Advanced Reactor Technologies (ART).** Similar to the LWRS program for LWR fuels, R&D on advanced reactor fuels requires a strong technical interface with the ART program. Reactor systems level performance under normal and transient conditions and various related tools and analyses should inform ongoing fuel design requirements. In addition, fuel performance and fission product behavior data and

models will provide important inputs to ART interests.

- **Versatile Test Reactor (VTR)**. Design options for the VTR are being researched. These designs will focus on user requirements for the advanced reactor community, specifically in the areas of testing fuels, materials, and coolants in a prototypical environment. VTR will be an essential tool for the United States to regain global leadership in developing advanced reactors. By providing fast neutrons, the test reactor could dramatically accelerate testing and the development of fuels and materials.
- **Reactor Campaign**. Any fuel form or type being developed to increase the efficiency of the existing LWR fuels must be compliant with the operation and safety envelopes of the existing reactors. For new reactor designs, strong collaboration is needed between system and fuel designers to achieve the desired operation and safety envelopes. Qualification of advanced fuels will require irradiation of LFAs, which will require the existence of a suitable facility (e.g., demonstration fast reactor).
- **Joint Fuel Cycle Studies**. AFC is funding the IRT-1 irradiation experiment in ATR for fiscal years (FY) 2019 and 2020. Future potential work includes continuation of these research activities under a new agreement including irradiation of already-finished specimens in the IRT-2 irradiation experiment.
- **Nuclear Energy University Program (NEUP)**. This program provides DOE funding to university-led projects with a nuclear technology emphasis. Some NEUP projects are directly related to goals and objectives of AFC. In addition to providing direct topical calls to the NEUP program, AFC encourages direct interface between laboratory technical staff and the principal investigators leading NEUP projects.
- **Gateway for Accelerated Innovation in Nuclear (GAIN) and National Reactor Innovation Center (NRIC)**. Campaign activities intersect directly with GAIN and NRIC objectives to demonstrate advanced reactors.
- **Advanced Reactor Demonstration Projects (ARDP).** The ARDP projects are important to specifically recognize as they generally have aggressive planning that includes fuels work. Some of these projects have potentially important overlapping interests with AFC expertise, capabilities, and work scopes. It is important to ensure AFC coordinates with relevant projects to ensure resources are used as efficiently as possible to accomplish the goals of DOE NE as well as individual private companies pursuing ARDP pathways.

2.5.2 Institutional Interfaces

The RD&D activities for the development of advanced fuels are led by the national laboratories on behalf of DOE-NE. Therefore, strong collaborations among the national laboratories and with other institutions outside the DOE complex are needed for a successful integration and execution.

- **National Laboratories**. As the DOE-NE lead laboratory, Idaho National Laboratory (INL) directs most of the advanced fuels RD&D activities. However, actual work is performed at AFC-associated national laboratories that have the critical expertise and research facilities needed for the successful execution of the program. This successful partnership works together to accomplish AFC objectives and scope.

- **Universities**. Strong collaboration with universities is essential for advanced fuel development. The intellectual participation of the universities will supplement much-needed innovative thinking for the implementation of a science-based approach to fuel development. Direct collaborations are increasing within NEUP. However, due to limited research activities in the previous decade, the expertise supporting fuel development activities is minimal and aging. There is an immediate need to educate the next generation of fuels engineers and scientists to provide continuity for long-term RD&D activities. Examples include the 2012 IRP issued for the development of ATF and the 2016 integrated research project on tool development for determination of ATF "coping time."
- **Industry and Electric Power Research Institute (EPRI)**. RD&D for advanced fuels is long-term, expensive, and high-risk with regard to the potential future payoff. Therefore, industry on its own will not perform the necessary research and will naturally focus on incremental improvements to today's technology. On the other hand, nuclear energy production is a private enterprise in the United States, and any advanced fuels developed under this program, if successful, will be commercialized by the private sector. Thus, it is important to partner with industry at the early research stages to facilitate the eventual and timely commercialization process.
- **International Organizations**. Because of the complicated nature of fuel development and the need to explore multiple options in the early phases of the program, international collaborations with nations that have considerable nuclear energy infrastructure is essential. Currently, AFC has strong collaborative ties with the Nuclear Energy Agency (NEA) Framework for Irradiation Experiments (FIDES), Japanese facility sharing cooperative research and development agreement (CRADA), Japan Atomic Energy Agency (JAEA), and the Joint Research Center's (JRC) QUENCH test facility operated at Karlsruhe Institute of Technology.
    - *NEA FIDES*: High-burnup Experiments in Reactivity-initiated Accidents (HERA) is a 3-year project (2021–2023) proposed under the NEA's new FIDES initiative. The HERA Project will investigate reactivity-insertion accident (RIA) failure mode dependence of transient pulse width and cladding hydrogen content using TREAT and Japan's Nuclear Safety Research Reactor (NSRR).
    - *Studsvik Cladding Integrity Program (SCIP), SPARE*
    - *Japan:*
        - Collaboration with JAEA includes ATF, as well as advanced fuels development and testing, potentially using Japanese fast reactors (e.g. Joyo). Strong collaborations with Central Research Institute of Electric Power Industry will continue on joint development of metallic fuels. Collaborations focused on ATF technologies are centered on development of fabrication methods for oxide-dispersion-strengthened FeCrAl and SiC/SiC cladding technologies, as well as identification of major technological challenges of longer-term ATF cladding concepts, such as SiC/SiC. Collaborations on FAST reactor fuel developments include collaborative investigations of the impact of fuel structure and chemistry on the properties of mixed oxide fuels (MOX) and joint modeling benchmarking of historic MOX performance based on existing data.

- Japanese facility sharing CRADA: Japanese Facility Sharing CRADA – ARES Project (Advanced Reactor Experiments for Sodium Fast Reactor Fuels) is a joint project to support qualification of next-generation fuels for sodium fast reactors by investigating transient fuel performance of advanced and high-burnup fuel designs.

- *European Union/JRC*: Collaboration with Halden and European Union Joint Research Centers primarily focuses on fundamental materials and fuels properties, characterization and post- irradiation examination (PIE) techniques, and M&S. The QUENCH facility simulates design-base loss-of-coolant accidents (LOCA) and reflood that can subject an instrumented miniature fuel rod bundle to the conditions anticipated while recording local temperatures and hydrogen production.
- *South Korea:* The collaboration with South Korea exclusively focuses on metallic fuel development for FAST-spectrum reactor applications, including fabrication and testing of metallic fuels prepared using feed materials obtained from recycling of LWR used fuel.

- **Nuclear Regulatory Commission (NRC)**. The NRC must license any new fuel before it can be deployed in commercial power reactors. Early involvement of the NRC in the RD&D phase will enable timely licensing of eventual products. This is especially true if there is a change in the licensing paradigm as a result of a goal-oriented, science-based approach to fuel development. Fuel development and qualification requires continuous interactions with NRC from the outset for a timely implementation of such fuels.

3. ADVANCED FUEL DEVELOPMENT RD&D

A typical fuel testing cycle is shown in Figure 5. This research methodology applies to any fuel type under development, including the AFC major research areas. Additional information is included in the subsections.

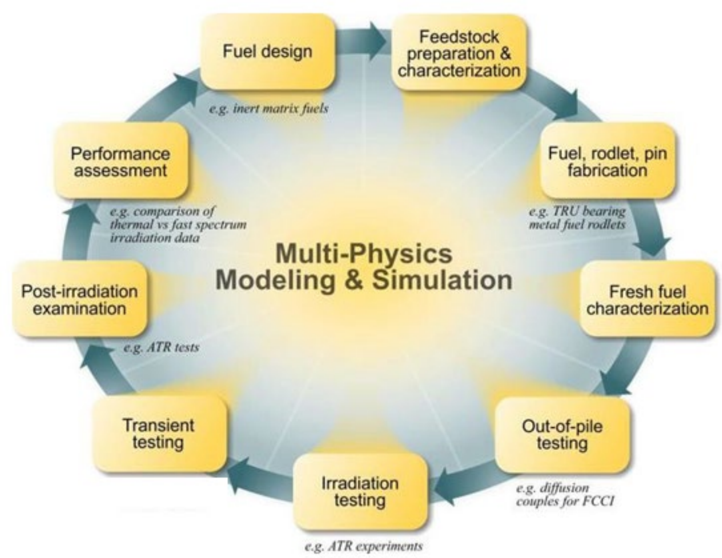

Figure 5. Elements of the fuel development cycle integrated with advanced modeling and simulation.

AFC supports the development of any fuel and target form in the different fuel-cycle categories, specifically, those needed to achieve sustainable nuclear fuel cycles. Additional fuel forms that become part of the nuclear energy RD&D portfolio needed to achieve the other DOE-NE objectives may also be included in the scope, if necessary. The major RD&D areas currently covered under the scope of AFC are shown against an RD&D timeline in Figure 6 and outlined in the subsequent sections.

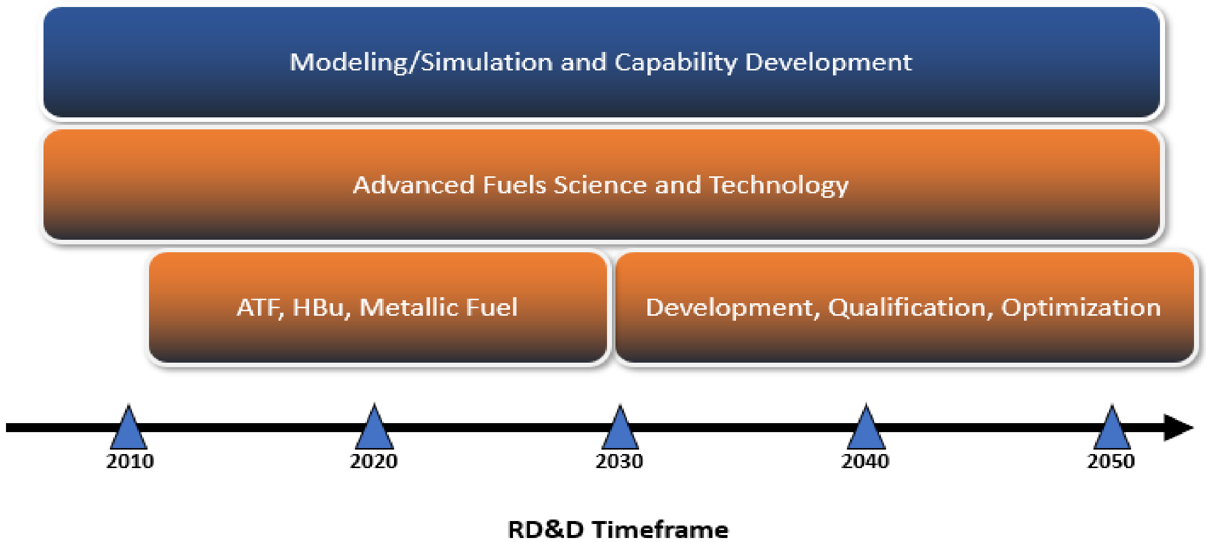

Figure 6. AFC research areas and capabilities-development timeline.

In order to provide a quantitative assessment for the maturity of a given system relative to its full- scale deployment, Nuclear Technology Research and Development (NTRD) adopted the technology readiness level (TRL) concept in order to track the technological maturity of various competing concepts and designs. Refer to Appendix A for additional information.

Implementation of the primary functions of the AFC includes a mix of near- and long-term development, qualification, and advanced science and technology activities. Continual innovation, development, and application will occur to move AFC science and technology forward. This structure allows AFC to be flexible and adaptable to program direction from DOE-NE based on national needs and strategy. Current Fuel Development and Qualification Programs have near-term goals (~10 years), with a long-term strategy to implement future fuel qualification programs, providing utilities compelling fuel options. Advanced Fuels Science and Technology is a longer-term research effort involving all aspects of fuel development and associated fuel-cycle implications. The technical areas integrate fuel qualification programs and advanced science and technology activities through the development of work packages and execution of technical scope.

Capability development focuses on crosscutting infrastructure, tool development, and resource application to enable the science required for all nuclear fuels development within DOE. These RD&D areas are described below.

4. GOALS, STRATEGY AND TACTICS

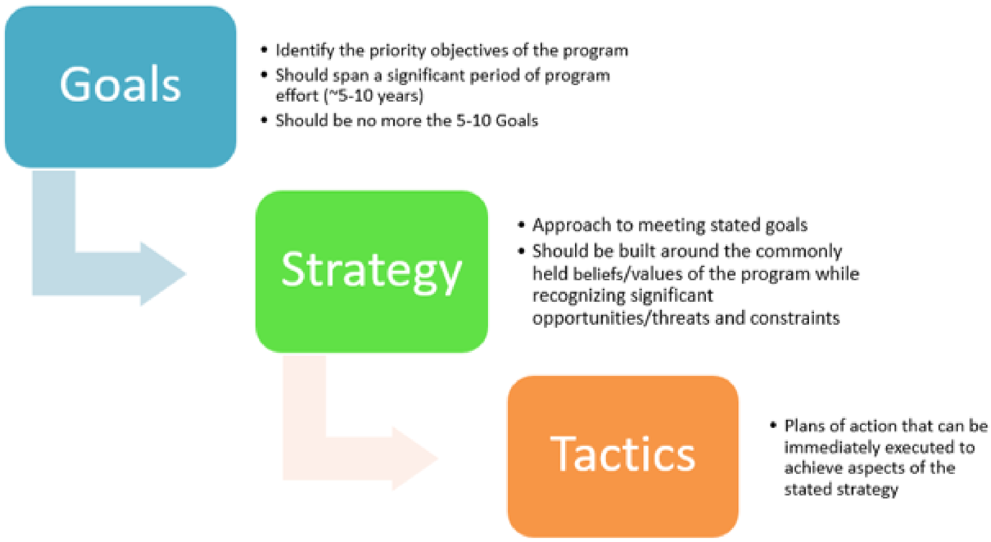

Figure 7. Systematic connection between mission and actions.

AFC Program Goals.

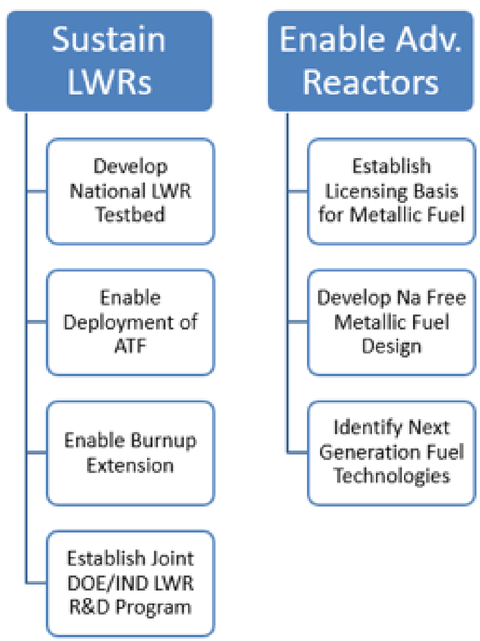

Figure 8. AFC Program Goals.

4.1 Sustain LWRs

4.1.1 Accident-Tolerant Fuel

The events in Fukushima prompted considerations for initiating R&D on light water reactor fuel with enhanced accident tolerance. The primary objective of the ATF Fuel Development and Qualification Program is to develop and qualify the coated zircaloy cladding ATF concepts being developed by each vendor. The goal of the program is the introduction of these enhanced fuels at reload quantities into the commercial LWR fleet within the next decade. A high-level schedule, provided in Figure 9, summarizes Phase II development and qualification activities leading up to the introduction of reload quantities of ATF in commercial reactors in the 2025–2026 timeframe.

Figure 9. Schedule for accident-tolerant light water reactor fuels.

The main role of the AFC in the development and qualification program is to perform the required fuel testing, which will produce the necessary data to license the new fuel designs with optimal operational margins to maximize its performance. Fuel testing during the development and qualification phase should produce data that can be used in at least one of three principal objectives described below:

1. Data used to develop a fuel or cladding material model (constitutive relationship).

Material models are essential to describing the behavior of a nuclear fuel system. These can involve relationships for a variety of mechanical, thermophysical, or chemical properties. These models need to account for the effects of changing temperature, changing neutron fluence, and changing chemical environment. Relationships most important for coated zircaloy cladding systems include those describing the cladding's creep and corrosion behavior.

2. Data used to establish a safety, design, or operational limit for the fuel.

A fuel's operational limits are expressed in terms of the fuel's allowable heat generation rate, allowable ramps or changes in heat generation rate, and total energy produced described as the fuel's burnup. Operational limits are derived by maintaining an acceptable margin to the most limiting design or safety limit based, which can vary throughout the fuel's life and can depend on the reactor's operational regime. Design limits are specified by the fuel designer and accepted by the regulator and are abbreviated as SAFDLs (Specified and Accepted Fuel Design Limits). SAFDLs can take many forms, but some examples include limits on the fuel temperature, plenum pressure, extend of corrosion, cladding temperature, or extend of pellet cladding interaction. Design limits must be specified for every known fuel failure mode to ensure that fuel failures do not occur as the result of normal operations or anticipated operational occurrences. Safety limits are dictated by the regulator and apply to design-basis accident scenarios and analysis. They are meant to ensure that fuel behavior (including potential failures) during design-basis accidents do not result in a loss of coolable geometry or result in radiological exposures to the public beyond a predefined evaluation grade.

3. Data used to validate some aspect of the fuel's performance.

Fuel performance codes and analytical methods are used to ensure that reactor core loadings and operations do not result in a violation of any of the specified design or safety limits. These codes use the derived material models and specified operational conditions to calculate fuel performance variables such as fuel temperature, plenum pressure, thickness of any oxide, corrosion, and/or crud layers, and cladding deformation during power maneuvers. Experiments that measure these values directly are then used to validate the performance codes to ensure their accuracy.

4.1.1.1 Joint Project Approach

Joint projects are a way of focusing limited resources (money, people, capabilities) on gathering the most critical data for ATF. Joint projects will be proposed by the laboratories in the AFC and will be sponsored by both DOE directly and indirectly through the vendor FOA awards. Direct DOE ATF laboratory supporting funding will be used to develop and demonstrate a given experiment, including acquisition of any new equipment needed to execute it. Direct DOE support may even extend to testing of generic Cr coated zircaloy-4 as a means of developing independent confirmatory data sets. After the experiment has been successfully demonstrated the fuel vendors (through their FOAs) will be responsible for funding the experiments on their specific ATF design. The joint project approach allows the DOE laboratories to most efficiently fulfil their roles in ATF development and qualification by providing industry with access to unique testing infrastructure and serving as an honest technical broker in the generation, development, and dissemination of accurate technical data.

Fuel development milestones are delineated in Table 1.

Table 1. ATF development and qualification milestones.

FY 2022	• Complete First hot cell PIE report on examinations from commercial Lead Test Rod (LTR)/Lead Test Assembly (LTA) material.
FY 2023	• Begin Testing of Instrumented Fuel Pins in ATR. • Begin in-pile LOCA testing of pre-irradiated rods in TREAT. • Issue independent technical report quantitatively describing the differences in corrosion and creep behavior of the different coated zirconium alloy claddings. • Demonstrate the ability to conduct dynamic (power ramp) testing in a flowing water loop at ATR.
FY 2024	• Begin irradiation testing of refabricated and reinstrumented fuel pins from commercial LTR/LTA in ATR.
FY 2025	• Irradiate refabricated and reinstrumented fuel pins from commercial LTR/LTAs to very high burnups ≥75 GWd/MTU in ATR.

4.1.2 Enable Deployment of ATF

Deployment of ATF is a vendor lead initiative within the Department of Energy's Nuclear Fuel Cycle Supply Chain (NFCSC) Program. The nuclear vendors who receive DOE financial assistance agreement for the deployment of ATF include: General Electric, Framatome, Westinghouse, and Westinghouse's subrecipient General Atomics. ATF is generally divided into near term and long-term technologies. Near term technologies include coated zirconium alloy claddings and doped (ppm level) UO2 fuels. Long term technologies include a variety of high density or composite fuel pellet types, as well as advanced claddings consisting of ferritic steels (FeCrAl) and Silicon Carbide Ceramic Matrix Composites (SiC-CMC). DOE has indicated that given limited nature of ATF funding priority should be given to the nearer term concepts. Deployment targets for ATF are as follows:

- 2023 – Introduction of reload batches of near-term ATF
- 2026 – Full cores of near-term ATF operating
- 2030 – Introduction of reload batches of long-term ATF

The national laboratories have three roles relative to ATF include the following:

1. Support ATF Vendors through partnering with them in the FOAs.
2. Establishing testing infrastructure required to generate necessary licensing and qualification data. *Discussed separately as part of "Develop LWR Test bed" AFC Goal.*
3. Conducting independent R&D on general behaviors of ATF materials.

Funding for ATF is provided through congressional appropriations which in recent years has been broken up into two categories:

1. \$55.6M + \$5M ATF Vendor Cooperative Agreements
2. \$20M ATF Laboratory Support

Funding for role (1) is supplied through the vendor agreements and is not part of the AFC annual planning process, each lab will work independently with vendors to address their testing and qualification needs. The ~\$20M allocated for ATF Laboratory Support needs to be used to achieve either roles (2) or (3) above. Role (2) is discussed separately and is assumed to require ~50% of the available funding. Thus, it is generally assumed that budget for Independent R&D on ATF is around \$8M to \$12M. Laboratory priorities for general ATF R&D are as follows:

1. Coated Cladding deformation and failure mechanisms specifically where performance differs from well understood behaviors of conventional zirconium alloys
2. Develop Coated Cladding and Doped Fuel databases (e.g. handbooks) and work with NEAMS to identify data gaps for fuel performance codes, where necessary fabricate reference samples for testing
3. Research on cross-cutting foundational technology development and critical feasibility issues for utilization of SiC/SiC composite as LWR fuel cladding SiC cladding
4. Assess vulnerabilities to longer term ATF fuel concepts (e.g. high uranium density fuels) and assist in mitigation strategies

Milestones for Enabling the Deployment of ATF are delineated in Table 2.

Table 2. Enable Deployment of ATF milestones.

FY 2022	• Complete PIE of medium burnup (~30 MWd/kgU) coated cladding irradiated in the pressurized water loop of ATR • Receive second shipment of Hatch LTRs and first shipment of Clinton LTRs for GE/GNF at ORNL • Insertion of national laboratory fabricated Cr-coated Zry-4 into HFIR • Perform PIE on HFIR irradiated coated cladding concepts • Evaluate suitability of accelerated irradiation testing and SET towards accelerated fuel qualification (AFQ) • Irradiate as-fabricated ATF cladding reference samples (tube geometries)
FY 2023	• Develop experimental test plan based on discussions with NEAMS for long term ATF • Complete initial PIE reports from commercial PIE undertakings at INL/ORNL • Receive shipment of second cycle ATF from Byron LTRs at INL • PIE of national laboratory fabricated Cr-coated Zry-4

	• Continue to provide PIE data to industry partners to support topical reports to NRC • Develop irradiation test plan for long term ATF (high density fuels, SiC, FeCrAl, etc.)
FY 2024	• Viability assessment of novel ATF fuel forms (TRL-1-2) • Complete PIE of high burnup (~55 MWd/kgU) coated cladding irradiated in the pressurized water loop of ATR • Receive shipment of third cycle ATF from Vogtle LTRs at INL • Receive shipment of third cycle ATF from Byron LTRs at INL • Receive third shipment of Hatch LTRs and second shipment of Clinton LTRs for GE/GNF at ORNL • Continue to provide PIE data to industry partners to support topical reports to NRC
FY 2025	• Perform PIE on industry sponsored HFIR irradiated SiC. Fabricate long term ATF test articles • Issue synthesis reports of coated cladding performance in LWR environments from information gained through irradiations in the pressurized water loop of ATR and the various LTR/LTA – PIE campaigns • Continue to provide PIE data to industry partners to support topical reports to NRC • Testing of irradiated long-term ATF reference fuels

4.1.3 Enable Burnup Extension

The U.S. nuclear industry is renewing efforts to build a technical basis to extend peak rod average burnup limits beyond the current regulatory burnup limit, 62 GWd/tU rod average. The primary driver is to economically increase cycle lengths to 24-month cycles, reducing the number of fresh fuel assemblies, reduce the number of outages, and possibly reduce core design constraints. For perspective, fuel cost or related core design efficiency limitations account for roughly 20% of the operating costs for a nuclear power plant (NPPs). The core design envelope available to operators is constrained by two key criteria, an enrichment limit of 5% U-235 and burnup limit of 62 GWD/tU. With appropriate development of a supporting technical basis, NPPs could be able to implement improved core designs that would enhance the economic viability of U.S. NPPs and possibly prevent plants from closing. The Nuclear Regulatory Commission (NRC) will likely require a new technical basis or modification to the existing technical bases to support enhanced high burnup core design prior to resuming normal operation, and the development of the required technical basis will require and greatly benefit from additional research and development (R&D) to investigate underlying separate effects and integral high burnup fuel performance.

In response to industry goals, Congress directed the U.S. Department of Energy (DOE) to prioritize research to support extending burnup with the overarching goal to enable and expand the safe and economic operation of the U.S. Light Water Reactor (LWR) fleet beyond current regulatory limits. The role of the Advance Fuels Campaign (AFC) High Burnup (HBu) program is to support this goal by identifying, prioritizing, and filling data gaps that will enable extending burnup beyond 62 GWd/tU. The campaign will develop required capabilities and perform the R&D needed to achieve this goal.

Additionally, this program recognizes further opportunities to mitigate the intense economic pressures plaguing the U.S. nuclear fleet. Therefore, with a prioritized focus on realizing the burnup limit goals of industry, the HBu program will also assess and prioritize fuel performance related activities limiting the economic viability of the nuclear fleet as resources may allow.

The U.S. nuclear industry has indicated their desire to extend the rod average burnup to ~75 GWd/tU by 2026. Given the aggressive schedule of this goal and limited available resources, it is necessary to prioritize, integrate, and coordinate parallel efforts being conducted by all stakeholders to the extent possible in order to fill technical knowledge gaps. This complex integration effort is being led by the Collaborative Research on Advanced Fuel Technologies (CRAFT) for LWRs program including representatives from major interests in industry, NRC, and from AFC program representation. The purpose of CRAFT is to disseminate the information provided by the technical community, assess their relative progress, and aid in R&D scope prioritization. The HBu program within the campaign has the role to develop and document the experimental and analytical activities required to generate critical path data and information to aid in regulatory review and inform Topical Reports related to the Burnup Extension mission. Technical objectives are expected to be met within the framework of the experimental tasks outlined in the HBu program plan incorporating input and feedback from the CRAFT committee. Furthermore, the HBu program intends to participate in ongoing HBu work (i.e., SCIP and Halden) to ensure work within the campaign is complementary and only duplicative when necessary. The aggressive HBu timeline will require advanced modeling and simulation as a complementary effort to the ongoing experimental activities within the campaign. Therefore, the campaign will closely coordinate efforts with the DOE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program as well as the Light Water Reactor Sustainability (LWRS) programs where as applicable.

For economic reasons, the U.S. nuclear industry is renewing efforts to build a technical basis to extend peak rod average burnup limits and uranium enrichments above the current regulatory limits, 62 GWd/MTU and 5%, respectively. The primary driver is to economically increase Pressurized Water Reactor (PWR) cycle lengths to 24-month cycles resulting in a reduction in the number of fresh fuel assemblies required and possibly reduce core design constraints that limit operational flexibility. Furthermore, achieving high burnup (HBu) is a critical springboard for the economical deployment of ATF technologies.

The U.S. nuclear utilities are leading a two-phased approach to meet this objective.

- Phase 1 culminates in loading fuel assemblies with >5% enrichment in 2023 with the intention of exceeding 62 GWd/MTU. Licensees must mitigate currently unresolved high-burnup fuel performance questions identified by the NRC, primarily fuel fragmentation, relocation, and dispersal (FFRD) and transient fission gas release, prior to being granted authorization. The technical basis for this phase will be based on mitigating FFRD by implementation of a "no-burst" criterion to rods exceeding the fragmentation onset burnup threshold (~67 GWD/MTU).
- Phase 2 culminates in loading fuel assemblies with >5% enrichment in 2025 with the intention to extend generating stations from the current 18-month cycles to 24-month cycles. This will require fuel assemblies to exceed the current 62 GWd/MTU limit to a targeted peak rod average burnup of the order of ~75 GWd/MTU. As noted above, the NRC expects the industry will resolve potential technical issues related to the impact of FFRD and transient fission gas release on high-burnup rods susceptible to bursting under postulated accident conditions.

The national laboratories will be expected to play a significant role in resolution of the specific technical issues related to FFRD and potential enhanced and transient fission product release under steady-state and transient conditions. The focus of this fuel qualification program is to provide the technical data required to inform the greater nuclear community on the technical issues regarding increased burnup of LWR fuel systems and, thus, support assessment of the HBu fuel utilization. This program will focus primarily on the standard zircaloy-UO2 fuel system; however, the foundational platform will also pave the way for deployment of advanced fuel forms (i.e., doped UO2 and ATF).

The consensus milestones in this section were developed by an industry-led initiative and informed by an integrated technical experts' group, the Fuel Performance and Testing Technical Experts Group (FPT TEG) populated by experts from utilities, fuel vendors, and national laboratories. FPT TEG is responsible for informing the industry, DOE, and the regulators of how both separate effects testing and integrated rod testing can address the technical issues regarding increased burnup of LWR fuel systems in support of the milestones and objectives laid out in the NRC Project Plan and the Nuclear Energy Institute (NEI) ATF Working Group. The FPT TEG will establish and execute the technical strategy and R&D execution plan for the advancement of high-burnup LWR fuel systems. The experts group operates under the authority of Collaborative Research on Advanced Fuel Technology (CRAFT). CRAFT is chartered to enables the deployment of high burnup/high enrichment in LWRs and was collectively launched by nuclear industry stakeholders (Utilities/DOE/EPRI/Fuel Vendors/NRC) in 2020 to facilitate broad technical coordination. FPT TEG will provide CRAFT with recommendations focusing on testing to address technical issues associated with FFRD and enhanced fission product release.

The recommendations of the industry-led CRAFT program will be implemented at the national laboratories using congressionally allocated funds to HBu to complete the technical milestones outlined in Table 4. To respond to evolving technical understanding of the HBu fuel performance data needs, the technical milestones beyond FY 2021-2022 may be updated as new data may influence the technical issues identified by FPT TEG and approved by CRAFT.

Milestones for Enabling Burnup Extension are delineated in Table 3.

Table 3. Enable Burnup Extension milestones.

FY 2022	• Demonstrate ATR and/or HFIR re-irradiation capabilities to generate new HBu material • Use DOE Modeling and Simulation tools to assess FAST and/or miniFuel abilities to accelerate burnup accumulation in order to generate new HBu LWR materials • Perform advance microstructure characterizations on HBu fuel provided by fuel suppliers with special emphasis to support LOCA and RIA experiments • Develop report linking modeling and simulation results and to existing PIE as well as support further advance characterization • Develop transient fission gas release experimental measurement capabilities in SATS and/or TREAT • Perform commissioning experiments in hot cell furnace/fission gas release furnaces

	• Perform SATS test on HBu commercial fuel to investigate FFRD phenomena with specific intention to compare to full integral TREAT LOCA test
FY 2023	• Develop journal manuscript to update current state of knowledge, disseminate results, and gap identification • Perform in-situ transient FGR measurements on high burnup fuel in furnace or in-reactor • Begin TREAT LOCA test on high burnup fuel in-parallel with complementary SATS test • Complete initial ATR and/or HFIR rodlet re-irradiations to investigate microstructural phenomenon associated with FFRD • Perform advanced microstructure characterization on ATR or HFIR re-irradiation samples • Complete phase I of the Human Event Repository and Analysis (HERA) program with RIA experiments on high burnup fuel segments
FY 2024	• Perform TREAT and SATS tests on reirradiated HBU fuels • Develop state of the art report on quantification of operating conditions on HBu microstructural formations • Benchmark TREAT LOCA/RIA and SATS against industry standard tests • Identify fuel performance limitation beyond burnup extension to enhance fuel utilization and operation efficiency • Develop R&D plan to investigate fuel performance limitations • Begin loop experiments in ATR on commercial HBu fuel segments to investigate operational performance parameters (e.g., dryout, thermal conductivity, etc.)
FY2025	• Write summary report for FFRD in HBu fuel during transients • Support Utility burnup extension topical reports • Execute R&D plan designed to address fuel performance limitations

4.1.4 Develop National LWR Testbed

Approximately 40 years ago there were at least nine special purpose material test reactors in the United States with relevant environments and capabilities for irradiation testing of Light Water Reactor (LWR) fuels and materials. State-of-the-art hot cell facilities were co-located on research campuses with these reactors to support Post Irradiation Examination (PIE). Less than half of these reactors remain operational today and, after a decades-long interruption in LWR fuels research and development (R&D) at the national laboratories, the LWR related testing capabilities significantly atrophied. Consequently, LWR fuels R&D activities were consolidated at a few international facilities, most prominently the Halden Boiling Water Reactor (HBWR) which supported testing needs of the full international community including the U.S. fuel vendors, advanced fuel technology developers, U.S. national programs, and the Nuclear Regulatory Commission (NRC).

Stage 1 – Revitalization: The U.S. Department of Energy (DOE) began engaging with the U.S. industry in 2009 to identify nuclear fuel technologies that could enhance the economic and safety performance of existing LWRs. As that program evolved, the impact of the 2011 Great Tohuko Earthquake and Tsunami on the Fukushima-Daichi plant refocused that program on the development of Accident Tolerant Fuels (ATF). To accelerate deployment of ATF, in 2019 DOE incorporated burnup extension and increased enrichment into the program to provide additional economic incentives for utilities to convert to the new products.

Execution of this program required rapid re-development of LWR Testing R&D infrastructure in the United States. Creation of this infrastructure has been a major success whose coming of age now warrants a focused effort to brand and market it as an integrated LWR testbed so that a diverse set of users may better access it. The Department of Energy's Advanced Fuels Campaign (AFC) has recently established the LWR Irradiation Testing Expert Group (ITEG) to help facilitate, develop, and maintain the testbed to maximize each reactor's unique capabilities. Recent successes include establishment of the following:

- Capsule and pressurized water loop fuels testing in the Advanced Test Reactor (ATR).
- Water loop cladding tests in the Massachusetts Institute of Technology Reactor (MITR).
- Water capsules for fuel safety testing in the Transient Reactor Test facility (TREAT).
- Accelerated, separate-effects irradiation capsules for testing fuels and materials in the High-Flux Isotope Reactor (HFIR).
- An array of collaborative agreements with international partner facilities.
- Numerous enhancements in PIE equipment, hot cell performance testing, and related logistic capabilities.

Stage 2 - Recovery: The recent and unexpected closure of HBWR obviated other capabilities that were still needed to support both ATF and high burnup (HBu) fuel testing. Essential testing environments were no longer available including in-pile LOCA testing, power ramp testing, the ability to outfit previously irradiated rod segments with crucial instrumentation, and general reduction of test throughput for various needs. As a result, a second wave of capability development was necessary to address the HBWR gaps including deployment of:

- A reflector-based loop at ATR ("I-Loop") to enable tests with power ramping and coolant voiding (essential for BWR applications).
- Blowdown capsule for LOCA testing in TREAT.
- Hot cell-based competencies for refabrication and instrumenting irradiated rod segments for subsequent testing.

Stage 3 - Harvest: Deployment of "evolutionary ATF" (coated-Zr, doped-UO2) and HBu license extensions is foreseen to be accomplished within the capabilities established in Stages 1 and 2. The testbed, however, will need to be maintained to support post-deployment optimization of technologies while supporting development of truly advanced fuel/cladding designs (e.g. SiC/SiC composite cladding, high-density/composite fuels) and other advancements needed to maintain the vitality of water-cooled reactors (e.g. LightBridge fuel, advanced small modular reactor (SMR) fuels, regulator driven confirmatory testing, etc.). Recent experiences with high temperature gas reactor fuel development has shown how quickly a capable testbed can be dismantled leaving an availability gap for necessary post-deployment optimizations. This experience shows that sustaining and enhancing the LWR testbed will require a stage 3 where steadfastness and strategic growth ensure that data capabilities are made available and retained for future LWR technology developments. At the same time, it has been recognized the cost to maintain infrastructure is much lower than development. Thus, users will be able to accomplish significantly more R&D at a much lower cost during this stage. In this regard, further testing capabilities will be assessed for future development (to expand overall experiment volume and meet specific scientific needs) including:

- Accelerated fuel testing capsules at ATR and expanded capabilities at HFIR
- Installation of a second cladding corrosion water test loop at MITR
- Deployment of a flowing water loop at TREAT
- Expansion of ATR capacity to two or more I-Loops
- Development of a thermosyphon system in HFIR

Prioritization, strategic planning, and commissioning of the necessary capability development projects, along with their integration into the broader testbed and transition to programmatic data production, remains a prominent effort for AFC.

4.1.4.1 I-Loop

The purpose of the I-Loop Project is to install a flowing water loop in one of the medium I positions in the ATR. The loop facility will be capable of testing fuels or materials in conditions prototypic of commercial power reactors. The loop will penetrate the reactor through the closure plate allowing experiment test trains to be inserted and removed through the top of the reactor in similar fashion to loops installed in the flux traps. To install this new facility at ATR, a modified closure plate is required. The project will design, procure, and install a new closure plate with the necessary features to support the I-loop. Refurbishment of the 1A cubicle where the Advanced Gas-cooled Reactor equipment currently resides will also be necessary to support the I-Loop. The Advanced Gas-cooled Reactor equipment will be removed and new pipping, heat exchangers, resin beds, detectors, pumps, pressurizers, control cabinets, and other equipment will be installed. The I-Loop project was started in Fiscal Year (FY) 2020 and is expected to be completed by FY 2023. Its development will be performed under the policies, requirements, and critical decision equivalent (CDE) responsibilities consistent with the U.S. DOE Order 413.3B, “Program and Project Management for the Acquisition of Capital Assets.” Its establishment is a result of the detailed evaluation of testing needs for U.S. industry and international capabilities found the essential need for additional loop facilities, especially to provide power ramp and boiling water reactor experimental environments (see INL/EXT-46101, Rev. 1, for more information). The CDE-0/1 milestone, which establishes DOE approval to proceed with final design, and establishes DOE oversight expectations is planned for completion this year.

Table 4. Milestones for I-Loop.

FY 2022	• Coolant System Final Design Review
FY 2023	• I-Loop System Installed

Figure 10. Develop National LWR Testbed.

Milestones for the Development of the National LWR Testbed are delineated in Table 5.

Table 5. Develop National LWR Testbed milestones.

FY 2022	• Deploy capability to irradiate UO2 materials in HFIR-MiniFuel under LWR relevant temperatures • Establish enhanced SiC cladding water loop irradiation capability at MITR • Deploy on-line instrumentation in Loop-2A experiments • Demonstrate shipment of LWR fuel segments from Europe (Studsvik/Halden) • Demonstrate full size LWR fuel pin examination in the Hot Fuel Examination Facility (HFEF) • Demonstrate Commercial Fuel Shipment to Idaho National Laboratory (INL)

FY 2023	• Demonstrate ability to refabricate and instrument pre-irradiated fuel rods (at both INL and Oak Ridge National Laboratory [ORNL]) • Institute competencies for LOCA testing on pre-irradiated specimens in TREAT • Deploy advanced refabrication instrumentation system • Deploy LWR Fission Accelerated Steady-state Testing (FAST) demonstration
FY 2024	• Commission capability to perform power ramp testing on previously irradiated fueled LWR specimens in ATR I-Loop • Implement sustainable funding model to maintain and operate testbed • Commission TREAT flowing water loop for enhanced performance margin identification
FY 2025	• Commission second ATR I-Loop to support both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) testing simultaneously • Implement sustainable funding model to maintain and operate testbed • Demonstrate thermosyphon in HFIR for accelerated advanced cladding development

4.1.5 Establish Joint DOE/IND LWR R&D Program

In 2012, following decades of dormancy, DOE funded R&D activities related to light water reactor (LWR) fuel applications were fully revived to enable the development and deployment of accident tolerant fuels (ATF). As this program gained momentum, the scope of the DOE mission expanded to also include R&D that would enable burnup extension and increased enrichment. Significant relationships were developed between the key stakeholder communities (industry, regulators, and researchers) during this time. While a majority of the DOE budget was targeted at supporting vendor lead technology development, a significant pivot is expected to occur following commercial deployment of ATF technologies. At this point, ATF technology is expected to become profitable and further R&D conducted at the national laboratories would need to become more collaborative, e.g. financially supported by all stakeholders (industry, regulator and DOE) in a manner comparable to historic joint projects like the Halden Reactor Project. A primary goal of the AFC program is to facilitate this transition over the next 5 years through development of a joint project model. This will help to maintain the strong relationships that have been built over the last decade, ensure continuity in the R&D activities, and optimize utilization of the LWR fuels testbed.

Joint projects are typically organized around common R&D themes that crosscut the needs of the participating partners. The AFC program goal is to develop a joint LWR R&D program that will emphasize irradiation performance tests aimed at collecting integral fuel performance data and/or establishing utilization limits for advanced LWR fuels in operational regimes near, at or above established design or safety limits. This data is essential for improving the general understanding of fuel behavior and to support assessment and validation of modern modeling and simulation tools used in design and licensing of nuclear installations. To support this objective, a commitment to development and implementation of advanced in-situ instrumentation within this project will be critical.

The scale and complexity of the experiments conducted under a joint program may vary and are expected to consist of both in-pile experiments in test reactors and furnace-based testing in hot cell facilities. Regardless of the testing environment, the experiments shall seek to replicate conditions found near, at or above established design or safety limits to study the limits of fuel performance associated with:

- Loss of Coolant Accident (LOCA) conditions
- Reactivity Initiated Accident (RIA) conditions
- Power Cooling Mismatch (PCM) conditions, beyond DNBR/CPR
- Aggressive power ramp conditions

R&D activities in all of these areas are currently being conducted under support of the existing ATF and HBU programs. However, emerging users are beginning to request access to meet advanced LWR fuel technology development objectives. The AFC program will work to integrate those activities into the overall program execution strategy and, thus, simplify the ultimate transition to an efficient joint program.

The test programs will utilize irradiated fuel samples harvested from commercial reactors. The test materials will principally consist of established fuel products although some new, upcoming, or novel fuel products may be considered for testing provided they have first achieved lead test rod (LTR) irradiations in commercial reactors. Test matrixes will be round robin in nature and will seek to include products from several fuel vendors if possible. To support this, the program will need to develop a network of irradiated fuel suppliers and efficient transportation and archival processes. Testing conducted on lower TRL technologies can also be performed through parallel open R&D programs lead by DOE researchers or commercially commissioned experiments.

A healthy, self-sustaining joint project of this type is expected to require ~$10-20M/yr of R&D funding to be successful. Assuming that the program follows a model similar to the historic Halden Reactor Project where the host institution pays ~50% (or more) of the costs and the external partners fund the remainder, it is anticipated that DOE would need to allocate ~$5-10M/yr to this effort from the AFC budget. To accomplish this, funding will be gradual shifted from LWR testbed development to joint project activities over the next 5 years. To recover the remaining costs, it is expected that the joint program will leverage broad participation in international programs with similar goals such as the Nuclear Energy Agency's (NEA) Framework for Irradiation Experiments (FIDES). A joint project focused on RIA behavior of high burnup fuel has already been incorporated into the first iteration of the FIDES program. It is expected that additional programs focused on LOCA and power ramp will be submitted in the future. As part of this initiative, the program will review the various ongoing joint projects to identify opportunities to partner or complement their missions (including the remnants of the Halden Reactor Project, SCIP, SPARE, QUENCH, NFIR, etc.).

The Establish Joint DOE/Industry LWR R&D Program milestones are delineated in Table 6.

Table 6. Establish Joint DOE/Industry LWR R&D Program milestones.

FY 2022	• Develop Program Organizational Framework and Establish high level Program Scope (e.g. should program focus on advanced materials or quantification of design and safety limits) • Coordinate R&D materials shipment from Studsvik to U.S. • Develop utilization, allocation, and management plan for critical irradiation test facilities (test loops)
FY 2023	• Develop more detailed scope and budget plan • Coordinate with LWR testbed to Identify needed strategic capabilities to execute program
FY 2024	• Complete iterations of scope, schedule, budget for the first 3 years of the program • Identify irradiated material of strategic interest to the program and make plans for securing it
FY 2025	• Prepare 2027 Budget Request to support launch of the program

4.2 Enable Advanced Reactors

4.2.1 Leading Innovation in Fuel Technology (LIFT)

The Leading Innovation for Fuel Technologies (LIFT) initiative will address cross-cuttin R&D needs of advanced reactor designs by providing:

(1) fuels R&D leading to qualification that supports crosscutting needs of the advanced reactor industry through development of relevant NRC topical report(s), and (2) innovation including accelerated testing to address data and technology gaps identified through this process. These topical reports will be the vehicle that guides technology advancements in support of advanced reactor prototypes and demonstrations.

As a primary initial target for LIFT, metallic fuel is the leading fuel technology for a number of advanced reactor designers due to its unique performance attributes developed and demonstrated by DOE laboratories. To enable the goals of the NRIC, a metallic fuel qualification program is needed with expertise to specify and qualify fuel designlimits to be used in advanced reactor applications. Although metallic fuel designs are very mature for some applications, metallic fuel technology has not yet been deployed at a commercial scale. Therefore, the necessary regulatory framework has not been fully developed to facilitate deployment. This foundational resource for advanced reactor design can be established via submission of topical report(s) tothe NRC for their review/approval, markedly reducing the time and burden of licensing for any industrial user. Additionally, modern reactor size scales and their unique design requirements vary greatly such that the existing metallic fuel performance database may be inadequate to support desired deployment timelines for all proposed advanced reactor applications.

Under LIFT, initial efforts will focus on a complete qualification of proven metallic fuel designs while developing and qualifying a sodium-free metallic fuel design. Figure 11 provides an overview of the planned topical report development reflecting the R&D pathway of the program.

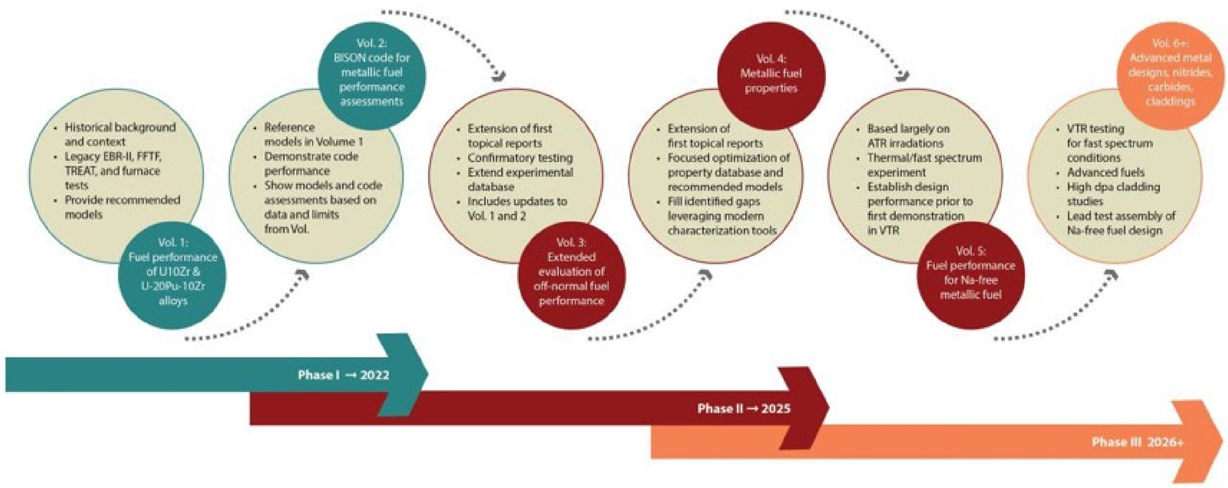

Figure 11. Subjects and timeline for NRC topical report completion for metallic fuel qualification.

LIFT is divided into three primary phases with connected, yet distinct objectives associated with each. These phases are represented by the arrows in Figure 11. The primary outputs of each phase are the topical reports also outlined in Figure 11.

Phase I: Reference Fuel Performance Basis and Modeling Platform

The objective of Phase I is to establish a reference fuel performance basis for U-10Zr[a] in D9 and HT-9 claddings as the reference fuel design. This activity has a primary focus of leveraging the existing metallic fuel database and materials archive to develop and publish topical reports that establish the reference fuel performance basis. This activity requires development of metallic fuel properties and irradiation performance databases with data qualified for use in licensing. The qualification of the existing EBR-II metallic fuels database has largely been supported by the Advanced Reactor Technologies (ART) program until now. The AFC program intends to complement that effort by expanding the existing database to include data from FFTF and ATR experiments. AFC will also focus on using this data to establish data supported design limits and models to predict associated fuel behaviors. This phase also necessitates coordination with the NEAMS program to develop a comprehensive and validated set of metallic fuel behavior models implemented in the BISON code (or available for use in industry developed codes) to support evaluation of all key fuel design limits identified in the fuel performance topical report.

[a] Metallic fuel, specifically U-10Zr in SS316/HT-9 cladding, is selected for the first qualification program since the existing irradiation performance data from the Experimental Breeder Reactor (EBR)-II and the Fast Flux Test Facility (FFTF) should be sufficient, although out-of-pile characterization, fresh and irradiated fuel property measurements, and perhaps some TREAT experiments to confirm safety behaviors are expected to be needed to fill existing data gaps. It is also the fuel selected by several current advanced reactor designers as a cross-industry focus. Qualification of other fuel technologies will be possible after the startup and operation of the VTR (since other fast-spectrum fuel technologies of interest to industry will require additional irradiation testing to support licensing).

FY 2023 Deliverables:

- Topical Report Vol. 1: Fuel Performance of U-10Zr Alloys in D9 and HT-9 Claddings
- Topical Report Vol. 2: Assessment of BISON for Metallic Fuel Performance.

Phase II: Reference Fuel R&D Opportunities and Sodium-Free Fuel Design Development

Phase II is focused on building on the reference fuel performance foundation established in Phase I while extending the defined performance envelope through additional R&D (see Figure 11). This effort will include an emphasis on confirmatory transient testing that will extend the existing database and reduce potential design limit uncertainties. This phase will also focus on design innovation to meet crosscutting industry needs with development of a sodium-free fuel design option as an already identified priority. The latter activity will be a priority focus for accelerated fuel qualification with a goal to achieve a qualified design by 2027. It will be the first-of-a-kind application of accelerated fuel development, with important validation by prototypic testing in Phase III. This concept is described more in the following section on accelerated testing.

FY 2025 Deliverables:

- Topical Report Vol. 3: Extended evaluation of Off-Normal Metallic Fuel Performance
- Topical Report Vol. 4: Metallic Fuel Properties (Fresh and Irradiated)
- Topical Report Vol. 5: Fuel Performance of Sodium-Free Metallic Fuel (developed using accelerated R&D methods for confirmation testing in Phase III)

Phase III: Fast-spectrum Testing for Advanced Design Qualification

This phase focuses on startup and use of the VTR to perform prototypic and accelerated testing to support qualification of innovative fuel designs. This phase includes validation of the accelerated development approach taken for sodium-free metallic fuel through lead test assembly testing. This transition allows next-generation fuel forms and R&D objectives to be developed with the advice and consent of industry stakeholders. Potential topical report subjects could include next-generation fuel forms (e.g., advanced metallic fuel designs, nitride fuels, or carbide fuels) and/or high-dose, low-swelling cladding alloys with enhanced creep resistance.

Accelerated Fuel Testing Developed and Validated Through LIFT

LIFT represents the systematic implementation of accelerated testing methodologies, described generally in Section 1.2.5 (Idealized Fuel Testing Paradigm), to qualify metallic fuel. Phase I activities are expected to be based largely on existing data. Phase II activities, to be started in parallel to Phase I activities, will require application of accelerated testing and advanced modeling capabilities as described above. Figure 12 provides an overview of the proposed first of its kind planned program to develop and qualify a sodium-free metallic fuel design. The importance of the proposed plan is to provide the first real demonstration of a complete accelerated fuel qualification effort in the first 5 years shown in the figure. The second 5 years is a key opportunity to truly enable these first attempts to gain meaningful confidence in these techniques by providing a full evaluation of the accelerated development approach in a confirmatory demonstration through fabrication, irradiation, and transient testing of a full prototype assembly. The AFC program will hold this as a flagship example of world-leading accelerated fuel R&D to provide the backbone to future fuel development programs.

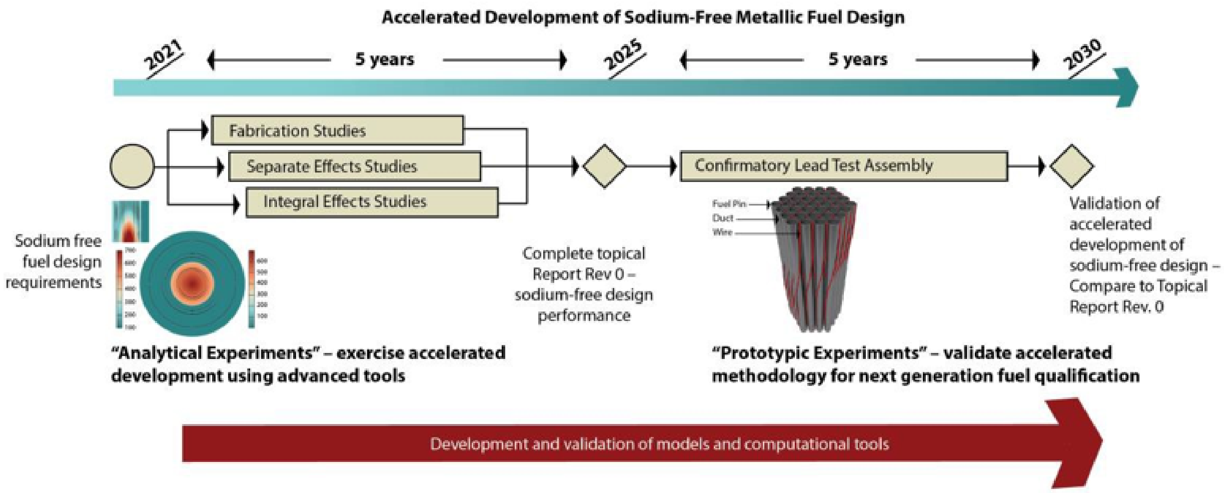

Figure 12. LIFT will apply accelerated fuel testing methodologies to sodium-free metallic fuel in a first-of-a-kind application of full methodology to be validated for use on the next advanced designs.

4.2.2 Establishing Licensing Basis for Metallic Fuel

The overarching goals in FY22 are rooted in the need to clearly establish the gathered data, current capabilities, and gaps needed to be filled in order to establish a licensing basis for metallic fuel. Zirconium-based metallic nuclear fuel has a rich history of utilization in the US, both as the driver fuel in EBR-II, and tested extensively in FFTF. In addition, several out-of-pile furnace tests, transient tests in TREAT, and separate effects tests of the fuel and cladding have been conducted that support the integral irradiations. Models developed to describe the behavior of the fuel system have evolved from descriptive to predictive capabilities, bolstering the understanding of metallic fuel during irradiation. This mountain of information provides an invaluable starting point for determining safety limits of the fuel, albeit with gaps in required data, especially for experimental transient tests of previously irradiated fuel. In order to fully leverage the existing data, while providing enough lead time for future tests, FY22 needs to focus on clearly establish the holes in data in order to put in motion appropriate and streamlined experimental campaigns and model development.

One of the key elements of any licensing effort is the database of experimental information on which to draw on for justification of safety limits. Although not necessarily developed under AFC, we need to be a strong partner on which database developers can rely in order to ensure our database needs can be fulfilled appropriately. This will require a thorough understanding of the strengths and weaknesses of the database, support with qualification, and bolster the data with either historical irradiations (FFTF) or new irradiations under AFC. Familiarity in the database will provide the basis on which to perform a gap analysis of the database in the context of licensing U-10Zr/HT9 (L2 report).

Development of a licensing basis for metallic fuel requires inputs from several stakeholders. With the NRC as the most likely consumer of such a report, early understanding of the requirements, format, and focus of such a report is required very early in the planning process in order to develop an appropriate execution plan. In addition, the applicability to industrial partners is essential in order to ensure the licensing basis fits into the needs of a realistic reactor design, and subsequent licensing. Establishing an early execution plan for an NRC topical report will help provide guidance in future years (L2 report).

Guided by the familiarity of the database and early understanding of the execution plan for the topical report, a strategy for filling the data gaps needs to be developed early in order to establish the appropriate solutions. Rooted in the technical basis for bolstering the qualification data, the current status of modeling, fabrication, and experimental capabilities needs to be determined. Culminating in a gap analysis, this early familiarity and identification of key technologies required can help support interactions with other programs (e.g., NEAMS), or focused development of missing capabilities (L2 report).

Finally, the tasks already underway in support of metallic fuel needs to be continued. This includes interactions between AFC and NEAMS on fundamental metallic fuel properties and advanced cladding models. Recovering previously irradiated mechanical test specimens in BOR60 and PHENIX and testing them in hot cells should be a priority due to their applicability for NEAMS model development. Establishing a joint AFC/NEAMS metallic fuel property handbook will provide a useful basis for key fuel performance metrics (L2 report).

The Licensing Basis for Metallic Fuel milestones are delineated in Table 7.

Table 7. Establishing Licensing Basis for Metallic Fuel milestones.

FY 2022	• Establish database • Establish execution plan for Topical report • Compile gap analysis to inform out-year planning • Continue on-going work
FY 2023	• Generate early draft of report using historical data • Initiate detailed design for transient testing focused by gap analysis and NRC feedback • Incorporate and continue model developments • Prepare for modern implementation of fuel system
FY 2024	• Submit Topical Report addressing NRC FQAR for reference fuel design to NRC for review • Complete assessment of fuel performance code (BISON) applicability to reference fuel design and identified SAFDL's (separate TR?) • Perform first transient tests on irradiated long-length FFTF specimens in Na loop • Irradiate accelerated testing experiments (FAST/Minifuel) • Add to joint AFC/NEAMS properties handbook with mechanics properties (pending on prior year down selection)

	• Summary report on thermal conductivity and fuel swelling behavior based on linking microstructure to operational history with modern PIE and modeling • Input new data on high dose material testing of HT9 into Fuel Cycle Research and Development (FCRD) Materials Handbook • Summary report on fuel cladding chemical interaction (FCCI) behavior based on additional modern PIE and modeling • Initiate in-pile experiment to measure thermal conductivity with direct linkage to modeling and PIE
FY 2025	• Complete assessment of limit refinement due to new modeling and experimental information • Apply lessons learned on modern fabrication to assess applicability of new fuel systems • Perform first furnace transient experiments on metallic fuels • Summary report on modern experimental evaluation cladding creep rupture behavior for modern cladding material • Start next volume(s) of Topical Report that addresses data gaps/opportunities identified early on (irradiated fuel properties, transient performance)

4.2.3 Develop Na-Free Metallic Fuel Design

The U.S. advanced reactor industry is rapidly progressing to deploy advanced reactors, which rely on metallic fueled cores, exemplified by the Natrium, Aurora, and Versatile Test Reactor projects. Most modern designs rely on historically developed sodium-bearing metallic fuel designs. In recent years, sodium-free metallic fuel designs have become of high interest to industry, primarily driven by economic benefits in once-through fuel cycles. Recent irradiation and modeling results in the AFC program have validated the feasibility of such designs. Along with extensive U.S. interests, literature indicates similar interest in sodium-free metallic fuel designs in Korea, India, and Russia. ***The AFC program intends to leverage the rich, world-leading U.S. knowledgebase in fast reactor metallic fuel to develop and establish the qualification basis for a sodium-free metallic fuel design with extended temperature performance by 2027. The ultimate product will be a documented knowledgebase and associated database along with the fabrication of a lead test rods (LTR) and/or lead test assembly (LTA) for fully prototypic testing.***

The approach to sodium-free fuel development will focus on developing, implementing, and validating accelerated fuel development and qualification (AFDQ) methodologies. The importance of the proposed plan is to provide a first-of-a-kind demonstration of accelerated fuel qualification tools to a R&D product in the first 5 years. The second 5 years starting after 2027 is a key opportunity to validate AFDQ – as no other fuel development program has before. The AFC program will use this as a flagship example of world-leading accelerated fuel R&D to provide the backbone to future fuel development programs.

Historically, metallic fuel design performance has been established based on limiting smeared density to approximately 75%, by accommodating initial free volume in the high-density solid fuel cross section by providing a gap between the fuel and cladding. To avoid issues of poor and nonuniform heat transfer from fuel to cladding, fuel designs incorporated a sodium fill that provides near ideal thermal contact. The advantages of this approach include near elimination of practical sensitivities to geometric fabrication tolerances and near recovery of irradiation-induced degradation to fuel effective thermal conductivity as sodium infiltrates into the gaseous pores during early irradiation.

The removal of the in-pin sodium from the fuel design has become a high value proposition by many reactor designers, especially in once-through fuel cycles. Some of the potential benefits include:

- Lessened hazards in the front and back end of the fuel cycle. Storage in a geologic repository requires removal of the in-pin sodium as additional steps to disposal. (The in-pin sodium is not nearly as consequential in a recycle economy.)
- Reactors utilizing coolants other than sodium have potential concerns for sodium-coolant interaction, which is a significant concern for existing designs.
- Improved neutron economy, especially in breed and burn reactor designs.
- Potential for reduced axial fuel swelling under normal operations.
- Reduction in net reactivity insertion in severe accidents.

The development effort will include a focus to develop a cladding solution to enable extension of current temperature limits of fast reactor fuels with comparable or higher total dose performance. This development will be important to fully enable the value proposition of developing other advanced fuels such as carbides and nitrides in the future. Due to the limitations of fast-spectrum testing environments, some important limits to full experimental validation of neutron irradiation performance are expected. Still, the advanced cladding concept will be down selected based on state-of-the-art candidate materials with a goal to develop LTRs as a companion to the primary targeted HT-9-cladded sodium-free design. To accomplish program goals, cladding fabrication and supply chain must be developed for HT-9 (working with VTR) and the high-temperature, high-dose cladding concept.

To maximize the impact of the ultimate deliverable, the design must follow the science-based engineering approach to design and development. The design will incorporate requirements from interested stakeholders, including (but not limited to) Terrapower, Oklo, GE-Hitachi, Westinghouse, ARC-100, Toshiba, NRC, EPRI, and to be identified utilities. Therefore, representatives from relevant stakeholders will be requested to participate in an advisory panel to provide input to the design and the developed R&D plan. The AFC program can also gain mutually beneficial outcomes and efficiencies through collaborations with DOE programs including ART, NEAMS, ASI, and VTR. While the focus is on fast reactor applications, inherent synergy is expected with design concepts for water reactor applications where sodium-coolant interaction is also an issue.

The milestones for Developing Na-Free Metallic Fuel Design are delineated below.

Table 8. Develop Na-Free Metallic Fuel Design milestones.

FY 2022	• Develop project R&D execution plan • Establish industry advisory panel

	• Define design options for following studies consideration (annular, slotted, porous, etc.) • Complete fuel fabrication trade study (define metrics) - fuel lifecycle cost assessment – once-through/recycle • "Perform state-of-the-art review and fuel performance-based predictive assessment of Na-free fuel design options • Evaluate modeling capability and impact (data is available for annular designs) • Identify potential key performance issues (fission gas release [FGR], creep, fuel-cladding mechanical interaction [FCMI], FCCI, thermal conductivity, …) (Quantitative Phenomena Identification and Ranking Table [QPIRT]?) • Early demonstration of fabrication for Na-free design with prototypic length and diameter • First transient irradiation of fresh annular fuel form in static capsule
FY 2023	• Incorporate 2021 findings into Project R&D execution plan • Regulatory and industry review for Na-free R&D plan • Finalize fuel design requirements and preliminary fuel specification • Demonstrate engineering scale casting for long length pins (for non-annular designs) • PIE and performance evaluation of fuel performance of annular fuel at high burnup in 2022 (1 fuel pin from AFC-4 series) • Companion PIE/analysis for annular fuel irradiated in FAST for continued higher burnup irradiation • Complete design for long-length pin irradiation experiment
FY 2024	• Optimized fabrication process producing "in spec" fuel slugs • Final fuel down selection for Na-free fuel for LTA • Demonstrate prototypic (FFTF) length element loading • Begin irradiation of long-length Na-free fuel design(s) • Begin FAST/Minifuel irradiations on Na-free fuel design/fabrication variants • Transient irradiation of fresh long length annular fuel in TREAT sodium loop • Assessment of fuel performance modeling capability for steady state and transient conditions
FY 2025	• Demonstrate full size element fabrication • Transient irradiation of low burnup Na-free designs from ATR • Draft report/manuscript for summary on performance of Na-free fuel including preliminary design limits • Transient furnace testing for slow transient behavior • Perform detailed PIRT in cooperation with independent experts
FY 2026	• Fabricate LTA for irradiation in prototypic environment

	• Complete fuel performance assessment report for Na free fuel (in preparation for NRC review?) • Transient testing of mid-burnup Na-free design • Complete detailed measurements of fuel thermal conductivity to high burnups (leveraging FAST/MiniFuel validated by ATR full scale specimens at lower burnups)

4.2.4 Identify Next Generation Fuel Technologies

Development and deployment of high-performance reactor concepts is limited by the availability of fuels and materials. Only three commercial fuel types have been developed through Technical Readiness Level (TRL)[6] (UO2, U-Zr, and tri-structural isotropic [TRISO]) with two other potential fuels (uranium carbide [UC], uranium nitride [UN]) at TRL 5/6, providing limited options for reactor designers. Advanced reactors concepts that use solid fuel are developed around existing and proven fuels (sodium fast reactor [SFR], very high temperature reactor [VHTR]) or with little consideration for fuel technology (gas-cooled fast reactor [GFR], super-critical water cooled reactor [SCWR], lead-cooled fast reactor [LFR]) during concept development. Although viable, the power conversion efficiency of the former is constrained by fuel (SFR) and material (VHTR) limits. The lack of performance data on fuels that match GFR, SCWR, and LFR requirements and environments prevents serious consideration of near-term deployment of these and similar reactor concepts. The Department of Energy (DOE) Advanced Fuels Campaign (AFC) is the central R&D figure in leading early (pre-licensing) development of these fuel technologies. The recent rapid expansion of interest in commercial reactor development provides an ideal framework to identify, assess, and prioritize R&D needs in this area. However, the advantages of these high-temperature fuel forms cannot be realized without accompanying high-temperature claddings. Advanced system development based on either ceramic or metallic claddings must be pursued in parallel,

By leveraging the strong relationships developed with both the emerging industry and regulatory communities, the AFC program will catalog the anticipated operating environments and performance requirements for advanced fuel systems. The AFC program will then conduct R&D aimed at accelerating deployment of these systems. This acceleration will take several forms starting with the evaluation of methodologies that simplify expression of fuel performance criteria (‘qualification data’) used in licensing actions through studies that improve basic understanding of fuel behavior such that fuel systems can be simultaneously designed and optimized for a variety of diverse applications. Through this prism, the fuels program will identify the highest priority cross-cutting R&D needs that provide broad support to classes of reactor systems.

For example, nuclear fuels have been used for more than 70 years where fuel development has been largely empirical. This results in a limited understanding of the links between fabrication, initial fuel chemistry, and performance and prevents reliable extrapolation of observed performance into a broad envelop of operating conditions. This dramatically expands the range of conditions that fuel must be tested under to demonstrate adequate understanding. In particular, there is evidence that life-limiting behaviors such as gas-driven swelling, gas release, and fuel-cladding-chemical-interaction can be managed, although the full extent and applicability to different classes of fuels has not been sufficiently explored.

This technical area focuses on working in coordination with the advanced reactor development community and the established nuclear industry to (1) identify and evaluate low TRL fuel technologies with potential economic, safety and performance benefits for advanced reactors and (2) to more fully understand fuel behaviors that most often lead to fuel design limits, and develop strategies to mitigate or extend these limits and meet the design requirement of advanced reactor systems.

Specifically:

1. **Next Generation Fuel Phases**: A forward-looking working group on fuels for advanced reactors will be established including thought leaders from DOE and industry. This group will forecast fuel requirements based on targets for reactor performance and evaluate economic, safety, and performance benefits of advanced fuels using a consistent and rigorous methodology. Viable fuel concepts will be selected for bench-scale fabrication and measurement of key properties and performance parameters (ex. corrosion, thermal, and mechanical behavior). If warranted, small-scale irradiation testing and post-irradiation examination will be performed. The goal of this activity is to develop enabling fuel technologies to the early proof -of-principle stage (TRL 4), to enable informed decisions on further development of fuel and reactor concepts.
2. **Advanced Clad Materials:** For next generation advanced reactor fuels, advanced clad materials are required that have improved high dose radiation tolerance at typical operating temperatures and increased operating temperatures for advanced reactor designs. Presently the leading materials are austenitic (316L) and ferritic martensitic steels (T91 and HT9) and ceramics (SiC). Scope will include investigating improvements to the leading materials as well as new materials such as oxide dispersion strengthened steels or novel new alloys. Research includes processing efforts to produce thin walled tubes of the alloys and weld development. Irradiation testing will be performed to down select for optimal alloy and processing development.
3. **Understanding and Mitigating/Extending Fuel Design Limits**: This task will conduct early-stage applied research focused on understanding and mitigating life-limiting phenomenon in current and advanced fuels from the perspective of the fuel phase. Scope will include mechanistic understanding of these phenomenon through lower-length-scale modeling, small-scale separate effects irradiation experiments, and post-irradiation examination at the microstructural level. The goal of this activity is to develop fuel-phase strategies to improve reactor economics by prolonging the useful life of the fuel.

Development of Next Generation Fuel Phases for Advanced Reactors milestones are delineated in Table 9.

Table 9. Development of Next Generation Fuel Phases for Advanced Reactors milestones.

FY 2022	• Initiate joint DOE/Industry Advanced Fuel Working Group • Publish AFC Next Gen Fuel/Materials Technology Roadmap • Implement methodology for AFC fuel technology incubator/Technology Maturation Plan using Technology and System Readiness Assessment (TSRA) methodology

	• Develop Standard process for welding of High dose radiation tolerant cladding tubing (Pressure resistance welding) • Standardize process for extrusion of thin walled Fe-Cr oxide dispersion strengthened (ODS) tubing for fast reactor fuels • Fabricate, characterize, and reactor insertion of high-potential next generation fuels in small-scale EPRI NFIR-8 and AFC tests
FY 2023	• Coupled BISON prediction / experimental observation of SiC/SiC bowing through saturation • Initiation of AFQ irradiation campaign to benchmark SET approach against either known (e.g. UO2/Zry) or challenge (e.g. UN/SiC) system • Begin post irradiation examination (PIE) on high dose irradiated Fe-Cr ODS samples from Phenix irradiation (MATRIX) • Begin PIE of next generation fuel test specimens from NFIR-8 and AFC tests
FY 2024	• TRL3 for LWR fuel designed for expanded LHR/BU operating window • Begin PIE on high dose irradiated Fe-Cr ODS samples from HFIR irradiation • Complete PIE of next generation fuel from NFIR-8 and AFC tests. Assess and report results. Develop plan for second phase testing.
FY 2025	• Progress report on initial AFQ PIE data collected using MiniFuel, FAST, etc. • Update FCRD materials handbook with high dose mechanical property data on Fe-Cr ODS cladding • Fabricate and characterize fuel samples for second round of next generation fuel testing

5. FUTURE QUALIFICATION PROGRAMS

Several ATF concepts are currently on a path toward formal fuel qualification in which they could receive approval from the NRC for use in commercial reactors. Similarly, the extension of current LWR fuels to higher burnups is also expected to culminate in a formal qualification activity. As such, if successful, they will achieve their objectives of NRC approval and come to an end as qualification programs. However, the longer-term, strategic R&D activities will be undertaken with a view to increasing the technological readiness level of other fuel types to the point where they can be transitioned to formal fuel qualification programs (assuming there is adequate industry stakeholder interest in and support for the fuel form). Currently, the next likely candidate to enter into a fuel qualification program is sodium-bonded and sodium-free metallic fuels for advanced reactors, which could leverage the extensive fuel performance database for sodium-bonded fuel types developed from decades of testing in EBR-II and FFTF. The sodium-free fuel design will likely include an effort to mature a high temperature, high dose cladding as an important bridge to advanced ceramic fuels options, which could be the next fuel selected for a qualification program. Although, their successful completion would likely be dependent upon the availability of the VTR to perform steady-state irradiation testing that will be needed for their formal qualification.

5.1 Capability Development

Capability development tasks support both the Fuel Development and Qualification and Advanced Fuels Science and Technology. To gain fundamental understanding and develop predictive models, testing and analysis capabilities are needed, but may not yet exist. This includes irradiation tests, furnace tests, in-situ measurements and control, advanced characterization and PIE techniques, and predictive modeling and simulation methods. We need to be able to change and control the test variables to develop the data sets and validate the models.

The decision to shut down and decommission the Halden Boiling Water Reactor in 2018 resulted in a significant loss of experimental capabilities for prototypical irradiation testing. AFC took the lead in assessing the impact of the loss of capabilities and made recommendations to DOE Headquarters on preferred options for replacing capabilities necessary to meet the needs of the ATF program. Two long-lead Halden recommendations were approved by DOE and are included in this section.

5.1.1 Fuel Rod Refabrication and Instrumentation

The most critical fuel performance data needs are typically associated with time dependent evolution and end-of-life fuel properties and behavior. However, the in-situ instrumentation required to collect that data is rarely robust enough to function effectively through the entire life cycle of a test. As such, the ability to extract fuel from the reactor and install instrumentation at the critical testing points is an essential capability. This capability (including techniques and infrastructure) was first developed at the INL in support of transient and steady-state testing but was shelved in the 1980s when U.S. investment in advanced LWR technology waned. International partners like Halden subsequently adopted these tools and built robust R&D missions around them. The revival of U.S. interest in advanced LWR technology (e.g. burnup extension and ATF) coupled with the closure of international facilities (like Halden and OSIRIS) calls for the recovery of these capabilities to support domestic priorities.

Follow-on irradiation testing of previously irradiated fuel rods enables highly instrumented experiments to be performed. This testing allows researchers the ability to assess the state of the fuel at any point in its life cycle. Follow-on irradiation testing is currently targeted to be performed using INL's Transient Test Reactor and Advanced Test Reactor. The ability to process preirradiated fuel rods of any length to achieve the desired form factor and include instrumentations providing online measurements is a crucial capability to support testing of ATF fuels.

Performing such follow-on irradiation requires the ability to refabricate previously irradiated fuel rods within INL's HFEF due to the high radiological doses of the irradiated fuel. The scope aims to establish basic refabrication capabilities at INL to enable these follow-on irradiation experiments. Basic refabrication consists of inspection to determine the desired segment to be cut from the source material, sectioning or cutting the segment, de-fueling the ends of the segment to make space for the instrumentation and new rodlet endcaps to be welded in place, removal of the oxide layer from the ends to prepare the surface for welding new endcaps, welding the new endcaps in place, evacuating the rodlet and backfilling with the desired gas mixture to the desired pressure, seal welding the rodlet, and inspections. Enabling these refabrication tasks requires designing, prototyping, and testing the Rodlet End Welding System to perform these functions prior to final equipment being approved for installation in the hot cell (5d window). Application of limited instrumentation to the rodlet will be possible in this system.

For advanced rod measurement designs, a complementary reinstrumentation system is under development in collaboration with Halden that will provide a modular and flexible platform for performing precision operations and handling of delicate instrumentation. Figure 10 shows the drilling unit that Halden fabricates for advanced reinstrumentation. The state-of-the-art Halden reinstrumentation process entails neutron or x-ray radiography, cutting and drilling out the fuel at the ends of the rod, removing the oxide layer from cladding surfaces, cryogenic freezing (e.g. filling the rod with liquid CO2 and freeze in liquid N2), drilling a rod center hole for instrumentation, outgassing in vacuum, insertion of centerline thermocouples, welding rod end plugs, adding inert gas and seal welding, and conducting helium leak checks. This system will allow INL to add instrumentation to irradiated fuel rods and improve future testing.

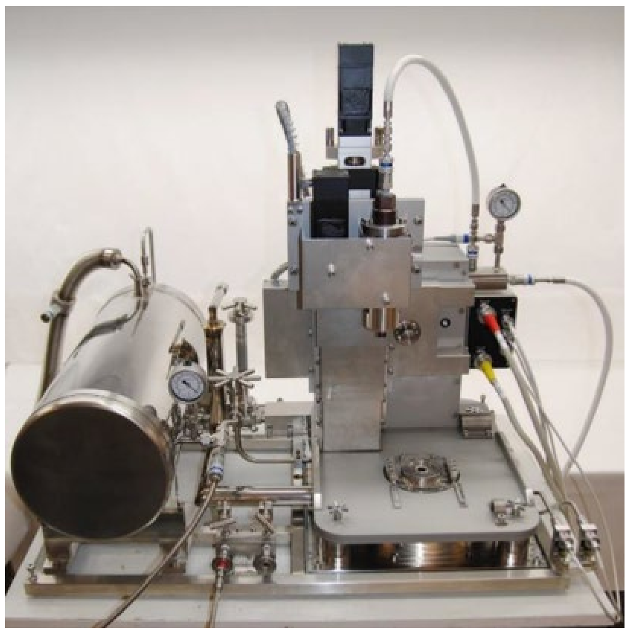

Figure 13. Drilling Unit.

Milestones for fuel refabricating capabilities are delineated in Table 10.

Table 10. Milestones for fuel refabrication capabilities.

FY 2022	• Complete refabrication of High-Burnup LWR fuel rod segments in HFEF and conduct transient testing in TREAT. • Complete design of refabrication/reinstrumentation system for irradiated fuels • Complete TESB modifications to support refabrication/reinstrumentation missions. • Complete design of the refabrication/reinstrumentation shielded enclosure.

FY 2023	• Complete fabrication and installation of the refabrication/reinstrumentation shielded enclosure in TESB. • Complete refabricated and instrumentation of irradiated fuel pin in TESB and conduct transient testing TREAT.
FY 2024	• Provide routine refabrication/reinstrumentation support for ongoing experimental missions. • Implement first-of-a-kind fuel performance instruments for advanced reactor fuel applications.

6. ADVANCED FUELS SCIENCE AND TECHNOLOGY

Advanced Fuels Science and Technology is the strategic, think-tank function in the campaign. This group of experts maintain partnerships with complementary DOE programs, nuclear industry, and the NRC for the purpose of advancing compelling fuel options that will meet the future needs of the nuclear industry. Responsibilities include integrating the identification, prioritization, and performance of DOE- led, long-term R&D. In addition, this group provides independent technical review of externally sponsored programs.

7. AFC STRATEGIC MILESTONES

AFC strategic milestones have been established to support DOE-NE's goals as well as to leverage M&S activities through 2050. level. The overall strategic milestones are outlined in Table 11.

Table 11. Strategic milestones.

FY 2022	• PIE of first test irradiation of coated Zry cladding concepts designed to benchmark ability of BISON to predict coating performance. • Report on suitability of accelerated burnup testing in ATR to represent fuel behavior from an analogous commercial LWR irradiation.
FY 2023	• Completion of separate effect/accelerated test irradiation experiments to isolate roles of microstructure, fission product behavior, and restructuring on susceptibility of UO2 to fragmentation. • Possible completion of Joint Project centered on NRC licensure data for industry coated Zry behavior.
FY 2024	• Use of data collected from accelerated irradiation test methodology and informed BISON model to predict LOCA performance of high burnup doped • UO2/Zry rodlet irradiated in FAST.
FY 2025	• Introduce initial reload quantities of ATF concept(s) in commercial power reactor(s). • Use of data collected from accelerated irradiation test methodology to predict LOCA/RIA performance of high-burnup UN/SiC.

FY 2030–2035	• ATF concepts in use in multiple commercial power reactors.

8. AFC ORGANIZATION

The AFC Management Team consists of the federal technical manager, national technical director (NTD) and deputy, systems engineering lead, fuel qualification and development program leads, technical leads and strategic area lead, who are subject-matter experts in specialized areas, and work package managers (Figure 14). The roles and responsibilities for each are summarized below.

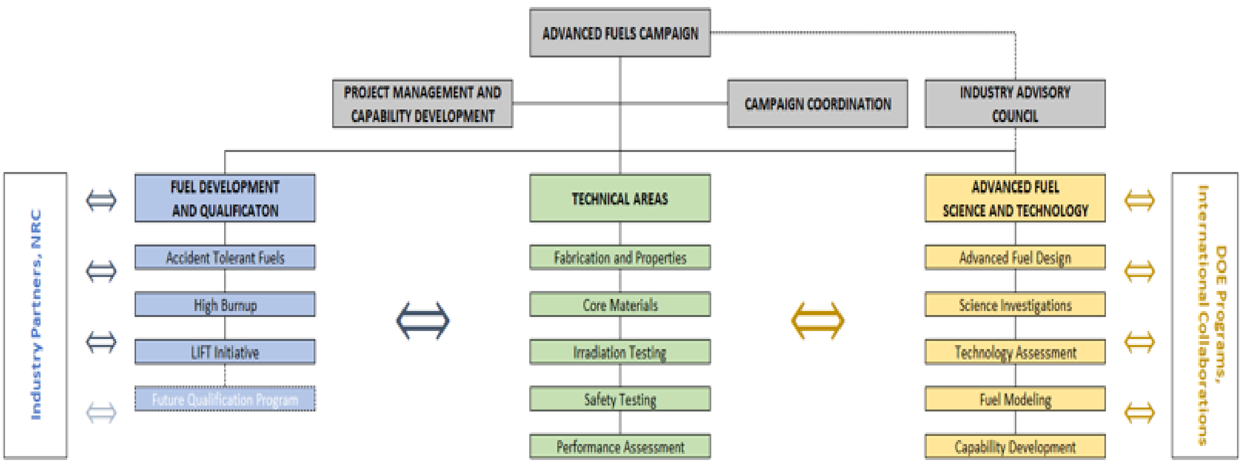

Figure 14. Advanced Fuel Campaign organizational structure.

Table 12 shows the primary roles and responsibilities of AFC personnel.

Table 12. Roles and responsibilities.

AFC National Technical Director	• Report to the federal technical manager for the Advanced Fuels under the NTRD Director • Define and execute the advanced fuel development plan following DOE guidance • Provide technical leadership for the national fuel development program • Participate in NTRD strategic planning and provide technical recommendations when requested by DOE • Assist DOE in developing and implementing international collaboration agreements pertinent to AFC • Participate in and/or co-chair (on behalf of DOE) international working groups related to fuel development

	• Participate in periodic NTD meetings, including biweekly teleconferences • Participate in internal and external review meetings • Assist DOE in performing technical and programmatic reviews of university programs • Coordinate with NRC and industry • Represent NTRD in relevant national and international working groups, workshops, meetings, and conferences (provide technical presentations with DOE's concurrence) • Chair the AFC Working Group meetings • Review and approve progress reports (monthly and quarterly) and technical reports generated by the campaign participants • Ensure the Fuel Cycle Technologies Quality Assurance Program Document requirements are implemented for all applicable AFC activities
AFC Deputy National Technical Director	• Report to the AFC NTD • Perform the duties of the AFC NTD as requested
Systems Engineering Lead	• Develop the functional and technical requirements for the AFC, based on input from the technical leads and the fuel design analysis • Organize and manage biannual AFC integration meetings • Organize and conduct yearly workshops with universities and researchers working in the fuel development area • Represent the AFC NTD in workshops, meetings, working groups, and conferences as requested • Compile and submit the monthly status reports from the technical leads • Organize, manage, and document AFC-related technical meetings to support decision analysis, strategic planning, and lessons-learned exercises • Compile and submit the AFC year-end accomplishments report • Develop and maintain high-level AFC documents
Fuel Development and Qualification Leads	• Partner with sponsor(s)/stakeholders(s) to develop specific strategies for technology development • Establish and implement technical strategy for development and qualification of specific fuel system(s) • Prepare/issue topical reports for regulatory review • Develop and maintain inter-institutional agreements (e.g., CRADA, Memorandum of Understanding [MOU], Strategic Partnership Project [SPP])

Technical Area Leads	• Direct execution of project scope developed in collaboration with Qualification Program Leads to support external sponsors • Direct execution of project scope developed in collaboration with Strategic Leads • Generate technical reports and external publications • Scope and activities defined by funded work packages
Strategic Leads for:	**Advanced Fuel Design** • Develop advanced fuel designs to support emerging opportunities in nuclear applications **Technology Assessment** • Identify and perform assessments of campaign concepts and externally sponsored programs **Science Investigations** • Identify and prioritize needed scientific investigations into existing or proposed fuel system components or fundamental behaviors **Fuel Modeling** • Develop and maintain an integrated M&S + experimentation strategy to support fuel development and accelerated qualification **Capability Development** • Ensure adequate stewardship of existing experimental infrastructure and capabilities necessary for the nuclear fuel development and qualification enterprise • Identify, prioritize, and plan for development of future capabilities

9. FUNDING NEEDS

The mission of AFC is to: (1) support the near-term development of ALF ATF technologies with improved performance/enhanced accident tolerance and burnup extensions for current LWR fuels, and (2) perform research and development on longer-term ARF technologies for future advanced reactors with enhanced resource utilization, once-through fuel cycles, and/or high-temperature applications. The budget required to fund AFC activities is extensive. In recent years, up to $55M/year has been allocated to the three industry FOA teams leading development of ATF concepts. Table 13 provides a summary of the direct budget needed to fund the AFC program and competitively selected industry projects.

Table 13. Advanced Fuel Campaign appropriated budget and future targets FY 2021–FY 2026 (total includes laboratory and industry funding).

Fuel Development Activity	Program Element	FY22	FY23	FY24	FY25	FY26
Accident Tolerant Fuels	Industry FOA (near-term ATF)	$40M	$40M	$40M	$40M	$40M
	Industry FOA (long-term ATF)	$30M	$30M	$30M	$30M	$30M
	Laboratory Support	$34M	$34M	$34M	$34M	$27M
High Enrichment/High	Industry FOA	$10M	$7.5M	$7.5M	$7.5M	$7.5M

Burnup	Laboratory Support (SPARE)	$20M	$13M	$9M	$9M	$6M
Metallic Fuel Qualification		$9M	$10M	$7.5M	$5M	$5M
Sodium-free Metallic Fuels		$5M	$5M	$7.5M	$7.5M	$7.5M
Advanced Ceramic Fuels		$1M	$2M	$2M	$5M	$5M
Capability Development	**Program Element**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**
Fuel Testing Infrastructure	ATR I-Loop	$10M	$7M	$2M	$2M	$2M
	TREAT Fuel Rod Re-fabrication	$4M	$4M	$2M	0	0
International Collaborations	**Program Element**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**
Joint Fuel Cycle Studies	Integrated Recycling Test-1	0	0	0	0	0
NEA-FIDES	HERA Experiment	$3.0M	$3M	0	0	0
Japanese Facility Access	ARES Experiment	$2M	$2M	0	0	0

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Appendix A

Technology Readiness Level

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Appendix A
Technology Readiness Level

To provide a quantitative assessment for the maturity of a given system relative to its full- scale deployment, a Technology Readiness Level (TRL) process was developed and used by the Department of Defense. Subsequently, the National Aeronautics and Space Administration also successfully used the TRL process to develop and deploy new systems.

The NTRD program adopted the TRL concept to track the technological maturity of various competing concepts and designs. This concept is explained in the Definition of Technology Readiness Levels for Advanced Nuclear Fuels and Materials Development.[6] To use the TRL as an effective progress-tracking tool, the first step is to create quantitative definitions with specific criteria for different TRLs. The levels range from 1 to 9, where 1 signifies a new, untested, and unproven concept and 9 signifies commercial-scale deployment. The TRL level assigned to a technology or its component depends on performance requirements. For instance, uranium oxide fuels for LWRs are a proven technology, and one would bin this technology at TRL 9. However, if a requirement was imposed on the fuel that it needed to achieve a burnup in excess of 100 GWd/tHM, this would lower the TRL to 1, provided someone had at least a concept of such a fuel. Many of the grand challenges for advanced fuels development are currently at a TRL 1 or lower (because concepts are still being formed). On the other hand, fuels that can achieve some fraction of the fuel-cycle objectives exist at TRL 4 or 5, due to the recent research in the United States and abroad. Thus, one way of looking at the dual-track approach would be to pursue options with TRL 1 in parallel to options that are relatively more mature but with lesser performance expectations at TRL 4–6. The use of TRLs in tracking the performance of fuel-cycle systems, subsystems, or components provides a quantitative way of measuring progress and comparing different alternatives.

The existing TRL definitions rely heavily on the classical empirical approach used for fuel development. As we move forward, elements of the science-based approach must be incorporated into the definitions. In the meantime, regardless of how they are achieved, the criteria shown in Figure B-1 will be used to define the TRLs.

TRL	Function	Definition
1	Proof-of-Concept	A new concept is proposed. Technical options for the concept are identified and relevant literature data reviewed. Criteria developed.
2		Technical options are ranked. Performance range and fabrication process parametric ranges defined based on analyses.
3		Concepts are verified through laboratory-scale experiments and characterization. Fabrication process verified using surrogates.
4	Proof-of-Prinicple	Fabrication of samples using stockpile materials at bench-scale. Irradiation testing of small-samples (rodlets) in relevant environment. Design parameters and features established. Basic properties compiled.
5		Fabrication of pins using prototypic feedstock materials at laboratory-scale. Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified. Fuel behavior models developed for use in fuel performance code(s).
6		Fabrication of pins using prototypic feedstock materials at laboratory-scale and using prototypic fabrication processes. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Predictive fuel performance code(s) and safety basis established.
7	Proof-of-Performance	Fabrication of test assemblies using prototypic feedstock materials at engineering-scale and using prototypic fabrication processes. Assembly-scale irradiation testing in prototypic environment. Predictive fuel performance code(s) validated. Safety basis established for full-core operations.
8		Fabrication of a few core-loads of fuel and operation of a prototype reactor with such fuel.
9		Routine commercial-scale operations. Multiple reactors operating.

Figure A-1. Criteria used to define nuclear fuel development technology readiness levels.

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Appendix B
Strengths/Weaknesses/Threats/Opportunities
(SWOT) Analysis

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Appendix B
Strengths/Weaknesses/Opportunities/Threats (SWOT) Analysis

Sustain LWRs

Table B-1. Enable Deployment of ATF SWOT.

Strengths • Cross-lab technical expertise in irradiated fuels and materials • Testing infrastructure • Integrated with NEAMS • CRADAs that allow us to work with intellectual property	**Weakness** • Fragmented nature of the program; lack of integration in structure • Fragmented funding • Access to relevant but non-proprietary materials (manufacturing capability for coated claddings or SiC) • Historical R&D are buried in proprietary projects; limited access to data; data not easy to find
Opportunities • Growing utility enthusiasm for ATF if it can be shown to be economical • Better integration with NEAMS to build codes and methods • Growing interest of ATF internationally; collaboration opportunities • NRC engagement	**Threats** • Near-term deployment emphasis will drain resources from R&D activities • Insufficient resources for application • Vendor concepts technically inadequate for deployment (not all data is in place); not economical • Age of fleet; recovery time for investment is shorter; not many new reactors being built

Table B-2. Enable Burnup Extension SWOT.

<u>Strengths</u> • PIE Facilities • Access to irradiation facilities (ATR/HFIR) • Multiscale application both experimentally and modeling & simulation • Integral and semi-integral test facilities • LWR community engagement	**<u>Weakness</u>** • Lack of commercial HBu material • Funding availability • Lack of commercial information • Data on fuel material for model validation • Regulatory guidance for accident analyses or what is needed for licensing
<u>Opportunities</u> • Ability to leverage multiple DOE programs • Access to commercially irradiated HBu material • Generate new HBu material • Access to international commercial irradiated materials • Partnership with the Framework for Irradiation Experiments (FIDES) Program • Cultivate relationship with NRC	**<u>Threats</u>** • Funding stability • Inherent business sensitivity and proprietary information • International organizations currently performing LWR research • Business strategies (Ps vs Bs) • Strong Opinions (for or against) – delineate strong opinions, how to handle/resolve issues • Lack of consensus on strategy with not enough resources on hand to accommodate • Industry timelines and LWR plant closures • Regulator does not engage (keeping reactors viable); will delay deployment (i.e., mixed messages)

Table B-3. Develop National LWR Testbed SWOT.

<table>
<tr>
<td><u>Strengths</u>
Unique neutron environments from prototypic to accelerated
Size scale capabilities from micro to macro
Options for real time in-situ data in neutron environments
World class hot cells and testing/exam equipment</td>
<td><u>Weakness</u>
Availability of pre-irradiated commercial LWR material
In-situ data capabilities limited in high flux environments
Logistics – transport of items (different every time)
Vague awareness of Funding Opportunity Announcement (FOA) vendor fuel development and qualification plans</td>
</tr>
<tr>
<td><u>Opportunities</u>
Logistics – transport of items (different every time)
Synergy resource-sharing through ITEG
Staff development (LWR specific)
Opportunities to expand, uprate, and enhance loop and thermosyphon capabilities at all testbed reactors</td>
<td><u>Threats</u>
Preference for FOA's to allocate their funding internally toward model vs. testbed experimentation
Capability development cost overwhelming program R&D scope, slows progress on both, hurting each other
Testbed is abandoned after major milestones (e.g., batch reload of ATF)
Testbed real estate is displaced by advanced reactor work
Closure of international facilities, besides Halden
Older infrastructure</td>
</tr>
</table>

Table B-4. Establish Joint DOE/IND LWR R&D Program SWOT.

<table>
<tr>
<td><u>Strengths</u>

Unique world leading reactors and hot cell facilities
Growing technical expertise in LWR fuels
Network of Industry contacts at Vendors and Utilities as well as international partners

</td>
<td><u>Weakness</u>

Lack of recent experience in conducting large scale LWR fuel experiments or test programs
Lack of good agreement structure to conduct joint R&D with multiple parties especially those that are commercial competitors.

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<tr>
<td><u>Opportunities</u>

Leveraging international programs such as FIDES
Lack of comparable testing facilities worldwide

</td>
<td><u>Threats</u>

Limited life of existing LWR fleet combined with limited new builds
Economic pressure on potential cost share collaborators
Inability to receive commercial fuel and high costs associated with transporting irradiated specimens
Industry drivers for enhanced economics versus fuel safety testing and margins that may be accessible via irradiation testing

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</table>

Enable Advanced Reactors

Table B-5. Establish Licensing Basis for Metallic Fuels SWOT.

Strengths • Access to legacy pins • Strong potential partnerships (ART, NRC, NEAMS) • Historical experts • Access to knowledge	**Weakness** • Ability to generate prototypic materials • Historical shifting (goals, leadership), non-consistent level of closure (AFC/NEAMS); hierarchical prioritization • Don't have pilot-scale fabrication methodology • Limited fuel safety data
Opportunities • Strengthen partnership with industry • Cladding, structural material (HT9, irradiated at Bor-60) up to 250 dpa exposure • NRC fuel qualification exercise • Complimentary partnerships (VTR, Natrium) • Extensive model development (experience with advanced mechanistic models) • Be connected; answer the questions	**Threats** • Database management • Simulation capability and utilization • Data is not good enough to satisfy NRC • Budget stability • Divergence of industry interest

Table B-6. Develop Na-Free Metallic Fuel Design SWOT.

Strengths	**Weakness**
• Existing database • Feasibility demonstrated by recent AFC tests on annular fuel • Fabrication process development capabilities • Access to NEAMS tools	• Limited cladding irradiation performance capability • No FAST irradiation test capability • Lack of pilot scale fabrication infrastructure for LTA or LTR
Opportunities • Deployment of accelerated fuel development and qualification methodologies • State-of-art Modeling and Simulation development • Collaborate with emerging fast reactor industry • Deploy ARCTIC for full length irradiation testing	**Threats** • Delay in VTR prevents deployment of LTAs • Potential conflicts with industrial patents • Lack of transient fuel performance code for BDBA • Overlapping too much with industry • Uncertainty in plutonium role in future fuel cycle

Table B-7. Identify Next Generation Fuel Technologies SWOT.

Strengths	**Weakness**
• AFC houses international expertise in all areas needed for nuclear materials development • Numerous national laboratories have established roles and collaborations at the principal investigator (PI)-level • Relevant material system research (fuel and cladding) has been initiated in several relevant areas	• Multiple years of funding below critical mass has diluted staff engagement in AFC • Zeroing of non-LWR activities has greatly eroded capabilities – zero funding in FY22 will be irreparable
Opportunities	**Threats**
• AFC is sole nuclear energy (NE) program equipped to address accelerated qualification challenge • Recent focus on industry driven ideas and expansion of tradition (limited) operating windows for established materials has highlighted materials R&D needs • Industry is supportive of long-term R&D within AFC	• NE budget remains overly driven by industry's stated near-term needs • Large number of programs, funding sources, etc. will compete for staff and capabilities