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Revision 9

Advanced Fuels Campaign Execution Plan

June 2024

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Rev.	Date	Affected Pages	Revision Description	
7	6/30/22	All	Formatting updates to text, figures, and tables	
		12–30	Updated milestone tables and 5-year strategic plan tables	
		33	Updated organizational chart	
8	7/17/23	All	Formatting updates to text, figures, and tables	
		15	Updated Organization chart	
		4–28	Updated milestone tables and 5-year strategic plan tables	
		27	Updated Table 9	
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9	6/03/24	All	Formatting updates to text, figures, tables, and reference list	
		4-29	Updated milestone tables	
		15	Updated organization chart	

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EXECUTIVE SUMMARY

The *Advanced Fuels Campaign 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 (RD&D) activities within the Nuclear Fuel Cycle and Supply Chain program. The Nuclear Fuel Cycle and Supply Chain program has been given the responsibility to identify and mature advanced fuel technologies for the U.S. Department of Energy using a science-based approach focused on developing a fundamental understanding of nuclear fuels and materials. This science-based approach combines theory, experiments, and multi-scale modeling and simulation to achieve a predictive understanding of fuel fabrication processes (and their resulting fuel microstructures) and fuel/cladding performance under irradiation (in contrast to more empirical, observation-based approaches traditionally used in fuel performance modeling and fuel qualification).

The traditional scope of the Advanced Fuels Campaign 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 their associated cladding materials. The once-through fuel cycle addresses advanced light-water reactor (LWR) fuels with enhanced performance and reduced waste generation. In fiscal year 2012, Advanced Fuels Campaign’s scope expanded to include RD&D for LWR fuels with enhanced accident tolerance.

Fuel fabrication activities include the development of innovative processes 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 will be conducted in the later phases of the program only after a fundamental understanding of the fuel behavior is established and performance characteristics can be predicted. Then, using the tools developed under the science-based approach, fuels will be designed to meet specific performance requirements, thereby avoiding the need to repeatedly perform large-scale, integral experiments over a wide parametric range as a means of experimental exploration, reserving such experiments for the final demonstration stage of fuel qualification.

Two significant initiatives have recently been launched within the Advanced Fuels Campaign. First, a gap analysis completed in early fiscal year 2019 identified critical irradiation testing needs that are lacking 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 failure; these needs exist for supporting current LWR fuels but are especially urgent relative to near-term development and qualification of accident tolerant fuels.

Recommendations that resulted from the gap analysis focused on enhancements at the Advanced Test Reactor and Transient Reactor Test Facility to fill these gaps in testing capabilities. 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. It combines the advances in mechanistic fuel modeling of recent years with a MiniFuel separate effects test program in the High Flux Isotope Reactor and a fission-accelerated steady-state testing semi-integral accelerated test program in the Advanced Test Reactor. The systematic approach is being tested/demonstrated using the metallic fuel system but if successful should be applicable to multiple fuel types and diverse applications.

This document includes an overview of the Nuclear Fuel Cycle and Supply Chain program, a definition of science-based development of nuclear fuels, near-term goals for advanced LWR fuels, and longer-term goals for advanced reactor fuels RD&D. The grand challenge for Advanced Fuels Campaign 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. 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.

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 accident tolerant fuel 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 accident tolerant fuel objectives. A detailed set of 5-year goals was developed and is 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-fuel technologies with improved performance and enhanced accident tolerance, with implementation of lead test rods/assemblies of one or more accident tolerant fuel concepts in commercial reactor(s) by 2022

- Perform innovative research and development on longer-term advanced-reactor-fuel technologies with enhanced resource utilization with applications to both once-through and recycle scenarios
- Continue the development and demonstration of the "science-based" approach, with state-of-the-art research and development infrastructure, required to accelerate further development of advanced fuel concepts
- Collaborate on the development of predictive, multi-scale, multi-physics fuel performance models and codes.

The 5-year milestones in the *Advanced Fuels Campaign 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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FIGURES

TABLES

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ACRONYMS

AOO	anticipated operation occurrence
AFC	Advanced Fuels Campaign
AFDQ	accelerated fuel development and qualification
AFQ	accelerated fuel qualification
ALF	advanced LWR fuel
ARDP	Advanced Reactor Demonstration Program
ARES	Advanced Reactor Experiments for Sodium
ARF	advanced reactor fuel
ART	Advanced Reactor Technologies
ASI	Advanced Sensors and Instrumentation
ATF	accident-tolerant fuel
ATF-TS	Testing and Simulation for Advanced Technology and Accident Tolerant Fuels
ATR	Advanced Test Reactor
BA	burnable absorber
BWR	Boiling Water Reactor
CEA	Commissariat a l’Energie Atomique
CNWG	Civil Nuclear Energy Research and Development Working Group
CPR	critical power ratio
CRADA	cooperative research and development agreement
CRAFT	Collaborative Research on Advanced Fuel Technology
CSNI	Collaboration on Nuclear Safety Installations
DB	design basis
DE	design extension
DNBR	departure from nucleate boiling ratio
DOE	Department of Energy
EBR	Experimental Breeder Reactor
EDF	Electricité de France
EGFM	Expert Group on Fuels and Materials
EGIFE	Expert Group on Innovative Fuel Elements
EGRFG	Expert Group on Reactor Fuel Performance

EGSM	Expert Group on Structural Materials
EML	Electron Microscopy Laboratory
EPIC	experiment preparation and inspection cell
EPRI	Electric Power Research Institute
FAST	fission-accelerated steady-state testing
FCCI	fuel-cladding chemical 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
FIPD	Fuels Irradiation & Physics Database
FOA	funding opportunity announcement
FPT	Fuel Performance and Technology
FY	fiscal year
GAIN	Gateway for Accelerated Innovation in Nuclear
HBu	high burnup
HBWR	Halden Boiling Water Reactor
HERA	high-burnup experiments in reactivity-initiated accidents
HFIR	High Flux Isotope Reactor
HRP	Halden Reactor Project
IAEA	International Atomic Energy Agency
IGR	Impulse Graphite Reactor
IMCL	Irradiated Materials Characterization Laboratory
INL	Idaho National Laboratory
IRSN	Institute for Radiological Protection and Nuclear Safety
JFCS	joint fuel cycle studies
LEU	low enriched uranium
LFA	lead fuel assembly
LHR	linear heat rate
LIFT	Leading Innovation for Fuel Technologies

LOCA	loss-of-coolant accident
LTA	lead test assembly
LTR	lead test rod
LUA	lead use assembly
LWR	light water reactor
LWRS	Light Water Reactor Sustainability (program)
M&S	modeling and simulation
MARCH	minimal activation retrievable capsule holder
MFF	mechanistic fuel failure
MITR	Massachusetts Institute of Technology Reactor
MOU	Memorandum of Understanding
MOX	mixed oxide fuels
NCS	Nuclear Science Committee
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
NFIR	Nuclear Fuel Industry Research
NNC	National Nuclear Center
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NTD	national technical director
NTRD	Nuclear Technology Research and Development (program)
NUREG	Nuclear Regulatory Commission Regulation
ODS	oxide dispersion strengthened
OECD	Organization for Economic Cooperation and Development
ORNL	Oak Ridge National Laboratory

PA	project arrangements
PCI	pellet cladding interaction
PCM	power cooling mismatch
PIE	post-irradiation examination
POC	point of contact
PWR	pressurized water reactor
QA	quality assurance
R&D	research and development
RD&D	research, development, and demonstration
RIA	reactivity-insertion accident
SATS	Severe Accident Testing Station
SCIP	Studsvik Cladding Integrity Project
SET	safety engineering test
SFR	sodium fast reactor
SiC-CMC	Silicon Carbide Ceramic Matrix Composites
SMR	small modular reactor
SPP	strategic partnership project
SS	stainless steel
tFGR	transient fission gas release
TREAT	Transient Reactor Test Facility
TRISO	tri-structural isotropic
TRL	Technology Readiness Level
TWG	Technical Working Group
UC	uranium carbide
UCO	uranium oxycarbide
UN	uranium nitride
VTR	Versatile Test Reactor
WGAMA	Working Group on Analysis and Management of Accidents
WGFS	Working Group for Fuel Safety
WP	Working Party
WPFC	Working Party on Scientific Issues of Advanced Fuel Cycles

WPFM	Working Party on Scientific Issues on Nuclear Fuels and Structural Materials
WPRS	Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems

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Advanced Fuels Campaign Execution Plan

1. INTRODUCTON

The *Advanced Fuels Campaign (AFC) Execution Plan* provides a summary-level description of how AFC supports the achievement of the overarching Department of Energy (DOE) Office of Nuclear Energy (NE) vision and mission. This execution plan, a living document updated annually, is guided by the *DOE-NE Strategic Vision* (Figure 1). The *DOE-NE Strategic Vision* is "[a] thriving U.S. nuclear energy sector delivering clean energy and economic opportunities" [2]. The mission of DOE-NE and thus of the AFC is to advance nuclear energy science and technology to meet U.S. energy, environmental, and economic needs. To accomplish this mission and achieve the strategic vision, DOE-NE has identified five goals:

1. Enable continued operation of existing U.S. nuclear reactors
2. Enable the deployment of advanced nuclear reactors
3. Develop advanced nuclear fuel cycles
4. Maintain U.S. leadership in nuclear energy technology
5. Enable a high-performing organization.

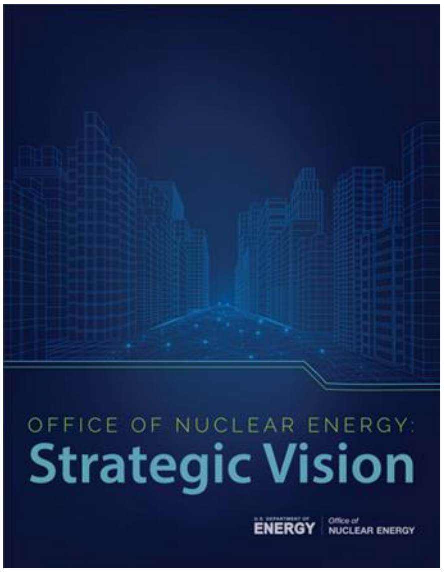

Figure 1. *DOE-NE Strategic Vision* document.

The AFC directly supports goals 1 and 2 by enabling the continued operation of existing U.S. nuclear reactors and deployment of advanced nuclear reactors. These goals are supported by clearly identified campaign objectives outlined in this execution plan. AFC supports DOE-NE's other three goals through its adaptable organizational structure and science-based engineering-driven approach to new fuel development. Additionally, the AFC is well integrated with other DOE-NE research and development (R&D) programs, actively engaged with the domestic nuclear industry, and involved in numerous international nuclear energy organizations and research programs.

2. ADVANCED FUELS CAMPAIGN GOALS AND OBJECTIVES

The AFC's goals mirror the first two goals of the DOE-NE Strategic Vision to enable both the continued operation of the existing light-water reactor (LWR) fleet and the deployment of advanced reactors. For each goal, the AFC has identified four objectives shown in Figure 2.

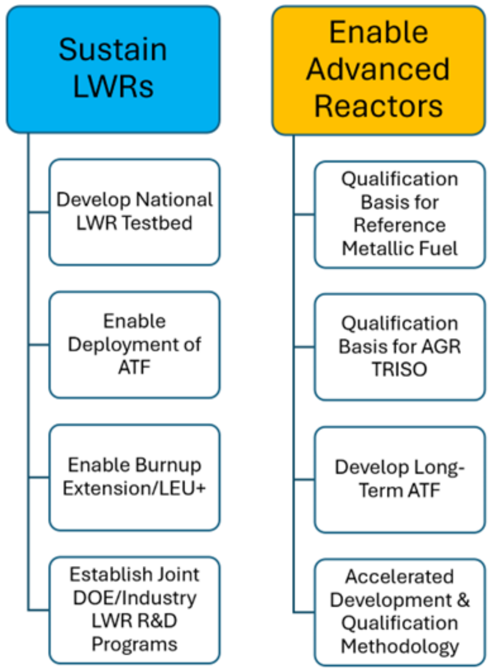

Figure 2. AFC goals and objectives.

2.1 Sustain Light-Water Reactors

Nuclear power has reliably and economically contributed approximately 20% of electrical generation in the United States over the past 2 decades and remains the single largest contributor (approximately 56%) of non-greenhouse-gas-emitting electric power generation. Operating the existing fleet of plants to 60 years, extending the operating lifetimes of those plants beyond 60 years, and, where practical, making further improvements in their productivity are essential to support the nation's energy needs: supply, reliability, and diversity. The existing domestic LWR fleet is focused on plant modernization, flexible plant operation and generation, risk-informed system analysis, materials research, and physical security [3].

2.1.1 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 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 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).

The U.S. DOE began revitalizing LWR testing capabilities in the preceding decade to enable the enhancement of LWR economic and safety performance as encompassed by accident tolerant fuel (ATF) and high-burnup (HBu) program objectives. Capsule and pressurized-water loop fuels testing capabilities are now established in the Advanced Test Reactor (ATR). Similar capabilities, but focused on un-fueled cladding materials, are now in use at the Massachusetts Institute of Technology Reactor (MITR). Water capsules devices have been established for fuel safety testing in the Transient Reactor Test Facility (TREAT). Irradiation capsules have been deployed to enable high flux testing of small fuel and material specimens in the High Flux Isotope Reactor (HFIR). These accomplishments now constitute a critical mass of capabilities worthy of being branded as the National LWR Testbed (see Figure 3).

More recently, the unexpected closure of HBWR created the need for a second wave of capability development to enable in-pile loss-of-coolant accident (LOCA) testing, pellet-cladding-interaction (PCI) power-ramp testing, and the ability to outfit previously irradiated rod segments with crucial instrumentation. Current projects are now underway to establish LOCA blowdown capsules for TREAT, competencies for instrumenting test specimens, power ramp capabilities in ATR water loops, and reflector-based loops "I-Loops" at ATR to enable increased capacity/flexibility in test programs.

The testbed will require further stewardship and enhancement to support the development of revolutionary ATF designs (e.g., SiC/SiC cladding and high-density/composite fuels) and other advancements needed to maintain the vitality of water-cooled reactors (e.g., LightBridge fuel, advanced small modular reactors [SMR] fuels, and regulator-driven testing). Safeguarding the testbed will require steadfastness in improving in situ instrumentation technology, creative approaches to accelerated testing strategies, and thoughtful development of the next generation irradiation testing experts. 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, remain a prominent effort for AFC. Milestones for developing the National LWR Testbed are delineated in Table 1 for each fiscal year (FY) until FY 2028.

Figure 3. Develop National LWR Testbed.

Table 1. Develop National LWR Testbed milestones.

FY 2024	• Early PIE assessment comparison report for accelerated LWR test • Recommission Severe Accident Testing Station (SATS) with "recapitalized" capabilities
FY 2025	• Inaugurate first I-Loop for fuel testing in ATR • Deploy Halden cryo-drilling system in the Experiment Preparation and Inspection Cell (EPIC) hot cell • Commence demonstration irradiation for accelerated LWR testing (fission accelerated steady-state testing [FAST], MiniFuel) • Commission pre-irradiated fuel HBu tests for Transient Water Irradiation System in TREAT (TWIST) in TREAT
FY 2026	• Commission capability for power ramp testing rods in I-Loop • Inaugurate second I-Loop to support simultaneous testing (boiling-water reactor [BWR], pressurized-water reactor [PWR], ramp, stainless steel [SS]) • Commission Gen 2 bolt-on mods for TREAT LOCA capsule

FY 2026–2028	• LWR application of accelerated irradiation testing methods
	• Upgraded loop corrosion testing capacity at MITR
	• Flowing water loop and bundle testing in TREAT
	• Opportunistic adaptations and capacities for a bigger circle
	  o Water-cooled SMRs
	  o International support (MOX [mixed oxide fuels], PHWR)
	• Bridges to the next generation of MTRs

2.1.2 Enable Deployment of ATF

In comparison with the standard UO_2-Zircaloy, ATF for LWRs can tolerate a loss of active cooling in the reactor core for a considerably longer time, while maintaining or improving fuel performance during normal operations, operational transients, as well as design basis and beyond design basis events.

Deploying ATF is a vendor-led initiative within the Department of Energy's Nuclear Fuel Cycle Supply Chain Program. The nuclear vendors who received the first DOE financial assistance agreement awards for parts 1, 2A, 2B, and 2C for deploying ATF include General Electric, Framatome, and Westinghouse. ATF is generally divided into near-term and long-term technologies. Near-term technologies include coated zirconium alloy claddings and doped (ppm level) UO_2 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 prioritized nearer term concepts in the vendor-led ATF projects due to limited ATF funding. Independent of the ATF vendor awards, DOE also released a fourth funding opportunity announcement (FOA) solicitation focused on deploying SiC-CMC technologies with allotments of $5 million, $10 million, and not less than $15 million for award in FY-21, FY-22, and FY-23, which were primarily granted to General Atomics.

The national laboratories in AFC have three roles or strategies relative to ATF as follows:

- Establishing and maintaining the irradiation testing and examination infrastructure required to generate necessary licensing and qualification data
- Generating material property and performance data of vendor-developed ATF materials through participation in the vendor-led FOA agreements
- Conducting independent and university collaboration R&D on general behaviors of ATF materials being pursued by the industry teams.

The milestones for enabling the deployment of ATF are delineated in Table 2.

Table 2. Enable deployment of ATF milestones.

FY 2024	• Receive Byron rods • First examination of second cycle ATF pins • Refabricating first rods from commercial pins
FY 2025	• Begin irradiation testing of refabricated and reinstrumented fuel pins from commercial lead test rods (LTR)/lead test assemblies (LTA) in ATR • Begin in-pile LOCA testing of pre-irradiated rods in TREAT
FY 2026	• Irradiate refabricated and reinstrumented fuel pins from commercial LTR/LTAs to very high burnups ≥75 GWd/MTU in ATR • Irradiations of Framatome CrM5 in ATF2 and PIE • Irradiations of GE FeCrAl in ATF2 and PIE • Irradiations of JAEA/Nippon/GEH/GNF-J FeCrAl in ATF2 and PIE • Develop and deploy a ramp test train in ATR Medium I Water Loops • LOC-HBu TREAT Testing Program (through FY-27) • Irradiations in PWR and BWR I-loop and PIE (through FY-28) • Irradiations of General Atomics SiCGA in ATF2 and PIE (through FY-28) • Irradiations of JAEA/MHI-coated cladding in ATF2 and PIE (through FY-28) • Launch operational transients joint project (through FY-28) • Fission gas diffusivity and bubble growth kinetics • Integrate creep experiments and modeling for metallic cladding • Small-scale testing for accelerated evaluation o FAST ceramic fuel irradiations (through FY-27) • Evaluation of bowing of SiC tubes (LWR temp) (through FY-27) • HFIR irradiation and PIE of GA SiC cladding fabricated by cost effective method (through FY-28) • Accident resistance of SiC cladding/liquid metal system (through FY-28)
FY 2027	• PIE of Westinghouse Cr-Opt Zirlo and Adopt (~75 GWd/MTU) from Byron • PCI Ramp Testing on Westinghouse Cr-OptZirlo w/ Adopt Pellets (through FY-28) • MiniFuel ceramic fuel irradiations (through FY-28) • See additional milestones above
FY 2028 (and outward)/5-year accomplishments	• Accident tests of irradiated SiC tubes (SATS and TREAT) • Update material property handbook • Develop and experimentally validate an advanced fuel performance modeling tool to predict cladding behavior

2.1.3 Enable Burnup Extension/Low Enriched Uranium (LEU)+

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, the number of outages, and possibly 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 (NPP). 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 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 developing the required technical basis will require and greatly benefit from additional R&D to investigate underlying separate effects and integral high-burnup fuel performance.

In response to industry goals, Congress directed the U.S. 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. LWR fleet beyond current regulatory limits. The role of the AFC HBu program is to support this goal by identifying, prioritizing, and filling data gaps that will extend the 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 wants 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 to fill technical knowledge gaps. Collaborative Research on Advanced Fuel Technologies (CRAFT) for LWRS program including representatives from major interests in industry, NRC, and from AFC program representation lead this complex integration effort. CRAFT's purpose is to disseminate the information from 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., Studvik Cladding Integrity Project [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) program where applicable. The milestones for enabling burnup extension are delineated in Table 3.

Table 3. Enable Burnup Extension milestones.

FY 2024	• Perform advance microstructure characterizations on HBu fuel provided by fuel suppliers with special emphasis to support LOCA and reactivity-insertion accident (RIA) experiments • Transport of Byron segment from INL to Oak Ridge National Laboratory (ORNL) for HBu testing • Perform SATS test on HBu commercial fuel to investigate fuel fragmentation, relocation, and dispersal (FFRD) phenomena with specific intention to compare to full integral TREAT LOCA test • Perform first refabrication of LTA segment • Develop state-of-the-art report on quantification of operating conditions on HBu microstructural formations • Identify fuel performance limitation beyond burnup extension to enhance fuel utilization and operation efficiency/develop R&D plan to investigate fuel performance limitations
FY2025	• Initiate TREAT and SATS LOCA test • 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 • Begin loop experiments in ATR on commercial HBu fuel segments to investigate operational performance parameters (e.g., dryout, thermal conductivity)
FY 2026	• Benchmark TREAT LOCA/RIA and SATS against industry standard tests

	• Perform TREAT and SATS tests on reirradiated HBu fuels • Revise LOCA test plan to include HBu ATF • Summarize tFGR test results • Initiate anticipated operation occurrence (AOO) failure criteria test matrix • PIE on ATR and HFIR irradiations
FY 2027	• Complete rev0 TREAT-SATS LOCA test plan • Complete AOO failure criteria test matrix • Execute plan to support HBu ATF • Complete PIE on ATR and HFIR irradiations
FY 2028 (and outward)/5-year accomplishments	• Expand HBu LOCA database and resolve critical questions • Inform industry topicals • Address LWR transient testing needs • Identify transient testing needs • Initiate Phase 2 (if needed) • Understand HBu microstructural evolution • Develop AOO failure criteria • Inform modeling and simulation (M&S) capabilities • Receive/generate prototypic HBu material • Complete PIE on HBu material • Support transient testing

2.1.4 Sustain Joint DOE/Industry LWR R&D Program

Following decades of dormancy, DOE-funded R&D activities related to LWR applications were revived in 2012 at the national laboratories to enable the development and deployment of ATF. As this program gained momentum, the DOE mission scope expanded to include R&D for enabling burnup extension. Significant relationships were developed between the key stakeholders (industry, regulators, and researchers) during this time. While a significant fraction of the DOE budget was targeted at supporting vendor-led technology development during the first decade of this program, a significant pivot is expected to occur following the deployment of this technology. 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 the historic joint project (i.e., Halden Reactor Project). One goal of the AFC program is to facilitate this transition over the next approximately 5 years through the 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 maintain the utilization of the LWR testbed for long-term use.

Joint projects are typically organized around common R&D themes that crosscut the participating partners' needs. This AFC program goal is to develop a joint LWR R&D program that will focus on irradiation performance tests aimed at collecting integral fuel performance data and/or establishing failure limits for ATF/HBu 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 supporting the assessment and validation of modern M&S tools used in the design and licensing of nuclear installations. To support this objective, a commitment to develop and implement advanced in situ instrumentation within this project will be critical.

The scale and complexity of the experiments conducted under the joint program may vary and are expected to consist of both in-pile experiments in test reactors and furnace-based testing in hotcell 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 such as:

- LOCA conditions
- RIA conditions
- Power-cooling mismatch conditions, beyond departure from nucleate boiling ratio/critical power ratio (CPR)
- Aggressive power ramp conditions.

The test programs will principally use 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 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.

A healthy, self-sustaining joint project of this type is expected to require ~$10–20M/yr of R&D funding to be successful. If the program follows a model similar to the historic Halden Reactor Project where the host institution pays ~50% 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 gradually 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 international participation in international programs with similar goals such as the Nuclear Energy Agency's (NEA's) 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. The milestones for the sustain joint DOE/industry LWR R&D program are delineated in Table 4.

Table 4. Sustain joint DOE/industry LWR R&D program milestones.

FY 2024	• Continue to irradiate joint ATF specimens in center flux trap
FY 2025	• Begin irradiation testing of refabricated and reinstrumented fuel pins from commercial LTR/LTA in ATR • Begin in-pile LOCA testing of pre-irradiated rods in TREAT
FY 2026	• Irradiate refabricated and reinstrumented fuel pins from commercial LTR/LTAs to very high burnups ≥75 GWd/MTU in ATR
FY 2027	• Demonstrate the ability to conduct dynamic (power ramp) testing in a flowing water loop at ATR
FY 2028	• Joint program on power ramp testing

2.2 Enable Advanced Reactors

2.2.1 Establishing Licensing Basis for Metallic Fuel

Metallic fuel for fast reactors is a unique technology developed and demonstrated by U.S. R&D programs for more than 7 decades. The fuel type has several advantages including favorable thermal properties, high density, ease of fabrication and low sensitivity to fabrication variability, and compatibility with proliferation resistant pyroprocessing recycling. The Nuclear Energy Institute Fast Reactor Working Group has identified metallic fuel as the most chosen fuel type of fast reactor designers, and interest for application extension to thermal reactors is also considered in industry. This work's primary outcome is establishing a complete set of fuel performance models, quantified performance limits, and supporting validation data, including unique new results, that can be used by research, commercial, and regulatory stakeholders for decades to come. The targeted fuel design is U-10Zr in HT9 and D9 claddings and potentially addressing the impacts of Pu addition to the fuel. The program goal is to accomplish this effort in less than 5 years while providing significant new data for opportunity gaps already being identified through recent evaluations performed to support licensing fuel for the Versatile Test Reactor (VTR) program.

The empirical basis for metallic fast reactor fuel performance is strong from driver fuel usage and testing in the Experimental Breeder Reactor (EBR)-II and the Fast Flux Test Facility (FFTF) combined with transient evaluation in furnaces and the TREAT facility. Yet, significant opportunity remains to establish a complete knowledgebase supporting metallic fuel continued development and licensing after the abrupt termination of the historic Integral Fast Reactor program. Several existing tools make this goal possible including advanced modeling toolsets (NEAMS BISON/MARMOT), databases for historical programs (FPID, TREXR, OPTD), advanced characterization tools (Irradiated Materials Characterization Laboratory [IMCL] and Electron Microscopy Laboratory [EML]), transient testing capability (TREAT), thermal reactor testing capability (ATR), and availability of DOE-irradiated materials over a broad range of conditions and designs. With these tools, the AFC program will need to undergo R&D in each of its five technical focus areas to achieve the overarching goals.

This work's primary deliverables will be the fuel qualification basis for the reference metallic fuel designs that captures state-of-the-art understanding and leverages modern toolsets to maximize the data extracted from a rich legacy material library. The fuel qualification basis will be achieved through datasets and analyses presented in various venues with culminating reports, currently targeting regulatory review. The current vision is a set of 2–3 volumes that will comprise the synthesis of current knowledge with extension to address data gaps and opportunities that will be identified and studied over the next 5 years. These reports are considered a significant achievement and end goal for fuel R&D, worthy of dedicated DOE program investment over the next 5 years. The licensing basis for metallic fuel milestones are delineated in Table 5.

Table 5. Establishing licensing basis for metallic fuel milestones.

FY 2024	• Perform measurements on irradiated HT-9 cladding to fill gaps/expand needed data sets for incorporation into handbook • Summary report on fuel thermal conductivity and fuel swelling behavior based on linking microstructure to operational history with modern PIE and modeling • Summary report on FCCI behavior based on additional modern PIE, image analysis, and modeling • Complete initial draft(s) of fuel performance data and models review for input to final qualification reports • Complete new thermal creep model for HT-9 to use in BISON modeling of life limiting fuel pin behavior • Complete final design of Na loop commissioning experiments • Complete final design of hot cell transient testing furnace
FY 2025	• Initiate in-pile experiment to measure thermal conductivity with direct linkage to modeling and PIE • 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) • Complete assessment of fuel performance code (BISON) applicability to reference fuel design and identified design limits. • Complete quality assurance (QA) on legacy data in the Fuels Irradiation & Physics Database • Demonstrate refabrication capability for metallic fuels

	• Complete selection of modern fuel fabrication techniques to replace current techniques, including waste reduction improvements, fabrication costs and product uniformity. (This will also include efforts to eliminate Na-bonding - see below).
FY 2026	• Complete assessment of limit refinement due to new modeling and experimental information • First experiments on irradiated specimens in hot cell transient furnace • Draft second and third fuel qualification reports focused on fuel properties and transient performance • Detailed evaluation of transient FCCI (fuel-cladding eutectic behavior) using transient furnace and model development • Demonstrate new fabrication techniques to build fuel pins for irradiation testing
FY 2027	• Complete transient testing and PIE on mechanistic fuel failure materials testing in TREAT and hot cell transient furnace for fuel qualification reports • Complete fuel qualification reports on fuel properties and transient testing • Perform first transient tests on irradiated long-length FFTF specimens in Na loop
FY 2028 (and outward)/5-year accomplishments	• Establish fuel design basis stemming from physics-based and empirically founded arguments • Analyze initial results of irradiation testing of new fuel made using improved fabrication. Compare date with parallel developed fuel performance models. • Close gaps in data and modeling • NRC topical reports are targeted goal as physical deliverables benefiting all stakeholders • Innovation stemming from an established fuel design basis • Fuel Type: U-10Zr in HT9 and D9 cladding (and U-20Pu-10Zr) o Harvest legacy material data

2.2.2 Develop Na-Free Metallic Fuel Design

Several thought leaders in the nuclear fuel field have recently focused their strategic thinking on methods that accelerate the fuel development life cycle. These philosophic approaches are becoming better published but plans for applying them to specific fuel technologies are sparse. Accelerating fuel development and qualification will require more rapid task execution as well as thoughtful planning. AFC is leading efforts to develop such a plan for proposed fast reactor metallic fuel technology without fuel-to-cladding alkali metal bonding (commonly called sodium-free fuel).

In recent years, sodium-free metallic fuel designs have become of high interest to industry. This interest is primarily driven by the simplification of fabrication processes, neutronic benefits (during both expected operation and off-normal events), and reduction of disposal hazard 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. Sodium-free metallic fuel has long been recognized for its value potential in enhancing fast reactor technology. Managing fuel thermal performance without a liquid metal bond requires geometric adaptation, revamped fabrication processes, and new irradiation performance data. Both the spectrum of necessary development tasks and the advanced reactor-enabling value potential of sodium-free fuel can be compared to the development of uranium carbide oxide tri-structural isotropic for high-temperature gas reactors in recent decades. The legacy of relevant metallic fuel data and advances in fuel performance understanding through modeling solidifies the potential to accomplish sodium-free fuel deployment in an abbreviated timeframe. However, obstacles such as fabrication process development and lack of a fast spectrum test reactor will require creativity and steadfastness to achieve sodium-free fuel qualification. The AFC program remains committed to this grand challenge. The milestones for developing Na-free metallic fuel design are delineated below.

Table 6. Develop Na-free metallic fuel design milestones.

FY 2024	• Prioritize candidates based on life cycle and performance models • Complete irradiation of FAST-01 remaining specimens • Final design of full-size pin ATR test • Design analytic experiment irradiation test series (e.g., subsize, accelerated, and instrumented) • Bench scale fabrication trials of candidate fuel fab processes • Spec out equipment and facility needs for pilot scale full-size pin fabrication options
FY 2025	• Screen candidates based on bench scale fab trials • Complete PIE and assessment report for FAST-01 • Begin analytic experiment irradiation tests • Fresh fuel tests in TREAT sodium capsule • Commission TREAT sodium loop with baseline fuel • Install full-size pin fabrication equipment • Full-size pin fabrication trials, establish fuel fabrication specifications
FY 2026	• Down select design for qualification based on analytic experiments • First batch PIE on analytic experiments (fab comparison down select) • Commission full-size pin ATR rig with baseline fuel • Perform fresh fuel TREAT tests on full-size pins • Fabricate full-size pins for qualification tests
FY 2027	• Complete PIE on analytic experiment specimens (properties-based model validation) • Begin irradiation of full-size pin qualification tests in ATR • Fabricate full-size lead test assembly
FY 2028	• Perform TREAT tests on full-size pins irradiated in ATR • Complete PIE on full-size pins • Produce fuel qualification report: NRC Regulation (NUREG) • Submit data for license amendment Natrium LTA • Begin LTA demonstration irradiation in Joyo and/or Natrium

2.2.3 Develop an Accelerated Fuel Development and Qualification Methodology

A typical fuel testing cycle is shown in Figure 4. This research methodology applies to any fuel type under development, including the AFC major research areas. Additional information is included in the subsections.

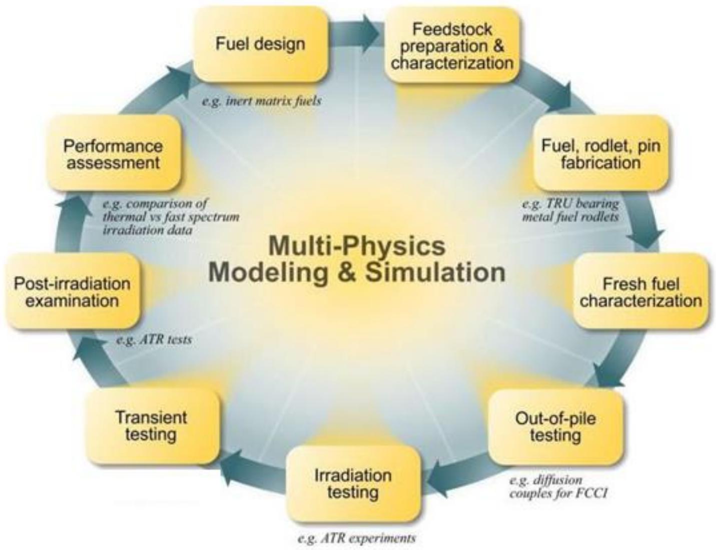

Figure 4. Elements of the fuel development cycle integrated with advanced modeling and simulation.

AFC supports developing 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 research, development, and demonstration (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 5 and outlined in the subsequent sections.

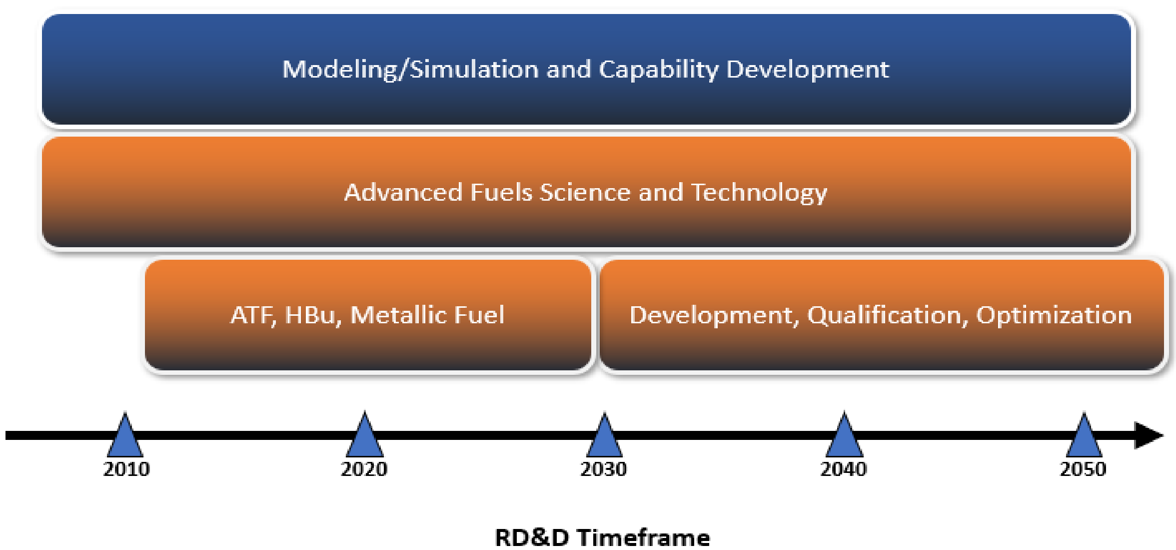

Figure 5. AFC research areas and capabilities-development timeline.

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 concept to track the technological maturity of various competing concepts and designs. Refer to Appendix A for additional information.

Implementing the primary function 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.

2.2.4 Identify Next Generation Fuel Technologies

The U.S. nuclear industry is investing in nuclear fuel technologies to improve the performance of current generation reactors as well as planning for future reactors, including advanced reactors (e.g., liquid metal cooled) as well as novel microreactor technologies. The primary driver for advancing fuel technologies is to improve the performance, economics, and longevity of nuclear fuel in reactors. Such improvements can be facilitated through incremental improvements to the uranium density as well enhancements to the thermophysical properties, while evaluating and mitigating potential risks associated when deviating from traditionally employed fuels.

Ceramic nuclear fuels have a demonstrated record of strong performance in reactors, including the traditionally utilized UO_2 in LWRs. Recent efforts within the DOE-NE to support ATF designs have improved the fission gas release performance of UO_2 by employing dopants (e.g., Cr, Al, and Si). Similar doping strategies have been proposed under the NEAMS campaign to improve not only the fission gas release behavior but also fuel pellet cladding interactions with minimal anticipated degradation to other fuel parameters. Likewise, interest in extending the burnup limit beyond the licensure case of 62 GWd/tU will require investment into burnable absorber (BA) and high suppression technologies to average out the burnup over the lifetime of the fuel in pile.

Longer-term ceramic nuclear fuels, such as high uranium density fuels and mixed oxide (MOX) fuels, are of interest due to the improved neutron economy and ability to support multiple reactor technologies. However, the lack of experimental data and need for improved cladding concepts that can support the anticipated lifecycle of the ceramic fuels will require further developments to extract the potential of the fuels. An avenue to accelerate the development and qualification of fuels is with accelerated irradiations (e.g., Fission-Accelerated Steady-State Testing at ATR and MiniFuel at ORNL) coupled with advanced modeling and simulations techniques to minimize costly PIE. Furthermore, non-destructive evaluation of pre- and post-irradiated fuel assemblies will expedite the PIE process to facilitate targeted examinations on fuel rods. Furthermore, broader interest from the international community in advanced ceramic fuels (e.g., MOX) as well as the relative maturity facilitate the need to engage in MOX-based fuel forms. The milestones for the development of next generation fuel phases for advanced reactors are delineated in Table 7.

Table 7. Development of next generation fuel phases for advanced reactors milestones.

FY 2024	• Initiate accelerated fuel qualification (AFQ) irradiation campaign to benchmark a safety engineering test (SET) approach against either known (e.g., UO_2/Zry) or challenge (e.g., UN/SiC) systems • Begin PIE on high-dose irradiated Fe-Cr oxide dispersion strengthened (ODS) samples from Phenix irradiation (MATRIX) • Begin PIE of next generation fuel test specimens from NFIR-8 and AFC tests
FY 2025	• TRL3 for LWR fuel designed for expanded linear heat rate (LHR)/BU operating window • Begin PIE on high-dose irradiated Fe-Cr ODS samples from HFIR irradiation

	• Complete PIE of next generation fuel from Nuclear Fuel Industry Research (NFIR)-8 and AFC tests. Assess and report results. Develop plan for second phase testing.
FY 2026	• Progress report on initial AFQ PIE data collected using MiniFuel, FAST, etc. • Update fuel cycle research and development 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 • Make selections of cladding/fuel types for final development • Engage industrial partners for developing large-scale fabrication operations for cladding and other core components • Engage industrial partners for developing large-scale fabrication operations for fuel and fuel pins
FY 2027	• Demonstrate development of large-scale industry fabrication of cladding and core components, and of fuel
FY 2028	• TBD

3. AFC ORGANIZATION

The AFC management team consists of the federal technical manager, national technical director (NTD) and deputy, systems integration 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. The roles and responsibilities for each are summarized below as well as the primary roles and responsibilities of AFC personnel (see Figure 6 and Table 8).

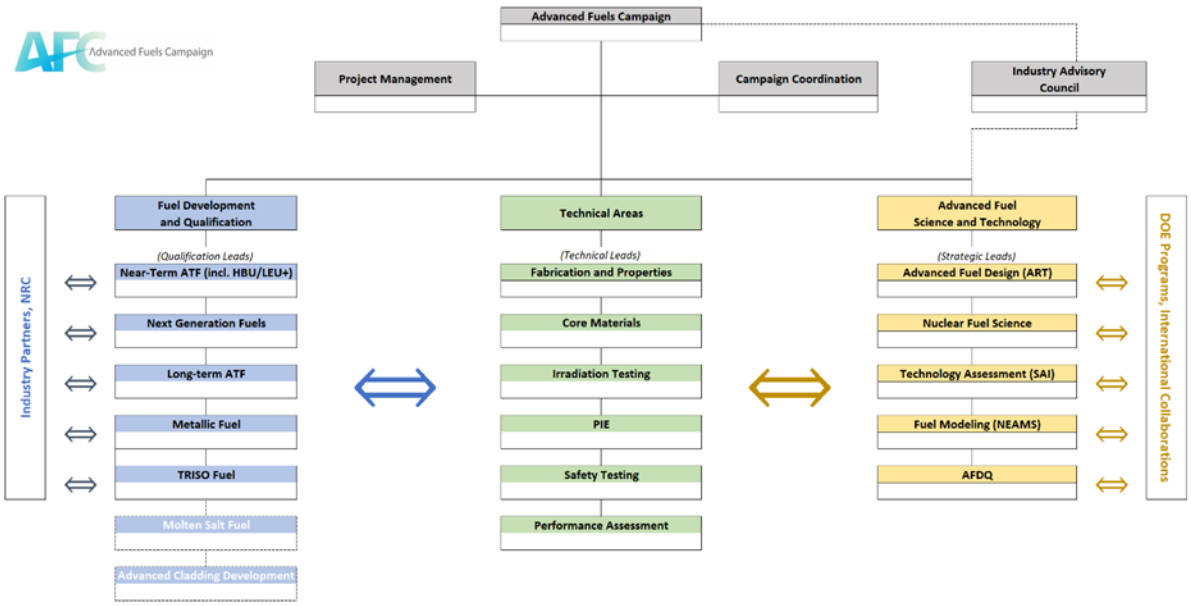

Figure 6. Advanced Fuel Campaign organizational structure.

Table 8. AFC personnel roles and responsibilities.

AFC National Technical Director	• Report to the federal technical manager for 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 and perform all NTD tasks as needed
Systems Integration Lead	• Build relationships with AFC Team, DOE, stakeholders, and other organizations to both learn about and provide feedback on AFC capabilities and activities • Assist with problem determination and resolution efforts within AFC • Develop standards, processes, and documents to support and facilitate AFC projects and initiatives • Create detailed AFC road maps, plans and schedules, update future releases as necessary • Organize project documents; periodically update and maintain documents in a shared location for AFC member access • Develop the functional and technical requirements for the AFC, based on input from the technical leads and the fuel design analysis • Organize and manage semiannual 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., cooperative research and development agreement [CRADA], memorandum of understanding [MOU], and 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 **Nuclear Fuel Science** • 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
Program Support	• Execute communications strategy • Milestone dissemination • Logistical arrangement for program review meetings (leads and annual review) and program internal/external visits • Review meetings (leads and annual review) • Maintain program meeting schedule • Maintain program contact information (program rolodex) • Administrative activities, including but not limited to managing the development, processing, and approval of security plans, travel logistics, and maintaining program records

4. SCIENCE-BASED ENGINEERING-DRIVEN 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 M&S, to optimize the number, cost, and objectives of engineering-scale tests (Figure 7).

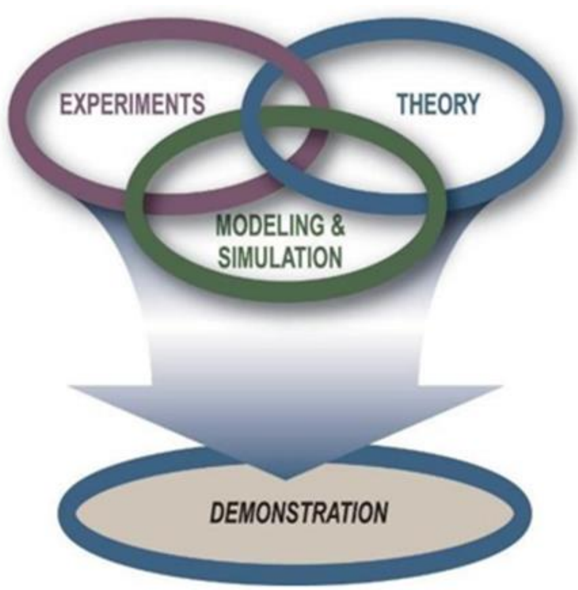

Figure 7. Goal-oriented, science-based approach.

4.1 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.

4.2 Theory

Essential elements of the science-based approach will build upon existing theories and 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.

4.3 Modeling and Simulation

The knowledge and data gained under experimental and theoretical elements of the science-based approach will be incorporated into advanced 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.

4.4 Demonstrations

Nuclear energy systems are large-scale, complex facilities characterized by phenomena that can span 10 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 using 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.

4.5 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. 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 8.

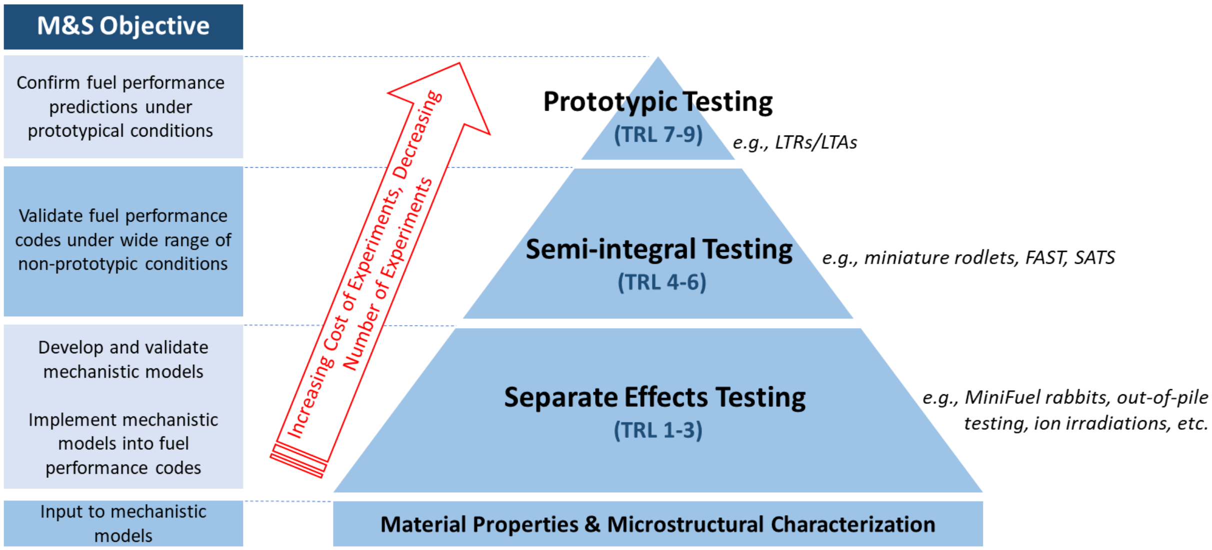

Figure 8. Idealized fuel testing paradigm.

Ultimately, an accelerated approach to fuel qualification involves 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:

- **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.
- **Modular and flexible irradiation test platforms**, such as the Minimal Activation Retrievable Capsule Holder 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.
- **Advanced in situ instrumentation** for irradiation testing, recently implemented at the TREAT facility and a focus of capability development for 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 Advanced Sensors and Instrumentation (ASI) program is working with AFC to establish these capabilities.
- **Advanced post-irradiation examination and experiment capabilities**, notably installed in the IMCL, that include a focus to obtain data that supports development of lower length scale models as well as transient performance evaluations, such as the SATS.
- **Mechanistic, multiphysics models and simulation tools** developed primarily under the 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 are necessary to validate these models.

The fuel qualification programs outlined in later sections are increasingly implementing these techniques. The Leading Innovation for Fuel Technologies 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.

5. AFC INTEGRATION

Advanced fuel development cannot be implemented in isolation from the other DOE RD&D programs, the domestic nuclear industry, and the international community.

5.1 Interfaces with Other DOE Programs and Program Elements

- **LWRS Program.** ATF requires a strong technical interface with LWRS. Limited work has been performed for advanced LWR fuels (ALF) under the LWRS program, previously including silicon-carbide cladding development and currently including 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.
- **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.
- **ASI.** The ASI program includes an 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 also to develop and implement next generation devices into representative reactor core environments via in-pile experiments. These tools are crucial for 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.
- **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 lead fuel assemblies, which will require the existence of a suitable facility (e.g., demonstration fast reactor).
- **Joint Fuel Cycle Studies.** AFC funded the IRT-1 irradiation experiment in ATR for 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 the goals and objectives of AFC. In addition to providing direct topical calls to the NEUP program, AFC encourages a 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.

5.2 Domestic Nuclear Industry and Regulatory Community

- **Industry and Electric Power Research Institute.** RD&D for advanced fuels is long-term, expensive, and high-risk regarding 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.
- **NRC.** The NRC must license any new fuel before it can be deployed in commercial power reactors. Early involvement of the NRC in the R&D phase will enable timely licensing of eventual products. This is especially true if there is a change in the licensing paradigm because of a goal-oriented, science-based approach to fuel development. Fuel development and qualification require continuous interactions with NRC from the outset for a timely implementation of such fuels.

5.3 International Collaboration Strategy

Effective international collaborations are essential to both support the development of new nuclear fuel technology and pave the way for strategic implementation around the world. International collaborations allow U.S. technical staff and leadership to be exposed to new ideas and the evolving environments that shape the world's overall energy ecosystem and the role nuclear energy can and should play in it. It also expands U.S. influence on international technology development trends. In some cases, collaborators offer access to unique facilities, complementary data on DOE's core technologies of interest, and/or access to the state-of-technology development currently outside the DOE research portfolio.

To enable the work, AFC maintains a network of relationships with individual countries and multi-national agencies. In all cases, DOE oversees and approves these relationships and collaborations. In some cases, they leverage unique laboratory-to-laboratory agreements or cooperative research contracts.

5.3.1 International Agencies

The DOE is an active participant in several integrated international organizations tasked with the responsible implementation of nuclear technology around the world. In all cases, DOE is formally responsible for representing the United States within the agencies. However, technical experts from the AFC are often assigned to participate as formal leaders or participants in the organization's official activities.

5.3.1.1 Organization for Economic Cooperation and Development – Nuclear Energy Agency

The objective of the NEA [4] is to assist its member countries in maintaining and further developing, through international cooperation, the scientific, technological, and legal bases required for a safe, environmentally sound, and economical use of nuclear energy for peaceful purposes. It provides authoritative assessments and forges common understandings on key issues as input to government decisions on nuclear energy policy and to broaden Organization for Economic Cooperation and Development (OECD) analyses in areas such as energy and the sustainable development of low-carbon economies.

This mission includes several areas of relevance to the AFC that are executed through two primary branches: the Nuclear Science Committee (NSC) [5] and Collaboration on Nuclear Safety Installations (CSNI). Each branch oversees a suite of working parties (WPs) responsible for specific technical areas that are often supported by expert groups. The activities of the WPs are executed as discrete tasks. In cases where cooperation requires additional funding, joint projects are formed with several (like the Halden Reactor Project) having sustained impact on the international research and development landscape. These groups are populated with technical experts from many countries. DOE-NE-4 (Jon Carmack) officially appoints U.S. representatives to these groups. AFC staff plays prominent roles in several of these groups.

Three NSC WPs are relevant to AFC including the WP on Scientific Issues on Nuclear Fuels and Structural Materials (WPFM), WP on Scientific Issues of Advanced Fuel Cycles (WPFC), and the WP on Scientific Issues and Uncertainty Analysis of Reactor Systems (WPRS). AFC participates directly or as an observer in the supporting experts' groups including the WPFM's Expert Group on Fuels and Materials (EGFM), WPFM's Expert Group on Structural Materials (EGSM), WPFC's Expert Group on Innovative Fuel Elements (EGIFE), and WPRS's Expert Group on Reactor Fuel Performance. In aggregate, the mission of these three WPs and their expert groups includes the full spectrum of fuel technology research, development, design, and deployment. AFC thus works in concert with other key DOE programs (most notably NEAMS, ASI, and separations) to support its activities (see Table 9).

Active participation in the NSC contributes meaningfully to several of the AFC's core strategic goals. First, it provides a broad international context for utilizing AFC's core technologies; whether it is ATF technology for LWRs or metallic fuels to enable deployment of advanced reactors or fuel-cycle closure. In particular, the mandate for the WPFM is focused on meeting one of the grand transformational challenges currently at the forefront of nuclear fuel R&D. This WP is embarking on the development and demonstration of a methodology required to dramatically accelerate innovation in nuclear fuel technology. In particular, the WP will emphasize: (1) the development of research methods that inherently blend modern data rich experimental methods conducted at multiple scales (length and time) with advanced modeling and simulation and (2) demonstrate how to "bridge the gap" as necessary to integrate both observation and modeling of multiscale behavior. Even though most national programs are focused on developing different technologies, these generic methodologies can be applied uniformly to all of them, thus, leveraging ongoing efforts to drive open and rapid collaboration.

The CSNI also oversees several WPs of interest to AFC. This branch places greater emphasis on safety and thus is more strongly represented by the regulatory community. The Working Group for Fuel Safety (WGFS) has been integral in the development of the AFC transient testing strategy through its various state-of-the-art reports on LWR fuel systems [6,7] and assessment of safety-related attributes of ATF technologies [8] due to the close collaboration with representatives from regulators and technical support organizations as well as plant operators. Regular DOE technical participation in this WG requires invitation from the NRC's official representative, which they have extended for the last few years. The WGFS is preparing to expand its mandate to include advanced reactor fuel safety in addition to LWR fuels.

CSNI also sponsors a WG on Analysis and Management of Accidents (WGAMA) [9] that was created to assess and strengthen the technical basis needed for the prevention, mitigation, and management of potential accidents in NPPs and facilitate international convergence on safety issues and accident management analyses and strategies. AFC has recently been invited to expand participation in this WG with interest in both LWR and sodium-fast reactor (SFR) fuel technology.

Table 9. Working Parties with Expert Groups and Member names.

Branch	**Working Party**	**Expert Group**	**Role**	**Name**	**Sponsor**
NSC					
	WPFM	N/A	Chair	Dan Wachs	AFC
		EGFM	Member	Luca Capriotti	AFC
		EGFM	Member	Boone Beausoleil	AFC
		EGFM	Member	Steve Novascone	NEAMS
		EGFM	Member	David Andersson	NEAMS
		EGSM	Member	Stu Malloy	AFC
		EGSM	Member	Jian Gan	INM
		EGSM	Member	Laurent Capolungo	NEAMS
	WPFC	EGIFE	Member	Luca Capriotti	AFC
	WPFC	EGIFE	Member		
	WPFC	EGIFE	Member		
NSC	WPRS				
CSNI	WGFS		Observer	Colby Jensen	AFC
CSNI	WGFS		Observer	Charlie Folsom	AFC
CSNI	WGAMA			Colby Jensen	AFC

NEA further provides a platform for conducting R&D activities that cannot be performed on an in-kind basis (e.g., experimental programs). These Joint Projects are formed by grouping organization from NEA member countries with a common interest in the topic. The historically most successful example of a joint project was the Halden Reactor Project (HRP) which operated for several decades until the host instruction in Norway decided to close the reactor. These programs often provide the community with access to unique materials, unique facilities, and a broader technical community with expertise in the full lifecycle of nuclear fuel technology. AFC is a contributing member to many of these programs. Typically, DOE will sign on as the official member and designate the national laboratories as third-party members. In most cases, DOE staff are assigned to joint project governing boards, and the technical staff from the labs is assigned to represent DOE’s interest on technical advisory boards. As shown in Table 10, AFC participates in the Halden Reactor Project (HRP) [10], SCIP [11], QUENCH-ATF [12], and FIDES [13] program.

Table 10. NEA Joint Projects with AFC.

Title	**Host**	**Role**	**Name**	**Sponsor**
HRP	Norway	Member	Jason Hales	NEAMS
SCIP	Sweden	Member	Jason Harp	AFC
SCIP	Sweden	Member	Fabi Cappia	AFC

SCIP	Sweden	Member	Jason Schulthess	AFC
QUENCH	Germany	Member	Nathan Capps	AFC
FIDES	USA	GB	Bill McCaughey	NE
FIDES	USA	GB-alt	Ken Kellar	NE
FIDES	USA	Co-chair TAG	Dan Wachs	AFC
FIDES	USA	JEEP PI High-burnup Experiments in Reactivity-initiated Accidents (HERA)	David Kamerman	AFC
FIDES	USA	JEEP PI [LOC]	Colby Jensen	AFC
FIDES	USA	JEEP PM [INCREASE]	Keith Jewell	ASI
FIDES	USA	JEEP PM [ATOMIC]	Boone Beausoleil	AFC

5.3.1.2 International Atomic Energy Agency (IAEA)

The IAEA engages in activities meant to encourage safe and economic utilization of nuclear technology through a network of Technical Working Groups (TWGs) [14]. These TWGs provide a forum among member states for information exchange, collaborative assessment, and cooperative research. AFC staff regularly contribute to the efforts of the groups.

The Technical Working Group on Fuel Performance and Technology (TWG-FPT) [15] broadly addresses fuel technology focusing its work on status and trends in nuclear power reactor fuel performance and technology. It also covers nuclear core materials R&D, fuel design, manufacturing and utilization, coolant chemistry, fuel performance analysis, and QA issues. It gives due recognition to all relevant aspects including safety, economy, management systems, nuclear science, and NPP operations. Additional TWGs have been established to support specific reactors technologies of interest (e.g., fast reactors, LWRs, and SMRs) and elements of the nuclear fuel cycle.

CRP-2236 on Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS) [16] executes three specific objectives: (1) perform experimental tests including single rod and bundle tests on ATFs' performance under normal, design basis, and design extension conditions, (2) benchmark fuel codes against new test data either obtained during the CPR or from existing data relevant to advanced fuel and cladding concepts from member states' experimental programs, and (3) develop LOCA evaluation methodology for ATF performance with a view for NPP applications.

5.3.2 Bilateral Collaborations

Direct engagement with specific international partner organizations can offer additional opportunities for deeper technical collaboration in specific areas of common interest. These collaborations are typically performed under the umbrella of government-to-government agreements approved by DOE. The modes of implementation are typically variable between countries and are a part of a DOE-managed network. AFC participates in virtually all these activities and is responsible for leading any fuels- and materials-specific activities. The activities underway with each county are outlined below.

5.3.2.1 France

Collaboration with France is currently focused on the two primary federally sponsored research organizations (Commissariat a l'Energie Atomique [CEA] and Institute for Radiological Protection and Nuclear Safety [IRSN]) with incidental interactions with its industrial organizations (Framatome and Electricité de France [EDF]). Opportunities to collaborate with new private and federally supported start-up companies are likely to expand in the future. These collaborations have been enabled by the U.S.-France Bilateral agreements for cooperation on nuclear energy for many years but are likely to be expanded by recent agreements [17,18] to collaborate on clean energy technology.

Joint activities with CEA are facilitated through the Working Group 3: Advanced Fuels and Materials. This group meets annually rotating sites between France and the United States and is currently chaired by the AFC NTD. Long-term collaborations are common in several topical areas with notable emphasis on fast reactor fuel technology, especially for actinide transmutation applications. Although the U.S. program is focused on metallic fuel forms and the French program oxide fuel forms, common interests exist including fuel performance codes, cladding materials performance, irradiation testing, and transient testing. Of particular interest to the technical teams is the development of a methodology for modern experimental methods including irradiation testing techniques, in-pile instrumentation, and advanced PIE. AFC is supported by representatives from NEAMS and ASI in this working group. The technical exchange on ATF technology is included in the discussions, but constraints on sharing commercial fuel vendor-related results limit opportunities for active collaboration.

Joint activities with IRSN are facilitated under a DOE-approved MOU between IRSN and INL created in 2017 as part of the DOE Resumption of Transient Testing program. Technical teams from each institution meet annually at a rotating site (Cadarache, France, and INL) and emphasis fuel safety research activities anchored around experiments conducted at TREAT and CABRI. The collaboration is focused on LWR technology (standard and ATF) through code validation exercises, sharing of experimental methods and results, and unique instrumentation development utilization (including the fast neutron hodoscope).

5.3.2.2 Japan

Extensive collaboration with Japan is being executed under several working groups within the Civil Nuclear Energy Research and Development Working Group (CNWG). There are three sub-working groups that focus on advanced reactor R&D, LWR R&D, and fuel-cycle R&D and waste management. Specific technical areas of collaboration under each sub-WG are described in project arrangements (PA) that are agreed upon by DOE and their Japanese counterpart. Collaborative technical activities are developed and managed through annual technical exchange meetings for each PA. Status is reported annually in the form of meeting minutes at annual CNWG meetings.

AFC provides input on SFR fuels R&D for PA-01, “Cooperation on Advanced Reactor Research and Development” (point of contact is Colby Jensen). The primary focus is providing status on the development of binary and ternary metallic fuel technology in the United States.

AFC leads PA-07, “Cooperation on Light-Water Reactor Research and Development” (POC is David Kamerman). Both the United States and Japan have active ATF technology development programs. Several joint irradiation programs are underway at ATR to test the performance of this technology. Technical activities performed at INL on Japanese materials are directly funded under a CRADA.

PA-11 superseded PA-06, “Cooperation on Fuel Cycle Research and Development and Waste Management” (POC is Ken McClellan). Both the United States and Japan remain interested in developing fuel technology to support actinide transmutation in fast reactors. The United States is focused on metallic fuel for this purpose, and Japan is considering the use of either metal or ceramic fuel technology. Efforts are focused on addressing the development and qualification lifecycle for these fuel technologies. Transient testing on pre-irradiated SFR fuel pins (MOX and metal) is being performed at TREAT under CRADA through a U.S.-Japan Facility Sharing Initiative.

A new area of collaboration of fuel safety research is emerging. A new PA is being drafted for this technical area.

5.3.2.3 Republic of Korea

For the last several years, the Joint Fuel Cycle Studies Initiative drove collaboration between the Republic of Korea and United States and was focused on exploring aspects of the implementing pyrometallurgical treatment for actinide separation and subsequent transmutation in a fast reactor. This agreement has expired and is being reviewed for extension. Randy Fielding is the AFC POC.

5.3.2.4 United Kingdom

The U.S.-UK Nuclear Energy R&D Cooperative Action Plan governs collaboration with the United Kingdom (UK). AFC leads the technical input for Working Group-3 (Advanced Fuels) which meets annually. The working group's objectives are centered on accelerated fuel development and qualification themes with emphasis on modeling and simulation and advanced PIE. Luca Capriotti and Jason Harp are the primary AFC POCs.

5.3.2.5 Kazakhstan

A Civil Nuclear Energy Workshop between DOE and Kazakhstan was held in 2015, which led to an MOU between INL and the National Nuclear Center to support collaboration between the TREAT and the Impulse Graphite Reactor facilities. There are currently no ongoing activities due to budget constraints.

6. 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 advanced reactor fuel 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 the development of ATF concepts. Table 11 provides a summary of the direct budget needed to fund the AFC program and competitively selected industry projects.

Table 11. AFC appropriated budget and future targets FY 2023–2030 (totals include laboratory and industry funding).

ATF	**FY-23**	**FY-24**	**FY-25**	**FY-26**	**FY-27**	**FY-28**	**FY-29**	**FY-30**
Baseline Budget	$26.1	$31.0	$32.5	$44.5	$44.5	$53.5	$62.5	$71.5
Industry Funding	$80.0	$80.0	$120.0	$120.0	$120.0	–	–	–
Metallic Fuels	**FY-23**	**FY-24**	**FY-25**	**FY-26**	**FY-27**	**FY-28**	**FY-29**	**FY-30**
Baseline Budget	–	$20.0	$25.0	$30.0	$30.0	$30.0	$40.0	$40.0

7. SUMMARY MILESTONE TABLE

AFC strategic milestones have been established to support DOE-NE’s goals through 2050. The overall strategic milestones are outlined in Table 12.

Table 12. Overall strategic milestones.

FY 2024	• Receive shipment and begin ATF Byron PIE • Complete TWIST LOCA system establishment • Commission TREAT sodium loop w/ baseline fuel • Refabricate the first fuel segment for testing • Complete TWIST commissioning
FY 2025	• Evaluation of instrumentation in ATR • WEC/LOCA program launch • SATS upgrades into hotcell • HERA WEC LOCA • Send segments to ORNL for HBu extension
FY 2030–2035	• Turn final, small-scale fabrication methods (extrusion, continuous casting, plasma sintering, etc.) into building of test pins for rapid irradiation testing (Fast, MiniFuel, etc.) to confirm microstructure/performance correlations as predicted

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Appendix A
Technology Readiness Level

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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 [19]. 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 of more than 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 U.S. 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 A-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.