WHITE PAPER

Use of National Research and Development Capabilities to Increase the Capacity and Enhance the Economics of Fuels for the Existing Light Water Reactor Fleet

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Executive Summary

The existing U.S. light water reactor fleet is central to meeting national goals of increasing reliable electricity generation. This report describes how current national research and development capabilities can be used to support power uprates, capacity expansion, and improved fuel-cycle economics for the operating fleet in the near term, generally before 2035. It focuses on the national infrastructure needed to generate fuel and materials data, support licensing decisions, and deploy new or improved fuel technologies while ensuring safety and reliability.

The Accident Tolerant Fuel (ATF) program provides a proven model for this work. Through coordinated engagement among the U.S. Department of Energy (DOE), national laboratories, fuel vendors, utilities, EPRI, NEI, and the U.S. Nuclear Regulatory Commission, the program moved fuel concepts from laboratory development to commercial reactor demonstration. Program outcomes include fuel dopants, cladding coatings, increased enrichment lead test assemblies, higher burnup activities, restored transient testing capability, and the use of national laboratory hot cells for post-irradiation examination. These accomplishments show that national laboratory capabilities can accelerate deployment when they are aligned with industry needs, commercial reactor experience, and regulatory expectations.

U.S. irradiation, examination, and analytical capabilities create a national nuclear fuels testbed. Key capabilities include steady-state irradiation in the Advanced Test Reactor, High Flux Isotope Reactor, and Massachusetts Institute of Technology Reactor; transient testing in TREAT; LWR-prototypic experimental loops; hot cell and post-irradiation examination facilities at Idaho National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory; and severe accident and out-of-pile testing capabilities. Together, these assets have generally provided an integrated testing and technical foundation that has helped qualify new fuels and support their efficient deployment and licensing.

The most important near-term industry priorities are tied to increasing output from the existing fleet while maintaining fuel reliability. These priorities include time-at-temperature work to support an alternative fuel integrity criterion for transients, analytical and operational margin improvement to enable longer fuel cycles and improved economics, and back-end storage and transportation considerations for advanced fuel technologies. To be optimally successful, industry-wide collaboration and coordination, including reliable access to irradiated materials, timely shipment of commercial samples to hot cells, standardized and trusted data, and improved throughput is needed across reactor, laboratory, and examination facilities. These factors will determine whether research campaigns can produce necessary data on schedules that support commercial deployment.

As technologies have advanced, several improvements to the national testbed are needed to meet industry needs. A domestic capability for prototypic LWR ramp-rate testing, including the ability to evaluate fuel performance under conditions relevant to higher power operation, would address a significant current gap. Improvements in post-irradiation examination facilities should focus on better data acquisition, higher throughput, standardized methods for irradiated and unirradiated materials, and greater operational efficiency. Non-radiological capabilities, including mechanical testing, environmental testing, burst testing, autoclaves, and prototypic thermal-hydraulic testing, can also help accelerate development by resolving issues before fuel or materials enter scarce radiological test space.

The paper also looks beyond immediate priorities. For mid-term extended power uprate applications, industry is evaluating whether additional uprates approaching 20 percent of original rated thermal power can be achieved economically. This work will require early identification of fuel limitations,

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coordinated use of DOE programs and testbed capabilities, and advanced modeling and simulation. Longer-term fuel development remains less defined, but future technologies will need to deliver integrated gains in economics, safety, fuel utilization, and deployment flexibility. Because modern LWR fuel is already highly optimized, future improvements will require sustained research infrastructure, reliable testing pathways, and strong alignment between technology development and commercial needs.

The central recommendation is to strengthen the industry-government collaborative model proven through the ATF program. DOE, national labs, and industry should improve transparency in laboratory and facility prioritization, provide clearer visibility into work execution status and outcomes, use lifecycle project planning for multi-year research campaigns, clarify funding mechanisms for industry-led and DOE-supported work, and ensure that economic drivers such as time-to-market and deployment value guide project selection. Maintaining a capable, available, predictable, and trusted national fuels testbed is essential to enable power uprates, capacity expansion, and preserve U.S. leadership in nuclear fuel technology.

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Table of Contents

1 Purpose and Scope 1

2 ATF Program Success and the Value of the Collaborative Model 1

3 Existing Infrastructure and Resources: A National Fuels Testbed 2

3.1 Components of the National Fuels Testbed 3

3.2 Steady-state Test Reactors 4

3.3 Transient Reactor Test Facility 5

3.4 LWR-prototypic Experimental Capabilities 6

3.5 Post-Irradiation Examination Facilities 7

3.6 Severe Accident Test Station 7

4 Proposed Testbed Improvements 8

4.1 Prototypic LWR Ramp Rate Testing 8

4.2 Post-Irradiation Examination Facilities 8

5 Industry LWR Fuel Research and Development Priorities 9

5.1 Near-term Industry Priorities Supporting Power Uprates and Increased Capacity within the National Fuels Testbed 9

5.1.1 Time at Temperature (t@T) 10

5.1.2 Analytical and Operational Margin Improvements 13

5.1.3 Used Fuel Considerations for Near-term Fuel Technology Deployment 15

5.1.4 Availability and Quality of Research and Testing Data 15

5.2 Mid-Term: Evaluating Options for Extended Power Uprate Plus (EPU+) 16

5.3 Long-Term Industry Fuel R&D Plans 17

5.4 New Fuel Technology Development 17

6 Opportunities to Strengthen the Industry-Government Collaborative Model 18

6.1 Improve Transparency and Communication in DOE Prioritization 18

6.2 Clarify Funding Mechanisms for Supporting Research 19

6.3 Implement a Three-year Planning Outlook to Support Capability Development 19

6.4 Ensure Economic Drivers Guide Project Selection and Execution 19

6.5 Support Efficient Use of Resources 19

7 Conclusion and Next Steps 20

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Table of Figures

Figure 1: Individual Components of the National Nuclear Fuels Testbed 3
Figure 2: Systematic View of the National Nuclear Fuels Testbed 4
Figure 3: Time at Temperature Testing Plan..... 11

Table of Tables

Table 1: Activities Supporting t@T..... 11
Table 2: Activities Supporting Improved Margins..... 14

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1 PURPOSE AND SCOPE

The purpose of this report is to identify how current national research and development (R&D) capabilities can be used to enable: (1) power uprates, (2) capacity expansion, and (3) enhanced economics for the existing light-water reactor (LWR) fleet prior to 2035. The report uses this end date since it represents a reasonable power reactor implementation target for testing already planned or underway using existing capabilities. For the purposes of this report, necessary steps for implementation include test requirement development, test design, testing, data collection, data validation, model and method development, regulatory approvals of methodology, high fidelity simulations, regulatory approval of reactor licensing basis implementation, and deployment.

In accomplishing its purpose, the report describes current infrastructure and test campaign needs for irradiation testing, out-of-pile testing, post-irradiation examination (PIE), and supporting capabilities to develop and deploy LWR fuel technologies that further enable increased capacity across the operating fleet.

The report first highlights the collaborative Accident Tolerant Fuel (ATF) program where national R&D capabilities were established and utilized to support the screening, development, and deployment of advanced LWR fuel technologies. Ultimately delivering ATF technologies including fuel dopants, cladding coatings for PWRs, increased enrichments, and higher burnup limits. The report then describes the key national capabilities that together create a testbed for near- through long-term LWR fuel innovations. Those capabilities are then tied to ongoing or future R&D campaigns that support power uprates, increased capacity, and improved economics for the existing LWR fleet. Finally, for future collaborative efforts, the report concludes with recommendations for improving the model utilized for the ATF program.

2 ATF PROGRAM SUCCESS AND THE VALUE OF THE COLLABORATIVE MODEL

The ATF program demonstrated the success of a collaborative engagement model between the U.S. Department of Energy (DOE) and the LWR industry. This model enabled coordinated development and testing activities and provided a pathway for data needed by the industry to be generated. Maintaining and strengthening this collaborative model is important to ensure continued progress on LWR fuel technology development and deployment.

Plentiful concrete evidence that a coordinated DOE-industry development model can move fuel concepts with safety and economic improvements from laboratory development into commercial reactor service exists. GE Vernova introduced the first US ATF lead test assemblies into Hatch Unit 2 in 2018[1] with shipment to Oak Ridge National Laboratory in 2020 for PIE, followed by 4 additional years of operating high burnup lead use assemblies with shipments to PNNL in 2025[2]. Calvert Cliffs Unit 2 loaded Framatome's complete PROtect lead fuel assembly in 2021 as the first full ATF assembly operated in a commercial U.S. reactor[3], and in 2025 that the same assembly had completed four years of operation and been reinserted following on-site examination[4]. Westinghouse delivered EnCore lead test assemblies to Byron Unit 2, received NRC approval for re-insertion of lead test rods and assemblies for higher-burnup operation, and shipped irradiated rods to INL for post-irradiation examination and

[1] https://www.ge.com/news/press-releases/gnf-delivers-accident-tolerant-fuel-assemblies-plant-installation
[2] https://www.energy.gov/ne/articles/national-lab-starts-examination-ge-vernovas-advanced-nuclear-fuel
[3] https://www.energy.gov/ne/articles/industrys-first-complete-accident-tolerant-fuel-assembly-operation-commercial-us
[4] https://www.energy.gov/ne/articles/framatome-advanced-fuel-assembly-completes-second-fuel-cycle

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transient testing[5]. In 2025, Westinghouse also announced the first U.S. deployment of increased enrichment lead test assemblies at Vogtle Unit 2[6], explicitly identifying DOE ATF program support as part of that milestone. These outcomes demonstrate that the collaborative model has enabled not only research output, but also the generation of qualification data under prototypic and commercial conditions, crucial regulatory interactions, and commercial deployment decisions.

The program has also yielded broader system benefits. Prototypic PWR loop irradiation capability has been established in ATR to enable commercial-relevant steady-state testing platforms for ATF and advanced fuel concepts, while TREAT was restarted and associated experiment vehicles have restored U.S. transient and loss-of-coolant accident testing capability for LWR fuels. The ability to transport, receive, and examine commercially irradiated test rods was demonstrated at three national laboratory hot cell facilities. These capabilities are directly relevant to current qualification needs for ATF, increased enrichment, higher burnup, and new LWR fuel concepts. The NRC's "Roadmap to Readiness," first issued in 2023 and revised in 2024,[7] reflects the maturity of this effort and the fact that ATF-related licensing issues are being addressed in a structured, iterative framework with stakeholder input, in part, using this data.

The collaborative model utilized in the ATF program should be described explicitly as a data-to-deployment framework: national laboratories provide unique infrastructure and independent technical capability; the broad community influences fuel technologies; vendors provide fuel design, fabrication and commercialization pathways; utilities provide operating reactor experience and validation of safety and economic benefits of technology deployment; while NRC interactions and engagements define the regulatory acceptance pathway.

3 EXISTING INFRASTRUCTURE AND RESOURCES: A NATIONAL FUELS TESTBED

The United States possesses the most extensive and versatile nuclear fuel cycle R&D capabilities in the western world. These capabilities, including test reactors, post-irradiation examination facilities, analytical laboratories, and scientists and engineers, support the advancement of nuclear fuel through DOE-led, industry-led, and collaborative testing campaigns. Together, they form an integrated national testbed for the development, testing, and qualification of LWR fuels. However, continued and improved functionality, availability, and access to the testbed is needed to provide the necessary capability to perform relevant irradiation and testing, offering the potential to maximize the value of the existing LWR fleet in the U.S., the fleet of the future, and the foundation for U.S. technology leadership worldwide. Upon its closure in 2018, the Norwegian Halden Boiling Water Reactor created a gap in LWR testing capabilities[8], strengthening the need for further investment and capacity in U.S. capabilities. Lastly, effective management of the testbed provides sufficient reliability: supporting predictable schedules, timely data delivery, cost effectiveness, confidence in results, and a steady source of technology innovation.

[5] https://westinghousenuclear.com/media/lh4gpjtw/westinghouse-encore-atf-program.pdf
[6] https://info.westinghousenuclear.com/news/westinghouse-achieves-first-deployment-of-leu-fuel-in-the-u.s
[7] https://www.nrc.gov/docs/ML2420/ML24204A011.pdf
[8] "Post-Halden Reactor Irradiation Testing for ATF: Preliminary Assessment and Recommendations," https://inldigitallibrary.inl.gov/content/uploads/50/2026/04/Sort_6087.pdf

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3.1 Components of the National Fuels Testbed

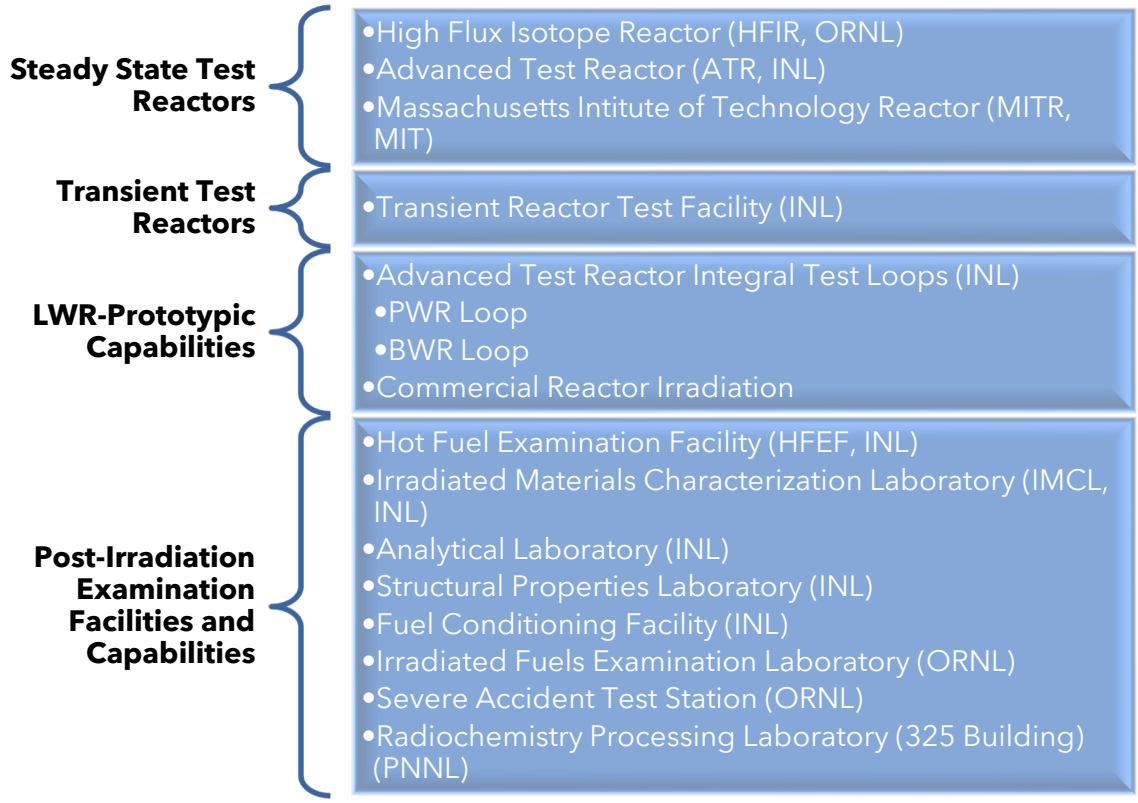


Figure 1: Individual Components of the National Nuclear Fuels Testbed

The following figure describes a systematic view of the national nuclear fuels testbed.

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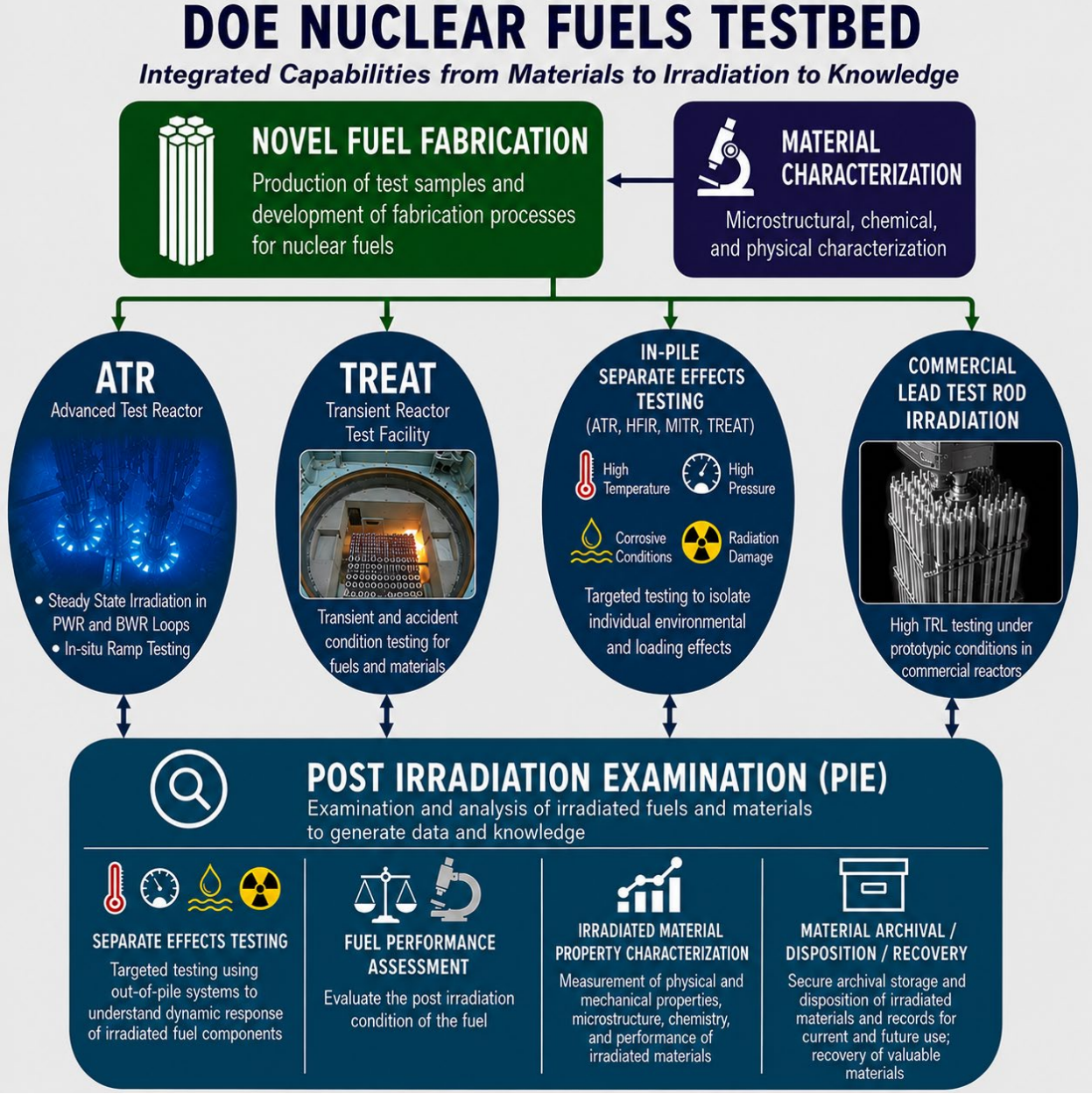


Figure 2: Systematic View of the National Nuclear Fuels Testbed

3.2 Steady-state Test Reactors

The U.S. steady-state irradiation base for LWR fuel testing currently centers on the Advanced Test Reactor at Idaho National Laboratory (ATR), the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, and the Massachusetts Institute of Technology Reactor (MITR).

ATR is described as the nation's premier fuel and materials test reactor with six in-pile pressurized water loops capable of providing prototypic PWR pressure, temperature, flow, and water chemistry conditions, with instrumentation and the ability to tailor neutron flux. In addition, the reactor has capacity for up to nine water loops. Experimenters installing test trains in these loops can tailor the loop

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parameters to meet unique experimental objectives. The loops can operate to deliver both steady-state irradiation conditions and controlled power manipulations to simulate various ramping events. Furthermore, the loops can operate with damaged fuel and employ on-line monitoring capability to capture the data. Associated in-canal examination stations allow experimenters to track evolution of fuel specimens throughout the irradiation. These attributes make ATR the principal domestic platform for prototypic fuel rod and materials irradiation under prototypic conditions, including ATF and increased-enrichment campaigns. However, not all testing space in ATR is devoted or even available to the commercial industry due to competing R&D programs and governmental priorities. This limits the amount of concurrent testing and increases commercial deployment timelines. A PWR loop has operated in the Center Flux Trap for nearly a decade. With availability estimated to begin in 2029, INL will install a BWR loop in the Northeast Flux Trap and enable ATR to create prototypic testing conditions spanning both LWR technologies. BWR and PWR test loops together would enable developing the next generation fuel concepts for the LWR fleet, supporting higher power uprates and capacity factors. This addition, however, would provide industry and associated DOE research initiatives with only two of the nine possible positions.

HFIR provides complementary testing capabilities through its extremely high neutron flux and a regular operating schedule. HFIR is an 85-MW flux-trap reactor that typically operates seven 23 to 27-day cycles per year and offers peak thermal fluxes up to 2.5×10^{15} n/cm^2/s in flux-trap positions[9]. Although HFIR does not provide LWR-prototypic loops like ATR, its high flux environment and dry irradiation positions make it important for accelerated materials and miniature-specimen testing relevant to fuel and cladding development.

MITR provides an additional niche capability for LWR-relevant irradiation, instrumentation development, and small specimen fissile material experiments. MITR generally operates continuously, 24 hours per day and 7 days per week except during planned maintenance outages and can perform in-core fissile-material irradiations, subject to limits including a 100 g fissile material cap and no forced-circulation loop. That operating profile and licensing basis make MITR valuable for smaller-scale, flexible campaigns, especially where shorter lead times, specialized instrumentation, or university-industry-laboratory collaboration are advantageous.

Taken together, ATR, HFIR, and MITR should be viewed as complementary rather than interchangeable. ATR is the primary domestic platform for prototypic LWR water-loop irradiation; HFIR offers very high flux and repeatable cycle scheduling; and MITR offers smaller-scale and more flexible in-core experimental options. The principal reliability and availability consideration for industry is not only whether each reactor can perform a given test, but whether the national testbed as a whole can provide predictable campaign sequencing from screening tests through prototypic irradiation and subsequent PIE. Continued availability of these reactors and testing space within is crucial to further advancing the safety and economics of LWR fuels.

3.3 Transient Reactor Test Facility

The Transient Reactor Test Facility (TREAT) is the United States' primary domestic capability for in-pile transient testing of nuclear fuels under postulated accident conditions. TREAT supports real-time monitoring of fuel and material behavior during postulated accident scenarios, can accommodate multi-pin test assemblies, and uses hodoscope-based monitoring to evaluate fuel behavior during tests[10].

[9] "High Flux Isotope Reactor," https://www.ornl.gov/sites/default/files/HFIR%20Main-R1.pdf
[10] "The Transient Reactor Test Facility (TREAT)," https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_111031.pdf

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These features make TREAT central to the U.S. capability for research on LWR accident scenarios such as a reactivity-initiated accident (RIA) and LOCAs.

For LWR applications, TREAT is being configured to support both RIA and LOCA-related work. The Transient Water Irradiation System for TREAT (TWIST) experiment vehicle restores LOCA safety testing capability to the United States, helps address high-burnup FFRD questions, and is planned for use with pre-irradiated fuel for both LOCA and RIA experiments.[11] The High-Burnup Experiments in Reactivity Initiated Accidents (HERA) program, conducted under the OECD/NEA FIDES framework, uses TREAT for high-burnup RIA testing and has progressed through multiple pre-hydrided and high-burnup experiment configurations.[12]

Current constraints are principally campaign complexity and throughput. TWIST commissioning required coordinated fabrication, inspection, instrumentation integration, and assembly across multiple INL facilities before reactor testing, illustrating that TREAT throughput depends not only on reactor availability but also on the readiness of specialized experiment vehicles, hot-cell preparation, and supporting instrumentation. This is an inherent feature of high-value transient testing, but it reinforces the need for integrated scheduling across multiple laboratory facilities if industry-relevant accident testing is to support licensing and deployment schedules.

3.4 LWR-prototypic Experimental Capabilities

LWR-prototypic loop capability is essential when the objective is to generate fuel and cladding performance data under representative thermal-hydraulic and chemistry conditions. These capabilities provide substantial advantages over simple capsule irradiations. ATR's pressurized water loop already provides prototypic PWR conditions, and the BWR loop deployment in ATR is intended to irradiate LWR-type fuel using an isolated loop system that can reproduce neutronic, thermal-hydraulic, and chemical boundary conditions representative of commercial BWR plants.[13] BWR and PWR test loops together would enable developing the next generation fuel concepts for the LWR fleet, supporting higher power uprates and capacity factors.

This makes the BWR loop capability particularly important for BWR-relevant data needs that cannot be addressed adequately through PWR loops or non-prototypic irradiation. The strategic value lies in the ability to generate BWR-specific fuel performance, corrosion, dryout response, and transient recovery data using instrumented tests under representative coolant and chemistry conditions. At the same time, because such loop systems are specialized and necessary to many projects, demand is likely to exceed near-term throughput if multiple vendor and utility campaigns move forward simultaneously.

Lastly, the prospect of using commercial operating LWRs as a component of the testbed must be considered as a step between developmental irradiations and lead test rods or assemblies. Segmented or part-length rods, insertions through instrumentation channels or other adaptations would represent an opportunity for truly prototypic irradiation conditions. Fully implementing this approach will require more reliable and predictable transfers of irradiated samples between commercial facilities and hot cells.

[11] "Inauguration of the LOCA Blowdown Capsule for TREAT," https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_72231.pdf
[12] "Fuel Performance Simulation of High Burnup Fuels in Planned Integral Design Basis Accident Experiments," https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_107646.pdf
[13] "AFC Two-Loop LWR Testbed," INL/RPT-26-93419.

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3.5 Post-Irradiation Examination Facilities

Hot cell capabilities are critical for post-irradiation examination, out-of-pile separate effects testing, archival of materials required to support ongoing and future research and development needs, and other supporting activities. Without hot cell capabilities, the overall value of the national testbed would greatly diminish because irradiation campaigns do not translate into deployment decisions unless the resulting data can be acquired, analyzed, and delivered on specific schedules. Investment may be needed to accelerate value to industry, including improvements in data acquisition and operational efficiency and are discussed further in Section 4.2.

The Hot Fuel Examination Facility (HFEF) at INL remains a major national hot-cell asset for handling and examining irradiated materials up to full-size LWR rods and for supporting disassembly and preparation steps needed for transient testing and subsequent PIE. At INL, HFEF is complemented by hot cells at the:

- Irradiated Materials Characterization Laboratory (IMCL) and Electron Microscopy Laboratory (EML) which are used to conduct microstructural and material property evaluation of irradiated materials;
- Analytical Laboratory which is used to conduct analytical chemistry on irradiated fuels and claddings;
- Structural Properties Laboratory (SPL) which is used to perform mechanical property testing on irradiated claddings; and
- Fuel Conditioning Facility (FCF) which houses specialty furnace testing systems for source term analysis (in addition to its recycle mission).

The Radiochemical Processing Laboratory (RPL) at Pacific Northwest National Laboratory (PNNL) supports post-irradiation examination of advanced fuels, alloys, and related materials important to nuclear energy applications, as well as broader work in radiochemistry, actinide processing, and spent fuel management. RPL offers a complementary capability to the national testbed for characterization and materials analysis that can support fuel development, post-test examination, and method development.

The Irradiated Fuels Examination Laboratory (IFEL) at the Oak Ridge National Laboratory is a facility designed for chemical, physical, and metallurgical examination of irradiated fuel elements and reactor parts. IFEL is capable of examining full-size LWR fuel, conducting high-temperature fission product release testing, and performing both full-length rod and fuel pin/segment nondestructive examination.[14]

3.6 Severe Accident Test Station

Also at Oak Ridge National Laboratory, the Severe Accident Test Station (SATS) is a modular facility for examining LWR fuel and core materials under design-basis and beyond-design-basis accident conditions. SATS can expose fuel and core materials to high temperature steam environments over a range of temperatures, pressures, and flow conditions, and includes both in-cell and out-of-cell modules. Integral

[14] https://www.ornl.gov/facility/irradiated-fuels-examination-laboratory

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LOCA testing up to about 1200°C, high temperature furnace capability up to about 1700°C, and additional modules for high pressure and thermogravimetric testing are all possible.[15]

SATS is important not only for near-term qualification of existing ATF features, but for broader new fuel development because it provides controlled accident environment data outside the reactor and, for irradiated materials, within hot-cell infrastructure. That makes SATS relevant to severe accident oxidation behavior, cladding/fuel interaction under high-temperature steam, integral LOCA response, and model validation across both incremental and more advanced fuel concepts. SATS should be treated as a core complement to TREAT rather than a substitute since TREAT provides in-pile transient response under prototypic nuclear heating, while SATS provides highly instrumented accident environment testing and follow-on severe accident examination capability.

4 PROPOSED TESTBED IMPROVEMENTS

4.1 Prototypic LWR Ramp Rate Testing

Expanding the nation's LWR irradiation experiment capability to include prototypic LWR power ramp testing, including the ability to fail fuel, is a crucial component of developing and deploying new fuel and cladding technologies and enabling industry's plans to enact larger power uprates. Currently, there is no facility commercially available to U.S. developers and very limited availability internationally that can provide such power ramp rate testing. This testing is a critical component to BWR reactor operations due to the frequent use of control rods and extreme axial power shapes in the reactor core throughout the operation cycle. Ramp testing is typically evaluated as a fast (e.g., seconds) transient to high power (e.g., 150% to 200% of initial pre-ramp power, or greater), emulating the withdrawal of a control rod, while it can also be performed more slowly over time (smaller power changes over hours) to emulate more core-wide power changes such as those induced by changes in reactor coolant flow and xenon-induced power transients. Both types of testing are used to establish fuel vendor guidance associated with power maneuvering. These performance tests interrogate pellet-cladding interaction (PCI) and are essential to qualify new materials at higher TRL levels. It is important to recognize the stochastic nature of PCI, as has been demonstrated by decades of experience, underscoring the need for high testing throughput to establish statistical certainty on material performance. While the industry strives to improve fuel reliability and eliminate fuel failures, fuel utilization and management strategies are expected to change due to power uprates, higher burnups and enrichment levels, and extended cycle lengths, potentially impacting the overall PCI risk.

4.2 Post-Irradiation Examination Facilities

Some areas where improved capability in the existing hot cell facilities would benefit industry include:

Better data acquisition: Investment should focus on digital instrumentation upgrades to collect on-line, real-time data, greater automation of routine examinations, and standardization of data products across all intra and inter-lab facilities so that irradiation and PIE campaigns produce more consistent outputs with less manual post-processing. These improvements would reduce cycle time from examination to usable engineering data, reduce costs of quality oversight and the potential for human error, and would improve comparability across campaigns and facilities.

[15] https://www.ornl.gov/sites/default/files/Severe%20Accident%20Test%20Station-final.pdf

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Higher throughput for data acquisition: Throughput improvements will require more than additional instruments alone. Queue management, campaign batching, specimen preparation capacity, trained hot-cell staffing, and alignment of destructive and nondestructive examination steps all affect total schedule. Because ORNL and INL facilities support multiple national missions, LWR fuel work benefits materially from clearer campaign planning and dedicated windows for industry-priority examinations.

Standardized methods against unirradiated materials: Where possible, methods used to characterize unirradiated fuel and material samples should match those methods used to examine irradiated fuel and materials. Aligning methods or techniques for tasks such as sample preparation, isotopic analyses, and microscopy can reduce variability in results. The same is true for equipment and instruments although some shielding may be necessary for PIE applications.

Operational efficiency: Operational efficiency can be improved by reducing the time required to introduce new tooling, modify fixtures, qualify methods, and transition between test campaigns. This can be achieved in a variety of ways but could include more frequent material inventory audits with inventory calculations including radioactive decay. The approach would expedite and add realism to material control and accountability efforts. For industry, the relevant metric is not simply available shielded-cell volume, but the ability to deploy or change capabilities quickly enough to support licensing decisions and fuel-development down selects. Additionally, investigating the possibility of a more streamlined process to coordinate irradiated fuel shipments from customer reactor sites to the lab's facilities should be considered to decrease project costs and risk.

5 INDUSTRY LWR FUEL RESEARCH AND DEVELOPMENT PRIORITIES

This section describes industry's LWR fuel R&D priorities for the domestic fleet. Near-term (i.e., prior to 2035) activities are discussed in detail. Details about mid- and longer-term activities are currently in development, and in some cases depend on near-term R&D outcomes.

Numerous recent successes demonstrate industry progress in LWR fuel development and deployment. Some utilities will use pellet dopants developed during the ATF program to achieve 24-month fuel cycles. Fuel vendors received approval of and submitted additional topical reports enabling the use of increased enrichment for specific fuel products, with those topical reports based on R&D performed at the SATS and TREAT facilities. With the recent NRC approval of EPRI's Alternative Licensing Strategy[16] and Framatome's Increased Burnup Topical Report,[17] near-term FFRD testing needs to support use of fuels with increased enrichment and higher burnup have been satisfied.

5.1 Near-term Industry Priorities Supporting Power Uprates and Increased Capacity within the National Fuels Testbed

The domestic fleet's near-term actions are focused on more efficient operation, reactor power uprates, and capacity expansion to increase the amount of affordable electricity on the grid. This focus is directly aligned with the administration's goal of expanding nuclear electricity generation and the Department of Energy's UPRISE initiative.

[16] "Loss-of-Coolant-Accident-Induced Fuel Fragmentation, Relocation and Dispersal with Leak-Before-Break Credit: Alternative Licensing Strategy," https://www.nrc.gov/docs/ML2604/ML26043A418.pdf.
[17] "Final Safety Evaluation for Framatome Topical Report, ANP-10358P, Revision 0, "Increased Burnup for Pressurized Water Reactors" (Non-Proprietary)," https://www.nrc.gov/docs/ML2605/ML26050A051.pdf

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Industry relies on the national testbed capabilities to support fuel and materials data needs associated with power uprates and capacity expansion.

5.1.1 Time at Temperature (t@T)

Benefits of Time at Temperature

Power Uprates – Allows approximately 2% additional power uprates fleet-wide
Capacity Expansion – Prompt return to service after unexpected select transients
Improved Economics – Up to 5% improvement in fuel power peaking which could result in fuel cost savings

One of the highest near-term industry priorities is the development of an alternative to the critical heat flux (CHF) based cladding integrity criterion currently used as a conservative determination of fuel rod failure during transient events or radiological dose consequences in off-normal reactor scenarios. Replacing the CHF-based criterion could enable up to 2% additional power uprates averaged across the existing fleet.[18]

Exceeding CHF and entering the transition boiling heat transfer regime does not, by itself, cause cladding failure. Nonetheless, the criterion was developed and has been used for decades as it is both conservative when compared to actual cladding failure phenomena, and relatively straightforward to calculate with an appropriately designed empirical equation. Due to the physics of BWR operation, preclusion of CHF becomes a significant limitation to the operating space.

The industry's effort to replace the CHF criterion is based on the fact that a fuel rod exceeding the CHF value and operating at the resulting elevated cladding temperature for a limited amount of time does not fail and release radioactive material. This effort is referred to as time-at-temperature (t@T).

The t@T effort proposes to define new cladding thermal failure limits that would allow for operation beyond CHF for short periods of time without cladding failure. Criteria for post-CHF return-to-service could also be defined, conditionally allowing for reuse of some fuel bundles even after a CHF event. The new limits would apply to both BWRs and PWRs.

Development of the technical bases for the new criteria for cladding failure and return-to-service will require acquisition of a variety of thermal-hydraulic and materials test data. The R&D scope includes mechanical testing, corrosion testing, and transient testing, as well as detailed characterization, on both unirradiated and irradiated materials.

Facilities including HFIR, MITR, SATS, and TREAT, as well as the corresponding hot cell facilities, are needed to perform the planned testing scope in support of t@T. The following figure describes the t@T R&D scope.

[18] "Test Matrix for Determining the Impact of Critical Heat Flux on Cladding Material Behavior," https://www.epri.com/research/products/000000003002029354

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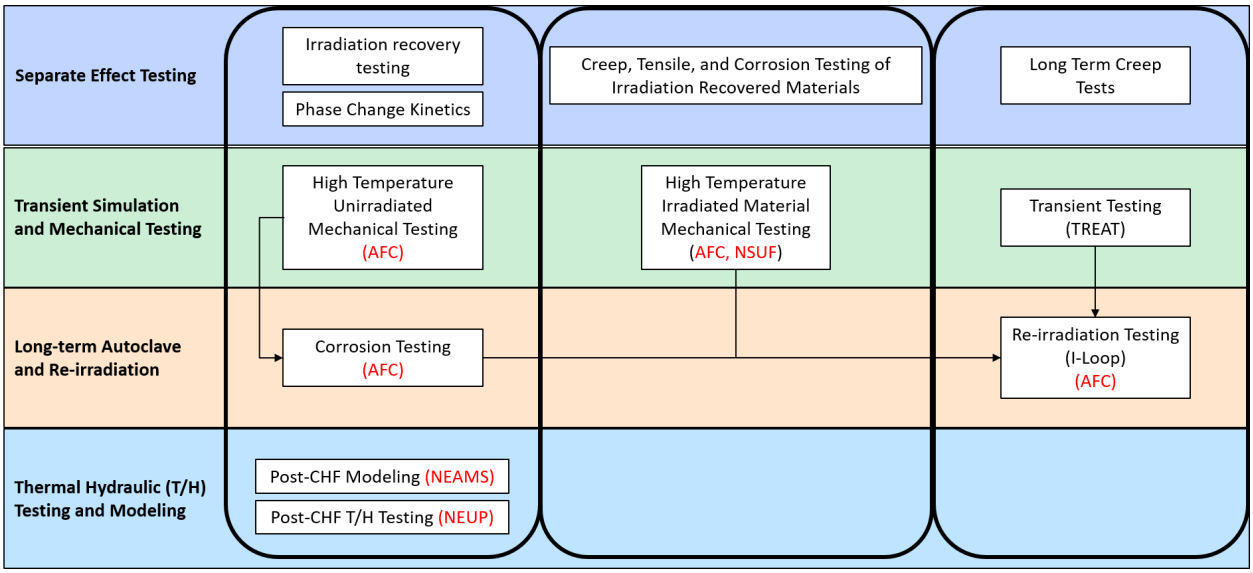


Figure 3: Time at Temperature Testing Plan

Necessary activities within the national testbed supporting t@T are shown in chronological order, in Table 1. This table is not intended to replace detailed test matrices developed by stakeholders (EPRI, national laboratories, etc.)

Table 1: Activities Supporting t@T

Activity	**Testbed Capability(ies) Needed**	**Expected Completion Date**	**Constraints**
TH t@T Tests - EPRI	Vendor Facilities	Q1 2027	Funding and equipment availability
Irradiation Activities CRAFT Collaboration	IFEL, HFIR	Q4 2027	Space availability in HFIR to support large scope, irradiated vs. unirradiated material handling and testing
Corrosion testing of BWR Materials	MITR, IFEL	Q4 2027	Facility availability, Shipment of irradiated material to hot cells
WEC FOA t@T work	IFEL, HFIR	Q4 2028	Competition with other programs for equipment and personnel availability

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Activity	Testbed Capability(ies) Needed	Expected Completion Date	Constraints
Characterization of Materials – CRAFT Collaboration	IFEL	Q4 2028	Very large scope and throughput requirements, FOAK R&D methods evolving alongside large scope requires thorough documentation and benchmarking
Rod Bundle TH t@T	Vendor Facilities	Q4 2028	Funding
TH t@T Tests – NEUP (UWM & UMiss)	University Facilities	Q4 2028	Funding and equipment availability
Material Report – EPRI & Labs	N/A	Q2 2029	Consensus between EPRI, AFC, and vendors will require work to ensure all parties satisfied
Vendor Topicals	N/A	Q3 2029	Proposed scope versus time to complete, will amount of data be sufficient to complete a topical in ~2029. Little margin in schedule for additional characterization if needed
Cladding annealing / transient testing	SATS / ATR / TREAT	Not yet scheduled	Facility availability and priority
Post-transient steady-state irradiations	SATS	Dependent on completion of new capability	Construction of NEFT BWR Loop in ATR and near-term capacity
Irradiated Sample Creep	In-cell creep-autoclave capable of internal or external pressurization	Dependent on completion of new capability	Hot cell autoclave capability
Irradiated sample short and long term out of pile corrosion	In-cell autoclave capable of BWR chemistry control	Dependent on completion of new capability	Hot cell autoclave capability

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Activity	Testbed Capability(ies) Needed	Expected Completion Date	Constraints
Short and long term in-pile corrosion	Second MITR BWR Autoclave Loop	Dependent on completion of new capability	Completion of second corrosion loop at MITR and loop capacity / availability
Integral fueled cladding performance	ATR NEFT BWR Loop	Dependent on completion of new capability	Construction of NEFT BWR Loop in ATR and near-term capacity

5.1.2 Analytical and Operational Margin Improvements

Benefits of Improving Analytical and Operational Margins

Capacity Expansion – enables longer cycle lengths, increasing reactor capacity factors over multiple cycles, ensures reactors can maintain flexible operations
Power Uprates – enables power uprates for some reactors
Improved Fuel Economics – allows for increased fuel residence time, reduced batch fraction, and lower fuel costs for reactor operators
Improved Operational Costs – reduces operational cost through increased operational margin, potential relaxation of safety-class systems

Realization of nuclear capacity expansion and power uprates in the existing fleet can also be enabled by unlocking improved analytical and operational margin. These efforts do not necessarily represent a traditional fuel development campaign, but rather a targeted set of experiments to assist in reducing uncertainty or improving assumptions in fuel performance and thermal-hydraulic methodologies. While engineering solutions currently exist that address these uncertainties, these R&D efforts endeavor to increase available thermal power or reduce the operations and maintenance cost for reactors. Industry's move toward longer fuel cycles and higher burnup fuels required similar R&D efforts. A specific example of R&D efforts that can improve margins are those supporting the development and commercialization of cladding coatings. Industry and DOE have spent significant resources developing these technologies towards commercialization, which is almost complete. However, R&D activities must continue and be prioritized such that all LWRs can derive the benefits from this near-term technology.

With the recent testing to support industry's near-term fuel fragmentation, relocation, and dispersal needs now completed, the current priority activities within the national testbed supporting improving analytical and operational margins are shown in no particular order in Table 2.

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Table 2: Activities Supporting Improved Margins

Activity	**Testbed Capability(ies) Needed**	**Expected Completion Date**	**Constraints**
Test advanced burnable absorbers in test reactor	HFEF, ATR, TREAT	Q2 2027	Availability of commercial material; facility throughput; for any TREAT advanced testing: complex sample refab requires long lead time with one window for fab, transport between facilities and truck lock throughput.
Test modified claddings at 1600°C for minimum oxidation and eutectic formation	HFEF, ATR, TREAT	Q3 2028	Same as above
RIA Testing	TREAT, HFEF	Q3 2029	Availability of commercial material; facility throughput; for any TREAT advanced testing: complex sample refab requires long lead time with one window for fab, transport between facilities and truck lock throughput. Sister tests at SATS also require inter-lab material shipment which has been difficult to accomplish thus far
LOCA Testing	TREAT, HFEF, SATS	Q3 2029	Same as above for RIA Testing
Commercial PIE	Hot cells	2029	Commercial material shipments, lab throughput

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Activity	Testbed Capability(ies) Needed	Expected Completion Date	Constraints
Ramp Testing	ATR, HFEF	2029	Ramp testing loop, instrumentation, capacity
High Burnup Irradiations	Commercial Reactors		Commercial reactor availability

5.1.3 Used Fuel Considerations for Near-term Fuel Technology Deployment

Licensing safe storage and transportation solutions for used fuel requires understanding many of the same fuel performance characteristics as licensing fuel for in-reactor use. Therefore, R&D efforts supporting in-reactor use must also consider back-end requirements to establish a rigorous technical basis that addresses regulatory information needs and resolves key technical gaps.

NRC-sponsored work has defined key information needs and research priorities, and existing post-discharge data from lead test and early deployment activities may address some of these gaps.[19] Key performance criteria to consider include:

- Used fuel conditions that bound back-end performance, including limiting rod internal pressure, oxide thickness, hydrogen content, and updates to fuel performance codes,
- Justification of cladding temperature limits for normal, off-normal, and accident conditions,
- Cladding and rod-level mechanical properties for accident analyses and fatigue evaluations,
- Cladding thermal properties at dry storage and transport temperatures,
- Time-dependent cladding degradation effects important to extended dry storage and subsequent transport,
- Release fractions for confinement and/or containment evaluations, and
- Fissile content and criticality modeling with appropriate uncertainties to support evaluations for increased enrichment and higher burnup conditions.

5.1.4 Availability and Quality of Research and Testing Data

Data are the natural outputs of research and development activities. These data come in many forms, such as raw data, photographs, videos, procurement records, laboratory notebooks, fabrication and inspection records. Data of appropriate provenance are required to license and thus eventually commercialize and implement fuel improvements at reactors. Without confidence in the data's

[19] "*Spent Fuel Storage and Transportation of Accident Tolerant Fuel Concepts: Cr-Coated Zirconium Alloy Cladding, FeCrAl Cladding, High Burnup and High Enrichment Fuel*," NUREG/CR-7310, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7310/index.

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provenance, industry cannot build a reliable case to the regulator or reactor operator that the eventual product will behave as described. Therefore, R&D campaigns envisioned to support licensing activities must generate trustworthy data. Many standards and approaches exist to ensure an R&D campaign generates data of appropriate provenance; however, to maximize efficiency and minimize resources, data requirements must be known prior to the start of a campaign. Experimental teams need to discuss data requirements with stakeholders, which can be accomplished through industry initiatives such as Collaborative Research on Advanced Fuel Technology (CRAFT), industry groups such as EPRI or NEI, or specific project team meetings.

For maximum efficiency, industry recommends a collaborative effort between CRAFT, DOE, and the national laboratories to generate a generic quality assurance program plan based around a standard like American Society of Mechanical Engineer's NQA-1 or ISO 9001, that can be implemented at any of the laboratories for research efforts that intend to create data for use in licensing. Specific test methods and other requirements will still need to be experiment- or campaign-specific, but the generic base plan will avoid each fuel technology developer and the experiment teams performing duplicative work.

Furthermore, data from R&D campaigns of interest to industry must be made available in a timely fashion once the experiment team completes any necessary quality control reviews. Delays in data provision can hamper downstream activities that aim to increase the safety and economic performance of the existing LWR fleet.

5.2 Mid-Term: Evaluating Options for Extended Power Uprate Plus (EPU+)

To support power uprates beyond what is achievable in the near-term, industry is interested in pursuing EPU+, which targets a 20% or larger increase in a plant's original rated thermal power. Achieving uprates of this scale in an economically viable manner may require significant changes to the methodologies used for core design, safety evaluation, and fuel performance assessment. These modifications will require support from the U.S. DOE, utilization of the national fuels testbed, and advanced modeling and simulation capabilities developed by the department. Industry is in the early stages of evaluating options to achieve EPU+ scale uprates and intends to work closely with various DOE programs – e.g., the Advanced Fuels Campaign (AFC), the Power Reactor Optimization (PRO) program, and the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program – as these plans develop.

Industry has begun work to identify fuel limitations to achieving EPU+. The Electric Power Research Institute (EPRI) is engaging nuclear suppliers and utilities, and relevant U.S. DOE programs to identify fuel limitations and develop a coordinated plan to address them. Early discussions have identified several limitations that will challenge existing fuel technologies as EPU+ is pursued. A non-exhaustive list of some common limitations, undifferentiated by PWR and BWR concerns, include:

- Rod internal pressure – high data uncertainty and already limiting for existing fuel products
- Shutdown margins – reactivity control under uprate and increased exposure
- Cladding thermal limits – methodology-sensitive; becomes more concerning with increased fuel power density
- Cladding oxidation and hydrogen pickup margins – of primary interest to fuel with high residence time

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- Crud-induced localized corrosion and power shift – risk increases with steaming rate
- Mechanical design limits – challenged with longer core lifetime and power density increase
- Fuel thermal limits – challenged with power density increase, increasing PCI risk

EPRI is currently working with industry to prepare a whitepaper that aims to identify focus areas for fuel design and licensing optimization in the context of additional power uprates, extended cycles, and increased fuel exposure beyond what is currently planned. The paper will identify fuel-related limitations that are likely to be encountered when increasing core power and will delineate physical limitations from licensing-related and modeling capability limitations. Potential solutions to overcome these limitations will be proposed, involving R&D to reduce uncertainties, licensing initiatives, or a combination of both. Activities will be prioritized based on the order in which fuel limitations may be encountered, as well as the likelihood of overcoming those limitations. Some of the R&D activities identified in this effort are likely to necessitate support from DOE and utilization of testbed facilities. The whitepaper is planned for completion in CY2027. It should be noted that the priority activities in Table 2 that support improved margins can potentially be expanded with minimal additional effort to support EPU+ with the proper foresight and additional planning.

Further identification and prioritization of industry R&D priorities and the fuel testbed capability needs to address them will be developed as industry continues to progress toward its EPU+ goals. Close collaboration between DOE and industry will continue to ensure that the R&D capabilities of the nation's fuel development testbed and other DOE programs are able to meet the capabilities, availability, and quality needs that industry requires.

5.3 Long-Term Industry Fuel R&D Plans

As described above, industry is engaged at many levels to develop and deploy fuel technologies to increase power generation capacity of the nation's nuclear fleet in the near- and medium-term. Longer term plans are, as expected, still in the early conceptual stages. As technology development progresses, R&D issues are resolved, and the regulatory landscape evolves, more details on these long-term plans will be provided.

As mentioned at the beginning of this report, the domestic nuclear fuel industry generally approaches fuel technology advancement holistically and prioritizes integrated performance gains by considering economics, increased safety, fuel utilization, and deployment flexibility. Given the current performance of modern LWR fuel products optimized over 50+ years, further improved by recent ATF features, there is a high bar to overcome for widespread adoption, requiring a significant TRL and testing infrastructure to ensure the fleet remains operating reliably without any degradation in reliability.

5.4 New Fuel Technology Development

National testbed capabilities are also relied upon for new fuel technology development, beyond ATF and traditional UO_2-Zr based systems, to generate irradiation and performance data needed to mature designs and support deployment decisions.

Relative to the original ATF program, priorities are likely to place greater emphasis on integrated performance gains in economics, increased safety, fuel utilization, and deployment flexibility, rather than on one-for-one substitution of pellet or cladding features alone. That means the testbed must

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support a broader range of qualification needs, including prototypic irradiation and testing, transient accident testing, severe accident furnace testing, and high-resolution PIE sufficient for model validation and licensing decisions. The ATF program has already demonstrated that this integrated sequence is feasible when reactor, hot-cell, and regulatory activities align.

The addition and support of non-radiological capabilities can assist in accelerating the development of new fuel technologies. Capabilities like mechanical testing facilities, environmental testing facilities (e.g., autoclaves), burst testing facilities, and thermal-hydraulic testing facilities that do not involve radiological material are excellent candidates to expand the usefulness of the national testbed and should be considered for future investment.

In addition to industry-government cooperative activities, commercial fuel vendors pursue other fuel technology development efforts across a range of maturities and designs. The national testbed provides shared capabilities that can be leveraged to evaluate these concepts efficiently, reduce duplication, and support consistent data generation.

6 OPPORTUNITIES TO STRENGTHEN THE INDUSTRY-GOVERNMENT COLLABORATIVE MODEL

DOE and industry engagement to develop and deploy accident tolerant fuels is a testament to the nation's capability and the value of public-private cooperation to achieve national goals. Continued DOE program engagement with industry through NEI Working Groups, and industry-driven collaborative forums such as CRAFT will ensure alignment and coordination remain a strong asset as all stakeholders pursue increasing nuclear power production and ensuring the nuclear industry continues to provide the nation with affordable, reliable, and safe electric generation.

6.1 Improve Transparency and Communication in DOE Prioritization

Improved transparency and communication in DOE prioritization for LWR fuel development (including the Next Generation Fuels (NGF) program), especially when the efforts are controlled and performed within a DOE-led program, can strengthen collaboration and improve alignment between national laboratory activities and industry needs. Areas where additional transparency is needed include:

1. **Specific laboratory and facility priorities and their determination processes**

   Laboratories are comprised of many separate facilities supporting users with differing objectives and potentially conflicting schedules. To effectively execute efforts that support increased electricity generation capacity, these efforts must be identified by industry and made known to laboratories and facilities and be prioritized within the existing prioritization processes at the laboratories and DOE Headquarters. Transparency of these prioritization processes will allow industry to best inform and engage laboratory and facility management.

2. **Work execution status and outcomes**

   Existing coordination and communication opportunities can be further improved to increase the transparency of project execution status. Opportunities for improvement include the presentation of project status reports highlighting existing risks to successful completion, presenting interim and final results, and workshopping issue resolutions. In a high-value collaborative model, all

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stakeholders are prepared to discuss their needs and limitations, resulting in the determination of an achievable goal for the project.

3. Lifecycle project and program planning

Many research projects, from inception to closure, span more than a single fiscal year thus emphasizing the importance of multi-year project and program planning. This lifecycle project planning can improve the collaborative model by removing the ability for annual resets on outcomes, activities, and milestones. Lifecycle project plans can also include decision gates or hold points, a critical feature for efficiently and effectively managing research projects. These decision gates allow for pivots based upon interim experimental results or project cancellations when the desired outcome is no longer possible.

6.2 Clarify Funding Mechanisms for Supporting Research

In addition, the funding mechanism for industry-led research needs should be clarified. While national laboratories offer contractual mechanisms to perform research funded by a private entity, existing programs funded by DOE through annual appropriations also perform and prioritize research that generally benefits the industry. These two pathways require coordination to maximize the benefits of each; therefore, NEI recommends continued and focused coordination between DOE, national laboratories, and industry. Coordination meetings should be timed appropriately to allow for DOE programs to plan for the upcoming year and reconcile changes against any applicable multi-year research plans (see below).

6.3 Implement a Three-year Planning Outlook to Support Capability Development

As mentioned, nuclear fuel R&D often involves projects spanning several years. Utilizing existing processes under CRAFT, stakeholders should be queried to identify research needs beyond just existing focus areas to support capability development. These needs are then integrated into existing plans such that capabilities can be available when needed. In cases that involve industry-wide efforts, NEI recommends a dedicated workshop to achieve this goal. Furthermore, any stakeholder engagement activity should be performed to align with federal budget cycles.

6.4 Ensure Economic Drivers Guide Project Selection and Execution

Economic drivers such as time-to-market and the safety and economic benefits enabled by new technologies should drive the conversation and selection of research projects. Through industry-led groups, utilities would validate these drivers to ensure an effective business case exists to implement the new technologies. Emphasizing these drivers helps ensure that industry can justify deployment of new technologies and that testbed activities are aligned to decisions and schedules that matter for implementation.

6.5 Support Efficient Use of Resources

As private companies, fuel technology developers naturally endeavor to develop and commercialize products in a timely manner. This enables these entities to be the best stewards of effective time management. A strong, contractually driven governance model between the participants (e.g., DOE, fuel technology developers, national labs) ensures that each participant is accountable for a particular scope

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and function. A model where funding, under a cost-sharing partnership, is provided directly to the fuel technology developers to support R&D at national laboratories (where applicable) provides the most effective means for ensuring an efficient use of resources. This approach is strengthened by DOE's review and approval of the contract, and the national laboratory's input during the development of the project's scope, schedule, and cost. Alternative funding models can succeed in specific areas such as establishing new capabilities, addressing industry-wide research needs, or developing exploratory fuel technology concepts. A mix of funding models may be appropriate and justified.

7 CONCLUSION AND NEXT STEPS

Maintaining a capable, available, and reliable national testbed is essential to support continued safe and economical operation of the existing LWR fleet and to enable power uprates, capacity expansion, and new fuel technology development through ~2035. Fuel performance in LWRs will always be limited by the material capabilities of its constituents. Over the decades, advances in materials, manufacturing, and plant operational strategies have largely mitigated excessive cladding corrosion, numerous fuel rod failure modes and created higher energy fuel; however, materials development for fuel application is costly, time-consuming and requires a fully functional fuel development engine. The greatest potential benefits may result from advanced materials, but materials development may be the most difficult to achieve. The opportunity space is vast. Under DOE's leadership and Congress's support of the ATF program, numerous capability gaps have been closed; however, significant gaps remain (e.g., BWR test reactor conditions, ramp testing, etc.) and scientific processes are still evolving. Building on the collaborative model proven through the ATF program, DOE and industry can strengthen alignment by improving transparency in prioritization and ensuring that economic drivers guide project selection and execution, supporting increased capacity and enhanced economics at the existing fleet of LWRs.

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