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Combined TREAT-LOC and SATS LOCA Experiment Plan

September 2022

Integral LOCA Experiments on High-Burnup Fuels

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Advanced Fuels Campaign

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ABSTRACT

The Transient Reactor Test Facility (TREAT) loss-of-coolant (LOC) and high-burnup (HBu) experiment series, along with the Severe Accident Test Station (SATS) HBu experiment series, are integral LOC accident (LOCA) experiments planned under the Department of Energy (DOE) Advanced Fuels Campaign (AFC) program, which aims to support burnup extension needs by addressing identified R&D priorities in order to achieve an improved understanding of fuel fragmentation, relocation, and dispersal (FFRD) of HBu fuel during LOCA events. Priorities have been identified by the Electric Power Research Institute (EPRI)'s Collaborative Research on Advanced Fuel Technologies (CRAFT) Fuel Performance and Testing Technical Experts Group (FPTTEG). The data produced under this plan will be used to further validate and confirm existing models and inform future R&D and model development. The experimental program was specifically developed to address data gaps and opportunities identified via detailed review of the existing public knowledge base on LOCA FFRD, as well as reviewing specific experimental development activities regarding prototypic LOCA conditions for light-water reactor (LWR) systems. The test program relies on a unique combination of in- and out-of-pile experimental approaches to provide a clear tieback to the existing integral and semi-integral LOCA experiment database, using state-of-the-art facilities. More importantly, the program will systematically investigate the impacts of prototypic HBu fuel/cladding thermomechanical behaviors under postulated LWR LOCA conditions not yet fully investigated. These conditions correspond with prototypic decay-energy heatup (DEH) and stored-energy heatup (SEH) conditions. First, TREAT's unique capability will enable the first evaluation of the impact of SEH conditions on HBu fuels. The test program will emphasize the development of an improved mechanistic understanding of key phenomena through independent experimental systems, development of a database to support fuel performance modeling tools, world-leading advanced materials characterization, and the most advanced approach to in situ diagnostics ever deployed to evaluate FFRD. The results will represent a significant leap forward in evaluating prototypic conditions and novel data to support modeling development and validation, as well as to inform the technical basis for LOCA-induced FFRD.

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ACRONYMS

AFC	Advanced Fuels Campaign
ATF	accident-tolerant fuel
ATR	Advanced Test Reactor
BNGS	Byron Nuclear Generating Station
BWR	boiling-water reactor
CRAFT	Collaborative Research on Advanced Fuel Technologies
DBA	design basis accident
DEH	decay energy heatup
DOE	Department of Energy
EOL	end of life
EPRI	Electric Power Research Institute
FFRD	fuel fragmentation, relocation, and dispersal
FMMS	fuel motion monitoring system
FPTTEG	Fuel Performance and Testing Technical Experts Group
FY	fiscal year
HBu	high burnup
HBWR	Halden Boiling Water Reactor
HERA	High burnup Experiments for Reactivity-initiated Accidents
INL	Idaho National Laboratory
IR	infrared radiation
LB	large break
LOC	loss of coolant
LOCA	loss-of-coolant accident
LWR	light-water reactor
NANGS	North Anna Nuclear Generating Station
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NRC	Nuclear Regulatory Commission
NSUF	Nuclear Science User Facility
OPTI-	out-of-pile-testing and instrumentation
ORNL	Oak Ridge National Laboratory

PCT	peak cladding temperature
PIE	post-irradiation examination
PWR	pressurized-water reactor
SATS	Severe Accident Test Station
SCIP	Studsvik Cladding Integrity Project
SEH	stored energy heatup
tFGR	transient fission gas release
TREAT	Transient Reactor Test Facility
TWIST	transient water irradiation system for TREAT
VVER	water-water energetic reactor

Combined TREAT-LOC and SATS LOCA Experiment Plan

1. PURPOSE AND OBJECTIVES

Nuclear- and furnace-heated loss-of-coolant accident (LOCA) experiments based on a first-of-a-kind experimental approach are planned in order to address fuel fragmentation, relocation, and dispersal (FFRD) in high-burnup (HBu) fuels [1,2]. The experiment methods were developed in special consideration of the impact of prototypical conditions on relevant FFRD phenomena, and by referencing the database of classical LOCA experiments conducted on HBu fuels. A primary aspect of the new methods pertains to the prescribed heatup rate of the cladding and fuel temperature profiles, in recognition of need to address stored energy heatup (SEH) and decay energy heatup (DEH) by applying *both* nuclear-fission-induced internal and external heating approaches. SEH conditions and the full nuclear heating of test fuel have never been explored in regard to HBu fuels. Thus, the primary objectives of the dual-facility experimental program are to systematically achieve the following:

1. Establish world-leading integral LOCA experiment capabilities by tying back to existing databases and leveraging integral hot-cell furnace and in pile experimental testing approaches
2. Evaluate the integral impacts of SEH and DEH conditions (depending on the HBu core design) on FFRD and transient fission gas release (tFGR) during a LOCA
3. Measure key behavioral phenomena in situ (e.g., cladding deformation and burst dynamics, tFGR, fuel relocation and dispersal, and cladding balloon surface temperature) to reduce the uncertainty in phenomena interdependencies (e.g., temperature profile and plenum pressure/volume), while also allowing for first-of-a-kind model development and validation
4. Perform LOCA tests on material samples with detailed relevant microstructural characterization pre- and post-testing
5. Provide expanded LOCA datasets for model development and code validation in regard to relevant HBu fuels near important burnup thresholds.

The experimental program will accomplish these objectives by performing experiments on fuel segments irradiated to HBu in commercial nuclear power plants. The experiment goals require usage of a semi-integral LOCA furnace, the Severe Accident Test Station (SATS), and the integral in-pile LOCA capability developed for the Transient Reactor Test Facility (TREAT). These integral tests will be further supplemented by more targeted separate-effects testing and characterization using the extensive post-irradiation examination (PIE) capabilities of various hot-cell laboratories located at U.S. national laboratories. This document provides an overview of the experiment test plan for conducting this work.

2. PROJECT ORGANIZATION

The loss-of-coolant (LOC)/SATS experiment plan is funded and led by the Department of Energy (DOE) Advanced Fuels Campaign (AFC) program, with the involvement of key personnel and facilities at Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL). Each institution will coordinate the execution of supporting PIEs and take full responsibility for their own testing facilities and results. Members of the Fuel Performance Testing Technical Expert Group (FPTTEG) under the Electric Power Research Institute (EPRI)'s Collaborative Research on Advanced Fuel Technologies (CRAFT) framework are primary stakeholders such as fuel vendors, utilities, the Nuclear Energy Institute, DOE, EPRI, and the Nuclear Regulatory Commission (NRC) [3]. These stakeholders support the test program in an advisory fashion, as well as potentially with in-kind contributions (e.g., experiment modeling evaluations, test materials). Coordination with the Organization for Economic Cooperation and

Development and Nuclear Energy Agency's Studsvik Cladding Integrity Project (SCIP) is a priority objective, though engagement is currently limited until DOE laboratories can obtain membership and full participation status within the SCIP. Participating fuel vendors and utilities are also needed to provide commercial HBu fuel source materials, along with agreed-upon material pedigree information (e.g., dimensions, enrichments, and power histories), to enable detailed evaluations of material performance during the simulated LOCA experiments. Specifics on the material selections and the associated data terms are not discussed further here. Westinghouse and Constellation are expected to provide first test materials from the Byron Nuclear Generating Station (BNGS), and potentially from HBu fuel segments taken from the North Anna Nuclear Generating Station (NANGS) and now currently residing at ORNL. This document will be regularly updated as necessary, per Section 11.

3. BACKGROUND

3.1 Loss-of-Coolant Accident

LOCAs are a family of postulated accidents in which the reactor core experiences loss of cooling due to a rupture in the primary coolant circuit. Typically, LOCAs are classified as representing either large-break (LB), intermediate-break (IB), or small-break (SB) conditions, depending on the size of the rupture area. In pressurized-water reactor (PWR) systems, a LB-LOCA is identified by a split break or double-ended break, typically most limiting with occurrence in one of the cold legs between the primary pump and the reactor vessel. This plan will focus on PWR LB-LOCA as the design basis accident (DBA) scenario of interest, with this focus likely shifting to IB and SB LOCAs over the longer term. Recently, these latter two scenarios have garnered greater technical interest, and will receive further consideration as needs develop in the coming years. The main phases of a LB-LOCA are the (1) blowdown, (2) refill, and (3) reflood phases. Upon rupture and blowdown initiation, primary coolant is expelled from the break, rapidly depressurizing the vessel (<30 s) and causing reactor sub-criticality and eventual full shutdown. Intermittent flow reversals occur as the core is initially cooled by the resulting two-phase mixture. The stored energy in the fuel redistributes as peak temperatures in the fuel centerline drop and temperatures in the fuel periphery increase. The magnitude and rates of the peripheral heatup depend on the prior operating linear heat rate, specific cooling conditions, etc. Following the associated blowdown phase of the aforementioned LB-LOCA case, the emergency core cooling system begins to refill the reactor vessel from the lower plenum, while the reactor core (devoid of liquid coolant) continues to heat up in a near adiabatic fashion due to decay heat generation in the fuel. The coolant rises through the lower vessel to the core over some tens of seconds, with a two-phase mixture initially forming in the bottom regions of the core. This mixture begins to enhance the heat transfer in the upper parts of the core. The reflood phase begins as the waterfront reaches the bottom of the core and passes over the fuel rods at a given axial location.

High temperatures and significant pressure differentials across the cladding walls make the cladding susceptible to oxidation, swelling/ballooning, and potential rupture. The strength of Zircaloy ([Zry]—which also applies to other zirconium-alloy-based cladding types) decreases dramatically with increased temperature, and cladding rupture becomes increasingly likely as temperatures exceed 700°C, depending on the fuel rod internal pressure. As temperatures increase, so do the diffusion rates of oxygen and hydrogen in Zry (including oxygen from outside and inside the cladding). This is compounded by the Zr alpha-to-beta phase transformation that occurs near 800°C, resulting in high-temperature embrittlement of the metal. Upon occurrence of the reflood phase and lower fuel temperatures, the principal embrittlement mechanisms are either a thinning of the load-bearing prior-beta layer, due to growth of the oxide- and oxygen-stabilized alpha layer, or the oxygen concentration threshold being exceeded in the beta layer. Classical LOCA safety limits of 17% equivalent cladding reacted and 1204°C peak cladding temperature were designed to restrict these embrittlement mechanisms [4].

3.2 Experimental Programs

Several review papers have summarized the existing LOCA database relevant to HBu light-water reactor (LWR) fuels [2,4,5,6,7]. For that reason, only a brief overview is provided here to aid in understanding key distinctions from the present LOCA test designs and test plans.

Ever since the 1960s, many experimental investigations of fuel performance under LOCA conditions have been performed, both in and out of pile [4]. The resulting primary LOCA safety criteria developed via these programs focus on cladding embrittlement limits, with peak cladding temperature and maximum oxidation limits, under the assumption that cladding openings would retain fuel [5]. In these programs, fuel pellet behavior was considered, but generally deemed a low-priority issue, putting the experimental focus on more cladding-centric evaluations of fuel system behaviors during LOCAs. Experimental approaches were adapted for evaluating the refill/reflood phases, with DEH in the cladding and in light of ramp rates of approximately 5 K/s (starting from isothermal conditions at operating coolant temperature)—a scenario considered appropriate and limiting for relevant cladding behaviors.

By the early 2000s, most in-pile test programs had been terminated. However, by the mid-2000s, the first LOCA experiments on HBu fuels (defined here as fuels that exceed the current U.S. limit of 62 GWd/t for rod average burnup, though in-pile experimental data at that time were only available for burnups of up to ~35 GWd/t [8]) were performed in the Halden Boiling Water Reactor (HBWR) as part of the IFA-650 experiment series. Before its closure in 2018, the HBWR performed a total of 13 experiments relevant to HBu fuel performance. These experiments encompassed seven PWR, two water-water energetic reactor (VVER), and four boiling-water reactor (BWR) rods, as summarized in Figure 1 [6]). Several out-of-pile integral LOCA experiments on HBu fuels were also performed throughout the world, mostly using hot-cell furnace configurations inspired by tests performed by Argonne National Laboratory for NRC in the 2000s [9]. The MIR.M1 reactor also performed a few in-pile LOCA tests on higher burnup fuels of VVER origin [10,11]. In all cases, it is notable that the experimental conditions were based on heating a specimen at rates of approximately 2–5°C/s from a starting temperature either at or below the average coolant temperatures for LWR systems (<300°C). The HBWR and MIR.M1 test specimens were fission heated (volumetric heating in the fuel), while all furnace test specimens were heated on the external surfaces of the cladding. The HBWR experiments also utilized an external heater to complement the nuclear heating for achieving the targeted peak temperatures. It should be noted that the HBWR and MIR.M1 experiments began the simulated LOCA transient from nearly isothermal conditions, with near-isothermal radial heatup conditions [6] like the furnace tests.

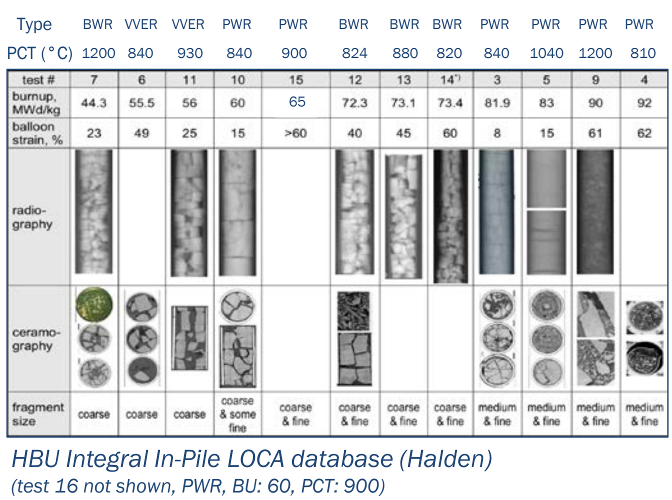


Figure 1. Summary of the HBWR IFA-650 experiments, adapted from [6].

3.3 Findings and Opportunities

Experimental data generally show a trend of increasingly fine fragmentation of the fuel with increasing burnup—typically correlating to the segment average burnup of a test specimen. Separate-effects data were used to develop an empirical relationship between burnup and peak terminal temperature[12], and these data generally show good agreement when compared with LOCA test [13]. A strong correlation is evidenced between the fuel microstructure (e.g., concurrent HBu structure and fission gas bubbles) and fragmentation behavior, and work continues to develop these relationships [14,15], though the microstructural data available for establishing the needed understanding are limited. A general research community focus is on the relationship between tFGR with UO_2 mechanical degradation and fuel fragmentation, where gas release is fundamentally driven by the overpressurization of gas-filled pores, as represented by the following simple equation:

$$P_{lim} = P_g - P_h - P_s \quad (1)$$

where P_{lim} is the pressure for fracture of the surrounding fuel, based on pore size/shape and fuel fracture strength; P_g is the internal gas pressure; P_h is the hydrostatic pressure from the 3-D stress state, which is influenced by many factors such as rod internal overpressure and fuel-cladding mechanical interactions; and P_s is the capillary pressure of the pore. Though not the only important consideration, quantification of each of these values remains a challenging yet important objective within the R&D community.

Some key independent parameters and behaviors influencing FFRD that were recently or are now actively under investigation include (addressing information in the public domain):

- Burnup dependency
- Peak specimen temperature
- Impact of pre-transient and irradiation history linear heat generation rate; experimental results indicate some effects [16]
- Specimen internal free volume and internal pressure [17,18]
- Relationship of rod balloon and burst behaviors to fragmentation—correlating cladding strain to fragmentation and relocation [6]
- Relationship of rod balloon and burst behaviors to dispersal—correlating burst opening size/shape and particle size to dispersal quantity
- Impact of the specimen's axial heating profile on cladding behavior, with an evaluation of prototypical vs. experimental conditions
- Axial gas communication—the Halden tests afford insights into gas communication between burst and plenum, limited separate effects data are available, and these data indicate impacts to post-failure behavior
- tFGR—integral test data, a few separate-effects studies on overpressurization effects on fission gas release (and fragmentation) [12], and temperature ramp rate effects [19].

Key problem characteristics not explored or with limited evaluation in previous integral testing, and that will be discussed further in the following sections, include:

- Rod (fuel pellet and cladding) heatup driven by SEH in the fuel during blowdown (see Section 3.3.1), resulting in different thermal behaviors in the pellet centerline and radial periphery
- Quantified timing and extent of fuel relocation—although in situ thermocouple measurements and PIEs for some Halden tests provide indications, uncertainty yet remains
- Detailed microstructural description of the test specimens in LOCA tests

- Relationship of rod heating and constraint to balloon behavior and FFRD—cladding azimuthal temperature distribution and physical constraints (cladding behavior is being explored in detail in ongoing out-of-pile experiments [20]); grid spacer effects were observed in two Halden tests, drawing mixed conclusions
- Axial gas communication—the full impacts of axial gas communication remain uncertain; while post-failure impact is likely, questions remain regarding the potential for local pressurization effects vs. plenum pressure, as well as the impacts of grid spacers
- tFGR—much remains to be explored, including rate effects, local vs. bulk effects, microstructural data linkages, and measurement uncertainties.

The existing HBu LOCA database is impressive when considering the inherent challenges of acquiring and working with HBu materials. Much of the current understanding was developed over the course of the various experimental programs, with data needs now being better understood. It is naturally difficult for the test planning for the various experimental programs to be sufficiently connected and systematically address the questions they discover (e.g., comparing results obtained by applying different methods to different samples). The irradiation histories of test materials, mostly of which come from commercial nuclear plants, frequently lack pertinent data describing the state of the fuel material. Therefore, a primary goal of this test plan is to fill in the data gaps and take advantage of opportunities afforded by the significant existing database and knowledge base. The linkages to recent and pre-existing experimental programs are of high priority, as is ensuring that test materials are adequately characterized (in terms of microstructure and fission gas characteristics). As noted earlier, LOCA testing strategies for irradiated materials have so far been largely based on evaluating cladding balloon behavior and cladding embrittlement criteria. Fuel behaviors relevant to FFRD should be identified and reflected in the FFRD LOCA test design.

3.3.1 SEH vs. DEH LOCA Conditions

The AFC LOCA design teams invested heavily in ascertaining prototypic or licensing-relevant conditions for FFRD in LB-LOCAs so that they could be translated for use in experiment design and test program development. As with any experiment or model, the assumptions made to represent the true application (i.e., full-plant LOCA simulation) are of paramount importance and were therefore scrutinized heavily. The general conclusions of these studies indicate that the LOCA conditions (i.e., fuel/cladding temperature and cladding wall pressure differential dynamics) experienced by fuel rods may vary rather widely, depending on many factors. However, some key behaviors under PWR LB-LOCAs may notably affect FFRD, including the impacts of SEH as compared to DEH conditions. These classifications are defined to highlight potentially important differences in temperature spatial/temporal evolution and rate effects. Notably few of the LB-LOCA temperature histories available in the public literature also show fuel centerline temperatures. Examples of predicted cladding temperatures for different plant designs can be found in [21,22,23,24]. The final reference in that series also shows some example fuel centerline temperatures for these cases.

While DEH conditions always exist in LOCAs, they may be masked by much more dominant SEH effects during the first 10–20 seconds of the transient event. The level of SEH contribution seems to be dictated by several factors, though the dominant ones include the pre-accident linear heat rate and the fuel burnup [24] and blowdown cooling parameters. The former also is an important input to decay heat levels, which play an important role in determining the peak cladding temperatures reached during LOCAs. SEH conditions were found to generally correspond to higher peak cladding temperatures. Figures 8 and 9 in [24] provide a good illustration and comparison of these conditions for both BWR and PWR LOCAs, respectively. For the BWR case, the fuel temperatures reach near-equilibrium during the blowdown phase and enter DEH conditions at ~35 seconds, at which point a ~5 K/s temperature ramp rate begins. The PWR case shows the SEH condition during the blowdown stage, with a very high temperature ramp rate (~100 K/s) during the first few seconds, followed by a slight temperature decrease and a further near radially isothermal temperature ramp with a DEH condition. Analyses are underway to further quantify and understand these dependencies.

To further illustrate the scenarios described above, Figure 2 provides LB-LOCA temperature prediction examples that specifically contrast the SEH and DEH conditions. The fuel and cladding temperature histories from the two LB-LOCA simulations are included. For both scenarios, Figure 2 also shows the radial temperature profile of the fuel at various times throughout the LOCA. The Scenario A simulation results come from a coupled BISON/TRACE LB-LOCA analysis of a generic end-of-life (EOL) Westinghouse 4-loop PWR with an HBu cycle core design. This work was performed by INL to support the development of the in-pile Transient Water Irradiation System for TREAT (TWIST) LOCA vehicle by identifying representative LOCA scenarios of interest. Scenario B stems from work performed by ORNL [25], who used RELAP5-3D and BISON to simulate a LB-LOCA in an EOL Westinghouse 4-loop PWR featuring an HBu core design. In both scenarios, the cores the fuel is operating at the same linear heat rate of ~21 kW/m prior to the LOCA, generating nearly identical radial temperature profiles through the fuel; however, the temperature response of the fuel rod following the LOCA vastly differs between the two scenarios.

In Scenario A, the coolant in the core flashes to steam within the first few seconds after pipe rupture, greatly reducing the coolant heat transfer capability. This results in a rapid redistribution of the fuel’s stored energy, causing temperatures in the central region of the fuel to decreases at a rate of ~100 K/s, while the cladding heats up at this same rate. After this SEH-driven heatup, core flow reversals decrease the fuel rod temperature for a period of time, followed by a second, slower, DEH-driven heatup of the fuel rod. In Scenario B, the coolant heat transfer capabilities directly following pipe rupture remain high enough to completely remove the stored energy from the fuel, such that the fuel rod is cooled to approximately the coolant temperature. In this scenario, there is no SEH-driven temperature peak, and the subsequent ~5 K/s temperature ramp is only due to the decay heat in the fuel.

The potential impacts of these different conditions may be of great importance for FFRD, but should also be considered in the context of specific events. Significant SEH influence may be absent in smaller break LOCA or BWR LOCA events [21]. The lack of data presently available makes the influence of heating ramp rates difficult to assess, especially when using models that lack appropriate validation and fail to account for all the necessary mechanisms. The maximum peak cladding temperatures (PCTs) for HBu rods are not expected to come anywhere near the current limits of 1204°C. Testing should be performed in a manner that aligns with the representative conditions that will influence the FFRD response. Ultimately, application of the test data should also align with the test conditions.

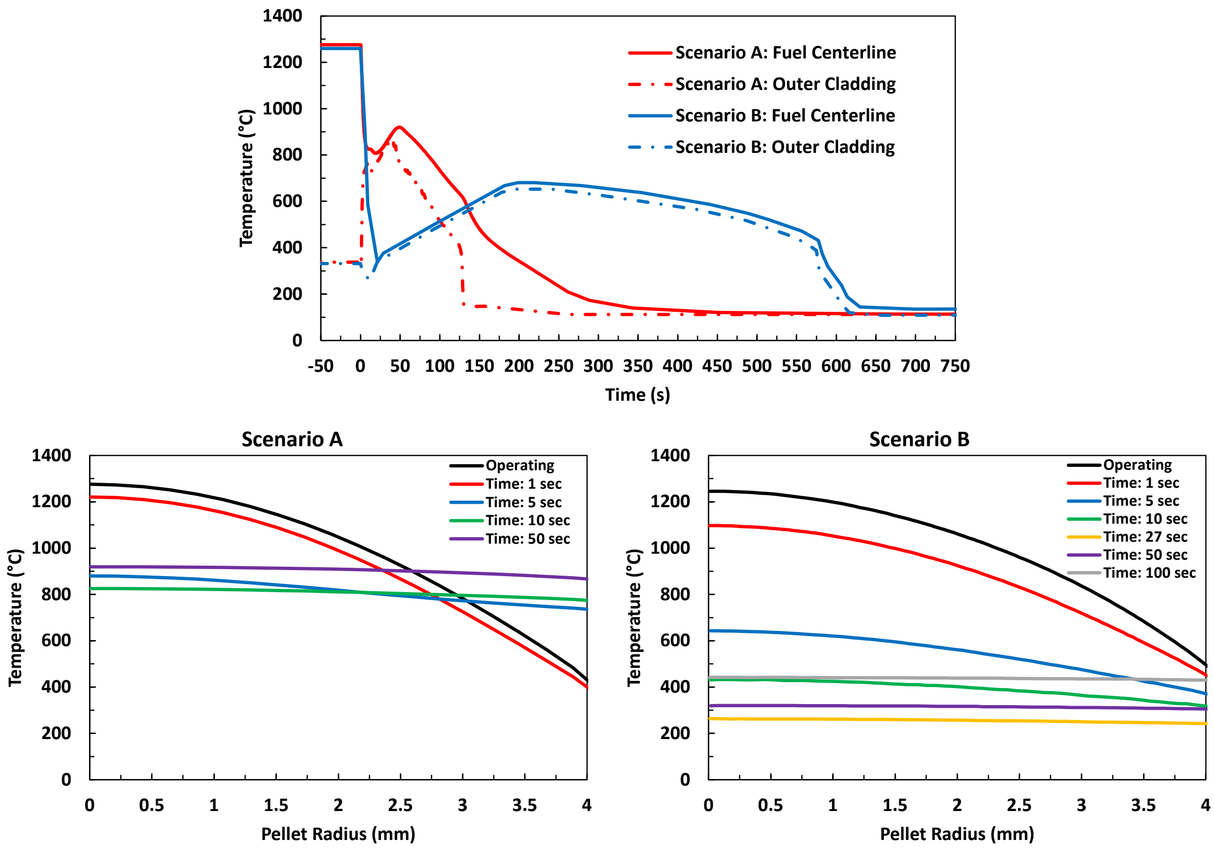


Figure 2. Examples of relevant LOCA heatup conditions, illustrating SEH vs. DEH. (Top) Fuel and cladding temperatures as a function of time for Scenario A, with a strong SEH effect, and for Scenario B, with no observed SEH contribution. (Bottom left and right) Radial temperature profiles in the fuel at different points in time during the transient progression for Scenarios A and B, respectively.

4. METHODS

In the last several years, DOE has invested in strategic capabilities to support nuclear fuel development through transient/safety testing. Notably, the TREAT facility at INL was restarted to support broad missions pertaining to transient testing of nuclear fuels and materials. The SATS system at ORNL was also recently developed, based on state-of-the-art integral furnace approaches, to keep Argonne National Laboratory's Alpha-Gamma Hot Cell fuel testing capabilities in the U.S. after being shut down. The Advanced Test Reactor (ATR) can perform reirradiations of whole segments in order to condition them for transient testing objectives. All these test facilities are complemented by advanced PIE facilities located at both INL and ORNL.

4.1 Severe Accident Test Station

The SATS system was initially developed to conduct high-temperature steam oxidation testing of unirradiated candidate accident-tolerant fuel (ATF) cladding concepts at ORNL [26]. Leveraging this experience, the out-of-cell SATS capabilities were replicated and modified for hot-cell operation. The system has been exercised through extensive commissioning exercises and has performed multiple experiments on HBu fuels [26]. Throughout the design of the SATS system, the hot cell's operational constraints (e.g., spatial and other constraints due to the manipulators used to operate the unit, and limitations on the volume and types of gases released from the system) were thoroughly captured to enable efficient transition from the out-of-cell module to the in-cell capability. Table 1 summarizes the range of test parameters for each module and test type, while Figure 3 schematically outlines the SATS thermal capabilities for in-cell integral LOCA testing on 300-mm rodlet samples. Figure 4 provides an overview of the two-module test station prior to insertion into the hot cell. Figure 4a shows the integral LOCA test apparatus (blue outline) and the high-temperature test furnace (red outline). A zoomed-in view of the integral LOCA test apparatus is shown in Figure 4b.

Table 1. Summary of the test parameters for each module and test type [13].

Parameter	Design Basis Accident Module		Beyond Design Basis Accident Module
	LOCA Integral Test	Oxidation-Quench Test	High-Temperature Test Station
Sample specification	Fueled rod	Defueled rod	Defueled rod or coupon with 3 mm hole
Sample segment (mm)	~200–300	~25–50	~25–50
Maximum pressure at 300°C (MPa)	~ 20	0.1	0.1
Maximum temperature (°C)	1,200	1,200	1,700
Heating rate, 4-lamp furnace (°C/s)	5, range 1–17	5; maximum 17	.25; maximum 0.33
Heating rate, 12-lamp furnace (°C/s)	30–60	30–60	N/A
Steam flow rate ($mg/cm^2 \cdot s$)	~5.7	~5.7	3.0–7.0
Gas environment	Steam or argon	Steam or argon	Steam or argon
Quench (°C)	@ 20–800	@ 20–800	None
Quench condition	Rising water around sample	Rising water around sample	None
Reflood elevation change rate (mm/s)	≥15	≥15	None
Test time (minutes)	≥30	≥30	Multiple days

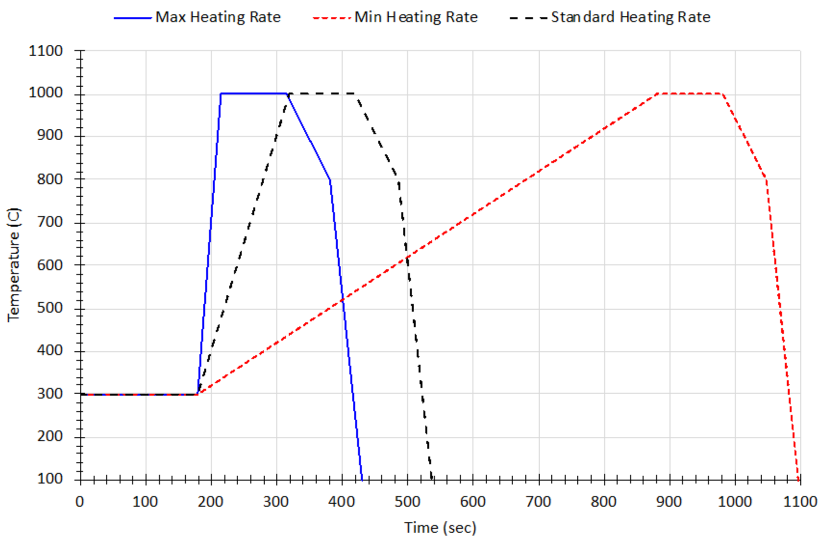


Figure 3. Representative cladding temperature histories in SATS for integral LOCA tests.

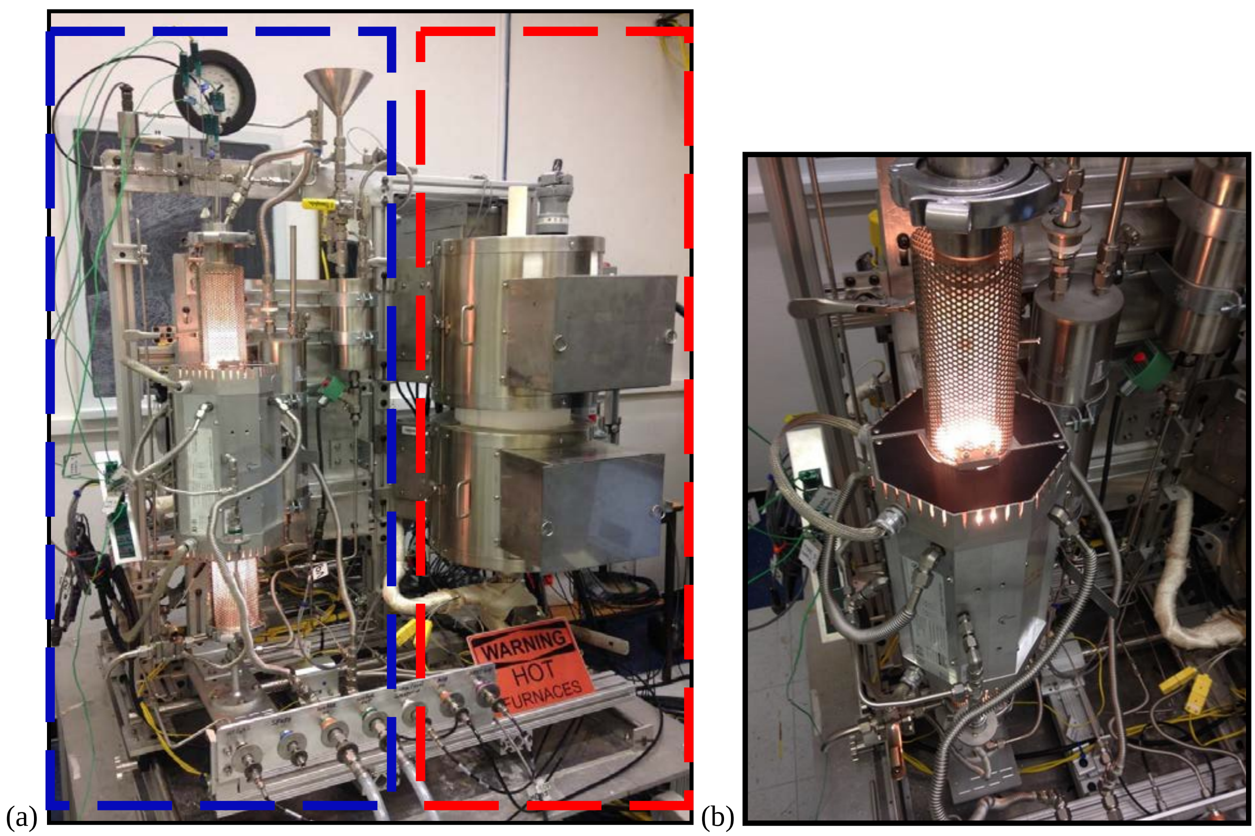


Figure 4. (a) Severe Accident Test Station, consisting of a single unit with two modules: one for DBA integral LOCA testing (outlined in blue), and one for beyond design basis accident high-temperature testing (outlined in red); (b) LOCA integral test apparatus [13].

The SATS LOCA integral test train is a 30 cm long fuel rod segment designed to be externally heat up to 1,200°C, using an infrared radiation (IR) furnace under high internal pressure (max ~20 MPa at 300^{o}C) inside the rodlet. The internal pressure is generated by high-pressure argon gas and is monitored via a digital output pressure transducer.

Cladding temperature control and monitoring are extremely important for understanding FFRD performance and for code validation. Analyses have shown there will be a difference between the cladding and fuel temperatures at high heating rates of 100^{o}C/s (corresponding to SEH conditions), and fuel temperatures remain flat (~25^{o}C across the fuel pellet) under DEH conditions (5°C/s). Slower heating rates consistent with DEH conditions produce greater uniformity between the cladding and fuel temperatures. Therefore, each test rodlet is fitted with up to four thermocouples: two at the specimen axial midplane, 180° apart; one positioned 5 cm above the midplane; and one positioned 50 cm below the midplane. Sample heatup occurs quickly for short samples, but temperature overshoot can be avoided by applying an integrated, well-instrumented control system.

A quartz reaction tube provides an enclosed volume for steam flow and water quench of the 30-cm rod segment; both steam and water are introduced through the bottom of the unit. Note that the rodlet length can range from 7.6 to 30 cm; however, the system is unable to heat samples longer than 30 cm. The test train is centered within the quartz tube by two perforated spacer disks. Swagelok fittings above the specimen connect to the high-pressure gas line and the top pressure gauge (~60 cm from the top of the quartz tube); below the specimen, they connect to the bottom pressure gauge line. The test train for the LOCA integral tests is supported at the top to minimize specimen bowing. Figure 5 shows a photograph of a SATS test train assembly.

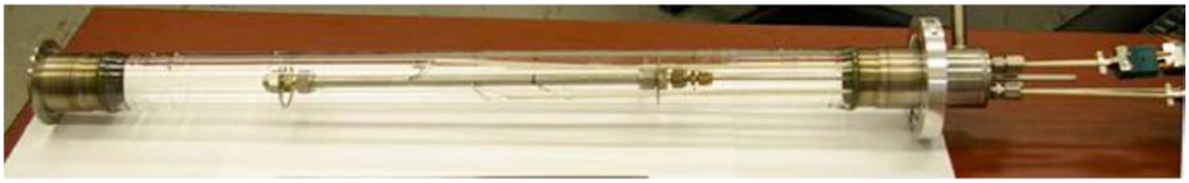


Figure 5. SATS LOCA test train.

4.1.1 Upgrades to SATS

The SATS system was designed and built based on historical LOCA testing approaches [9]. However, as noted in Section 3, LOCA testing needs are now expanding beyond cladding embrittlement evaluations and toward integral fuel system responses. SATS-relevant FFRD data gaps pertain to heating rates, peak terminal temperatures, burnup effects, and tFGR impacts on cladding and fuel response. Historically, infrared (IR) furnaces were designed to target 5 K/s, DEH conditions. Furthermore, these limiting test conditions have been the primary focus for HBu LOCA test programs to date, and additional data in these specific testing regimes would likely limit substantial progress in FFRD R&D. Therefore, upgrades to the SATS capability are under development to address these gaps and will be made available to support this test plan. The notable enhancements are the increased heating rate capability and temperature profile control, in situ tFGR, and in situ cladding deformation monitoring (including through rod bursting). The SATS enhancements are expected to be complete by fiscal year (FY) 2024 to support the LOCA test program.

The original SATS furnace contains four IR lamps, with a 20 A and 480 V power requirement. The new IR furnace is three times that size and contains 12 IR lamps, with a 50 A and 480 V power requirement. The expected output is ~3x that of the previous furnace and should provide heatup rates of 45–60 K/s, enabling SATS to evaluate FFRD behavior under SEH heating rates through external heating. Additionally, the fact that the new furnace is larger both in terms of height (+2 in.) and diameter (+7 in.) is expected to reduce axial and azimuthal temperature variations, leading to a more controlled experiment. Currently, over a 2-in. axial span, the azimuthal temperature gradient ranges from 25 to 50°C, and the axial temperature gradient varies between 10 and 25°C [27]. Additionally, SATS modifications are underway to support LOCA and creep testing requiring modifications to facilitate furnace swapping. In addition to the standard LOCA furnace describe above, an additional furnace of the same size and power is required to support in situ cladding deformation measurements capability. This furnace will contain a view port by which cladding diameter changes can be measured online using a laser-/LED-based high-resolution optical micrometer.

SATS will also be capable of measuring tFGR using three modes operation: (1) no burst transient, with post-test puncture; (2) burst transient with post-test measurement; and (3) real-time monitoring via a charcoal trap system. The third option is the most complicated but provides the most value, as FGR is measured in real-time using a radiation detector system. Figure 6 shows the charcoal trap system design for capturing real-time fission gas release during a LOCA test.

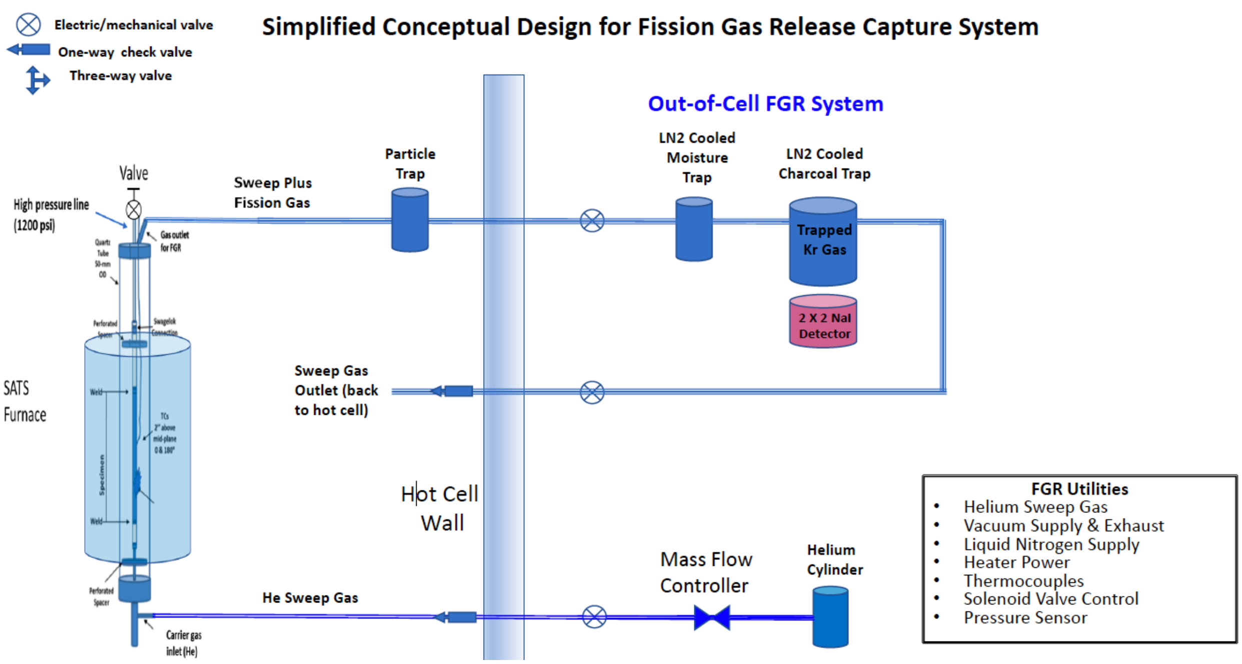


Figure 6. Design for a tFGR capability using charcoal traps to capture and measure Xe^{85} in real-time.

The aim of this system is to capture the tFGR onset temperature and the amount (moles of gas) of tFGR for a segment experiencing a representative LOCA transient. Another goal is to measure the tFGR amount without burst. ORNL's approach is to cut irradiated fuel into 15–30 cm segments that will then be refabricated with end caps and connected to a pressurization system. Online pressure measurements will be made, but it is infeasible to circulate high-pressure gas through the segment and then out of the hot cell and into a fission gas trap during a test. It is also possible to simply heat the fuel segment under representative LOCA ramp and pressure conditions, then capture the total amount of tFGR released by the sample—either through rupture or before rupture. However, the tFGR onset temperature and evolution will not be captured in this type of test. The third mode of operation intends to heat the sample in a stepwise manner to a predetermined temperature at a specified ramp rate; the content of the segment would be expanded into a larger volume and sent to the fission gas traps—out of cell and at atmospheric pressure—for evaluation by counting the released Kr-85 content. The test will then proceed to the next hold temperature, until the final temperature is reached.

4.2 Transient Reactor Test Facility (TREAT)

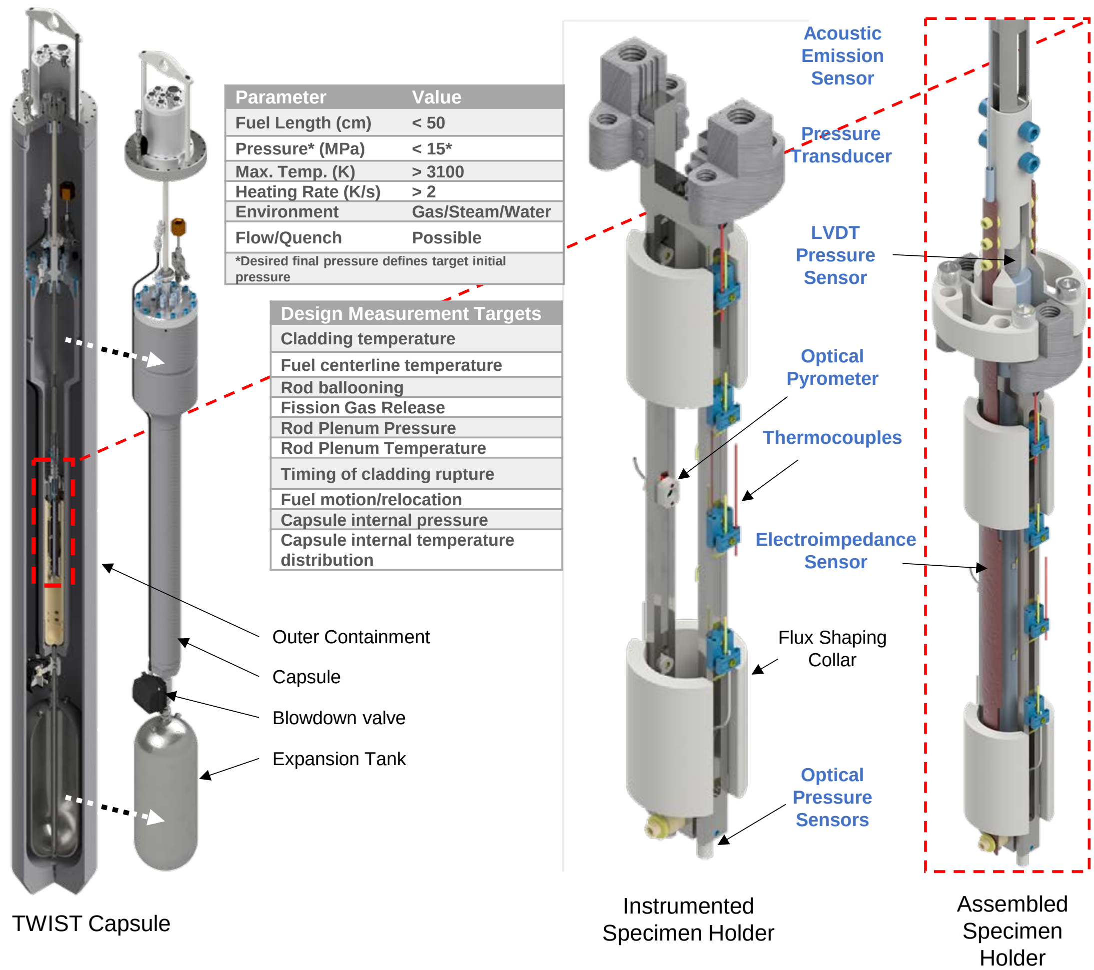
The TREAT facility offers the unique flexibility to serve many fuel and reactor designs by enabling a modular experiment strategy, as well as a highly agile control rod system for tailoring desired power histories for experiments [28]. Special experimental devices have been (and are currently) under development to aid in performing integral LOCA experiments and related separate-effects studies [29]. TREAT is an adiabatic, transient-shaping reactor with an air-cooled core. In terms of thermal capacity, the core is limited to a total deposition energy of near 2500 MJ, with the ability to deliver that total over a period ranging from ms to several minutes. Relative to other transient reactors, TREAT is especially well suited to drive HBu low-enriched specimens to nearly any power level.

While TREAT has a rich history of conducting LWR safety experiments [30], recent experimental work has demonstrated several of its unique capabilities for investigating LWR transient fuel performance. Since the facility restart in 2017, LWR fuels have been tested in two primary configurations (i.e., a gas capsule and a water capsule) for reactivity-initiated accident conditions. The Nuclear Energy Agency's ongoing High burnup Experiments for Reactivity initiated Accidents (HERA) project, a Framework for IrraDiation ExperimentS Joint ExpErimental Programme, is already capitalizing on these capabilities.

One of TREAT's greatest capabilities is its integration with in-situ instrumentation, including the Fuel Motion Monitoring System (FMMS), or hodoscope [31]. The FMMS, which is integral to the reactor design and one of only two in the world (the other being located at the CABRI facility), can provide real-time monitoring of fuel location via a 2-D array of detectors, each aimed at the test specimen via a slot in the core and a movable collimator. Additionally, a wide variety of instrumentation has been exercised in TREAT to demonstrate a range of measurement capabilities and provide mature diagnostics, including for post-transient exams. Focused instrumentation development has provided capabilities for both contact and non-contact instrumentation, most notably for optical-fiber-based systems such as infrared pyrometry and electroimpedance sensing.

4.3 TREAT LOCA Device

With static-gas and -water capsules being routinely used in TREAT, a static-water blowdown capsule called the TWIST device is under development to enable control of relevant heat-transfer boundary conditions in order to create a testing capability that specifically addresses fuel behaviors and FFRD during LOCAs. Figure 7 gives a schematic overview of the TREAT TWIST capsule design, with tables showing its capabilities. A detailed evaluation study for a similar first-generation TREAT device is found in [32]. The primary difference in that study is a smaller capsule that has since been expanded with TWIST to accommodate longer length specimens (i.e., up to 50 cm in fueled length) and to afford improved instrumentation options.



Parameter	Value
Fuel Length (cm)	< 50
Pressure* (MPa)	< 15*
Max. Temp. (K)	> 3100
Heating Rate (K/s)	> 2
Environment	Gas/Steam/Water
Flow/Quench	Possible
*Desired final pressure defines target initial pressure	

Design Measurement Targets
Cladding temperature
Fuel centerline temperature
Rod ballooning
Fission Gas Release
Rod Plenum Pressure
Rod Plenum Temperature
Timing of cladding rupture
Fuel motion/relocation
Capsule internal pressure
Capsule internal temperature distribution

Figure 7. Schematic overview, key specifications, instrumentation measurement targets, and test train overview of the TREAT LOCA device, TWIST.

The TREAT TWIST design experiment strategy represents a unique opportunity for LOCA testing (one not previously explored for HBu fuels), with the primary objective being to use unique instrumentation to investigate thermal histories, starting from full-power conditions. Figure 8 is a schematic representation of the nominal design conditions for a TREAT experiment, for which each segment may be tailored to suit the specific objectives. For example, representative calculation results for fuel response are shown in a later section of this document. The capsule relies on careful selection of specimen power input to reach nucleate boiling conditions and prototypic linear heat rates (so as to generally not overheat beyond EOL conditions) in the specimen prior to opening an expansion tank valve while simultaneously reducing the reactor power. This simplistic approach creates a suitable balance between heat input and heat rejection in order to control the rate of temperature change across the fuel/cladding radii. For example, the relative timing of liquid blowdown, the rate of blowdown, and the power reduction in the rod can be fine-tuned to achieve specific targeted conditions. This approach was developed to represent certain LOCA events of great importance to LWR limiting conditions and has been shown to provide the flexibility to achieve that goal. The reflood capability is not currently considered an immediate testing requirement and has thus not yet been incorporated into the TWIST capsule but could be added with basic modifications. The capsule is designed to provide a range of boundary conditions corresponding to LWR LOCAs, and more specific targets are described in the test series description sections.

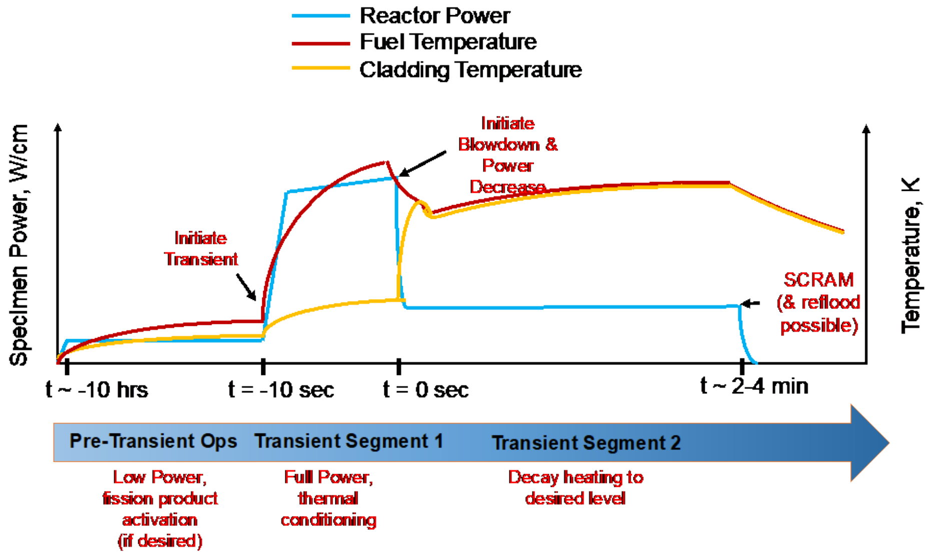


Figure 8. Schematic representation of the TREAT LOCA experiment sequence in the TWIST device.

4.4 High-Burnup Rodlet Reirradiations

A Nuclear Science User Facility (NSUF) project awarded to EPRI and NRC aims to tailor pre-transient fuel operating conditions and the resulting fuel microstructure to a targeted state. Currently, the ATR is the only reactor in the Western world that features a pressurized-water loop (with additional loops currently under development) able to accept integral-scale fuel rods. (Several other such loops are used for non-civilian applications.) Included with the water loops are several drop-in positions designed to afford boundary condition control. The ATR is ideally suited to test integral-scale fuel rods, including by reirradiating segments of rods from commercial or research reactors to a targeted operating condition. However, the NSUF project is awaiting material availability at INL in order to perform irradiations that would supplement the proposed LOCA test plan. The ideal approach (within facility constraints) for preserving the as-operating microstructure is an important consideration in the ATR experiment design. While a proposal outlines general experiment goals, the details of the reirradiation conditions, including specific shutdown protocols, have yet to be determined by the NSUF project. Further reirradiations may also consider testing in the High Flux Isotope Reactor, pending evaluation of opportunities and needs.

5. TREAT LOCA COMMISSIONING SERIES: LOC-C

The TREAT LOCA test series are designated as the loss-of-coolant (LOC) series. The first of these will be the LOC-Commissioning (LOC-C) experiments. The first experiments to be run in the TWIST device at TREAT will primarily serve to aid in fully commissioning the entire testing apparatus, and will provide important validation of reactor-to-fuel power coupling under relevant conditions. Each of these experiments serves a crucial role in enabling the TREAT LOCA platform. All experiments will use PWR-sized fuel rods with a U^{235} enrichment of 3.2%. The fuel will be UO2 in a Zircaloy cladding (likely Zry-4). The specific instrumentation objectives for each test will vary but will overall serve to validate instrument performance considering nearly all targeted phenomena. Table 2 presents an overview LOC-C test matrix.

Table 2. Test matrix for the TREAT LOC-C test series, all using fresh UO2 in Zircaloy cladding.

Test ID	Fuel Length (cm)	Fuel Segment Free Volume (cc)	Initial Pressure (cold) (MPa)	Peak Cladding Temp. (K)	Purpose
LOC-C-1	25	15	0.1	Cladding – 520 Fuel – 1600	Fuel power validation, pre-blowdown, centerline thermocouple
LOC-C-2	25	15	0.1	1173	Fuel power validation, post-blowdown, centerline thermocouple
LOC-C-3-A through E	25	15	0.1	multiple transients on the same capsule	Detailed thermal hydraulic validation, instrumentation validation, centerline thermocouple
LOC-C-4	25	15	~6	1173	Balloon/burst, instrumentation validation
LOC-C-5	50	15	~6	1273	Long rod evaluation, balloon/burst, instrumentation validation

- LOC-C-1/LOC-C-2: The first two experiments in the series are primarily intended for measuring the axial power input to the specimens in the test device in TREAT in order to validate the neutronic modeling predictions of the experiment. Fuel centerline thermocouples will be used to directly measure the enthalpy change in the fuel meat, and axially scanned gamma spectroscopy will be used in post-transient examination to obtain the axial distribution of total fission events. For all the tests, power input to the specimen is a key experimental parameter to be quantified.
- LOC-C-3: The LOC-C-3 experiment will consist of multiple power transients simulating various thermal-hydraulic boundary conditions in the capsule. These results, along with those of the out-of-pile characterization experiments, will be used to validate the modeling results. The general approach will be to drive varying power levels in the water-filled and -drained states of the capsule. Two transients will first drive power above and below a nominal peak fuel/cladding temperature target. The third will drive nominal target conditions, including opening the blowdown valve and entering the steam heatup condition. The remaining two transients will drive the cladding below and above the nominal conditions with the water now located in the blowdown tank.
- LOC-C-4: The LOC-C-4 experiment will use a pressurized rod to drive a predicted cladding balloon size to burst. To be most representative of later HBu fuel tests, the rod initial pressure will be selected based on final thermomechanical predictions.
- LOC-C-5: The LOC-C-5 experiment is planned to commission the capsule for the testing of “long” fuel pins as a capability to aid in exploring potential rod length effects. Such a capability is not available in any known integral furnace system and will help fill the void left by the HBWR.

The first four LOC-C experiments are currently planned for completion in 2023, in preparation for the experiments on irradiated fuels.

6. TREAT LOC-HBU AND SATS-HBU SERIES

Utilization of both the TREAT and SATS facilities is a key opportunity and feature of the LOCA test program. Specifically, both experimental approaches are fully independent, yet feature some overlap in the available test conditions so as to reduce uncertainties and allow for enhanced interpretation of results in an optimal manner. Materials that feature similar burnups and are of identical origin (sister materials) or composition will, after consideration of their operational history, be used to systematically reduce the associated uncertainties. The companion hot-cell facilities are also independent and provide state-of-the-art characterization capabilities, allowing for increased throughput between both institutions. Table 3 provides an overview of the planned LOC-HBu and SATS-HBu experiments. The specific test goals are to:

- Commission and validate the TREAT TWIST platform for LOCA simulations, via tieback testing
- Perform the first-ever HBu-fuel integral experimental evaluation of the impact of SEH temperature transients during simulated LOCAs, alongside DEH experiment conditions
- Systematically evaluate LOCA experiments under full nuclear heated (in-pile) vs. externally heated (furnace) conditions
- Assess the effect of well-characterized pre-accident power history conditions on fuel fragmentation behavior
- Measure/quantify real-time tFGR, cladding balloon extent, fuel relocation, and cladding temperature at balloons
- Extend the database related to fuel plenum and axial gas communication effects on FFRD

Table 3. Joint LOC-HBu and SATS-HBu experiment test matrix overview. Each line represents a paired experiment conducted at TREAT and SATS. Applicable differences in test conditions are noted by dual inputs.

Test ID	Seg. Burnup (GWd/t)	PCT (K)	Max. Temp. Ramp Rate (K/s)	Fuel Length (cm)[a]	Rod Free Volume (cc)	Purpose
LOC-1 SATS-1	~65	1173	5	25	15	HBWR IFA 650.10/15 and SCIP test 36U-N05 tieback, simulate “classic” Halden/furnace condition
LOC-2 SATS-2	~65	1173	<100 50	25	15	SEH heatup comparison to test #1
LOC-3 SATS-3	~75	1173	5	25	15	SCIP tieback with higher burnup
LOC-4 SATS-4	~75	1173	<100 50	25	15	SEH vs. DEH heatup comparison with higher burnup (comparison test #3)
LOC-5 SATS-5	~75	1173	<100 5	25	15	Evaluate different failure conditions; target failure of the rod at a distinct point in the heatup history, blowdown vs. refill phases
LOC-6 SATS-6	~75	1173	<100 5	25	15	Evaluate non-failure conditions, targeting similar conditions as in #3–5, without rod burst; tFGR data with no burst and no burst effects
LOC-7 SATS-7	~85	1173	<100 5	25 25	15	Very high burnup
LOC-8 SATS-8	~75	1173	<100 5	50 25	15	Length effects, plenum size, axial gas communication effects, SCIP complements
LOC-9 SATS-9	~75	1173	<100 5	50 25	5	Length effects, plenum size, axial gas communication effects, SCIP complements

a. Fuel length will be limited to the distance between grid spacers or would include a grid spacer if present in the commercial irradiation (likely applicable for 50-cm-long specimens in TREAT). Most semi-integral furnace tests have involved segments with lengths of around 30 cm.

The test matrix defines several planned experiments that will proceed at a nominal rate of 2–3 per facility, per year, and are envisioned to provide a balance between a significant data generation rate to the R&D community for interpretation and still allowing for opportunity to incorporate learning from previous experiments. Ultimately, the throughput will likely be determined by the available resources (and demand). Currently, INL is expected to receive the first test materials, which will be collected from HBu commercial fuel, from ORNL and/or BNGS in the spring and/or winter of 2023 (some BNGS and NANGS materials are already available at ORNL), with testing beginning in 2024. Materials available from other commercial sources and international facilities are also being considered, as the latter can provide direct linkage to results from R&D programs. Preliminary assessment of potential materials indicates flexibility in selecting up to very high burnups. Final burnup selections will be made once the material shipments to INL are finalized.

The rod design parameters are expected to initially be very similar to those of the LOC-C tests (see Table 2) but may evolve later. Like the IFA-650 experiment series, the nominal rod free volume is selected to be like a full commercial rod [33] rather than another scheme such as matching fuel-plenum volume to a commercial rod, knowing that experiments show a larger free volume exacerbates FFRD results. The free volume in the rod changed from a practical minimum to beyond commercial rod size. While limited gas communication is expected in prototypic LOCA from the hot spot to the plenum, currently no qualified models are available to justify a smaller free volume size for the nominal test design.

The following paragraphs detail specific considerations and objectives for each experiment described in Table 3.

- LOC/SATS-HBu-1: The HBu-1 experiments will include the first test to be performed with previously irradiated fuel in the TREAT TWIST device, and as with all the HBu tests, a companion test will be conducted in the SATS facility. The experiments will be designed to imitate a Halden IFA-650 series experiment to the greatest extent possible. In addition, SCIP test 36U-N05 was performed on a segment from the same rod as IFA-650.15. The IFA-650.10/650.15 experiments were chosen as the models for experiment boundary conditions and specimen design, thanks to their peak terminal temperature conditions and burnup being the highest of the tested PWR rods until ~82 GWd/t. These test conditions are complementary to current targets. Selecting a segment in the mid-60 GWd/t burnup range aligns with current U.S. burnup limits and will aid in the interpretation needed for making validation comparisons to existing data (vs. initial testing of a higher burnup rod initially that may introduce additional uncertainty). A primary limitation of these tests—relative to the Halden tests—is the inability to precondition the fuel at low power for several hours prior to the accident simulation. In addition, the segment lengths will be shorter than in the Halden tests (i.e., closer to 50 cm), but similar to those in the SCIP test. As an important added benefit, IFA-650.10 was recently the subject of an extensive benchmarking and uncertainty analysis exercise [34], heightening its value and increasing the potential for the TREAT/SATS tests to impact the broader nuclear community.
- LOC/SATS-HBu-2: These will be the first LOCA experiments ever performed to impose SEH conditions on previously irradiated fuel. The SATS companion test will also include a significantly increased heatup rate. In the TREAT test, the fuel centerline will initially be brought to normal operating (“pre-accident”) temperatures before the blowdown and reactor scram occur. The blowdown thermal-hydraulics act to remove heat from the fuel while the residual stored energy diffuses to the coolant boundary. During the fuel cooldown, the cladding can quickly heat up until the fuel-cladding approaches temperature equilibrium (in reality, a small temperature gradient will still exist, driven by decay heat levels). The fuel centerline temperature does not drop all the way down to coolant temperatures, while the periphery of the fuel experiences a significantly more rapid heatup. The temperature evolution associated with this condition imposes different local stress fields in the

fuel, as well as a distinct minimum temperature threshold toward the fuel centerline. The SATS test will target the maximum heatup rate of the system (~50°C/s), extending well beyond other furnace tests to date. Combined, both tests will provide an important comparison against tests based on a standard heatup of 5°C/s, and, when compared with test number 1, are expected to illuminate integral behaviors under such conditions. Furthermore, the test will explicitly highlight the impacts of prototypic temperature rate effects during the LOCA event, as they are believed to be most important in those rods most susceptible to rupture. The increased heating rate in the cladding will also impact cladding balloon behavior, since the integrated temperature over time will be much lower than for the typical DEH ramp rate used in LOCA tests to date. The impact of cladding restraint on fuel fission gas release and fragmentation is still not well described, though empirical relationships show a limit of ~3–5% cladding strain for FFRD [2,6]. These conditions are potentially important because the local stress field and material properties will dictate fission gas release behaviors, as described in Equation (1). Separate-effects experimental data also indicate that temperature ramp rates influence fission gas release, with trends showing increasing release under higher ramp rates [19]. Ultimately, the integral dependency of these behaviors will be explored with models and validated by these tests. Comparison with the results of test #1 should provide an interesting contrast to understand the impacts of important prototypic conditions.

- LOC/SATS-HBu-3 and 4: The purpose of these tests is to provide an evaluation at near the target burnup limit of ~75 GWd/t. The test design will be nominally equivalent to tests number 1 and number 2. In line with test number 2, the increased ramp rates in test number 4 will serve as the second set of data ever collected on previously irradiated fuel. Pending discussion with SCIP, test number 3 will be tailored to represent a relevant SCIP test for fuel at the corresponding burnup.
- LOC/SATS-HBu-5 and 6: These tests will continue the direct evaluation of SEH and DEH conditions, with similarities to tests number 3 and number 4. The temperature ramp rate in SATS will be held to the traditional ~5 K/s to provide a bridge to the existing database and enable the behavior to be contrasted against that seen in the TREAT test. The goal of these tests is to modify the failure point, within prototypical bounds, so as to evaluate the impact of failing near the initial fast temperature ramp (blowdown) vs. the slower heatup phase that follows (refill). In the second case, the goal will be to progress the fuel behavior near to—but without initiating—cladding burst. This test goal was achieved in the IFA-650.14 test and compared against a test in which burst occurred: IFA-650.13. For the TREAT test, this will allow improved quantification of tFGR in the rod plenum. For SATS tests, fission gas release will be observed post-burst via the online detection system or during post-experiment characterization. Other options for this test include running the SATS experiment with open cladding to measure tFGR from the rod segment—obviously without rod overpressure—or with incremental heatup and FGR measurement steps until peak temperatures are reached.
- LOC/SATS-HBu-7: This experiment is planned to address burnups slightly in excess of the licensing target as a limiting case, again under conditions similar to those in the previous tests. Again, the SATS test would be maintained at a more typical temperature ramp rate. The SCIP and/or Halden tests could again be used for comparison against both tests. As with all the tests, the intention is that test segments for both tests be selected from the same parent rod so as to best ensure direct comparison between TREAT and SATS. Additional testing may also be considered for this burnup regime, as few existing data are available.

- LOC/SATS-HBu-8 and 9: These experiments are planned to (1) explore the impact of increased rod segment length in the TREAT test, and (2) further explore the effect of rod free-volume size on LOCA behaviors. Rod free-volume size has been studied elsewhere, as mentioned earlier. Currently, the SCIP is performing studies on these effects; therefore, the LOC/SATS tests will be designed to complement the existing datasets and the SCIP to the greatest extent possible. The longer rod in the TREAT tests is of a length (50 cm) similar to that of the segments tested in the Halden tests. The capability of testig such long rods will be unique in the Western world and can aid in evaluating certain length effects (e.g., balloon extent) and conducting certain assessments of axial gas communication (based on plenum pressure measurement), as have been demonstrated in several IFA-650 tests. The tests will also expand datasets and show repeatability at this important burnup threshold (as with tests #3 and #4), which corresponds to the burnup limit targeted by the nuclear industry. The SATS test will be performed on a ~25-cm rodlet and will provide a baseline comparison (FFRD and gas communication) against the 50-cm fuel samples. For the longer segment, incorporation of a grid spacer in the experiment design is an option but will require prioritization as a unique design adaptation to ensure appropriate experiment boundary conditions. If no grid spacer mimic is used, the test segment will be selected from a rod that features a section free of grid spacers.

6.1 Future Potential Test Objectives

As the test program progresses, new insights may impact the current testing plan. A description of planned updates to the plan is provided in Section 11. Some possibilities to be considered include:

- Additional tests in any of the categories listed in Section 6. Upon completing a test, more tests may be necessary to reassess, confirm, or expand the parameterization of a certain test type. Additionally, individual test design parameters in existing plans may also be evolved as new information is generated in FFRD research.
- Lower burnup data gap: Test fuels with lower burnups comprise the current database. NRC shows publicly available data ranging down to a burnup of nearly 60 GWd/t, and defines the threshold for fine fragmentation to be approximately 55 GWD/t [2], as extrapolated from their evaluation of the existing database.
- IB and SB LOCA: These conditions may have greater importance depending on the outcome of specific licensing strategies still in development. The capabilities described in this plan should allow for meeting these needs, though the specific conditions of interest must be defined to allow for specific definitions of corresponding test parameters (blowdown behavior, PCT, temperature ramp rates).
- BWR LOCA evaluation: Expanding the limited datasets on BWR materials, with a focus on ensuring the prototypically of test conditions for those materials. No integral LOCA experiments have been performed on BWR materials under relevant prototypic BWR conditions.
- ATF designs (additional doped fuel testing over a wider burnup range, coated claddings, etc.): The availability of irradiated materials at target burnup (i.e., HBu) will likely drive this to be a greater opportunity later in the test program. Few to no LOCA performance data are publicly available for ATF fuel designs, but so far, the indicated performance suggests some general potential benefits that may provide useful applications.
- Cladding embrittlement criteria: As was noted, this plan focuses on the study of FFRD, but evaluations of LOCA design limits related to cladding embrittlement criteria represents a particularly obvious opportunity, especially as applied to novel fuel and cladding types.

- Pre-accident fuel power effects: Pre-accident fuel power conditions are hypothesized to play a role in the extent of fuel fragmentation. Yueh et al. produced experimental results revealing a correlation with the extent of fragmentation, and results from Halden and integral furnace tests corroborate their hypothesis [16]. Power could influence the microstructure across the fuel radius, leading to variations in fission gas morphology, grain structure, and cracking. As noted earlier, accurately defining the irradiation conditions for HBu fuel is difficult, particularly due to information from commercial irradiations being typically limited. As an extension, the relationship between fuel microstructure and general fuel power history has not been sufficiently characterized to understand the implications on potential fragmentation behaviors. Two approaches to investigating such behavior are currently being considered. One is based on reirradiating HBu fuel segments in the ATR to provide well-characterized conditions for the EOL fuel state. The second is to directly target EOL low- and high-power segments from commercial irradiations. Both options are viable at this point, though the latter is more straightforward. Again, test segments will be prepared for both TREAT and SATS under these conditions, so that direct comparison of results and pre-test assessments (if possible) can be performed to understand the microstructure and operating conditions (i.e., fuel temperatures).
- Grid spacer effects: While a potential target for the late tests described in Table 3, further interest in grid spacer impacts may merit more experimental studies involving grid spacers. Experimental studies with grid spacers remain somewhat limited, but their potential role in localizing a variety of fuel behaviors during LOCAs could be valuable to credit during analysis.
- Bundle effects: To date, no LOCA experiment has been performed on a small rod bundle containing irradiated fuel except in Russia. Such experiments are merely conceptual at this point but are envisioned to provide an integral validation of such a condition, complementing bundle experiments on heated cladding (e.g., QUENCH and other testing programs). The purpose would be to explore more prototypic bundle heating effects on a central rod, the resulting FFRD effects on neighboring rods, and the related implications of post-rupture fuel dispersal. Testing would clearly be developed as an integral complement to separate-effects experiments, which are largely thermal-hydraulic in nature. A forced convection steam/water capability in TREAT—not described here nor currently prioritized for deployment—is a primary target for executing such a test, such that the opportunity to evaluate post-failure FFRD behaviors is maximized.

7. EXPERIMENT DATA

Significant experiment data streams will result from pre- and post-transient characterization and in situ measurements. Characterization activities at both INL and ORNL will be coordinated and are expected to be planned out in a similar fashion. The inherent design differences between the two experiment facilities mean different opportunities for in situ data, as described in this section.

7.1 Pre-transient Characterization

Background data on irradiated source rods, needed to assess LOCA-relevant fuel microstructure and LOCA performance, will be supplied by the corresponding fuel vendor and utility. These data will be made available to stakeholders, but ownership of the data will remain with the sources. These data will include but may not be limited to:

- Initial fuel dimensions and enrichments of parent rods
- Complete power histories, including axial peaking factors, of the parent rods for all cycles of irradiation, including end-of-cycle shutdowns
- Coolant pressure and temperature histories.

Pre-transient characterization will include a comprehensive evaluation of fuel and cladding states via a host of available tools ranging from basic to state of the art to advanced. For irradiated fuel segments, the data expected to be produced include but are not limited to:

- Plenum pressure, fission gas composition, profilometry, and axial oxide thickness of the parent rod
- High-resolution photographs of the test segment at various phases of the refabrication process
- Analytical measurements of fuel burnup from adjacent fuel segments
- Analytical measurement of cladding hydrogen and oxide/oxygen content from adjacent cladding segments
- Metallography images of the fuel and cladding in adjacent fuel/cladding segments
- Further microstructural characterization of the regions adjacent to both ends of a test segment
- The results of any mechanical or thermal testing on adjacent cladding segments.

7.2 In Situ Data in SATS

Table 5 provides an overview of the SATS in situ measurement capabilities. Note that SATS, while a semi-integral test facility, may require separate-effects-style testing to generate specific data. Several capabilities are consistent with the most advanced capabilities for IR furnace LOCA experiments. The overall data objectives are intended to provide a comprehensive and time-dependent suite of data to support a detailed understanding of FFRD-related phenomena and multiscale advanced modeling efforts within DOE R&D programs.

Table 4. Overview of in situ instrumentation in the SATS-HBu experiment series.

Target Parameter	Measurement Mechanism	Instrument
Clad thermal response	Contact cladding measurements along the fuel axial and azimuthal directions	Four sheathed thermocouples attached to the cladding
Fission gas release	Xe85 collection in charcoal trap	Sodium Iodide scintillation detector
Cladding circumferential deformation	Laser-/LED-based system for measuring cladding diameter changes	High-resolution optical micrometer
Coolant level/phase change	Dielectric change with water phase change/absence	Electroimpedance sensor
Fuel/cladding elongation	Displacement of fuel and/or cladding	Linear variable differential transformer (LVDT)-based elongation transducer
Timing of cladding rupture	Pressure change in the rod plenum from gas released by the fuel	LVDT-based pressure transducer
	Acoustic emissions caused by cladding rupture and/or coolant expulsion	Acoustic emission sensor

7.3 In Situ Data in TREAT-LOC

Table 5 gives an overview of the instrumentation design in the TWIST device, itself illustrated in Figure 7. Several of the instruments align with the most advanced capabilities for in-pile LOCA experiments, while several more represent a leap forward in diagnostic approaches pertaining to important aspects of LOCA characterization. The overall data objectives are being driven by data needs stemming from multiscale advanced modeling efforts within DOE R&D programs. First-of-a-kind in situ instrumentation approaches that have been developed and are currently being integrated into the TWIST device include:

- Several optical-fiber-based sensing approaches for non-contact temperature measurement of the cladding balloon region
- Sensors for rod internal thermodynamic and gas composition parameters (gas composition measurement may aid to reduce corresponding uncertainty compared to the typical pressure measurement approaches)
- An electroimpedance sensor to measure the balloon extent (as well as the water conditions prior to and during blowdown)
- TREAT FMMS-based in situ monitoring of fuel relocation to provide low uncertainty in regard to the timing and amount of relocated material during the event (the only comparable device is located at the CABRI facility).

Table 5. Overview of in situ instrumentation used in the TREAT LOC experiment series (not including operational instruments).

Target Parameter	Measurement Mechanism	Instrument
Fuel thermal response	Contact cladding measurements along the fuel axial length	Sheathed thermocouples welded to the cladding
	Infrared emission from the cladding surface located at the axial hotspot	Optical-fiber-coupled infrared pyrometer
Environment temperature distribution	Direct temperature sensing in the capsule free volume and along capsule internal walls	Discrete sheathed thermocouples along boundaries
		Distributed temperature sensing (fiber Bragg grating)[a]
Cladding balloon extent	Effective dielectric change in the specimen region, caused by cladding deformation	Electroimpedance sensor
Fission gas release	Gas composition changes in the rod plenum	Optical fiber sensor [a]
	Gas pressure (and temperature with the fiber sensor) change in the rod plenum	Optical fiber sensor [a]
		LVDT-based pressure transducer [a]
Coolant level/phase change	Dielectric change with water phase change/absence	Electroimpedance sensor
Fuel/cladding elongation	Displacement of fuel and/or cladding	LVDT-based elongation transducer [a]

Target Parameter	Measurement Mechanism	Instrument
Timing of cladding rupture	Pressure change in the rod plenum from gas released by the fuel	LVDT-based pressure transducer
		Optical fiber pressure sensor [a]
	Acoustic emissions caused by cladding rupture and/or coolant expulsion	Acoustic emission sensor
Fuel motion/relocation behaviors	Fast neutrons born in the specimen and collected via a detector array with a collimated line of sight to the experiment	Fuel Motion Monitoring System (i.e., hodoscope)
Local neutron flux	Neutron interaction with emitter material	Prompt-response self-powered neutron detector [a]

a. Optional but not the primary configuration

7.4 Post-transient Characterization

Detailed post-transient examinations will be defined in a follow-on plan. These will include data similar to those generated within the pre-transient scope, but with an emphasis placed on:

- Overall cladding deformation and rupture: profilometry and metallography at failure site and adjacent regions and characterization of the burst opening.
- State of the fuel: radiography of the test train and specimen, quantification of potential relocated and/or dispersed fuel and the overall fragment size distribution, metallography and advanced exams (SEM, SIMS, EBSD, EPMA) to evaluate cracking and fission gas bubble morphology at all scales, fission gas in the fuel radius, etc.

All the exams are part of a comprehensive HBu PIE plan, from which source materials will be taken. The key point is that the in-pile TREAT/SATS experiments are closely connected, with both involving a variety of engineering- to atomic-scale exams and separate-effects testing (e.g., fission gas release and cladding mechanical properties). The connectivity of well-characterized materials through comprehensive R&D investigations is considered high priority and should aid in reducing uncertainties in the existing knowledge base.

8. DATA QUALITY AND SHARING

The experimental program, as well as the data collection/storage activities conducted under it, will be performed in accordance with the respective laboratory quality assurance programs. Per their respective quality assurance requirements, stakeholders will be responsible for their individual potential usage of these data—with assistance from the laboratories or AFC program, when necessary.

The data and results collected under this plan are intended for sharing in DOE reports and peer-reviewed publications. To the greatest extent possible, all information will be reviewed for public release and made available to interested stakeholders. The AFC program will work with fuel vendors to make available the needed data pertaining to test material pedigree, while also ensuring that proprietary information is protected under the existing non-disclosure agreements, when applicable.

9. OUT-OF-PILE TWIST PROTOTYPE TESTING

The Out-of-Pile Testing and Instrumentation (OPTI)-TWIST was constructed to support detailed thermal-hydraulic evaluations of the TWIST device, along with instrumentation qualification for the

TREAT experiments. The facility, now operational, is beginning testing to support the validation of model predictions. Upon request, these data may also be shared with stakeholders as they become available. Figure 9 shows the OPTI-TWIST setup at the INL facility.

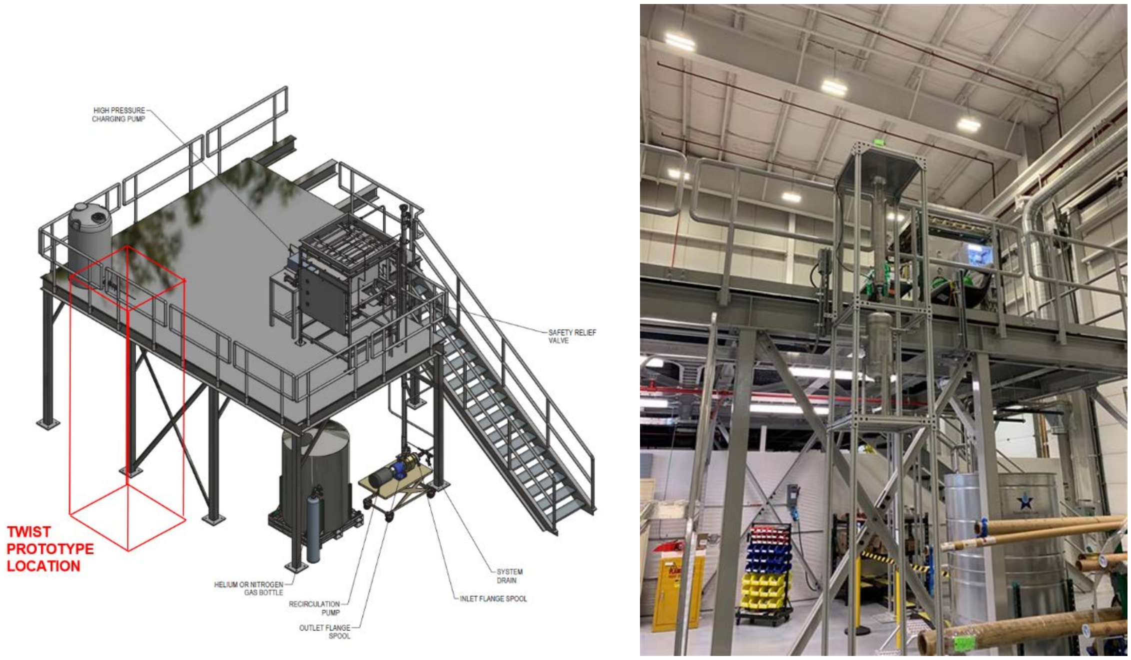


Figure 9. OPTI-TWIST setup at INL. (Left) Rendering of its location on the mezzanine. (Right) Photo of the OPTI-TWIST device at its current location.

10. MODELING AND SIMULATION

A variety of modeling and simulation activities will be used to develop the test methods and experiment designs for this project. For TREAT tests, the Monte Carlo N-Particle code will be used to predict all material heating rates, while the RELAP5-3D code will serve as the primary tool for thermal-hydraulic evaluations regarding safety and best estimate cases. The Abaqus software will be employed for detailed heat transfer and structural evaluations of the test device, and the BISON code will be applied to detailed fuel performance analyses of the test specimen in the TREAT and SATS experiments.

10.1 Modeling for Design and Pre-test Predictions

Test design development has utilized predictions of LOCA behavior, based on full-core PWR model results and information from HBWR and furnace experiments. The result was the TWIST design, which enables useful comparison to a wide range of prototypic thermal boundary conditions [32]. These studies have also included preliminary parametric evaluation of the impacts of cladding plenum volume and pressure on cladding response, along with detailed investigation into fuel thermomechanical response. Ultimately, some of the key effects targeted by these experiments are difficult to evaluate comprehensively, as current models inadequately (tFGR) or too conservatively (cladding ballooning and rupture) account for their effects. Still, a comprehensive evaluation of predicted test outcomes is now underway, with the expectation that some effects will carry large uncertainties to be addressed through the experiments.

Some key remaining modeling tasks specific to the planned tests include a detailed best estimate evaluation of fuel as-irradiated conditions, rate effects on cladding deformation and failure, tFGR, fuel fragmentation, all potential limiting conditions for heatup rate with furnace testing, evaluations for the final selection of the initial pin pressure, and initial heatup targets (based on OPTI-TWIST results). Existing fuel performance models are expected to be limited in their capacity to address certain key impacts of SEH and stand to benefit from advanced modeling approaches. Application of advanced tools to provide early predictive insights into experiment outcomes is needed and will be pursued by collaborating with the DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program and thus benefitting from their expertise. Appendix A provides a detailed description of the TWIST device to support modeling. It also presents some examples of the predicted device test conditions.

10.2 Collaborative Modeling for Pretest Evaluations

A primary goal of these experiments is to enhance the LOCA model development and validation database. To best accomplish this, the AFC program is encouraging (soliciting) interested organizations to perform their own pre-test predictions of experiment outcomes. To this end, a modeling description of the planned LOCA tests is provided in Appendix A and further information is available from the authors.

11. SCHEDULE, BUDGET, AND FUTURE REVISIONS

The targeted schedule for the TREAT/SATS LOCA program is shown in Figure 10, assuming budget availability and commercially irradiated fuel material availability. The SATS facility has already been fully commissioned through fresh fuel and irradiated fuel testing and is being utilized for a variety of testing to support AFC program and industry objectives. The TREAT TWIST device will perform fresh fuel commissioning in 2023, followed immediately by the testing of HBu material starting in 2024, aligning with availability of HBu rods. SATS testing for this plan would be expected to occur simultaneously to allow for test materials to be shared between laboratories. Deliverables will include annual progress reports, quick-look data reports based on the available data from each experiment, and summary reports covering the full scope of the experiment data and analysis, likely organized according to the primary test goals.

To execute the program as proposed, a rough estimate of $5–6M/yr from FY-23 to FY-26 is needed to cover all aspects of testing, characterization, modeling, and analysis at both INL and ORNL.

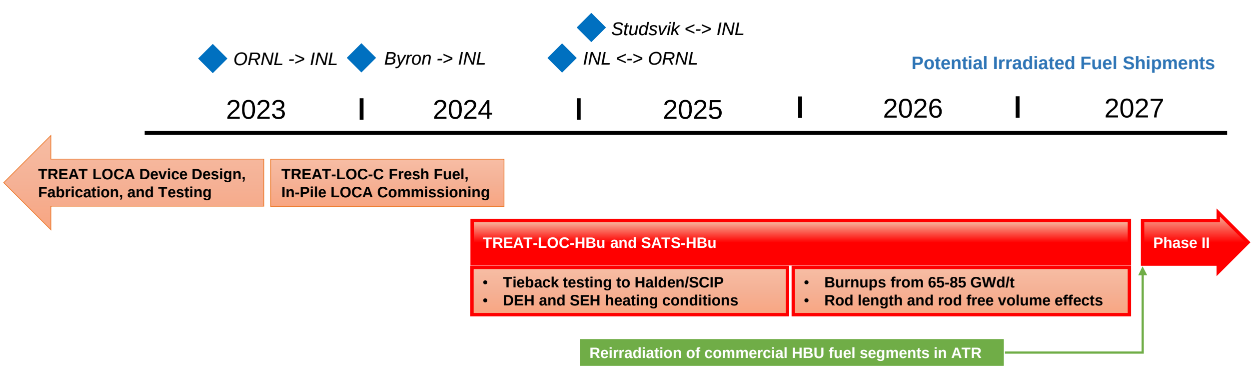


Figure 10. Overview of the TREAT and SATS schedule. The projected timeline is based on executing 2–3 experiment sets per year, starting in 2024. Fresh fuel commissioning tests in TREAT will begin in 2023.

Finally, this test plan was developed based on current state-of-the-art information and input from all stakeholders. The ongoing research programs on this subject and the results generated during plan execution will necessitate regular assessment—and potential revision—of the test matrix. The end of Section 6 lists some potential candidate test objectives deemed worthy for further consideration for incorporation in the test plan described herein, or in a next-phase test plan. Thus, at minimum, an annual review of the plan and the newly generated results will be held with stakeholders. Input will be solicited regarding any desired updates and additions. The FPTTEG will be requested to serve this purpose. Additional discussions between stakeholders and the AFC program may be requested as needed. Progress and updates will be shared via regular interaction in FPTTEG meetings.

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Appendix A

AFC LOCA Experiment Model Description

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Appendix A
AFC LOCA Experiment Model Description

To improve stakeholders' ability to contribute to the test program, a description of the experiments is provided here for the purpose of allowing models to be developed and analyzed (pre-test) for:

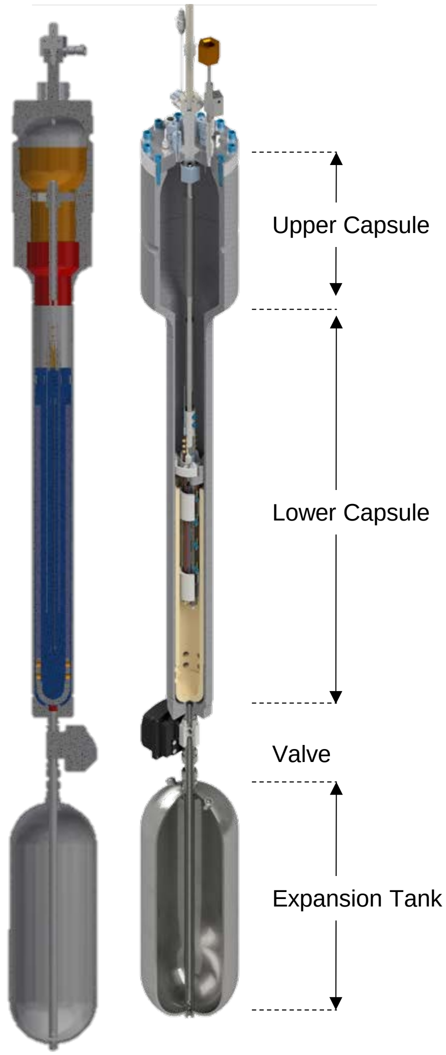
- Thermal-hydraulic boundary conditions on the test specimen in the TREAT TWIST device
- Fuel performance boundary conditions during experiments for both TWIST and furnace heating (calculated temperature boundary conditions are also provided here to allow for fuel performance predictions without thermal-hydraulic modeling).

The provided information will be updated as specific design conditions evolve, new findings from prototype testing change assumptions, etc. One specific goal is to not overwhelm interested parties with too many cases or too much to consider. Therefore, the specific modeling inputs are given below for two cases based on fresh fuel testing (the irradiated fuel case[s] will follow later, though the specimen parameters may be assumed as desired).

Suggested cases for consideration are shown in Table A-1. Using data from the figures specified in that table, Figure A-1 provides an overview of primary capsule hydraulic dimensions and relevant modeling parameters. Figure A-2 provides an overview of the TWIST test specimen design. Figure A-3 presents the calculated temperature history for the cladding outer surface (needed if not modeling a thermal-hydraulic system). The figure also shows the corresponding specimen linear heat rate (axial distribution not provided here but available upon request). The capsule pressure history will be varied to mimic prototypic conditions. Figure A-1 presents the nominal initial conditions (with the possible variations in parentheses). The capsule depressurization rate will be controlled to depressurize to a final pressure of 15% the initial capsule pressure over approximately 15 seconds. Figure A-4 shows the temperature history for a typical DEH furnace experiment, for comparison with TWIST. In some planned experiments, the SATS temperature ramp rate will be made faster than for typical DEH conditions. A more prescribed modeling exercise is planned for development in the coming year and will include a more detailed description of modeling inputs.

Table A-1. Modeling cases to support LOCA experiment development and pre-test evaluations.

Case	Fuel	Specimen	Specimen Power History	Specimen Cladding Temperature
1 – LOC-C-4	Fresh	Figure A-2	Figure A-3	Figure A-3, or derived from the model based on information in Figure A-1
2 – LOC-HBu-1	Generic UO2/Zry 65 GWd/t	Figure A-2 (other)	Figure A-3	Figure A-3, or derived from the model based on information in Figure A-1
3 – SATS-HBu-1	Generic UO2/Zry 65 GWd/t	Figure A-2 (other)	n/a	Figure A-4



Region	Parameter	Value
Upper Capsule	Gas Volume (cm³)	2000
Lower Capsule	Inner Diameter (cm)	7.79
	Total Height (cm)	78.4
	Water Height (cm)	78.4
	Gas Height (cm)	7.62
	Water Volume (cm³)	1940
	Gas Volume (cm³)	426
Valve	Diameter (cm)	1.02
	Length (cm)	15.2
	Opening Time (s)	1.5
Expansion Tank	Inner Diameter (cm)	17.5
	Height (cm)	50.8
	Volume (cm³)	10400
Thermodynamic Conditions	Initial Temperature (°C)	25 (up to 200)
	Initial Capsule Pressure (MPa)	8 (up to 15)

Figure A-1. Overview of the TWIST capsule thermal-hydraulic parameters.

Parameter	Value
Fuel Diameter (mm)	8.204
Fuel Pellet Height (mm)	9.83
# Fuel Pellets	24 50
Fuel Density (kg/m³)	10420
Cladding Outer Diameter (mm)	9.5
Cladding Thickness (mm)	0.5715
Plenum Pressure (MPa @ 20°C)	0-18
Plenum Volume (cm³)	2-15

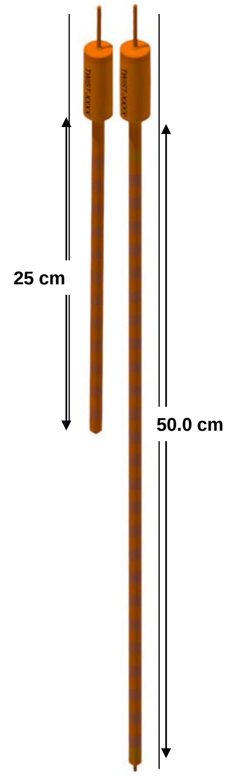


Figure A-2. Fuel performance modeling inputs for a TWIST specimen.

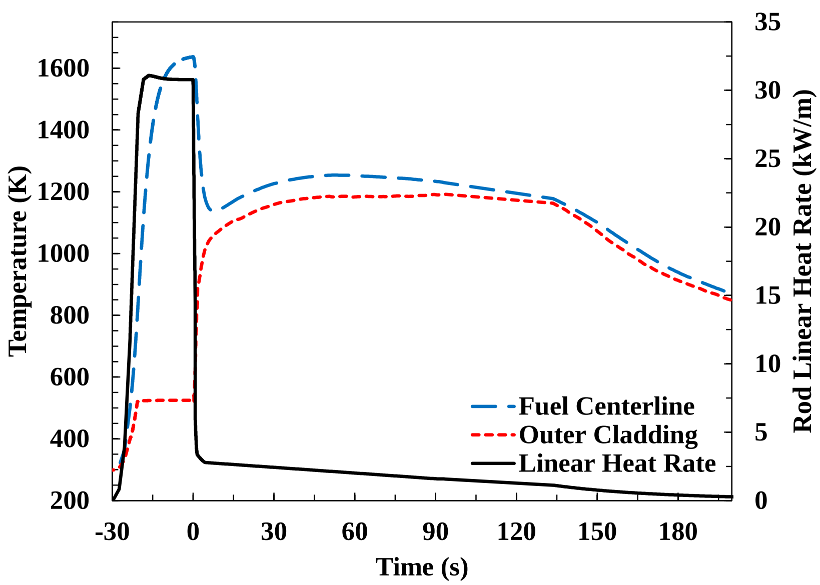


Figure A-3. Specimen power and temperature boundary conditions for the cladding outer surface for LOC-C-4. The capsule pressure history is described in the text above.

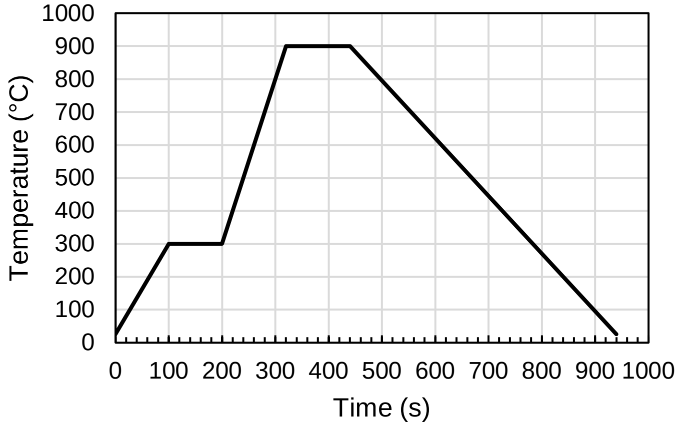


Figure A-4. Temperature boundary condition for the cladding outer surface for a traditional DEH furnace scenario. The ramp from 200 to 900°C could be increased to nearly 50°C/s, including with multiple temperature ramp rates. A final scenario remains to be determined.