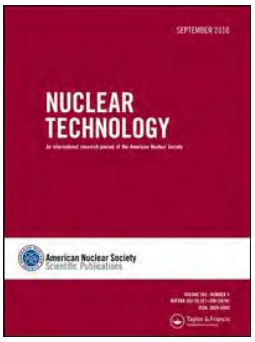

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Nuclear Technology

ISSN: 0029-5450 (Print) 1943-7471 (Online) Journal homepage: https://www.tandfonline.com/loi/unct20

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To cite this article: Nicolas Woolstenhulme, Clint Baker, Colby Jensen, Daniel Chapman, Devin Imholte, Nate Oldham, Connie Hill & Spencer Snow (2019): Development of Irradiation Test Devices for Transient Testing, Nuclear Technology, DOI: 10.1080/00295450.2019.1590072

To link to this article: https://doi.org/10.1080/00295450.2019.1590072

Published online: 18 Apr 2019.

NUCLEAR TECHNOLOGY

DOI: https://doi.org/10.1080/00295450.2019.1590072

Critical Review

Development of Irradiation Test Devices for Transient Testing

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Received October 26, 2018
Accepted for Publication February 28, 2019

Abstract — *The Transient Reactor Test facility (TREAT) resumed operations in 2017 in order to reclaim its crucial role in nuclear-heated fuel safety research. TREAT's historic era of operation (1959 to 1994) was best known for integral-scale testing of large fuel specimens/bundles under postulated reactor plant accident conditions, but TREAT also supported smaller-scale phenomena identification tests that elucidated fundamental behaviors and paved the way for these integral-scale tests. Advances in modern computational capabilities and a resurgence of interest in novel reactor technologies have created an opportunity for emphasizing modernized science-based and separate effects tests once again at TREAT. An innovative approach to this type of testing has been developed to leverage minor radioactivity built in during brief TREAT irradiations by arranging smaller fuel specimens in low-activation hardware so that they can be easily extracted and shipped for postirradiation examination within weeks. This recently established capability, termed the Minimal Activation Retrievable Capsule Holder (MARCH) irradiation vehicle system, includes capabilities for cost-effective simplified environment testing of centimeter-scale fuel samples of various geometries, temperature-controlled irradiations of millimeter-size samples for lower-length-scale model development, liquid metal–bonded heat sink capsules for controlling transient temperature response in fuel rodlets, and an innovative approach to high-throughput irradiation of transient sensors and instrumentation. The MARCH system's capabilities will also set the foundation for fuel safety research performed in larger integral-scale test devices with coolant environments representing reactor plants. Based upon historic approaches, but modernized to meet current nuclear technology needs, these larger irradiation devices include flowing pressurized water (including the ability to depressurize to steam) as well liquid metal cooling loops for various fuel rod and small bundle specimens. This critical review describes the recently established MARCH system and current trajectory to enabling advanced transient science with a suite of irradiation test devices.*

Keywords — *Nuclear fuel safety research, irradiation testing, in-pile instrumentation, irradiation environment, nuclear testing.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Nuclear transient testing is a term often used to describe a branch of fuel safety research where nuclear heating is used to study fuel performance, fuel environment interactions, and resulting reactor system response under overheating and/or undercooling scenarios. Transient conditions can include myriad hypothetical scenarios where postulated reactor plant accidents are typically of greatest interest due to implications in development and licensing nuclear technologies. Power-cooling mismatch scenarios which can challenge the integrity of fuel materials are particularly important in this branch of research, sometimes receiving even greater emphasis than fuel performance under steady-state operations. A good measure of credible fuel safety research can be conducted outside of nuclear test reactors using electrical heating, but nuclear heating is needed when the phenomena of interest require thermomechanical energy

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distributions only possible with internal heating, when rapid heating ramp rates are needed, or when other coupled nuclear environment effects are important.[1]

Historic transient tests conducted at the National Reactor Testing Station (NRTS) and Argonne National Lab West (ANL-W), both of which are now combined into the Idaho National Laboratory (INL), sometimes researched these conditions through testing of entire reactor systems such as those conducted under the Special Power Excursion Reactor Test (SPERT) program,[2] at the Loss of Flow Test Facility[3] (LOFT), and during the Experimental Breeder Reactor-II (EBR-II) Shutdown Heat Removal Tests.[4] Other approaches to this branch of research gained crucial insights through postmortem studies of the nuclear industry's rare but pivotal nuclear accidents. The SL-1 reactor accident and Three Mile Island fuel exams both occurred at the NRTS and contributed to its heritage in fuel safety research. These plant-scale research opportunities provided important data pertaining to full integral system response, but did not represent the most voluminous type of nuclear transient testing due to the onerous and rare nature of the data. Instead, the most plentiful type of transient fuel safety research was conducted using specially designed reactors whose core and plant systems could withstand power excursions while driving smaller fuel specimens within the core to more extreme conditions. Notable reactors at the NRTS and ANL-W that performed this type of testing included the SPERT Capsule Driver Core,[5] Power Burst Facility[6] (PBF) and the Transient Reactor Test facility[7] (TREAT).

Nuclear transient testing was a mainstream effort at the NRTS throughout the 1960s to 1980s and constituted one its greatest contributions to the nuclear industry. By 1994, however, all of the aforementioned reactors had been shut down due to lack of support for this type of research. Unlike its contemporaries, TREAT was left in a recoverable standby mode owing to the facility's simple maintenance protocol, its foreseen restart at some future point, and continued use of the building for other research. In order to address a resurgence of innovative fuel designs, as well as other data gaps with existing designs, the U.S. Department of Energy (DOE) supported a remarkably successful project to refurbish and resume operations at TREAT, culminating in first critical operations in 2017.

II. TREAT'S UNIQUE CAPABILITIES FOR FUEL SAFETY RESEARCH

TREAT first began operating in 1959 as one of the pioneer facilities in nuclear transient testing. While the facility was upgraded, reconfigured, and improved over its many decades of operation, the fundamentals of its nuclear design have remained the same throughout. The core itself is constructed from graphitic blocks with a dilute dispersion of uranium oxide particles. This graphite-based design creates a heat sink for transient energy that doubles as the primary neutron moderator so that power excursions cause an upward shift in thermal neutron energy, increased neutron leakage, and negative reactivity behavior for self-limiting transients. The hydraulically driven transient control rods, in concert with an automatic reactor control system, manipulate various transient power shapes ranging from tens of milliseconds (e.g., prompt pulses with up to ~20 GW peak core power) to a few minutes (e.g., ramp-type transient in the tens of megawatts reactor power range). When coupled with the ability to provide active feedback from irradiation experiment–based instrumentation to the reactor control system, TREAT provides unparalleled flexibility in controlling power transients. Forced air cooling hastens the core's return to room temperature following a transient and enables it to operate steady at modest power levels (currently <120 kW) for neutron radiography and various calibration activities.[8]

The core's fuel blocks are stacked vertically and encompassed in evacuated zirconium alloy canisters to form 1.2 m of active core length. A few adjacent fuel assemblies (each 10-cm-square cross section) are typically removed from the core center position to create an experiment cavity. The core is reflected on all sides by unfueled graphite and sits slightly above ground level surrounded by concrete biological shielding. Removable plugs through the sides of the shielding along with configurable fuel assemblies, some of which have voided slots, permit access to center-position experiments for various reasons including the present day fast neutron hodoscope and historic use of high-speed videography. Typical experiments are lowered into the core through an opening in the upper shield structure. Most experiments are handled outside of the core using overhead cranes and shielded casks that currently limit radioactive experiments to 25 cm in diameter. Compatibility between casks and the shielded hot cells at INL's materials and fuels complex enable TREAT to accept pre-irradiated and plutonium-bearing specimens for transient research. Among material test reactors TREAT's lack of water pool or pressure vessel are unique, but provide remarkable access for experiment-centric instrumentation and immense flexibility in configuring the core to support various experiment types.

TREAT's physical layout is well suited to experiment devices in the form of "package-type" irradiation vehicles. This approach combines all necessary features needed to afford the desired specimen environment, support specimens and instrumentation, and safely contain any hazards into a single mechanical unit that can be handled in shielded casks. Support lines are typically connected to the top of these experiment packages during reactor installation including instrumentation, electrical power, and secondary fluid service. Fluids in direct contact with the specimen are not typically plumbed outside of the reactor shielding to facilitate radiation protection. This approach generally increases the emphasis on compactness in experiment hardware, but is a crucial strategy in enabling TREAT to rapidly transition between different test vehicles and specimen coolant environments.[9] An isometric section view of TREAT's core, rod drive room, and shielding is shown in Fig. 1.

II.A. Historical Approaches: TREAT's Capsule Period

Starting shortly after TREAT's commissioning in 1959 a series of irradiation tests were performed using a small gas-filled capsule apparatus to evaluate the response of various fuel materials proposed for use in the EBR-II sodium fast reactor[11] (SFR). While TREAT was only basically capable at the time, being limited to pulsed operations and experiment devices no larger than standard fuel assemblies, this approach was crucial in identifying fuel failure phenomena on primarily fresh fuel specimens which, owing to the brief nature of TREAT irradiations, enabled quick turnaround and high throughput on postirradiation examinations (PIEs) outside of conventional shielded hot cells. An adaptation of this device placed a small water-filled capsule "autoclave" in the same outer canister to enable fundamental research on interactions between the coolant environment and light

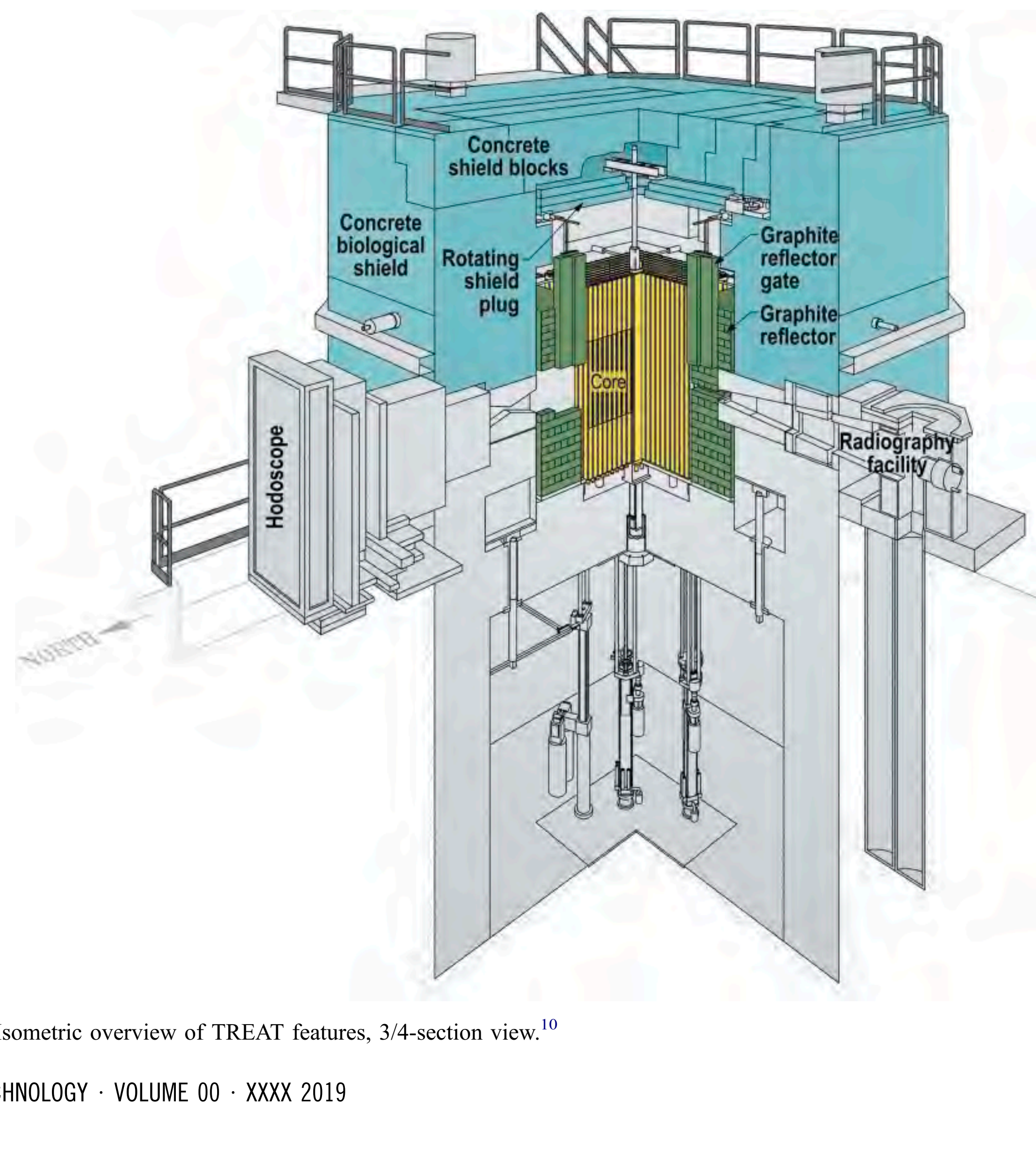

Fig. 1. Isometric overview of TREAT features, 3/4-section view.[10]

water reactor (LWR) fuel materials.[12] Enlarged versions of the autoclave design followed shortly thereafter to enable transient testing of lengthened rodlets, including candidate driver fuel designs for the to-be-constructed PBF reactor and other small rodlet bundles.[13,14] A similar approach later made use of a solid metal heat sink bonded to fuel rodlets using a thin annulus of molten sodium to approximate the effects of heat rejection to flowing coolant and resulting fuel temperature distributions without the burden of more complicated loop experiments.[15] Images describing some historic TREAT capsule-type irradiation devices can be seen in Fig. 2.

In this same time period an innovative approach to in situ data acquisition made use of a unique side-loading experiment capsule that permitted a high-speed film camera to ascertain fuel performance via an optical path through one of TREAT's side slots. This notable approach was used to perform inert-gas environment testing of SFR fuels and unpressurized water environment testing of LWR fuels.[16,17] Both the original autoclave and video capsule were also adapted for testing of graphite-based nuclear thermal space propulsion fuels where transient power ramps where not just of interest for postulated upset conditions, but were expected events in operation of these unique reactors.[18,19]

Although capsule-based tests for phenomena identification, technology screening, and quantification of separate effects were occasionally employed in later campaigns (post ~1970), this initial ~10-year period of TREAT's history was dominated by capsule tests and coincided with a formative era of commercial nuclear power innovation. As a result, the variety and magnitude of fuel specimens irradiated during this capsule period have not been surpassed. Accordingly, this period was also characterized by specimen coolant environments not

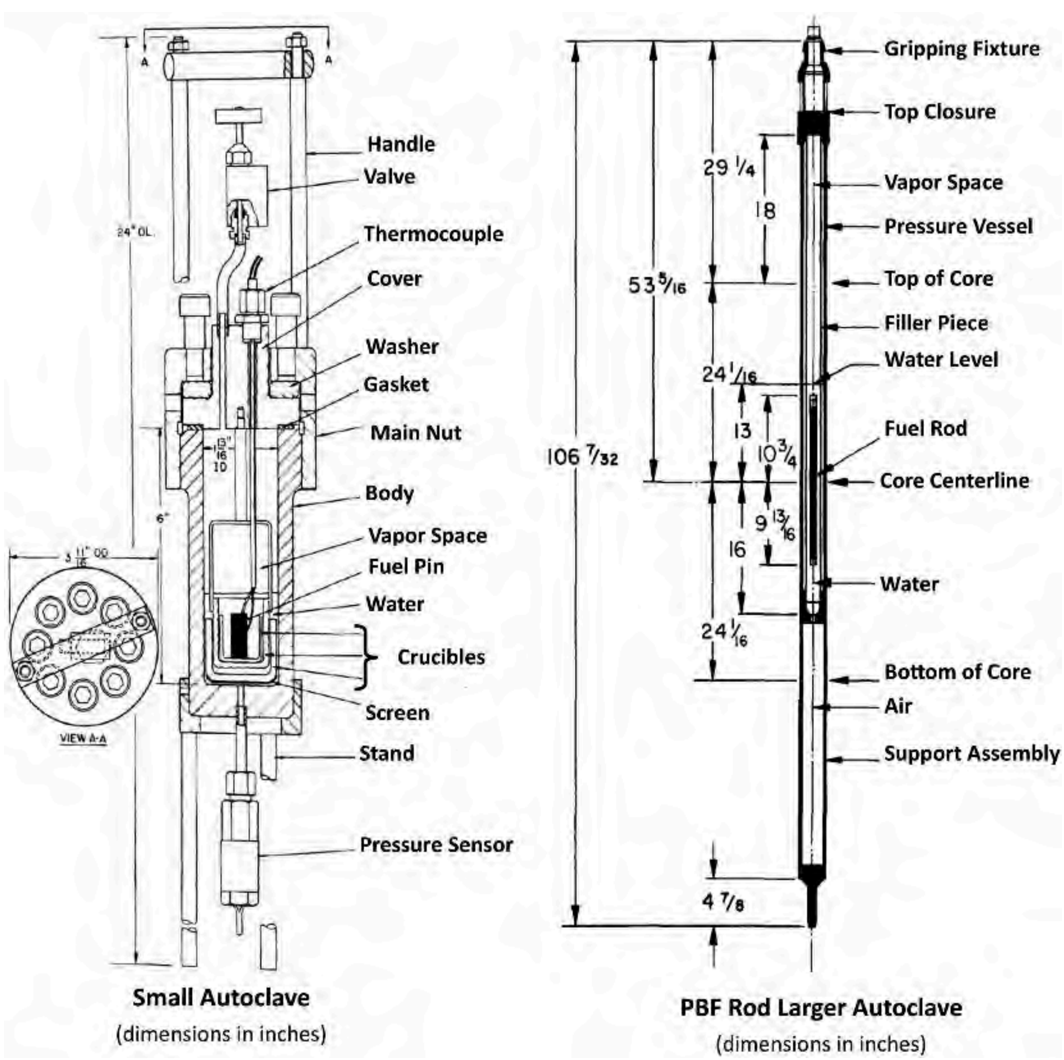

Fig. 2. Small autoclave capsule and larger PBF rod autoclave (images adapted from Refs. 12 and 13).

highly representative of candidate plants, somewhat minimalistic in situ instrumentation approaches, and a high ratio of fresh fuel to pre-irradiated samples.

II.B. Historical Approaches: TREAT's Loop Period

Most of the prominent work from TREAT's second era occurred in the 1970s and 1980s and was characterized by flowing coolant–based testing in purpose-built test loops. Contemporary facilities including PBF and LOFT were coming online in this timeframe to service LWR-related data needs. While some notable exceptions exist, TREAT's second era began to tailor its capabilities more toward the SFR community with flowing sodium loops as the workhorse for addressing application-specific testing in more representative environments and better approaching engineering-scale behaviors. Accordingly, a greater emphasis was placed on pre-irradiated specimens in these tests. Building upon success in previous package-type capsule experiments, the first of these loops (termed the Mk-I design) was essentially a small annular capsule filled with sodium that was melted using electrical heaters and recirculated by means of a compact electromagnetic pump.[20] Later evolutions of the Mk-series loops, including the Mk-II and -III designs, used two parallel pipes including a larger pipe for the test section insertion through an upper flange and another pipe for the pump leg using specially developed annular linear induction pumps.[21]

The Mk-series loops were designed to be reusable since the fuel-bearing test sections could be extracted and replaced in hot cells. Highly disrupted fuel specimens, however, sometimes required loops to be destructively sectioned to preserve the posttransient state of fuel specimens. Each evolution of the Mk-series loop (Mk-I through Mk-III) was roughly twice the size of the former and was enabled by or coincided with various facility infrastructure and capability improvements such as enlarged handling casks, reconfigured transient rod drive systems, and elevated core energy capacities via facility safety bases revisions. The Mk-series loops were modular platforms able to support SFR fuel pins of varying compositions (e.g., metal fuel or oxide fuel) ranging from single specimens, two to three specimens in individual flow tubes, and seven pin bundles.[22,23] A major enhancement of the Mk-series concept, referred to as the advanced TREAT loop,[24] was designed in great detail to continue in the tradition of extending TREAT's engineering-scale SFR testing capability, particularly with regard to bundle size, but was never irradiated in TREAT due to shifting priorities in the U.S. SFR program at the time. Representations of the Mk-III and advanced TREAT loop can be seen in Fig. 3.

Another flowing sodium system used at TREAT made use of a once-through flow path driving sodium from a pressurized feed tank to another discharge tank.[25] While not technically a recirculating loop, and one of a few exceptions to TREAT's package-type approach to test device design, this irradiation vehicle did not find as widespread use as the Mk-series loops due to limitation in loading pre-irradiated fuel, but was considered a superior approach with specific regard to driving coolant through bundles following fuel failure partial coolant channel blockages. Similar to this once-through flowing sodium apparatus, and perhaps even more exceptional to TREAT-typical SFR-related work during its second era, two discrete and impactful test campaigns used once-through flowing steam devices to evaluate LWR rod failure behavior in accidental depressurization scenarios.[26,27]

Finally, following suspension of TREAT's operation in 1994, and noting that the SPERT and PBF facilities had been shut down by that time, a full-recirculating pressurized water loop was designed and proposed for construction at TREAT to support data needs pertaining to LWR reactivity-initiated accident (RIA) research. Like the previously described flowing steam vehicles, this recirculating loop would have been supported by ex-core support equipment for discrete control of pressurized water boundary conditions.[28] Although a flowing water vehicle was never realized at TREAT historically, this water loop concept and the RIA mission it would have addressed were a forward-looking capability proposition for TREAT with modern applicability.

II.C. TREAT Modern Era of Irradiation Capabilities

The need to test accident-condition response of current and next-generation LWR fuels was one of the primary impetuses for refurbishing the facility and resuming reactor operations at TREAT. One of the most prominent programs in this category is the DOE's Accident Tolerant Fuels (ATF) program which aims to develop and deploy new fuel systems with enhanced resilience to loss of active cooling compared to the present UO_2 in Zircaloy system.[29] The ATF initiative intends to enable this advancement while maintaining or improving steady-state performance and resilience to overpower accident categories as well. Candidate ATF designs include a range of technology readiness levels from steam-resistant Zircaloy coatings and UO_2 additives which improve thermomechanical properties to more novel approaches including advanced iron-based claddings, ceramic claddings, and fuel compounds with

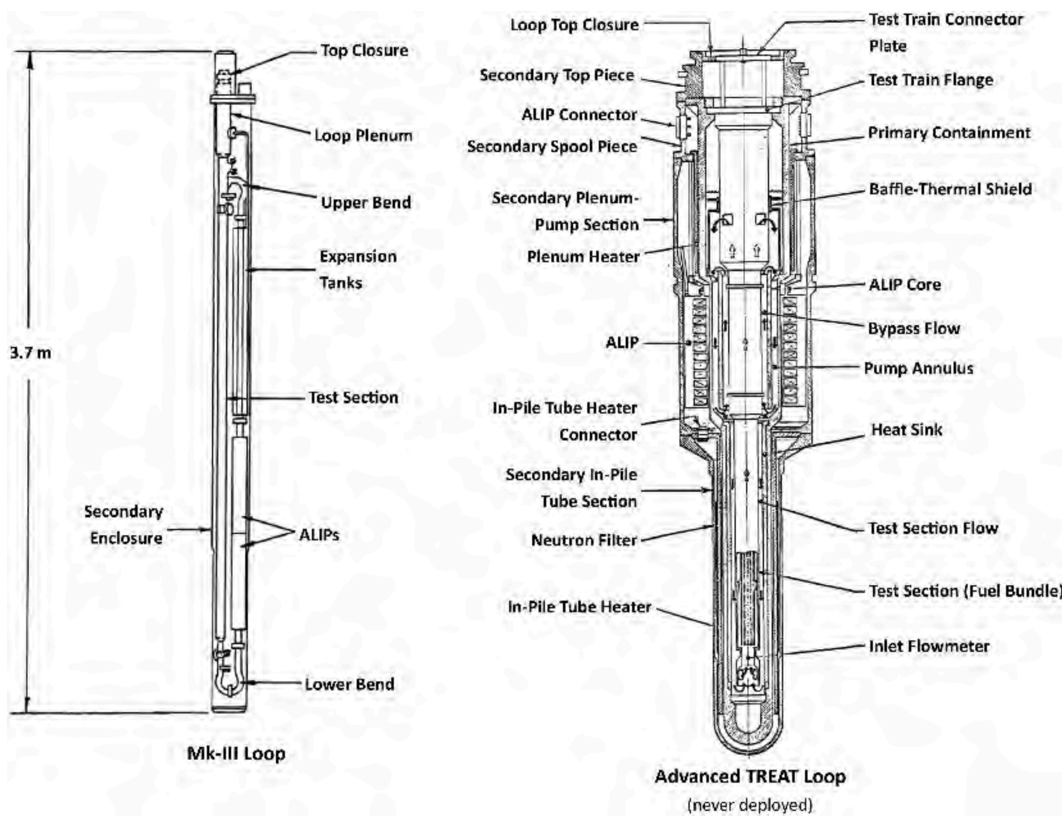

Fig. 3. Mk-III and advanced TREAT loop overview (images adapted from Refs. 23 and 24).

increased uranium density. The ATF program plans to deploy batch fuel reloads in commercial plants in the mid 2020s that will require transient testing to support licensing, especially for the more revolutionary ATF fuel systems. Even in cases where batch reloads can be authorized based on current data, existing models, and conservative strategies, transient testing will likely be needed in order to fully credit ATF performance advantages in plants' licensing bases.

In order to support ATF transient testing needs, and noting that TREAT's more recent historic era did not establish an adequate capability suite for full LWR safety research programs, a concerted project is underway to develop LWR irradiation vehicles for TREAT. The LWR transient testing capabilities for TREAT will need to replicate the crucial capabilities represented by historic projects (e.g., PBF) and ongoing international programs executed by the Nuclear Safety Research Reactor (Japan), the CABRI International Project (France), and the Halden Reactor Project (Norway). The novel nature of some ATF designs also requires that TREAT's capabilities not only represent state-of-art testing approaches (most of which are focused on the most prominent phenomena for UO_2-Zircaloy fuels), but also comprehensive capabilities to help identify whether critical performance phenomena exist in segments of accident progressions currently less relevant for UO_2-Zircaloy fuels. Finally, the more accident-tolerant nature of these advanced fuels requires TREAT's capabilities to extend beyond limitations of the UO_2-Zircaloy system in order to quantify ATF's full capability. The ATF's range of candidate technologies and aggressive deployment plans require future capabilities to enable early phase phenomena–focused tests (reminiscent of TREAT's first capsule-centric era) as well as full-accident-progression simulations (similar to TREAT's second loop-focused era).

The situation is similar for modern advanced reactor initiatives where a resurgence of interest in next-generation designs, in addition to a backlog of underaddressed data gaps in more mature technologies, combine to create the need for TREAT capabilities that concern advanced reactor environments and specimens through the full spectrum of early-phase separate effects tests up to integral-scale demonstrations. For these reasons the irradiation capabilities under development for TREAT's third era include phenomena-focused capsules, integral-scale loops, and modularity to bridge the gaps between with combined effects and semi-integral hybrid testing. TREAT's third and modern era of fuel safety research is expected to be characterized by an engineering-driven science-based approach where multiscale tests are integrated by advanced computational modeling.

III. SEPARATE EFFECTS AND SCIENCE-BASED IRRADIATIONS

The Minimal Activation Retrievable Capsule Holder (MARCH) design was originally conceived to support irradiations where precisely monitored temperature conditions could be combined with neutron irradiation of small characterization–scale fuel samples. The purpose of these irradiations is to enable development of fundamental damage mechanisms in lower-length-scale modeling tools. TREAT is not particularly effective as a high-power steady-state reactor and the flux integral through a typical transient is also relatively low, especially when compared to the neighboring Advanced Test Reactor. TREAT, however, is an ideal research tool for these types of irradiations because its layout facilitates in situ temperature control and monitoring, in addition to its neighboring facilities for fabrication and characterization of irradiated and transuranic-bearing fuels, so long as the phenomena can be observed after relatively low fluence. Lower-length-scale fuel performance fundamental phenomena in this very low–burnup category are actually rare data since typical tests in material test reactors are often at least the length of a normal irradiation cycle (weeks to months long) at which point many fuel specimens exhibit several combined effects from fission damage, material interaction, and other environmental exposure.

The experiment components supporting these types of irradiations include (1) a containment structure referred to as the Broad Use Specimen Transient Experiment Rig (BUSTER), (2) a high-temperature heater module able to provide up to 700°C electrical preheat, and (3) an assembly that supports and encapsulates the specimens termed the Characterization-scale Instrumented Neutron Dose Irradiation (CINDI) module. The CINDI module is arranged mechanically to support a few specimen-containing instrumented capsules that are made from affordable commercial thermocouples and compression seal components. The relatively small fuel samples (5 mm diameter × 5 mm length), the use of low-activation hardware materials, and the brief irradiation time in TREAT enable the CINDI module to be extracted vertically while the BUSTER containment structure remains below grade in storage holes. This approach enables BUSTER's large stainless steel components to be reused as they become radioactive through multiple irradiations while more affordable one-time-use capsules can be extracted and shipped for PIE within weeks with very low dose to personnel. See Fig. 4 for representations of the BUSTER, heater, and CINDI modules.

A fundamental design approach for the MARCH system is its modularity. In this strategy BUSTER's primary pipe weldment is credited as the safety containment boundary, which requires elevated engineering rigor in the design and procurement of nuclear-grade vessels, while the modules placed within are considered convenience features for contamination control. This approach reduces the cost of module development, adaptation, and fabrication while enabling less conventional materials to be used when needed to support specific test objectives. This philosophy pervades the MARCH system design approach to create an adaptable system with the agility to support rapid innovation, increase testing throughput, and facilitate cost-effective data generation. Working from the basic platform developed for the CINDI tests, several other irradiation modules have been created to support various missions.[30]

One such module has been termed the Separate-Effect Test Holder (SETH). This single-capsule test assembly enables transient testing of centimeter-scale fuel specimens such as pellets, rodlets, miniplates, compacts, extrusions, and other compatible fuel forms. The internal capsule volume enables specimens and instrument packages to be irradiated in SETH's inert gas–filled chamber up to 3.5 cm in diameter and 20 cm in length. Compression seal instrument penetrations enable reconfiguration of the sensor package for different test objectives. While not terribly representative of most reactor coolant environments, SETH's inert gas–filled capsule creates stable boundary conditions for simplified and cost-effective melt progression studies, phenomena identification, in situ properties measurements, and other separate effects tests. Two configurations of the SETH capsule are presently being staged for two discrete irradiation campaigns, the first of which will be irradiated as TREAT's commissioning fueled irradiations under the ATF program (ATF-SETH). The ATF-SETH configuration includes fresh UO_2 in Zircaloy small rodlets (10 pellets) with fast-response cladding thermocouples and first-of-a-kind transient application infrared pyrometry for noncontact cladding thermometry. Also, as a first-of-a-kind application in transient testing, and facilitated by the capsule-in-containment MARCH design philosophy, the SETH capsules are designed to be manufactured by direct laser metal sintering as both an advanced and more economic fabrication option. See Fig. 5 for SETH module design depictions and capsule photographs.

The initial ATF-SETH tests include a series of five fueled capsules, the first of which includes thermal

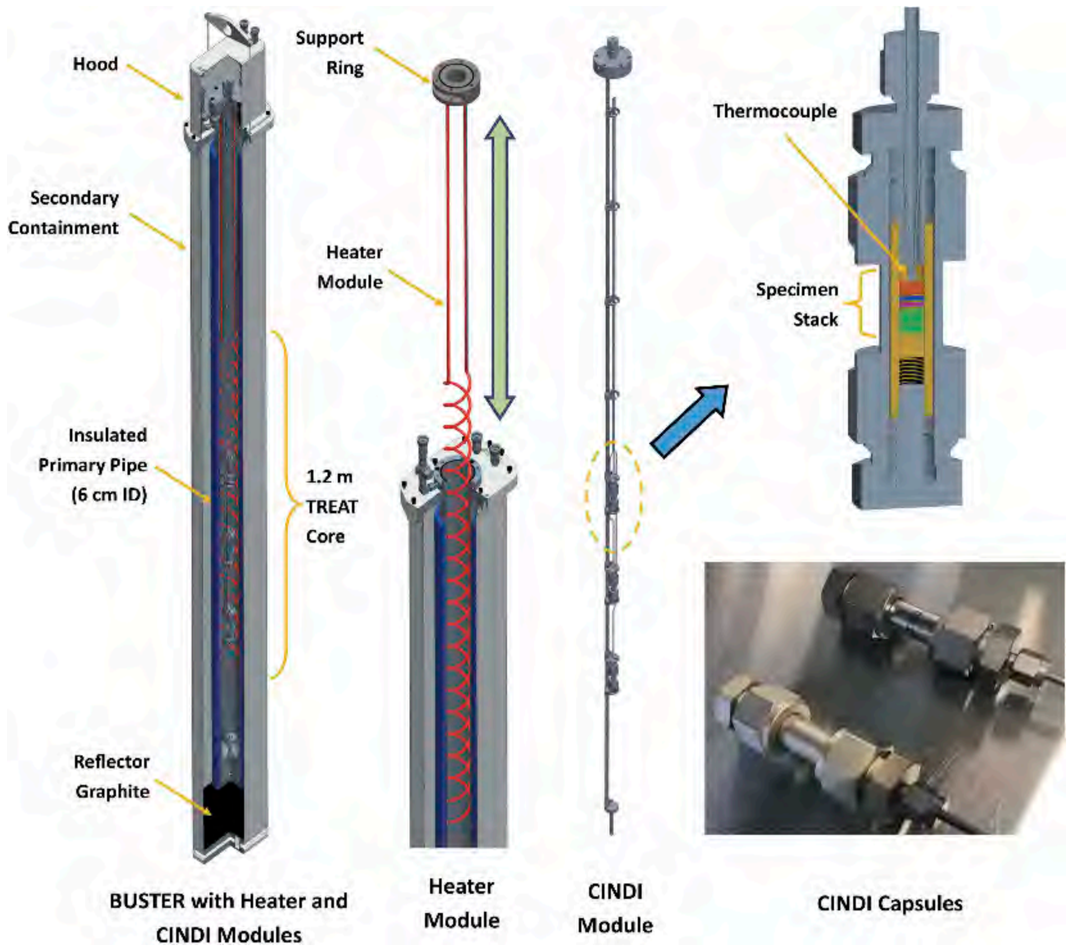

Fig. 4. Overview of BUSTER, heater, and CINDI modules.

insulation wrapped around the rodlet for in situ quantification of specimen-to–core energy coupling via calorimetry, where the latter four capsules are planned to be irradiated under progressively higher energy pulse depositions up to fuel melt as part of commissioning TREAT's capabilities to predict, control, and quantify transient specimen energy injections. The second configuration of the SETH capsule will follow shortly where a solid metal heat sink will be clamped around UO_2 pellets in lieu of cladding to enable pellet radial temperature gradients. This capsule configuration uses electrical preheat in concert with ramp-shaped transient fission heating profiles to create pellet temperature gradients representing operation in LWRs. While this temperature distribution will only exist for tens of seconds, it is extremely difficult to simulate using out-of-pile methods and is adequate in creating vital validation cases for pellet-cracking mechanics models in fuel performance codes. These irradiations will include various temperature sensors including a first-of-a-kind transient application of fiber optic–based distributed temperature sensors for highly resolved three-dimensional mapping of heat sink temperature for comparison to as-run pellet-cracking models of these irradiations.

A different larger capsule module makes use of a solid metal heat sink to absorb specimen fission energy in order to approximate the temperature distribution evolution in fuel rodlets during postulated transient overpower events. This capsule, referred to as the Temperature Heat-sink Overpower Response (THOR) module, uses a liquid metal–filled annulus between rodlet cladding and the capsule wall for intimate heat transfer. This approach is inspired by similar historic designs[15] and is particularly useful for approximating the early-phase temperature response of sodium-cooled fast reactor fuels in safety case scenarios. The THOR module also has applicability for testing of LWR rodlets in scenarios where cladding chemical conditions are not of interest, but rapid heat rejection from the cladding surfaces is needed. The THOR capability is optimal for cost-effective experiments intended to

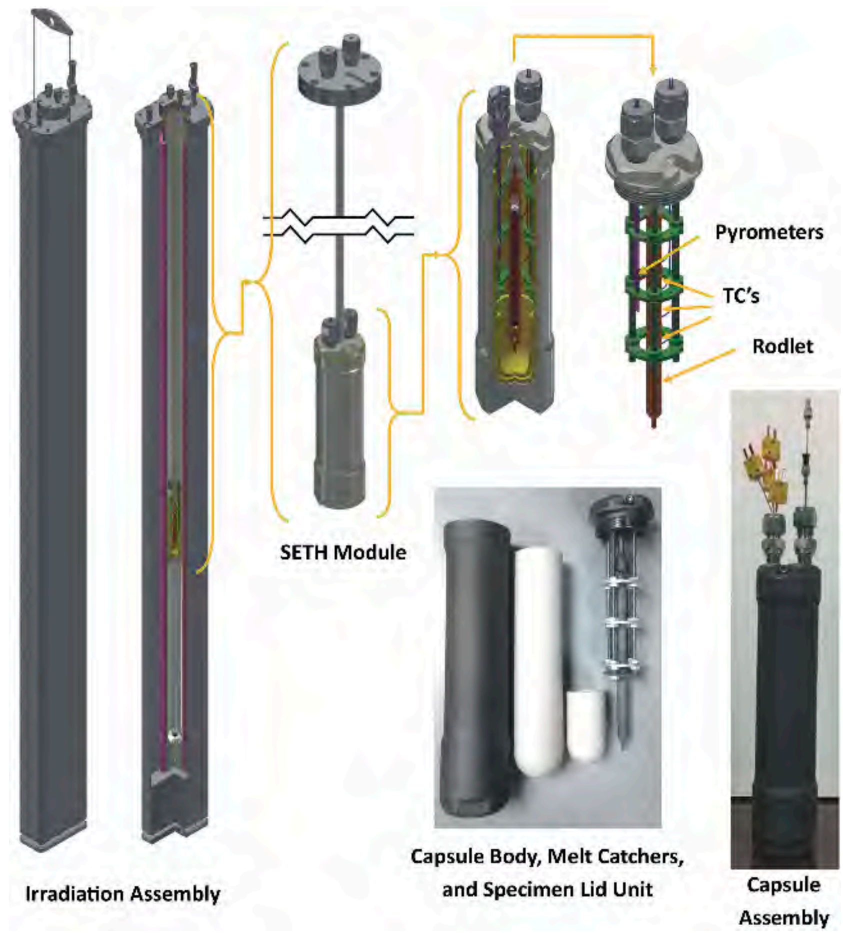

Fig. 5. SETH design and photographs.

identify performance phenomena and pave the way to more sophisticated integral-scale tests in flowing coolant loops.

In situ instrumentation is another crucial area for transient testing that is enabled by both TREAT's structural layout and relatively low chronic irradiation damage to sensor materials. In situ instrumentation, however, can also be a challenging prospect due to acute exposure in extreme conditions, the need for rapid response time, and the inability to perform troubleshooting during brief irradiations. MARCH's flexibility and ease of use make it a well-suited capability to demonstrate sensor survival, rehearse instrument implementation, and quantify nuclear-induced signal artifacts for candidate measurement technologies to be used later in fuels testing. MARCH's ability to control environmental temperature, combined with TREAT's ability to manipulate fission heating histories, creates an ideal venue for demonstrating measurement techniques and quantifying fundamental material properties in the presence of neutron irradiation. Last, TREAT's ability to provide an enormous range of neutron/gamma fluxes make it well suited for demonstration and calibration of nuclear detectors over several decades of magnitude.[31] For these reasons, a MARCH module termed the Materials and Instrument Modular Irradiation Capability (MIMIC) is dedicated to enabling instrument irradiations. The MIMIC design is essentially a series of adjustable and configurable fixture pieces for supporting instrumentation of various form factors and managing lead routing inside the BUSTER pipe and heater module. In order to realize this mission area fully in terms of cost effectiveness, the MIMIC design is paired with an analysis tool programed with pre-analyzed enveloping nuclear parameters so that safety permissions can be obtained for testing instrumentation based on constituent masses alone, bypassing the cost of geometry-specific safety modeling.

A major adaptation of the SETH capsule enables testing of roughly the same LWR rodlet size used in ATF-SETH, but in the presence of pressurized water. The principle modifications to create this module, referred to as the MARCH–Static Environment Rodlet Transient Test Apparatus (MARCH-SERTTA), are the addition of a larger lid with internal expansion volume to accommodate water vaporization and a major overhaul to the specimen holder and instrumentation package in order to focus on water-environment performance phenomena. The starting pressure upon capsule assembly and an internal cable heater enable MARCH-SERTTA to adjust pretransient subcooling and water/steam phase conditions to study different transient thermal-hydraulic conditions. MARCH-SERTTA is outfitted with detectors to indicate environment pressure, environment temperature, fuel cladding temperature, fuel internal pressure, fuel axial expansion, and water-phase change. This design gives a full suite of fast response data for evaluating specimen boundary conditions, determining the timing of crucial performance transitions, and comparing to transient fuel performance models. Irradiation of current LWR fuels, ATF fuel technologies, and special purpose specimens for transient critical heat flux studies are planned for use of the MARCH-SERTTA module (see Fig. 6).

IV. INTEGRAL-SCALE FUEL TESTING FOR WATER-COOLED REACTORS

The MARCH-SERTTA capsule will enable affordable testing of rodlet and similar fuel specimens in representative water environments, but the geometric constraints associated with the containment pipe in the MARCH system limit the specimen size scale, energy capacity, instrumentation density, and ability to include features that actively manipulate thermal-hydraulic conditions. A similar, but larger experiment vehicle, referred to as the Super-SERTTA is equipped to access these enhanced data opportunities. Due to its size the Super-SERTTA does not fit within the MARCH system, but does fit within the same overall form factor as the historic Mk-series loops. This approach requires the specimen-supporting capsule and safety containment boundary to be one component. While this layout makes the design, safety analysis, and hardware fabrication costlier compared to MARCH-based tests, the majority of the Super-SERTTA containment weldment is reusable and individual test–specific adaptation can be affected by design modification of the single-use internal test train. The replaceable top-loading test train approach was used historically in the Mk-series sodium loops and facilitates hot cell assembly and transport using purpose-built shielded casks. While transient testing of pre-irradiated

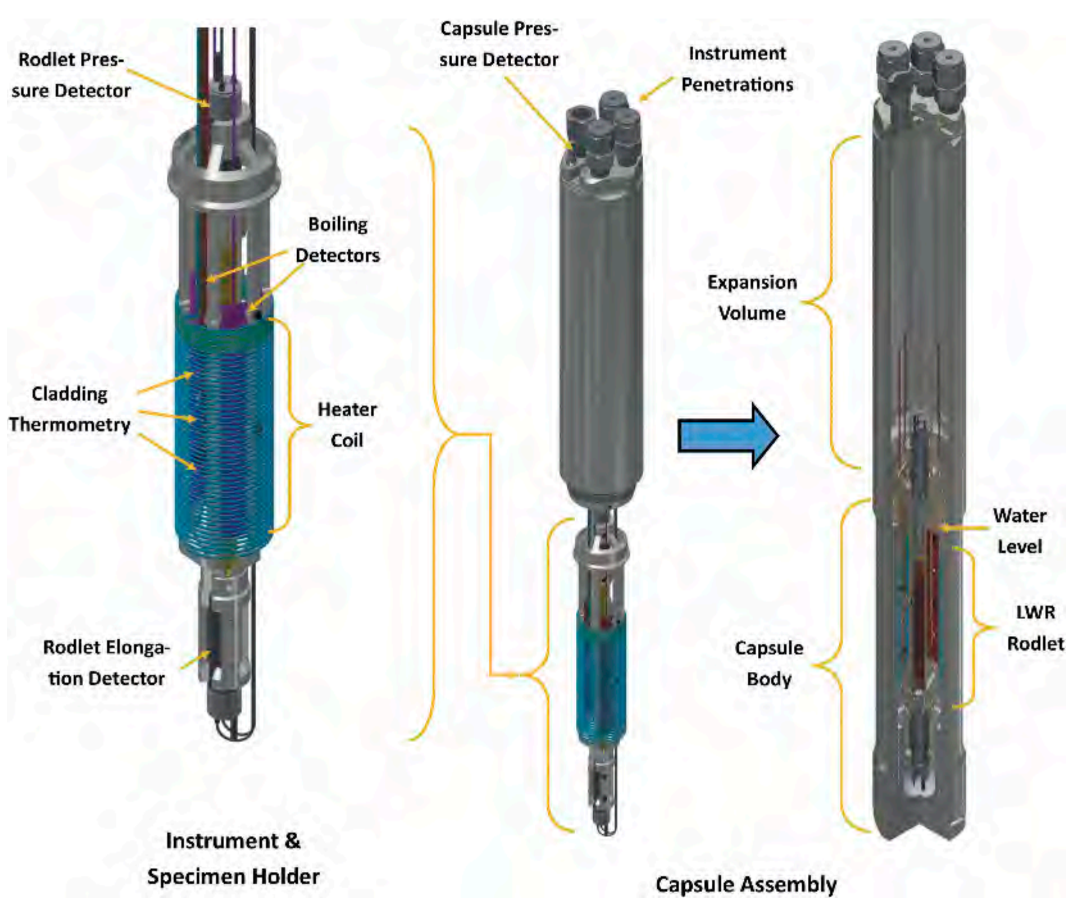

Fig. 6. Overview of MARCH-SERTTA module.

samples is viable using the previously described MARCH modules, Super-SERTTA is specifically designed for remote handling compatibility in order to access the full data potential associated with pre-irradiated specimens, many of which represent years of investment prior to their arrival at TREAT.

Super-SERTTA can establish a reasonable natural convection flow condition when equipped with a test train that forms an annular flow path between it and the main pressure pipe by using system heaters in the lower specimen region and coiling coils near the top. This flow regime is not able to fully achieve typical forced-convection conditions in LWRs, but can be adequate to establish a known thermal equilibrium point prior to transient initiation and can support brief flat top–type transient segments to establish the desired stored specimen energy prior to triggering nuclear and thermal-hydraulic excursions. This annular flow path surrounds the specimen and helps to further thermalize neutrons from the core and reflect specimen-born neutrons to boost specimen-to-core power coupling for extended transient energy injections. A large expansion tank adjacent to the primary test pipe can be accessed intentionally with a trigger blowdown valve line to simulate LWR depressurization accidents [e.g., loss-of-coolant accident (LOCA)] or through a pressure-relief line for extended safety capacity. Mist spray and reflood lines help control the post-blowdown system pressure, water vapor fraction, and timing of water reflood events. The replaceable test train approach enables different instrumentation and heater packages to better suit boundary conditions and data objectives for LOCA, RIA, or other scenarios of interest.

The Super-SERTTA device offers enhanced testing of LWR capabilities while fitting within the overall form factor as the historic Mk-series sodium loops. This approach aids timely testing owing to compatibility with existing fixtures, approaches, and general infrastructure, but cannot support boundary condition simulation for full forced convection in LWR safety research. In this light Super-SERTTA is a stepping stone to the ultimate TREAT water loop, referred to as the TREAT Water Environment Recirculating Loop (TWERL), where the same test-train-in-pipe approach is adapted to house LWR rods and small bundles in flow tubes. The piping network is modified for attachment to a compact high-pressure water pump encased in an enlarged cylindrical secondary canister that makes use of the full available volume in existing shipping casks. Similar to the Mk-series loop strategy, this approach is adequate to provide hydraulic conditions for a few rodlets and mitigates risk for radioactive contaminant transport through plumbing outside of TREAT's shielding, but necessitates modification of established core interface hardware, fixtures, tools, and handling interfaces. An alternate approach to the TWERL design largely maintains the Mk-series form factor with pumps and support equipment housed outside of TREAT concrete shielding. This approach enables hydraulic conditions adequate for nine-rod LWR bundles, which TREAT is neutronically capable of driving to fuel performance limits for design-basis accidents and beyond, but carries with it the engineering burden of fission product filtering and potential posttest decontamination practices for the plumbing routed outside the shielding. Development of the TWERL design is planned to proceed as data objectives become apparent and are prioritized through preceding capsule-based tests to realize the TWERL as TREAT's seminal LWR testing platform. Conceptual representations of the Super-SERTTA design and pump-in-can approach to the TWERL design are shown in Fig. 7.

V. LOOP TESTING CAPABILITIES FOR ADVANCED REACTORS

While TREAT's more recent historic era involved a tremendous amount of fuel safety research for SFRs, the general decline in SFR-related research during the latter end of this era left several outstanding data gaps, especially for metal-fuel designs, that persist to this day. TREAT's legacy in SFR safety research unquestionably demonstrates its strength in this arena, but much of the institutional knowledge, infrastructure, and design details surrounding these historic approaches, including the engineering bases for the workhorse Mk-series loops, has been diminished by the generational gap that formed during TREAT's operational hiatus. A resurgence of interest in advanced reactors, many of which are based around metal-fueled liquid metal–cooled reactors, requires TREAT to revive and modernize this mission area. Modern technologic advances in fuels, materials, instrumentation, and simulation all drive the need for an updated liquid metal–cooled loop capability at TREAT. This modernized TREAT sodium loop will build upon the fundamental approach that was so successful historically, but will require modern materials to increase neutron economy for testing high-burnup and low-enriched fuels while accessing higher temperature capabilities for reactor designs with increased thermal efficiencies or liquid-metal coolants other than sodium. While a great deal of the fluid-handling infrastructure and support equipment for liquid-metal and water-based systems will be separate for chemical compatibility reasons, the concurrent development of the TWERL and the modern

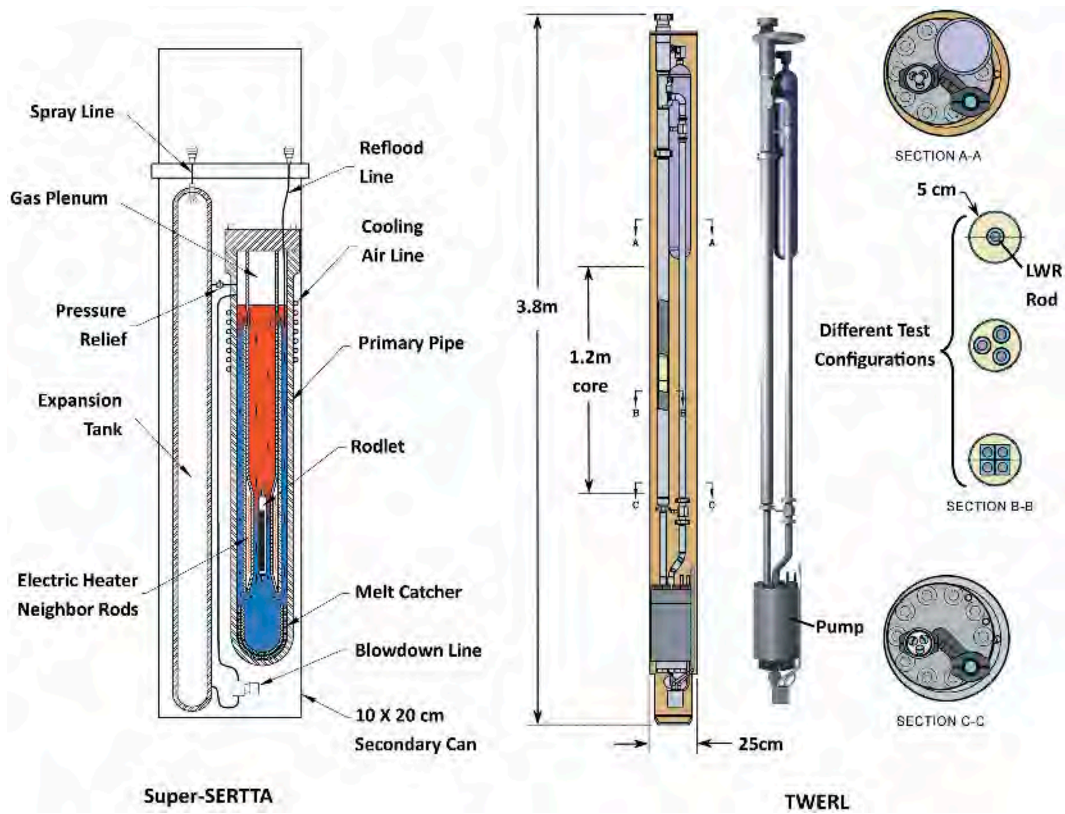

Fig. 7. Super-SERTTA and TWERL conceptual representations.

TREAT sodium loop offers significant opportunities for deployment of common infrastructure, especially for equipment that enables assembly transport, handling, installation, and core interfacing.

VI. SUMMARY OF MODERN IRRADIATION CAPABILITIES

The modern nuclear fuel developer community is addressing refinements and data gaps in current-generation fuel technologies while researching future advancements ranging from evolutionary to revolutionary. TREAT's brilliantly basic facility design provides the opportunity for these many technologies to be researched under extreme nuclear heating conditions in concurrent endeavors. The ability to install both small and large experiment capabilities, with flexibility in specimen boundary conditions and coolant types, requires a new generation of irradiation vehicle designs to span the spectrum of needs. In some cases, historic approaches to TREAT experimentation can be modernized and revitalized, while in other cases innovative new approaches are needed.

The MARCH system provides the framework for irradiation testing in TREAT when small-to-moderate specimen sizes are suitable. The MARCH-based tests provide access to higher throughput testing via simplified logistics and modular approaches to consumable hardware, especially when fresh fuel samples are of interest. The CINDI module provides a multicapsule capability where tens of characterization-scale fuel samples can be irradiated simultaneously in electrically preheated conditions for investigation of lower-length-scale and fundamental damage mechanisms. The MIMIC design is also compatible with CINDI's high-temperature heater module and provides the same fundamental capability, except with a focus on mechanical needs for demonstrating the method, response, and resiliency for in-pile instrumentation. The SETH capsule provides an inert-gas environment for instrumented fuel samples whose size represents integral-scale phenomena such as rodlets, pellets, compacts, miniplates, etc. These three MARCH-based modules (CINDI, MIMIC, and SETH) constitute the family of inert-gas-environment devices tailored toward low-cost and high-throughput testing campaigns where PIE can typically be accomplished in glove boxes.

The MARCH-SERTTA capsule provides a capability similar to SETH, except with capability for enhanced instrumentation and liquid-water boundary conditions focused toward pulsed-transient fuel melt and pellet-cladding interaction studies on ATF and other LWR fuel rodlets. The Super-SERTTA device offers similar water-environment capabilities, but lives outside of the MARCH system's geometric constraints to offer more test volume for increased instrumentation, specimen size, and energy injection capability with greater compatibility for hot cell–based assembly of previously irradiated LWR fuel specimens. The Super-SERTTA provides additional water and expansion volume for post-dryout quench in RIA testing and blowdown/reflood capability for LOCA research. Last, the TWERL builds upon the Super-SERTTA device to provide pump-forced convection to enable development of prototypic pretransient temperature distributions and investigation of rod-to-rod interactions in bundle testing. These three LWR-environment vehicles cover the salient capability range available to LWR fuel safety researchers across a few historic test reactors, but now consolidated to TREAT alone in order to address modern needs at any level of technology readiness.

Finally, the single-pin THOR capsule and bundle-capable sodium loop provide capabilities for heat-sink capsule and forced-convection liquid metal testing, respectively. These devices are similar to the workhorse designs used historically in TREAT, but with modernizations to access current data needs, advancements in materials/instrumentation, and greater synergy with infrastructure common between TREAT's LWR capabilities. A graphical summary of the experiment devices presented in this critical review and their general placement within these many spectrums of engineering considerations is shown in Fig. 8.

VII. CONCLUSIONS

TREAT is a stupendous machine able to provide a wide range of shaped fission power histories in nuclear fuel specimens to support fuel safety research and other scientific objectives well suited to nuclear transients. After an extended hiatus the facility has resumed reactor operations

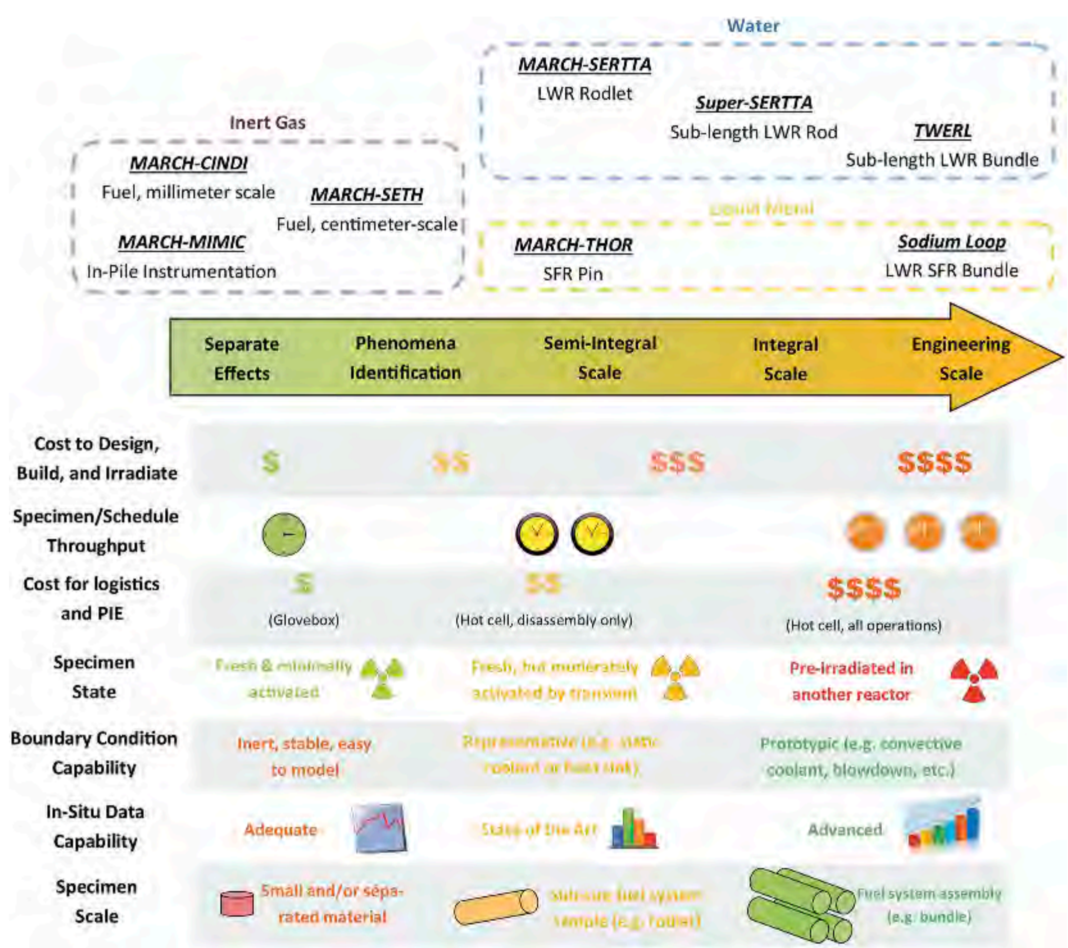

Fig. 8. Graphical summary of TREAT irradiation capabilities.

to support various programs ranging from state-of-the-art and accident-tolerant LWR fuels up to advanced and novel reactor designs. Where TREAT's first and second historical eras were defined by phenomena-focused capsule test and loop-based integral-scale irradiations, respectively, this modern third era is being structured around a synergetic union of these two strategies with an emphasis on test outcomes strengthening advanced modeling's role in integrating the performance envelope. Accordingly, a modular approach to the design and implementation of irradiation capabilities enables various boundary conditions, specimen types, and instrumentation needs to be addressed with strong synergy between testing platforms for increased testing throughput and reduced cost. These irradiation capabilities are undergoing detailed engineering while several of the commissioning tests are under final preparation for TREAT's inaugural fueled irradiations in this modern era. TREAT's facility design, bolstered by a tradition of facility improvement and collocation with INL nuclear research centers, combine with these new irradiation capabilities to enable a tremendously versatile institute for transient testing.

Acknowledgments

The original development of the MARCH system was supported through the INL Laboratory Directed Research and Development Program while much of its design, development, and deployment for experiment-specific test designs was supported through the DOE's Advanced Fuels Campaign, both under DOE Idaho Operations Office contract DE-AC07-05ID14517. Accordingly, the U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

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FUNDING

This work was supported by the U.S. Department of Energy: [Grant Number AC07-05ID14517].

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