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Capabilities Development for Transient Testing of Advanced Nuclear Fuels at TREAT

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Abstract. The TREAT facility is a unique capability at the Idaho National Laboratory currently being prepared for resumption of nuclear transient testing. Accordingly, designs for several transient irradiation tests are being pursued to enable development of advanced nuclear fuels and materials. In addition to the reactor itself, the foundation for TREAT's capabilities will also include a suite of irradiation vehicles and supporting infrastructure to provide the desired specimen boundary conditions while supporting a variety of instrumentation needs. The challenge of creating these vehicles, especially since many of the modern data needs were not historically addressed in TREAT experiment vehicles, has necessitated a sizeable engineering effort. This effort is currently underway and maturing rapidly. This paper summarizes the status, future plans, and rationale for TREAT experiment vehicle capabilities. Much of the current progress is focused around understanding and demonstrating the behavior of fuels designed with enhanced accident tolerance in water-cooled reactors. Additionally, several related efforts are underway to facilitate transient testing in liquid sodium, inert gas, and steam environments. This paper discusses why such a variety of capabilities are needed, outlines plans to accomplish them, and describes the relationship between transient data needs and the irradiation hardware that will support the gathering of this information.

Keywords: TREAT, Transient Testing, Accident Tolerant Fuels

INTRODUCTION

Transient testing is the study of nuclear materials under events that are brief in duration or changing in instantaneous conditions. Generally speaking, this category of events includes practically any scenario, hypothetical or expected, except long-term sustained steady state operation. While some of these transient scenarios can be rather benign, a significant portion of postulated off-normal, accidental, and upset conditions in nuclear reactors are of great interest because they represent power-cooling mismatches that can challenge the integrity of fuel materials. For fuel developers, utilities, and regulators alike, fuel performance during power-cooling mismatch scenarios can be as important as performance in steady state operations. Examples of power-cooling mismatch scenarios are illustrated in Figure 1. Among the many potential transient scenarios, some are slow enough in duration that the salient performance phenomena can be exhibited by testing in facilities generally thought of as steady state nuclear reactors. Other scenarios are loosely coupled enough to irradiation effects (e.g. neutron and gamma) that they can be simulated to some degree with out-of-pile tests. However, several transient scenarios require very rapid power excursions, the correct distribution of heat generation within nuclear fuel specimens, and irradiation effects to accurately represent fuel behavior. These scenarios must be simulated with nuclear heating in reactor facilities specially adapted for this purpose.

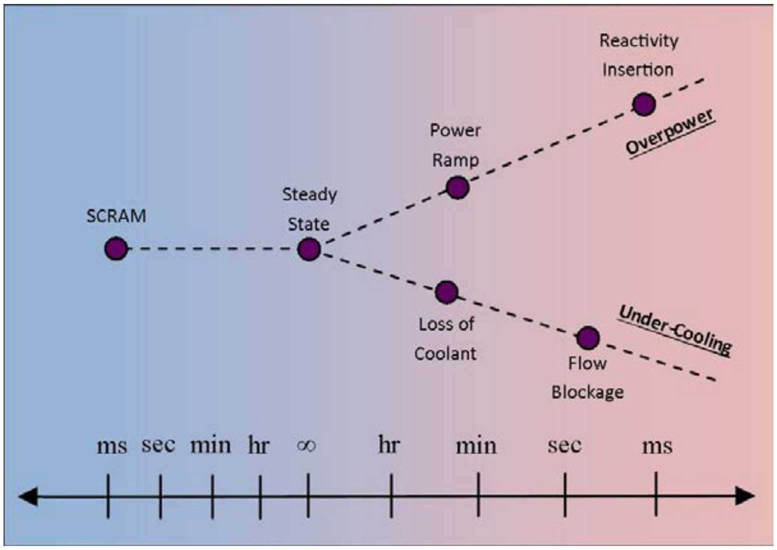

FIGURE 1. Illustration of Power-Cooling Mismatch Scenarios

The Transient Reactor Test Facility (TREAT) is one of first reactor facilities ever built for the purpose of nuclear transient testing. Constructed in the 1950's and first operated in 1959, TREAT provided thousands of transient irradiations for an immensely diverse set of experiment programs [1]. During 35 years of operation the facility was updated, reconfigured, and improved until 1994 when it was placed in operational standby due to reductions in domestic Sodium Fast Reactor (SFR) programs. Continued use of the facility for other reasons, combined with its brilliantly simple and low-maintenance design, ensured that TREAT's physical condition remained unspoiled up to the present day. While there were a few contemporary transient test reactors collocated at what is the now the Idaho National Laboratory, only TREAT has endured to the present day without being decommissioned. In light of the Department of Energy's (DOE) recently-established Accident Tolerant Fuels (ATF) program, which aims to develop Light Water Reactor (LWR) fuels able to tolerate power-cooling mismatches better than current fuels, an intense project is underway to prepare TREAT for operation once again.

In addition to ATF, TREAT will also support experiments aimed at augmenting transient-performance data for current-generation LWR and SFR fuels, demonstrating transient performance of novel fuel systems, and investigating scientific behaviors that are otherwise well-suited to TREAT's unique characteristics. Given the current interest level manifest by various future users, combined with latent testing needs backlogged from decades of dormancy in US-based transient testing, it is apparent that the future TREAT will need to both maintain its multi-mission physical capabilities and provide flexible options for various experimenters to access the facility. Some options for accessing TREAT are expected to include the Gateway for Accelerated Innovation in Nuclear (GAIN) and Nuclear Science User Facilities (NSUF) for transient tests focused on commercial and academic needs, respectively.

TREAT Background

TREAT is an air-cooled reactor where the driver core is made up of urania dispersed in graphite blocks and encapsulated in zirconium alloy cans. The substantial graphite thermal mass provides the primary heat sink for transient-deposited energy with pronounced negative reactivity temperature feedback. This self-limiting characteristic makes the reactor inherently safe and relatively easy to operate. The square-pitch gridplate can accommodate 19 × 19 fuel assemblies, each being 10cm square in cross section with 1.2m of active core length. Hydraulically-driven fast-acting transient rods can provide prompt reactivity step insertions and virtually any combination of transient shaping to simulate a brief periods of steady state operation, power ramps, and post-SCRAM nuclear decay heat (see Figure 2). The reactor's capabilities are limited only by the amount of available excess reactivity in the transient rods and the energy that can be deposited in the fuel blocks without causing excessive oxidation of the zirconium alloy cans. TREAT is able to deposit more than 2000MJ core energy in natural-shaped pulses less than one second in duration with instantaneous powers as high as 16GW. TREAT's core can deposit 2900MJ energy in shaped transients ranging from a few second to several minutes in duration [2]. Large step insertions that are quickly followed by rapid reintroduction of control rods can produce "clipped" pulses for core energy releases of approximately 1400MJ with very brief durations (pulse width less than 100ms) [3].

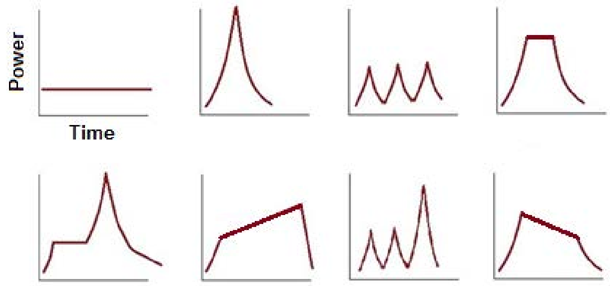

FIGURE 2. Simple Representation of Various Transient Shapes [4]

Four viewing slots through each side of the reactor shielding allow line-of-sight view of the center experiment. Various devices have made use of these slots historically including a high speed video facility [5]. Two slots are currently occupied, one by a neutron radiography facility, and the other by a fast neutron hodoscope. At steady state the core can provide up to 120kW of thermal power to allow for neutron radiography, hodoscope calibration, dosimeter irradiation, and instrumentation check out. See Figure 3 for an overview of the reactor and associated experiment facilities.

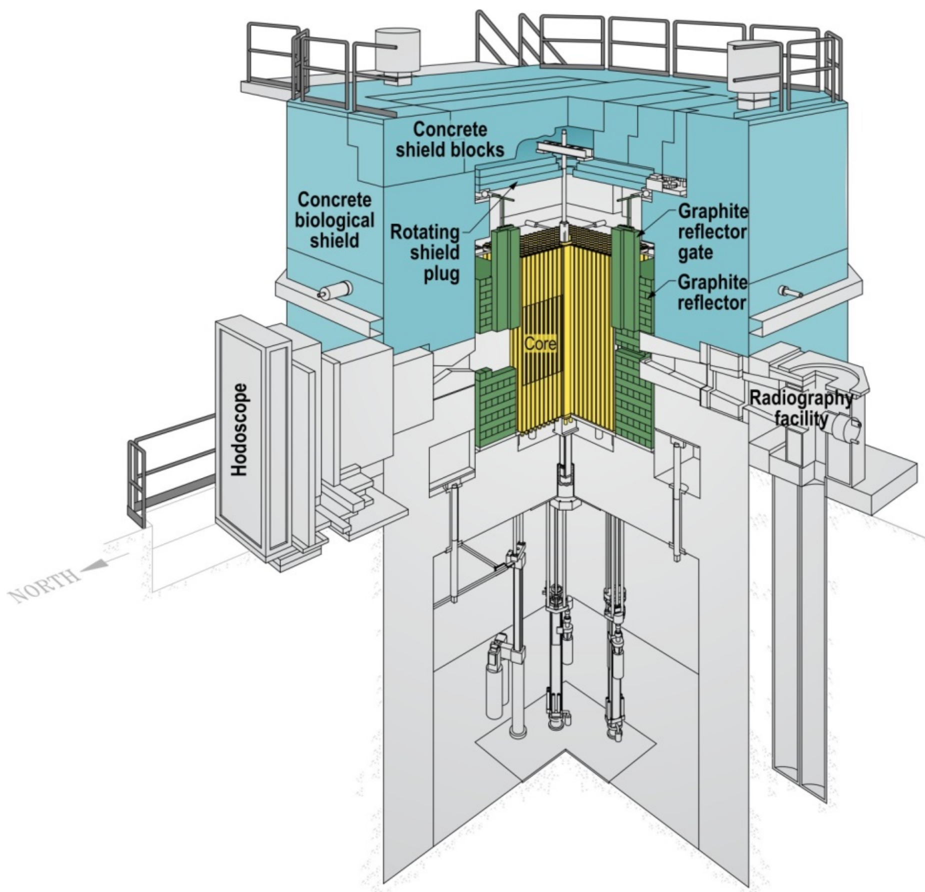

FIGURE 3. Overview of Treat Features [6]

While TREAT is a stupendous machine, its primary role is to provide the desired neutron flux to the experiment and has no innate capabilities for simulating the other boundary conditions necessary for transient tests. One of the most successful experimental approaches in TREAT has historically been to provide all of these other boundary conditions (pressure, temperature, coolant medium, convective heat transfer), along with support for specimens and instruments, within “package-type” experiment vehicles [7]. Since the reactor has no inherent pressure vessel or containment structure, the experiment vehicle’s containment structures must allow for adequate neutron flux to reach the specimen within while safely containing energy from pretest pressures/temperatures, transient-deposited nuclear heating, and the potential for exothermic chemical reactions. While this approach can create challenging design constraints for experimental vehicles, it also allows TREAT to support multiple test programs with little down time between. For example, a self-contained sodium loop could be installed one week, and a PWR-environment vehicle could be installed the next week. Since TREAT is one of few remaining transient test reactors in the world, and since various future programs will likely have transient test needs which are both concurrent in time and disparate in desired boundary conditions, it will be important that TREAT retain this “easy-in easy-out” capability for different test vehicles.

Experiment vehicles are typically lowered into the core through an opening in the upper rotating shield. Experiments with radioactive constituents are handled outside of the reactor with shielded casks and stored in subfloor storage holes. Experiment devices typically displace a few driver fuel assemblies in the central region of the core. The test vehicle cross sectional area is constrained by the number of driver fuel assemblies displaced from the core, each being approximately 10 cm square, and the available shielded casks which have inner diameters up to 25 cm. TREAT experiment devices are typically designed to be self-contained and can be assembled/disassembled remotely in hot cell facilities, transported in shielded casks, and lowered directly into the core with plug-in connections for power, instrumentation, and other necessary leads (see Figure 4 and Figure 5). [8]

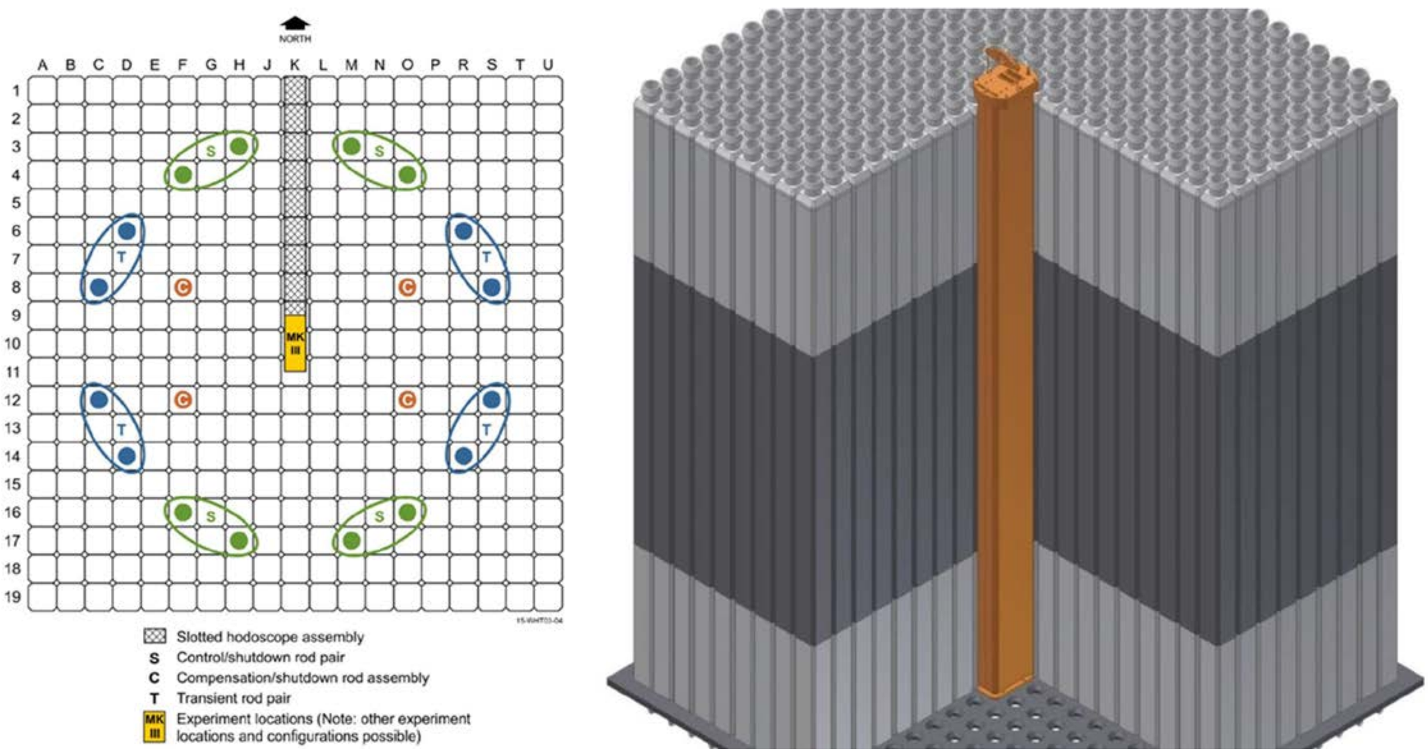

FIGURE 4. Example Core Map Left [9], Package Type Vehicle in TREAT Core ¾ Section View

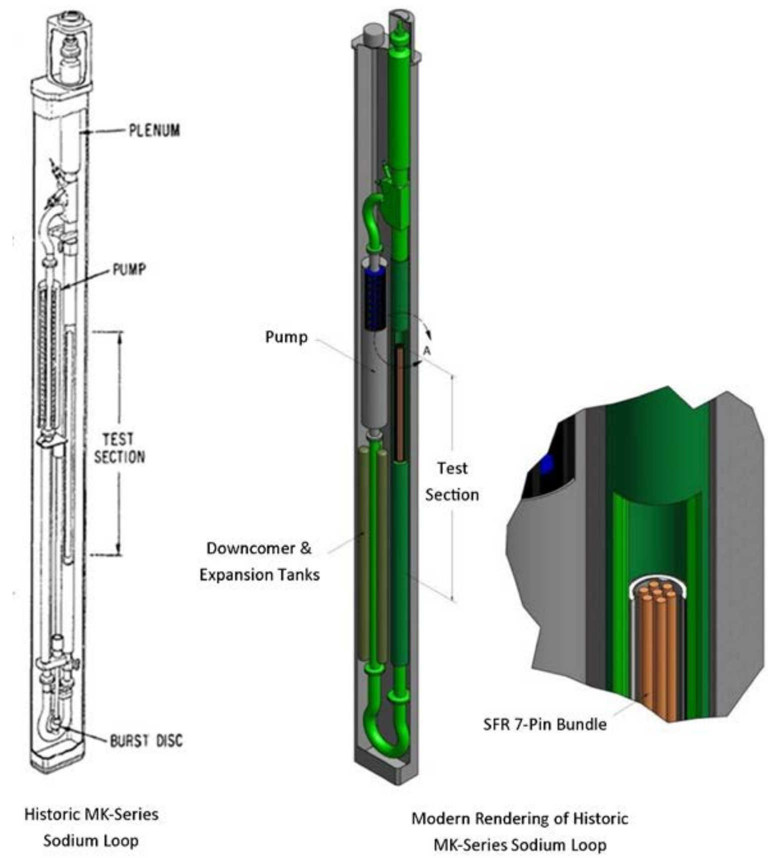

FIGURE 5. MK-II Sodium Loop, Historic Rendering Left [10], Modern Rendering Right [8]

CURRENT EFFORTS AND PLANS FOR MODERN IRRADIATION VEHICLES

Although TREAT historically supported all kinds of nuclear fuels, including LWR's, SFR's, space nuclear propulsion, research reactor plate-type fuels, and even fuels for use in the driver core of other transient test reactors, the majority of TREAT's more-recent experiment programs revolved around SFR's and sodium-environment test capsules and loops. [4] The workhorse test vehicles for the these experiments were the MK-II and MK-III sodium loops, the primary difference between the two being that the latter could house longer specimens up to 2.4m in length. This design approach, shown previously in Figure 5, enabled SFR coolant and heat transfer conditions to be provided to various test train configurations including one, two, or three fuel pins in individual flowtubes, or up to seven fuel pins in a hexagonal cluster. Removable inserts in the core gridplate enabled the MK-III sodium loop to be set at different axial locations in order to place the fueled region of the pin in the TREAT active core. One or two Annular Linear Induction Pumps (ALIP's) and burst-disc overpressure lines to expansion tanks could be installed as needed to provide the necessary pump and energy capacity. [11]

MK-series loop experiment-specific test trains could be outfitted with a variety of instruments to monitor test and specimen conditions while the fast neutron hodoscope collected information about fuel movement before, during, and after transient excursions. MK-series loops were evaluated within safety analysis envelopes which allowed new experiments to be performed with relatively simple analysis to demonstrate compliance with the pre-analyzed envelope, or to specifically evaluate deviations from the envelope as needed. MK-series loops could be assembled either in or out of the Hot Fuel Examination Facility (HFEF) shielded hot cells depending on specimen needs. This approach enabled MK-series loops to serve as more than just a single design, but as a modular platform for supporting various SFR transient testing needs.

Although the project was never completed, a rather mature design existed and a sizable amount of infrastructure was established to support a scaled-up version of the MK-series concept, known as the Advanced TREAT Loop (ATL). The ATL was purposed to support testing of larger 37-pin bundles [12]. A capability similar to the ATL could be envisioned for TREAT in the future. Looking to the future, the modern TREAT experiment team has been focused on recovering the MK-series design and infrastructure. Combined with modern SFR testing needs and advances in materials and instrumentation, the design for a MK-IV sodium loop will emerge to support future SFR transient experimenters.

While the MK-series design philosophy will provide the basis for many other future TREAT experiment vehicles, some sizeable adaptations will be needed to support LWR-environment test vehicles such as those needed for ATF transient testing. Much of TREAT's experiment history, especially in the more recent decades (1970's-1990's) was focused on testing in recirculating sodium loops. While TREAT performed some capsule-based testing of LWR specimens in static water during the 1960's, executed a laconic campaign with a once-through steam system during the 1980's, and proposed a full PWR-condition water loop in the 1990's, there is much less engineering and design information to be harvested from the past in support of future LWR transient test capabilities [4]. Historic and modern examples of LWR transient tests in other transient test reactors can also be leveraged to varying degrees, but specific implementation at TREAT and unique ATF data needs will drive future TREAT experiments to deviate somewhat from proven historic formulas in this new era of US-based LWR transient testing.

One such example is planned to be the first new test vehicle used in the restarted TREAT. This device is a multiple capsule version from the family of vehicles known as Static Environment Rodlet Transient Test Apparatuses (hereafter referred to as Multi-SERTTA). The SERTTA devices will be general purpose vehicles capable of providing inert gas, water (up to PWR conditions), steam, or perhaps even molten sodium environments within vessel-like capsules. The Multi-SERTTA vehicle design is particularly novel as it makes use of the full active core length in TREAT to test four small rodlets (~12cm length), each within its own hermetic boundary. This approach will aid in high-throughput testing during the early phases of ATF transient testing to better serve fuel concept evaluation and phenomena identification. Further detail on ATF transient testing plans can be found elsewhere [13].

Looking from the outside, Multi-SERTTA's secondary containment shell has the same form as MK-series loops; making it compatible with fixtures, core support, storage hole, cask, and other ancillary hardware existing at TREAT. However, Multi-SERTTA's internal primary containment structures are uniquely designed. Tremendously-strong nickel-based superalloys are used to maximize geometry available for specimens and instrumentation while minimizing through-wall neutron absorption for stronger core-to-specimen power coupling and maximizing containment safety margins. Each vessel is connected to an adjacent expansion tank strategically placed axially between rodlets to maximize neutron delivery to the specimen. Previous Multi-SERTTA designs connected the expansion tank with a burst-disc for overpressure protection. Recent design and analysis efforts have changed this approach by removing the burst disc and extending the tank volume to give comparable containment capacity [14]. This design modification will enable the vessel pressure to remain below supercritical water conditions during planned testing for better simulation of PWR boiling and post critical heat flux quench. See Figure 6.

Multi-SERTTA is inherently limited in geometry available for instrumentation, but careful placement and specially-designed brazed penetration for leads enable a respectable array of instruments including several cladding thermocouples, capacitance-based boiling detectors, micro-pocket fission detectors, optical pyrometry, environment pressure-transducers, and vessel-mounted accelerometers. The desired environment pressure and temperature is achieved by gas pre-charge and electrical heaters prior to initiating the transient excursion. The current Multi-SERTTA specimen holder and instrument package is intended for ATF rodlets in PWR environments. Like MK-series loops, the head unit is modular to support different specimen and instrument needs in the future. Refractory crucibles and a melt catcher protect the vessel from attack should molten fuel be ejected from rodlets. Neutron-absorbing (e.g. hafnium, dysprosium) can be wrapped around the vessel to adjust core-to-specimen power coupling to achieve the desired energy deposition level in each of the four specimens. See Figure 7.

The first design configuration for Multi-SERTTA will use flux shaping collars to counteract TREAT axial flux profile; thereby equilibrating energy depositions in each of the four vessels. This will be paired with PWR-water starting environment conditions and short-pulse transients intended to simulate PWR hot zero power reactivity initiated accidents (HZP RIA). Future designs configurations may use the axial profile advantageously, and could even exacerbate this axial gradient with flux collars, to give markedly different specimen energy injections in each vessel.

Such a test could be particularly useful in achieving four distinct specimen energy injections with a single fixed pulse width. A series of these tests could be performed with different combinations of reactivity insertion and pulse clipping to create a comprehensive study, all other things equal, of the effect of pulse width and specimen energy injection. Similarly, the Multi-SERTTA could be operated with inert gas environments for comparison to similar water-environment tests to isolate the effects of boiling boundary conditions; thereby isolating phenomena such as pellet-cladding mechanical interaction.

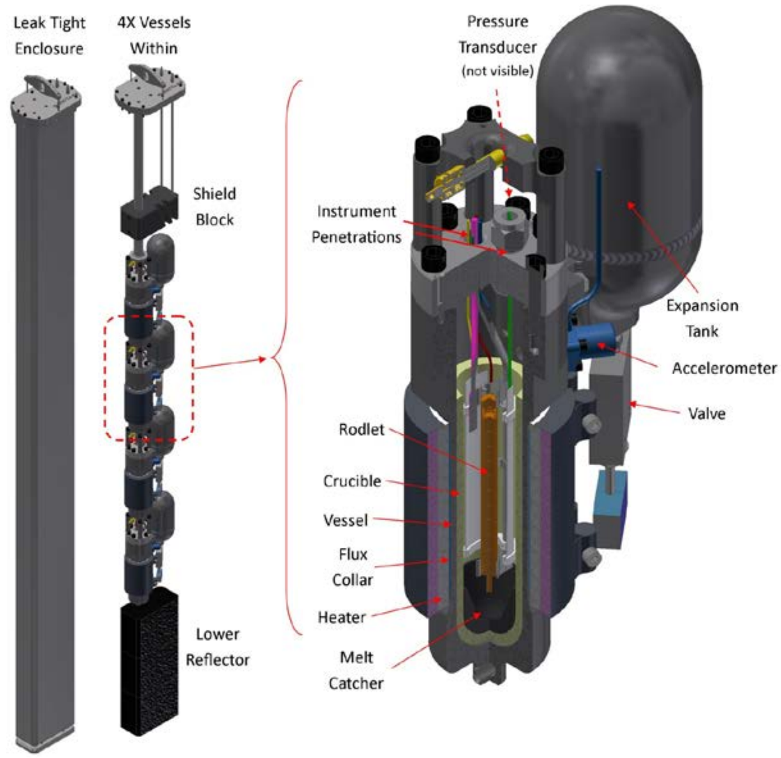

FIGURE 6. Multi-SERTTA Full Assembly

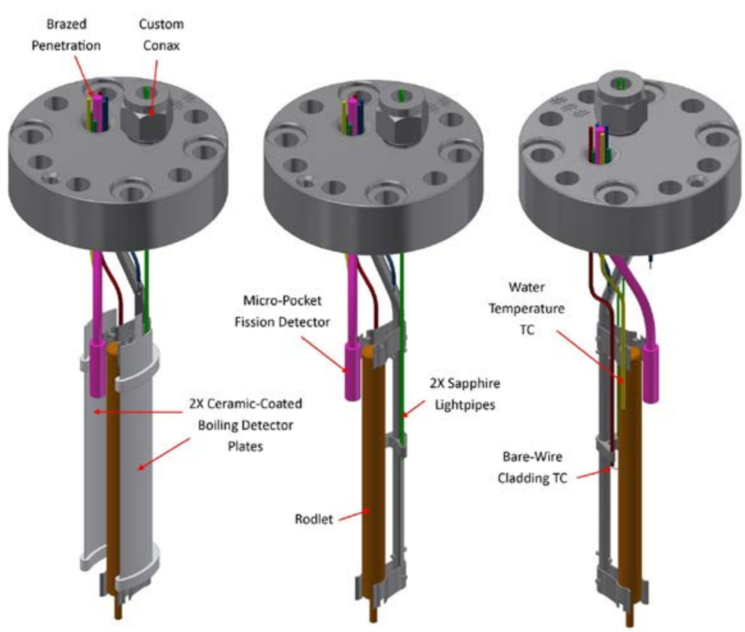

FIGURE 7. Multi-SERTTA, ATF Instrument Array

The Multi-SERTTA vehicle design represents a substantial effort and a relatively aggressive debut test vehicle for the future TREAT experiments team. Still, Multi-SERTTA is not capable of providing all of the features needed to adequately simulate transient phenomena. For this reason, a companion vehicle termed Super-SERTTA will also be deployed a short time later primarily to expand upon several data opportunities. First, the Super-SERTTA will be a single-vessel design in order to give greater useable test volume. This will allow for longer specimens, and perhaps even small bundles, combined with more instrumentation. A larger internal volume will give enhanced energy handling capabilities. TREAT's experiment safety analysis derives from the reactivity available in the transient rods prior to test initiation, and limits energy release solely upon the reactor's negative temperature feedback [15]. As a result, Super-SERTTA's enhanced energy containment capacity will be needed to allow for pulses initiated at TREAT's minimum period, with the intent to perform a clip shortly thereafter either with existing control, or further enhanced by a to-be-installed ^{3}He injection system [16], in order to achieve pulse widths truly representative of HZP RIA's. Lastly, Super-SERTTA will represent a simpler internal containment structure, akin to MK-series loops with only one closure flange near the top, greatly facilitating the prospect of loading pre-irradiated fuel specimens remotely in the HFEF hot cell. Although Multi-SERTTA is capable of housing pre-irradiated specimens, the scarcity of such specimens, and time invested into their irradiation prior to transient testing, will likely make Super-SERTTA the vehicle of choice for these crucial tests. Additional adaptations or modules to Super-SERTTA are envisioned to enable sodium-environment testing and water-to-steam blowdown capabilities to simulate Loss of Coolant Accidents (LOCA). See Figure 8.

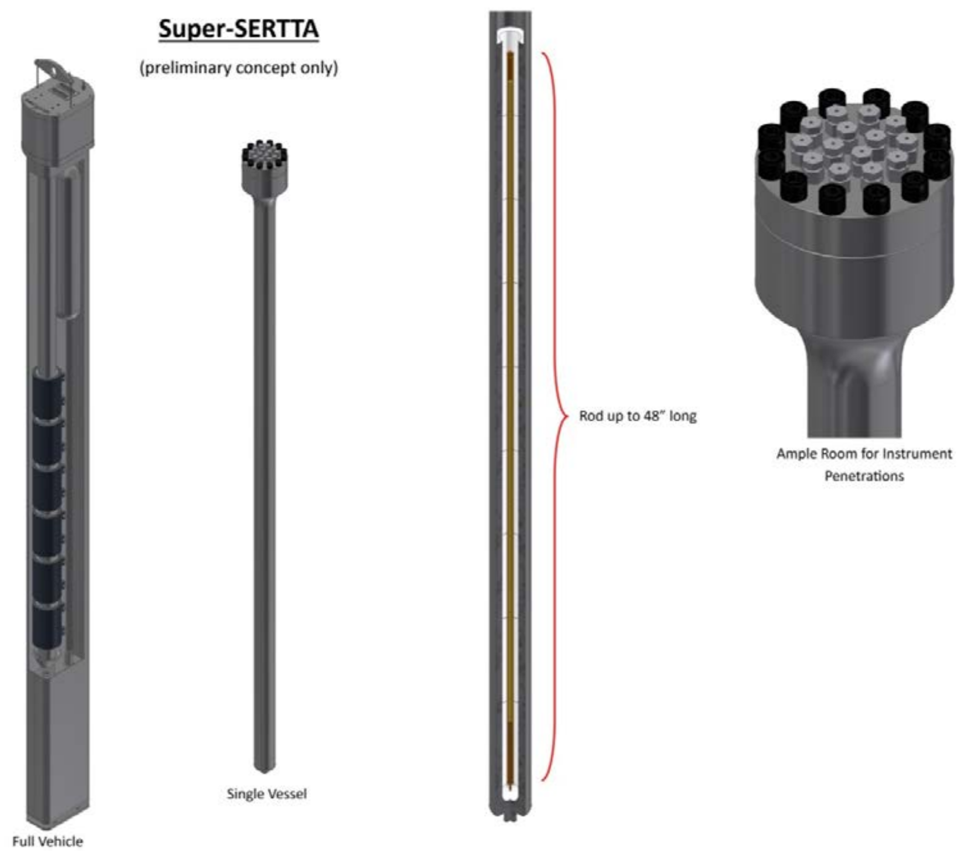

FIGURE 8. Super-SERTTA Concept

A wealth of good work can be accomplished in static environments, especially owing to the relatively ease of designing, constructing, and operating static environment vehicles. Still, many transient scenarios cannot be adequately simulated without forced convection heat transfer representing the reactor design environment. As discussed previously, recirculating loop capabilities existed historically and will be revitalized for future SFR tests in the MK-IV sodium loop. A new-to-TREAT corresponding capability will be made for LWR tests in the TREAT Water Environment Recirculating Loop (TWERL). The current concept for the TWERL will retain all of the LWR functionality of the Super-SERTTA, with added enhancements for forced convection. Again following the MK-series loop design philosophy, the TWERL will consist of a simple high-pressure piping system with heaters, pumps, and operational instruments (flow meters, pressure transducers, coolant temperatures) all self-contained within a leak-tight metallic canister. Interfaces for test train loading in HFEF, hoisting, instrument/power connections, and pump-cooling lines will all exist at the TWERL's top region. The principle difference between MK-series loops and the TWERL will be the fluid pump, which in the case of the TWERL necessitates a larger cylindrical core footprint to make room for a canned-motor centrifugal pump. The baseline TWERL design will support modular test trains as one highly instrument rod, or two/three PWR rods in individual flow tubes, or even a four-rod bundle. Additional modules and adaptations of Multi-SERTTA will enable rapid loop pressure blowdown to simulate LOCA conditions. Lastly, although a sufficient-capacity compact water pump has not yet been designed, core physics analysis show that TREAT is capable of driving a nine-rod bundle of high burnup PWR fuel for transient testing in a future water loop concept known as the Super-TWERL [17]. See Figure 9.

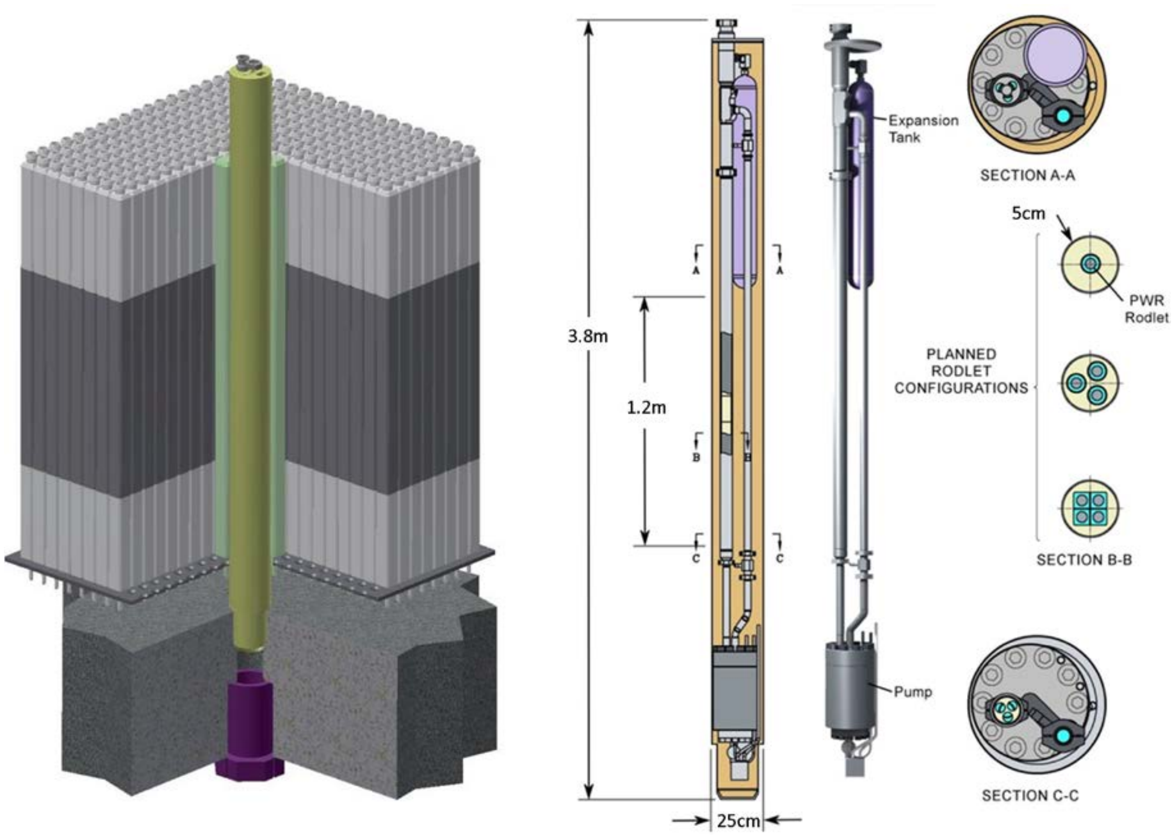

FIGURE 9. TWERL in Core ¾ Section View Left, TWERL Conceptual Layout Right

CONCLUSION

The TREAT facility will resume operation of transient testing in the very near future. After a drought of domestic transient testing for more than two decades, a tremendous effort is underway to prepare for the future testing needs in multiple sectors of the nuclear industry. Particularly, revival of historic sodium loops will serve future needs for SFR-based experiments, while a new suite of LWR-based experiment vehicles will enable testing of ATF, PWR, and other LWR fuel systems in various phases of maturity and under a wide range of test conditions. Careful design and advanced instrumentation will pave the way to a transient testing future filled with opportunities to develop, deploy, license, model, and better understand the performance of nuclear fuels under power-cooling mismatch scenarios.

REFERENCES

[1] L.W. Deitrich, C.E. Dickerman, A.E. Klickman, and A.E. Wright, “A Review of Experiments from the Transient Reactor Test (TREA) Facility,” ANS Winter Meeting, Washington, D.C., Nov 15-19, 1998.

[2] “TREAT Baseline Description Document”, October 1992, Document Number Z0003-0004-OJ-12.

[3] D.C. Crawford, L.W. Deitrich, R.E. Holtz, R.W. Swanson, and A.E. Wright, “Experimental Capabilities of the Transient Reactor Test (TREAT) Facility”, ANS Winter Meeting, Washington D.C., Nov 15-19, 1998.

[4] N.E. Woolstenhulme, J.D. Wiest, “ATF Transient Testing Pre-Conceptual Design and Engineering Considerations Summary”, INL Report INL/EXT-13-29898, August 2013.

[5] C.E. Dickerman, G.H. Golden, and L.E. Robinson, “In-Pile Photographic Studies of EBR-II Mark-I and Fermi Core – A Sample Meltdown”, Nuclear Science and Engineering, Vol 14, No 1, Sep 1962.

[6] John D. Bess, Mark D. DeHart, “Baseline Assessment of TREAT for Modeling and Analysis Needs”, INL/EXT-15-35372, Idaho National Laboratory, September 2015.

[7] D.C. Crawford, L.W. Deitrich, R.E. Holtz, R.W. Swanson, and A.E. Wright, “Experimental Capabilities of the Transient Reactor Test (TREAT) Facility”, ANS Winter Meeting, Washington D.C., Nov 15-19, 1998.

[8] N.E. Woolstenhulme, J.D. Bess, C.B. Davis, G.K. Housley, C.B. Jensen, R.C. O’Brien, and D.M. Wachs, “TREAT Irradiation Vehicle Designs, Capabilities, and Future Plans”, Proceedings of the PHYSOR-2016 Conference, Sun Valley Idaho, May 1-5, 2016.

[9] INL Document SAR-420, “TREAT FSAR”, DOE review draft, April 2016.

[10] W.R. Zench and M.T. A-Moneim, “Coupled Hydrodynamic-Structural Analysis of An Integral Flowing Sodium Test Loop in the TREAT Reactor”, 5th SMiRT Conference, Berlin, Germany Aug 13-17, 1979.

[11] “System Design Description for Mark-III Loop Experiment Systems” System Design Description R0250-1000-SA, rev 2, 8/89.

[12] “37-Pin and 7-Pin Advanced Treat Loop Title II Design Report Prepared for Argonne National Laboratory Argonne, Illinois Contract No 31-109-33-5614 Volume 1”, Prepared by AMETEK, Straza Division, Dec 15, 1981.

[13] R.C. O’Brien, et al., “ATF-3: An Overview of the Accident Tolerance Fuels Transient Testing Campaign in the TREAT Reactor”, proceedings of ANS summer meeting 2015, San Antonio, Jun 7-11, 2015.

[14] C. B. Jensen, C. B. Davis, N.E. Woolstenhulme, C. P. Folsom and H. Ban, "Thermal-Hydraulic Response of the TREAT Multi-Vessel Static Environment Test Vehicle," Proceedings of the PHYSOR-2016 Conference, Sun Valley Idaho, May 1-5, 2016.

[15] “Guide for Irradiation Experiments in TREAT”, INL Document Number Z0004-0001-OR-04, May 1991.

[16] D.C. Crawford, A.E. Wright, R.W. Swanson, and R.E. Holtz, “RIA Testing Capability of the Transient Reactor Test Facility”, Proceedings of the IAEA Technical Committee Meeting on Fuel Cycle Options for LWRs and HWRs, Victoria, Canada, May 1998, IAEA-TECDOC-1122, pp. 99-109.

[17] Connie M. Hill, Nicolas E. Woolstenhulme, James R. Parry, John D. Bess, and Gregory K. Housley, "TREAT Neutronics Analysis of Water-Loop Concept Accommodating LWR 9-Pin Bundle," to be published in Top Fuel 2016 Conference, Boise Idaho, September 11-16, 2016.