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Status Report on Development of MARCH Module Designs

Nuclear Technology Research and Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign
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SUMMARY

The Transient Reactor Test (TREAT) facility was constructed in the late 1950's, provided thousands of transient irradiations before being placed in standby in 1994, and was restarted in 2017 in order to resume its crucial role in nuclear-heated safety research. Advances in modern computational capabilities and a resurgence of interest in novel reactor technology have created an opportunity for emphasizing modern science-based and separate effects test capabilities at TREAT. An innovative approach to this type of testing leverages the relatively low radioisotope accumulation during brief TREAT irradiations by arranging small fresh fuel specimens in low activation hardware "modules" so that they can be easily extracted and shipped for examination within weeks. The concept was termed the Minimal Activation Retrievable Capsule Holder (MARCH) irradiation vehicle system, and its maturation began under a Lab Directed Research and Development (LDRD) project starting in fiscal year 2017. Within the first year of this project, enough design and predictive modeling had been performed to prove the principle and ascertain support from major direct-funded DOE fuel development programs including the Accident Tolerant Fuels (ATF) program that sponsored the first modern fueled test to be performed in TREAT using the MARCH system. Since the design was modular in nature, it was straightforward for other sources to adopt and mature viable test modules while the LDRD project continued concurrently for two more years in conceptualizing and demonstrating the viability of other innovative modules. Many of these modules were adopted for continued development and irradiation under the Advanced Fuels Campaign and other direct sources. This report summarizes the MARCH modules that were conceptualized, designed, and deployed to date with the primary aim of providing reference information to future experiment designers.

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FIGURES

TABLE

ACRONYMS

ATF	Accident Tolerant Fuels
BUSTER	Broad Use Specimen Transient Experiment Rig
CHF	Critical Heat Flux
CINDI	Characterization-scale Instrumented Neutron Dose Irradiation
DMLS	Direct Metal Laser Sintering
DOE	Department of Energy
DRIFT	Dry In-pile Fracture Test
EBR-II	Experimental Breeder Reactor-II
LDRD	Lab Directed Research and Development
LOCA	Loss of Coolant Accident
LVDT	Linear Variable Differential Transformer
LWR	Light Water Reactor
MARCH	Minimal Activation Retrievable Capsule Holder
MIMIC	Materials and Instruments Modular Irradiation Capability
MIMIC-N	MIMIC Neutron sensor test
M-SERTTA	MARCH Static Environment Rodlet Transient Test Apparatus
NSUF	Nuclear Science User Facilities
NTP	Nuclear Thermal Propulsion
PWR	Pressurized Water Reactor
RIA	Reactivity Initiated Accident
RUSL	Resonant Ultrasound Spectroscopy - Laser
SETH	Separate Effects Test Holder
SFR	Sodium Fast Reactor
SIRIUS	An acronym-less star for which an NTP test capsule/series was named
TC	Thermocouple
THOR	Temperature Heat-sink Overpower Response
TREAT	Transient Reactor Test Facility

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STATUS REPORT ON DEVELOPMENT OF MARCH MODULE DESIGNS

1. INTRODUCTION

The Idaho National Laboratory (INL) Transient Reactor Test (TREAT) facility is an air-cooled reactor fueled by uranium oxide dispersed in graphite blocks. These blocks are stacked vertically in 1.2 m long columns and encapsulated in evacuated zirconium alloy sheet metal canisters with unfueled graphite reflectors fastened to the top and bottom ends to create fuel assemblies. While capable of steady state operations at ≤120 kW core thermal power, which is useful for calibrations and non-destructive imaging of experiments in the adjacent neutron radiography stand, TREAT's greatest capability lies in its transient operations. Transient nuclear heat generated in fuel assemblies is quickly absorbed by the graphite fuel blocks to give neutron spectral shifts and strong negative temperature feedback. Automated control of hydraulically driven transient control rods enables virtually any power history shape (pulse, ramp, etc.) within the core's energy capacity of 2500 MJ in a fashion that is both safe and self-limiting. A few fuel assemblies, each having a square cross section of approximately 10 cm, can be removed from the gridplate to create an experiment cavity (typically in the core center) where experiment vehicles are placed. TREAT's 1.2m long active core provides neutrons to the test section while experiment vehicles provide mechanical interfaces, afford specimen boundary conditions, safely contain potential hazards, and support specimens with desired in-situ instrumentation [1]. Radioactive experiments and fuel assemblies are lifted vertically through a slot in the reactor's upper shield plug, handled outside of the reactor in shielded casks, and stored below grade in storage holes. Unlike typical research reactor facilities, the absence of water pools and reactor pressure vessels dramatically simplifies instrument lead routing into the core for enhanced real time data. See Figure 1 for an overview of TREAT.

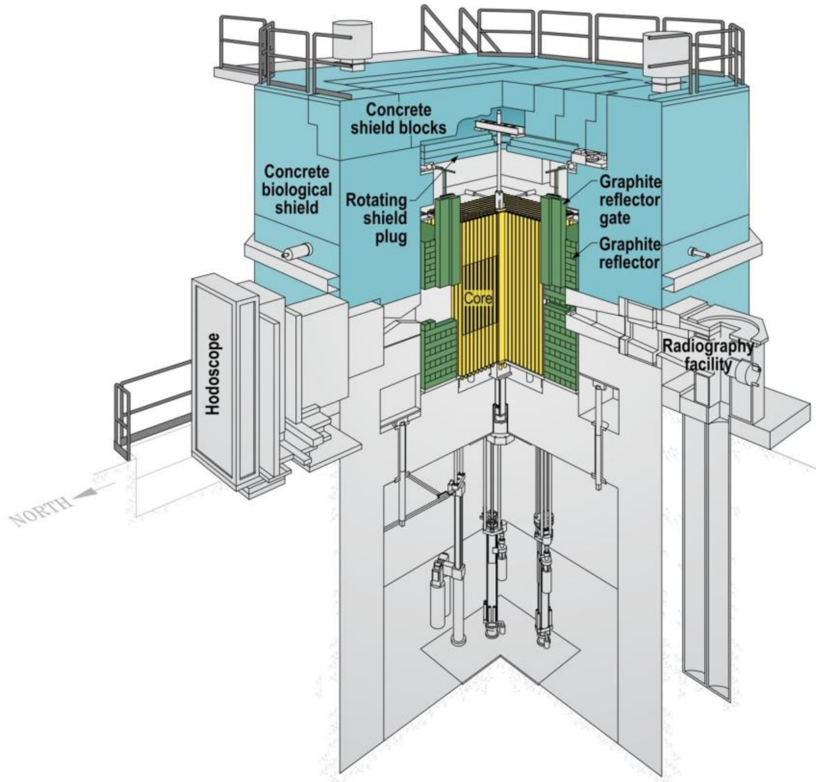


Figure 1. Overview of TREAT. [2]

TREAT was constructed in the late 1950's, provided thousands of transient irradiations before being placed in standby in 1994, and was restarted in 2017 in order to resume its crucial role in nuclear-heated safety research. Advances in modern computational capabilities and a resurgence of interest in novel reactor technology have created an opportunity for emphasizing modern science-based and separate effects test capabilities at TREAT. An innovative approach to this type of testing leverages the relatively low radioisotope accumulation during brief TREAT irradiations by arranging small fresh fuel specimens in low activation hardware "modules" so that they can be easily extracted and shipped for examination within weeks. The concept was termed the Minimal Activation Retrievable Capsule Holder (MARCH) irradiation vehicle system, and its maturation began under a Lab Directed Research and Development (LDRD) project starting in fiscal year 2017. Within the first year of this project, enough design and predictive modeling had been performed to prove the principle and ascertain support from major direct-funded Department of Energy (DOE) fuel development programs including the Accident Tolerant Fuels (ATF) program that sponsored the first modern fueled test to be performed in TREAT using the MARCH system. Since the design was modular in nature, it was straightforward for other sources to adopt and mature viable test modules while the LDRD project continued concurrently for two more years in conceptualizing and demonstrating the viability of other innovative modules. Many of these modules were adopted for continued development and irradiation under the Advanced Fuels Campaign and other direct sources. This report summarizes the MARCH modules that were conceptualized, designed, and deployed to date with the primary aim of providing reference information to future experiment designers.

Three main components make-up the MARCH system including: 1) a multi-purpose containment structure (termed the Broad Use Specimen Transient Experiment Rig, BUSTER), 2) an optional high temperature heater capable of 700°C electrical preheat, and 3) various assemblies which support specimens referred to as "test modules". The MARCH philosophy dramatically simplifies logistics for small specimen irradiations by enabling these smaller modules, most which include specimen capsules, to be extracted from the 6 cm inner diameter of the larger BUSTER pipe weldment on the working floor at TREAT for shipment in small drums. Since the BUSTER pipe weldment is credited with the experiment's safety containment function, including the non-trivial burden of providing protection equal to national pressure vessel consensus standards, this approach is also crucial in enabling the experiment capsules to be treated as convenience features for contamination control rather than providing a safety containment function. This strategy enables capsules to be constructed from affordable commercial compression fittings, manufactured by novel methods (e.g., Direct Metal Laser Sintering [DMLS]) or from less common structural materials selected for their low isotopic activation (e.g., titanium or vanadium) with the intent being to provide flexibility for reduced cost and unique scientific objectives. The more expensive BUSTER hardware is considered reusable while it is generally more pragmatic to consider capsules to be consumable. The result is a highly adaptable system that supports cost effective, high throughput, and rapid innovation cycles in irradiation experiments. See Figure 2 for an overview of the MARCH System.

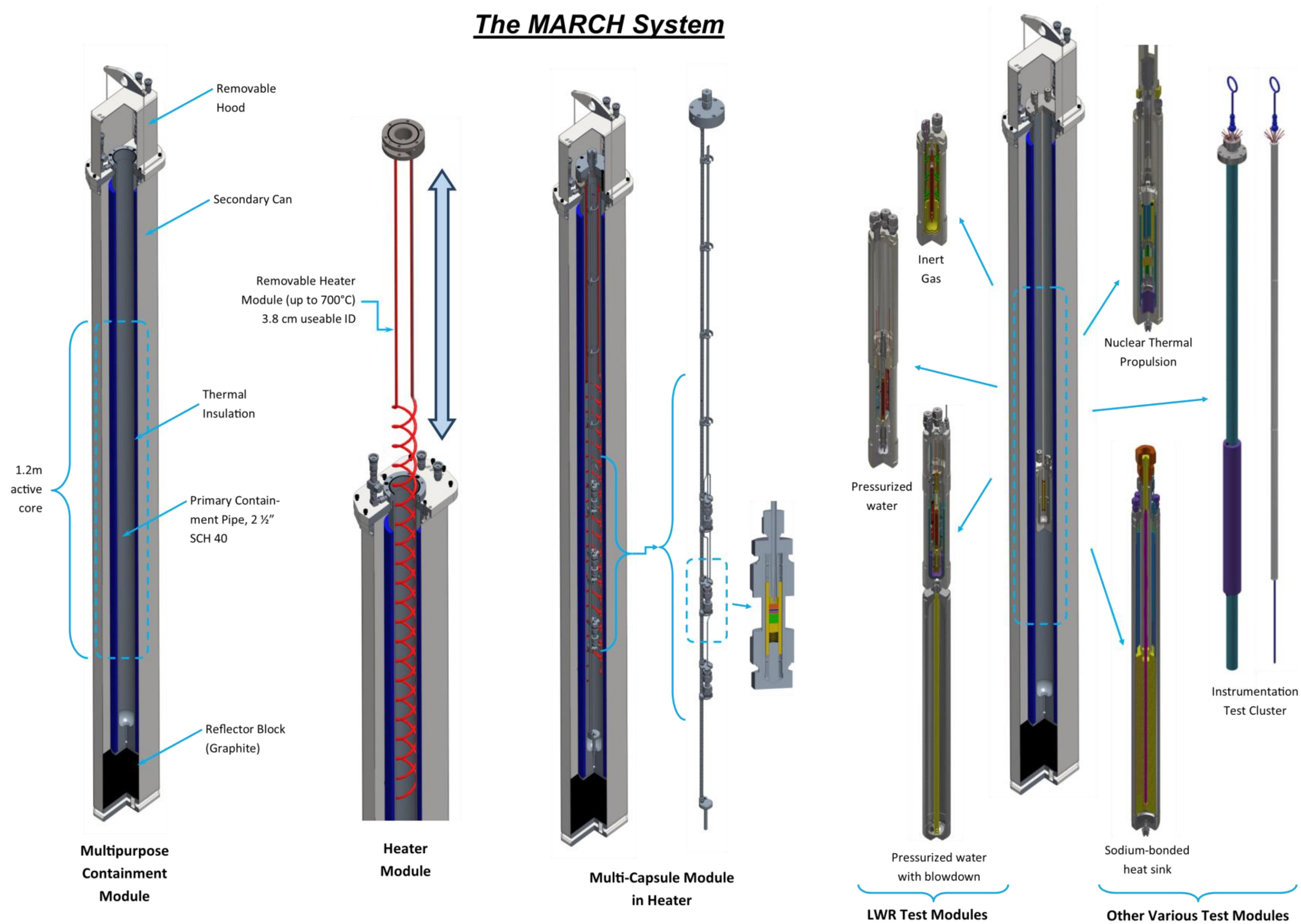


Figure 2. Overview of the MARCH System.

2. BUSTER

The BUSTER is the heart of the MARCH system consisting of a reusable stainless-steel pressure pipe (with 6 cm useable inner diameter), thermal insulation, and sheet metal secondary enclosure. Categorically, the BUSTER pressure pipe is the primary nuclear grade safety component in the MARCH system that enables more rapid and affordable design innovations, hardware fabrication, and test execution for the inner modules which are considered commercial grade. A valve line attached to the top of the BUSTER pipe flange enables leak testing, inert gas purging, and post-test gas sampling for contaminants. The BUSTER pipe weldment is designed and tested for maximum pressure rating of 6.9 MPa (1000 psi). The pre-test cold pressure in BUSTER is typically 1 atmosphere of argon or helium. Once purged and backfilled, the primary pipe valve is closed prior to irradiation. Pressurized boundary conditions for specimens, when needed, are typically born by the inner module (capsule), so that the BUSTER pipe pressure capacity is available for unplanned “safety case” conditions.

Annular segments of thermal insulation surround the BUSTER pipe weldment. This microporous insulation has extremely low thermal conductivity and minimizes heat transport from the experiment to TREAT’s neighboring fuel assemblies or vice versa, providing future capability for higher energy transients and/or electrically heated test modules. A stainless-steel sheet metal rectangular enclosure surrounds the primary pipe to form the core interface geometry. The rectangular flange joins the secondary canister with the primary pipe flange and an optional sheet metal hood. The hood is installed to constitute two levels of containment for tests which contain plutonium or specimens previously irradiated in other reactors. In these cases, the primary pipe still bears the pressure vessel containment function for safety purposes while the secondary containment mitigates contamination spread in the event of mechanical seal leakage from the primary. The flange on the secondary enclosure, along with special storage hole fixturing, enables the BUSTER assembly to be supported by fixtures at floor level over TREAT storage holes for experiment operations including loading/unloading of experiment modules, primary pipe leak testing, and instrument connection checks. The geometry and handling interfaces of BUSTER’s secondary canister are like that of historic TREAT sodium loops for compatibility with existing shipping casks and other hot cell interfaces. High radioactivity from specimens irradiated previously in other reactors negates the value of MARCH’s low activation design approach, but these compatibility design features enable irradiation of these specimens in a cost-effective manner. See Figure 3 for an overview of BUSTER.

A graphite block in the bottom of the secondary canister helps align the pipe and reflect neutrons during irradiation. A tube from the secondary flange routes purge gas throughout the secondary enclosure. Connection fittings enable purge gas to actively sweep through the secondary canister during irradiation. The secondary gas sweep is typically nitrogen and exhausts to TREAT’s filtration and cooling system. The weight of an assembled BUSTER is born by the spring-loaded foot on the bottom of the secondary can resting upon a pedestal flush with TREAT’s gridplate. To date, four BUSTER modules have been fabricated to enable a higher throughput in loading, irradiation, and disassembly of several tests concurrently. See Figure 4 for a cross section view of BUSTER with an experiment module installed.

To date, all MARCH-based irradiation experiments have been analyzed and performed in a core having a full-height (~1.2 m) full-length hodoscope slot from north to south where assemblies in three of the four corners (north-east, south-east, north-west) are unfueled dummies and one (north-east corner) is the source assembly. BUSTER has a core footprint equivalent to two adjacent fuel assemblies (~10cm X ~20cm) but is centered in the core so that half dummy assemblies are adjacent on the north and south sides as an open slot and graphite filled dummy, respectively. All other assemblies are fueled (standard, instrumented, and control rod assemblies as appropriate). A detailed neutronic characterization of the MARCH system in the full-slotted core can be found in reference [3]. See Figure 5 for an overview of the core map.

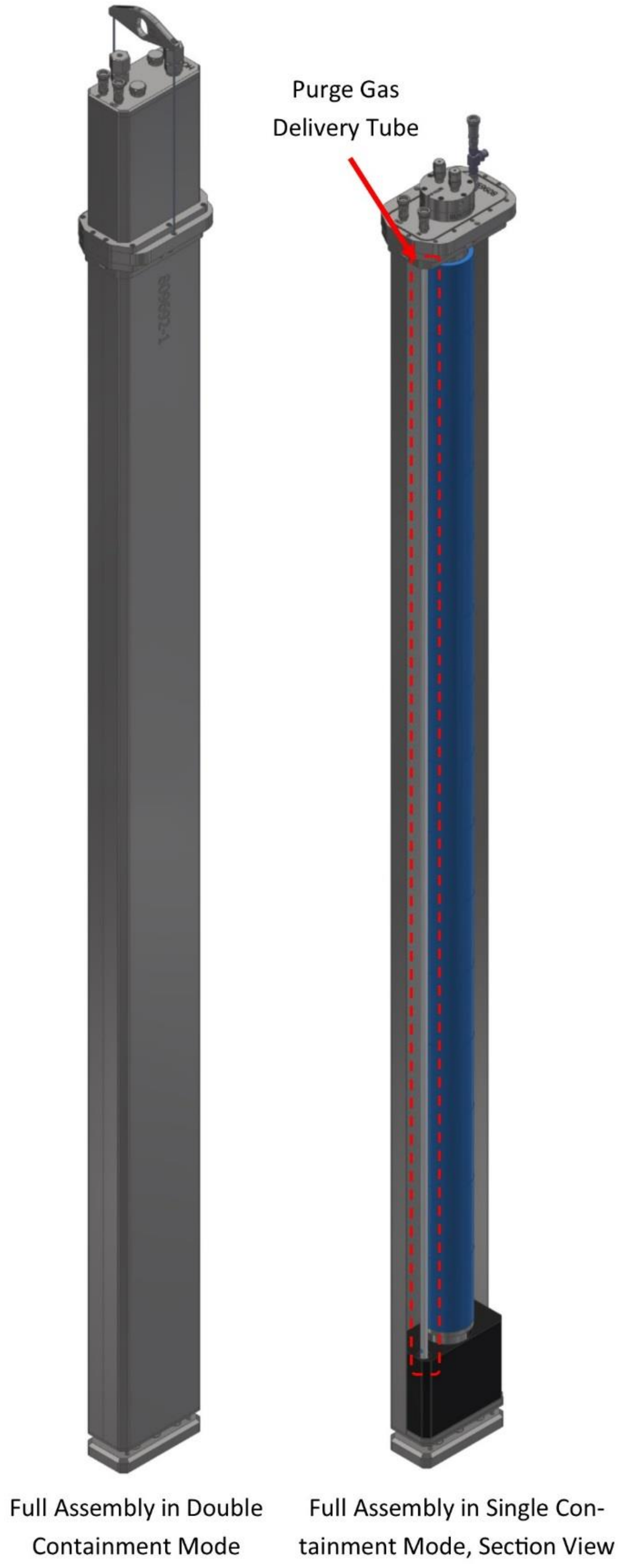


Figure 3. Secondary Can, Hood, and Primary Pipe Overview.

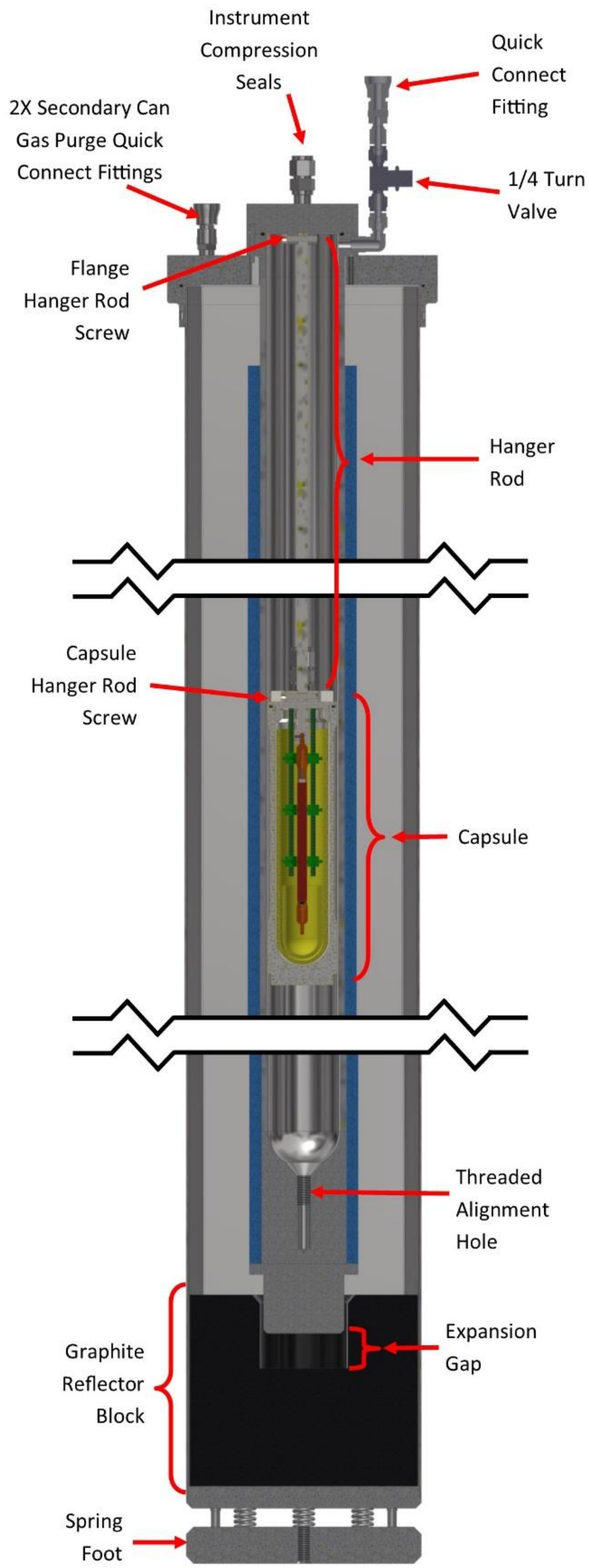


Figure 4. Final Assembly Section View, Single Containment Mode.

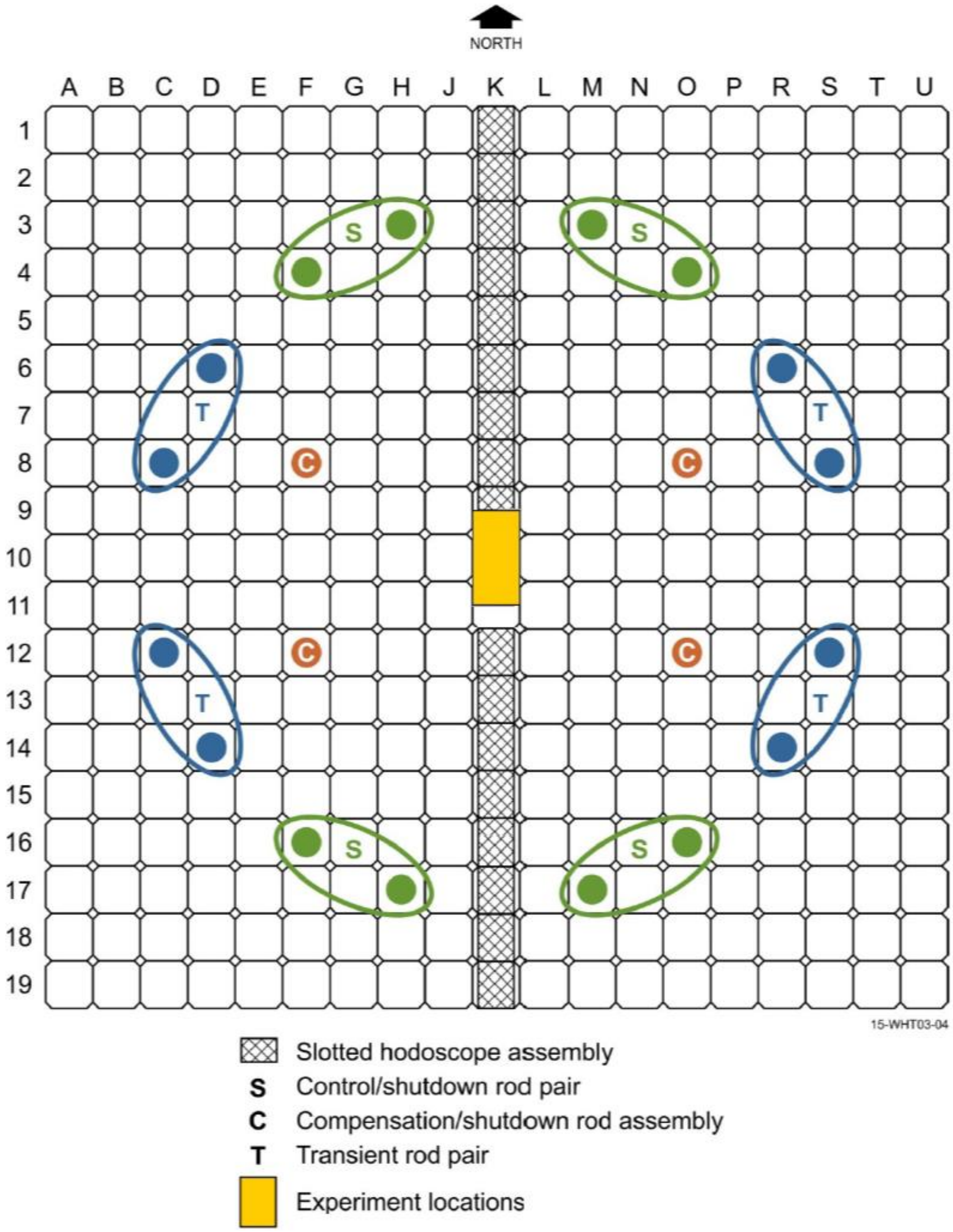


Figure 5. MARCH Full-Slotted Core Map.

3. SETH MODULE

The Separate Effects Test Holder (SETH) is a small titanium alloy capsule that enables rodlet-scale fuel irradiations in inert gas. SETH enables transient irradiations of various "centimeter-scale" fuel specimens for separate-effects tests such as melt progression studies, phenomena identification, and in-situ properties measurements. The titanium alloy SETH capsule is fabricated more affordably by direct metal laser sintering (DMLS) (a world first use for irradiation capsules) and is outfitted with off-the-shelf hardware; this combination creates a well-placed tool for timely and cost-effective science-based irradiations. The first modern fueled irradiations in TREAT were performed using SETH on small Pressurized Water Reactor (PWR) rodlets supported under the ATF program. This five-capsule campaign successfully made measurements for core-to-specimen energy coupling by multiple methods including a world first use of multi-spectral pyrometry in-situ [4], commissioned several pieces of experiment support systems at TREAT (including a modern data acquisition system), and demonstrated functionality of the fuel motion monitoring system and neutron radiography for ascertaining the timing and state of fuel disruption. See Figure 4 (above) for a rendering of SETH in BUSTER. See Figure 6 for an overview of the SETH capsule design.

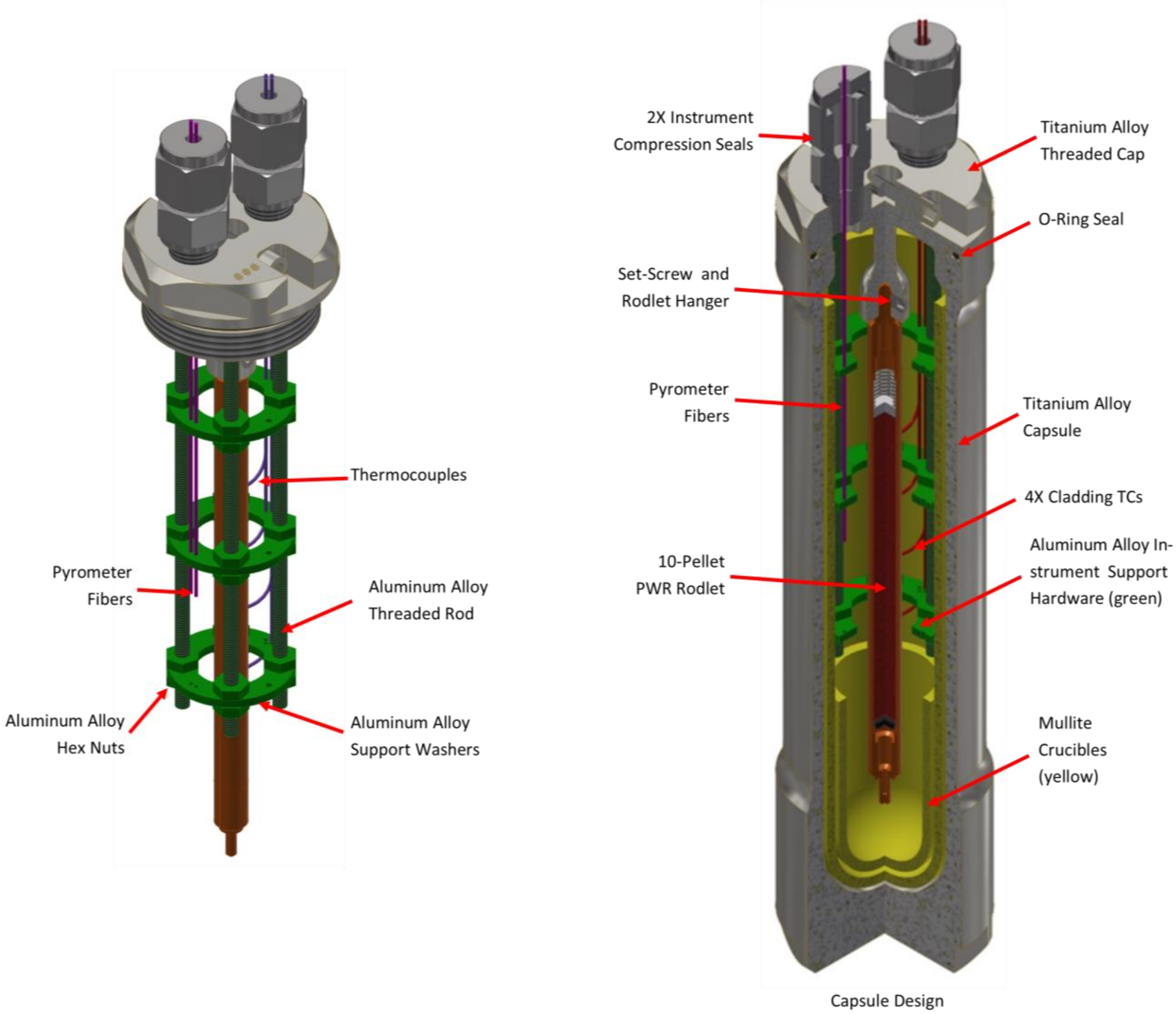


Figure 6. Overview of SETH Capsule.

Following its successful commissioning, more SETH capsules were irradiated, including a capsule half filled with water to ascertain the water moderation effect on specimen fission rate, a calibration test with Nuclear Thermal Propulsion (NTP) fuels, and an ongoing campaign studying the fuel meltdown effects for ATF designs including U_3Si_2 fuel pellets and SiC/SiC composite cladding. The Department of Energy (DOE) Nuclear Energy University Partnership program is also supporting an adaptation of the

SETH capsule with a heat-sink ceramic pellet holder for thermal gradient cracking irradiations and model benchmarking of the same phenomena. The pellet heat sink holder design, termed the Dry In-pile Fracture Test (DRIFT, see Figure 7) is also presently under adaptation to house novel fuel specimens proposed for use in Micro-Reactor fabricated by advanced manufacturing.

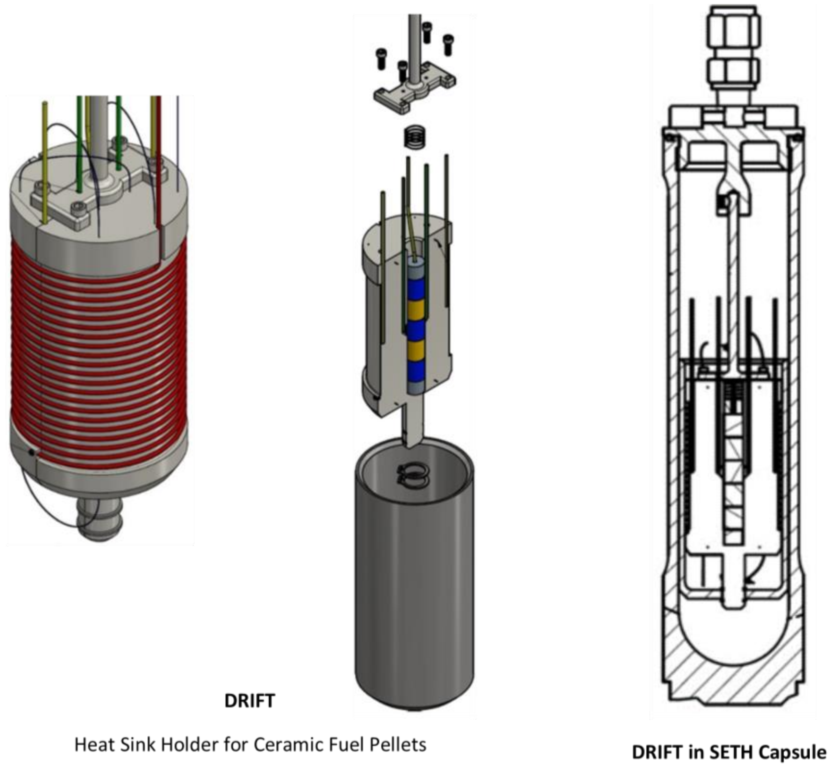


Figure 7. Overview of DRIFT Specimen Holder in SETH capsules.

4. M-SERTTA MODULE

The MARCH Static Environment Rodlet Transient Test Apparatus (M-SERTTA) is a modified version of SETH with additional instrumentation and expansion volume to enable pressurized water testing of Light Water Reactor (LWR) rodlets. M-SERTTA is currently being assembled for its first irradiations in 2019 and is expected to be a mainstay in the ATF research program. A few capsules are presently under final assembly for irradiations to fully commission the M-SERTTA capability using fresh UO_2 in zirconium alloy rodlets. Shortly thereafter, pre-irradiated rodlets, which are slated to be discharged from an ongoing ATF irradiation campaign in the Advanced Test Reactor, will be assembled into M-SERTTA capsules at the Hot Fuel Examination Facility (HFEF) and subsequently irradiated in TREAT.

The M-SERTTA lid is approximately the same size as the capsule itself. This expansion volume is the principle modification which enables water-environment testing. While the capsule lid is designed to accommodate pressure increases during transient testing, an integral burst disc on the top of the lid enables M-SERTTA to relieve pressurize into the BUSTER pipe in the event of an unexpected pressure rise. A small commercially available pressure transducer is placed on top of the lid to monitor internal capsule pressure. Three compression seal fittings for instrument lead penetrations are also placed on top of the capsule lid; enabling up to 15X 1mm instrument leads to penetrate the capsule. A hanger rod interface like that used for SETH connects to a closure flange which is compatible with the existing BUSTER pipe. See Figure 8.

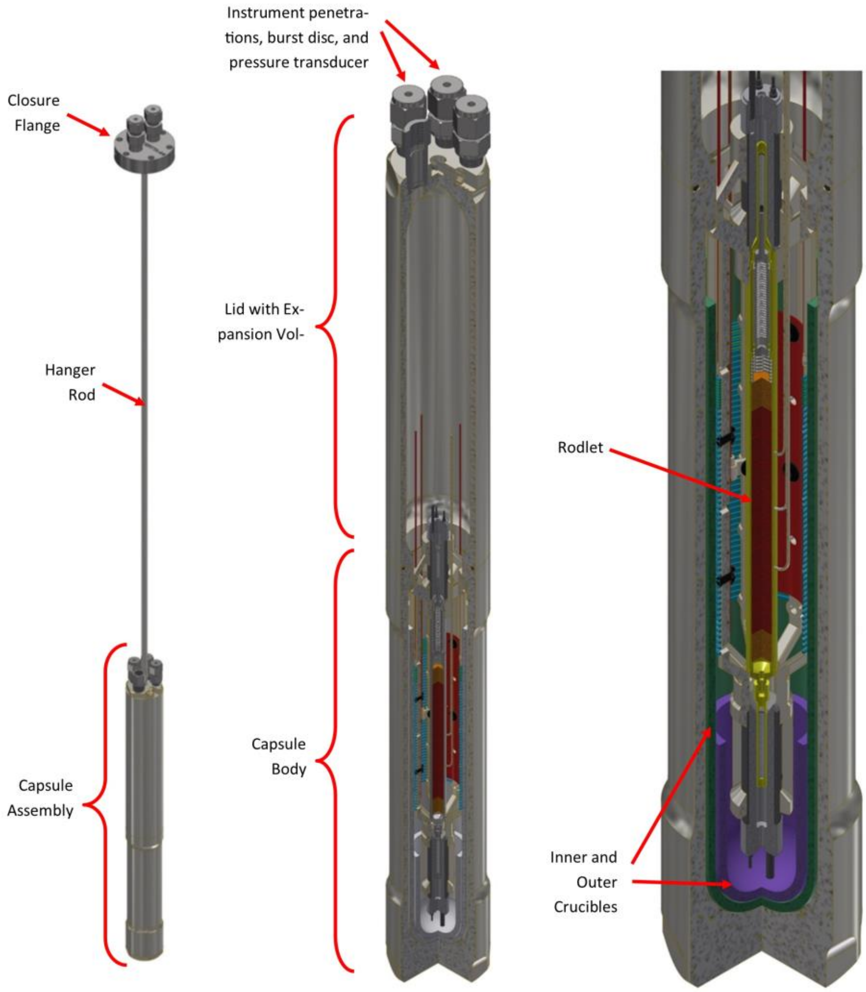


Figure 8. M-SERTTA Module Overview.

The M-SERTTA rodlet and instrumentation package are supported from a skeleton-frame holder suspended from the bottom of the lid with small screws. This holder can support several instruments and be easily configured for different testing purposes. The present design is arranged to support Reactivity Initiated Accident (RIA) testing of a ten pellet rodlet at typical pressurized water reactor diameters. The rodlet design is based on an established approach where an internal bellows in the upper plenum deforms as pressure increases, thus moving a ferritic wire downward so that Linear Variable Differential Transformer (LVDT) instrumentation can detect pressure change. Similarly, an encapsulated ferritic wire is attached to the bottom cladding end cap so that an LVDT can detect cladding elongation. A few thermocouples (TC) are attached to cladding surfaces by spot welding. An optical fiber also views the cladding surface for fast-response non-contact pyrometry. Both cladding temperature measurement approaches were successfully employed in the SETH capsule, although further experience, both in lab and reactor environments, will be needed to fully develop high confidence data in water environment testing. Two semi-cylindrical metal plates are also fastened to the frame on either side of the rodlet so that change in capacitance between them can be correlated to water density for boiling detection. These plates are coated in a high temperature polymer to minimize noise that would otherwise arise from conductive contact with water. Lastly, a small diameter electric cable heater and TCs are wrapped around the instrument holder frame to enable water temperature to be elevated prior to transient initiation. A cross section of the specimen/instrument can be seen in Figure 9.

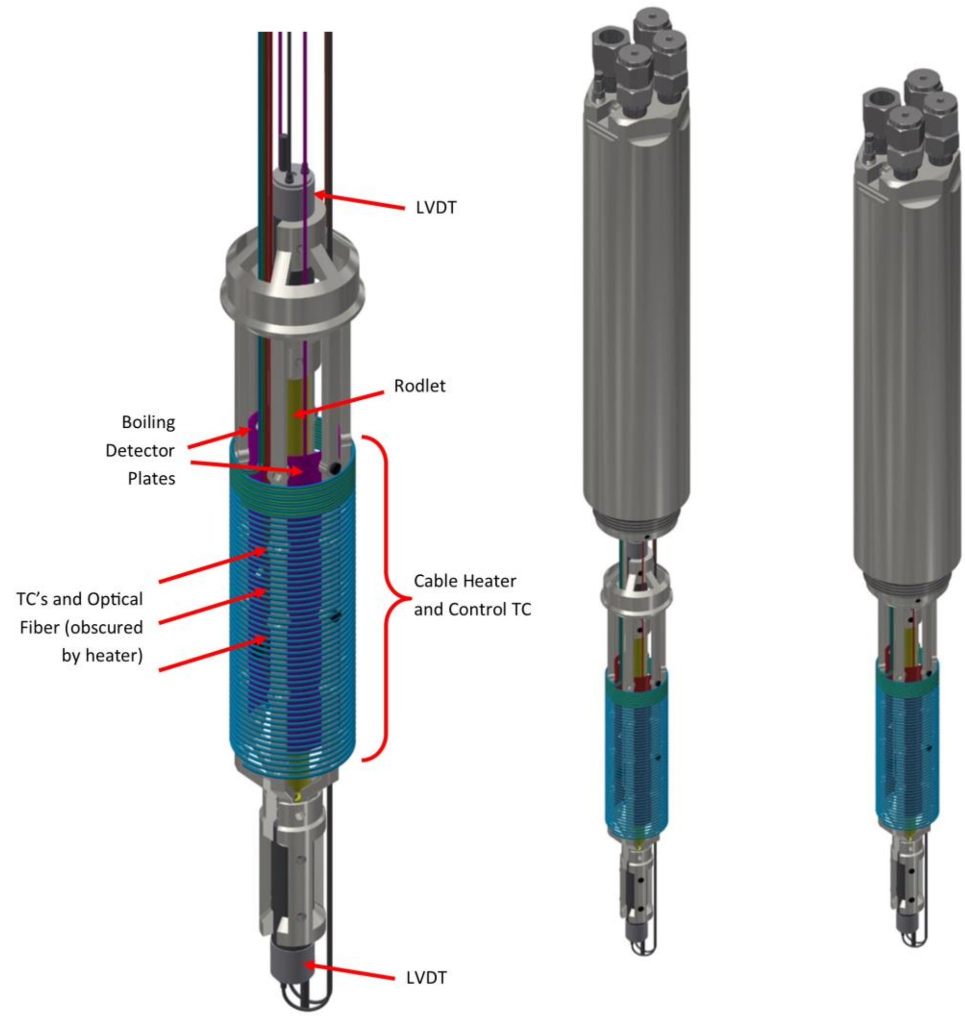


Figure 9. M-SERTTA Instrument and Specimen Holder Overview.

Another adaptation of M-SERTTA is presently under final preparation for first irradiations in winter 2019. This configuration is designed to gather data for transient nuclear-heated Critical Heat Flux (CHF) in support of an enhanced understanding of this crucial thermal hydraulic phenomenon (which is known to be markedly different under transient nuclear conditions). The so-called CHF-SERTTA tests use a borated stainless-steel rod where heat deposited by ^{10}B neutron capture and alpha particle ejection drives the rod into CHF. An adapted sensor package includes pyrometer temperature sensing inside of the rod, larger boiling detector plates, and acoustic boiling detection via accelerometer to focus in-pile data on the CHF behavior. Ultimately, these tests will pave the way to fueled CHF-centric test campaigns, but the present nuclear-heated surrogate approach enables strategic removal of complicating phenomena (e.g., pellet cladding contact conditions) and alternate instrument approaches (internal pyrometry) to help elucidate this important hydraulic behavior in a reactor environment. Adaptations of the CHF-SERTTA design are also under consideration with advanced fuel developers where borated surrogates can be used to investigate the CHF effects of non-cylindrical geometries. See Figure 10.

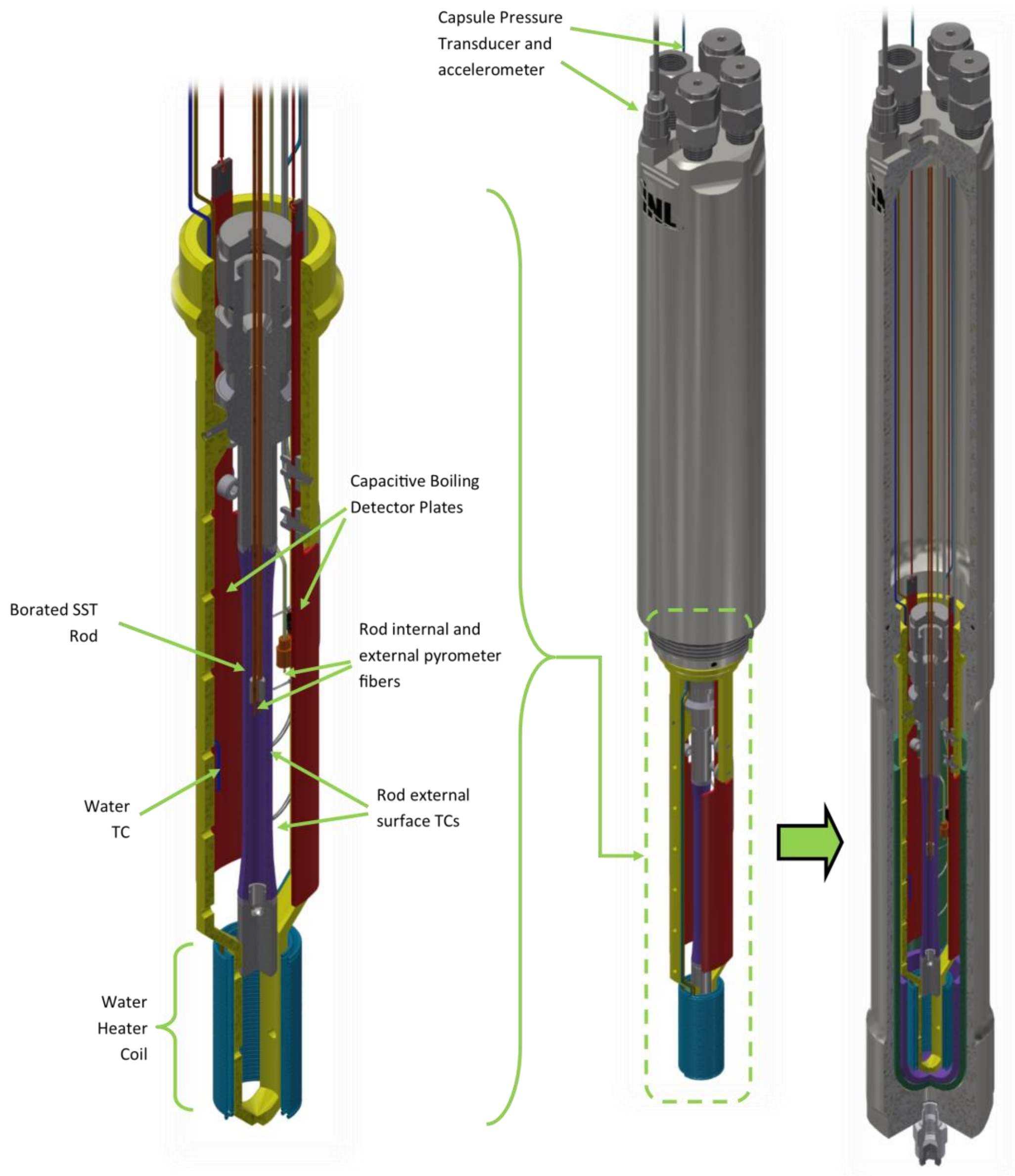


Figure 10. CHF-SERTTA Design and Instrument Package Overview.

5. OPTICAL ACCESS MODULES

TREAT's early history included a high-speed film camera which ascertained fuel performance through a periscope in the reactor's concrete shielding [1]. The historic handling casks for these unique experiments, however, were disposed long ago. Noting that modern fiber optics should enable small form factors in optical deployments, MARCH modules have been developed which exploit optical paths for in-situ data. Problems with fiber darkening have plagued the use of optical fibers in other test reactors but are well-suited in TREAT; this is due to the short exposure time and irradiation damage as demonstrated by the successful use of pyrometry in the inaugural SETH tests. The SIRIUS capsule was developed with an integral optical path in the capsule lid to enable repeated high temperature measurement of NTP fuels. Here, specimens were repeatedly ramped within seconds and held at temperatures exceeding the calibrated range for any known thermocouple type. An optical fiber is held in the capsule lid ~38 cm from the specimen and integrated with a magnifying lens, alignment/adjustment features, and high temperature sapphire sight glass to protect it from overheat during irradiation. This instrument assembly is referred to as the "pyroscope" and successfully measured specimen temperature during the inaugural SIRIUS-1 experiments performed in summer of 2019, paving the way for future use and temperature measurements up to 3000°C. See Figure 11 for an overview of the SIRIUS capsule.

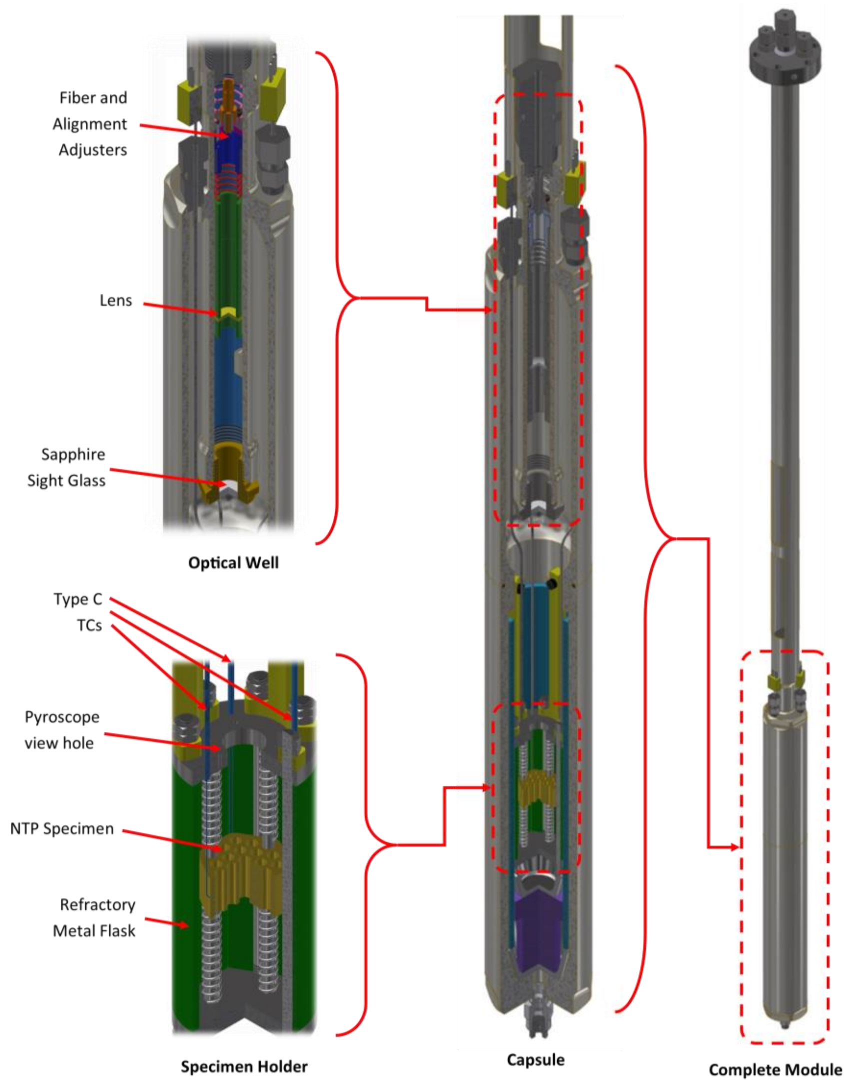


Figure 11. SIRIUS-1 Module Overview.

The capsule's optical well could conceivably use any optical probe which fits in its 20 cm long X 1.7 cm diameter. The high temperature sight glass can be omitted when test conditions allow, and the compression seal on the top can be used for other lead types. One promising technology for enhanced topical access in TREAT capsules is the use of a small bundle of thousands of fibers for image transmission. Commercially available as fiberscopes, these bundles can transmit 100,000 pixels to camera receivers with 1000 frame/sec capability. A lab-based project was undertaken to demonstrate the use of a fiberscope within MARCH geometric constraints which showed that small fiber bundles can be used to both transmit illumination into the capsule and receive high frame rate images. This effort also showed that fiber bundles can pass through hermetic penetrations and that they can be cleaved, prepared, and rejoined with small reusable connectors with little loss in image quality (both of which are unique and highly important considerations in lead management for TREAT experiments). Future irradiation capsule designs may make use of these advanced optical access methods for in-situ observations of coolant phase change, fuel melt/damage progression, speckle pattern digital image correlation, laser interferometry, infrared thermography, and other viable optical data strategies.

6. HIGH TEMPERATURE MODULES

The heater module can be installed in BUSTER to enable electrical heat up to 700°C prior to irradiation or to create longer duration temperature-controlled histories during irradiation. The heater module essentially consists of an Incoloy-clad tubular heater wrapped in a helix, with attached thermocouple for overtemperature protection, which mounts on an upper ring to enable smaller test modules to path through (3.8 cm inner diameter). To date, one heater module has been constructed (with a second underway) and used successfully. The first fueled irradiations using the heater module are planned for 2020 using the Characterization-scale Instrumented Neutron Dose Irradiation (CINDI) module. The CINDI module consists of a few Swagelok ® capsules, each with thermocouple temperature monitoring and the ability to house several 5mm diameter disk-like specimens, arranged in a vertical hanging structure for elevated temperature irradiation. The CINDI capability essentially transforms MARCH into a tube furnace surrounded by a reactor in order to support low-dose irradiations (up to ~1E15 fissions/gram) in a well-controlled and monitored temperature environment for post irradiation characterization and development of lower-length-scale fundamental fission damage models. One recently awarded Nuclear Science User Facility (NSUF) project also plans to use the CINDI design with irradiations starting in 2021. See Figure 12 for an overview of the CINDI test configuration.

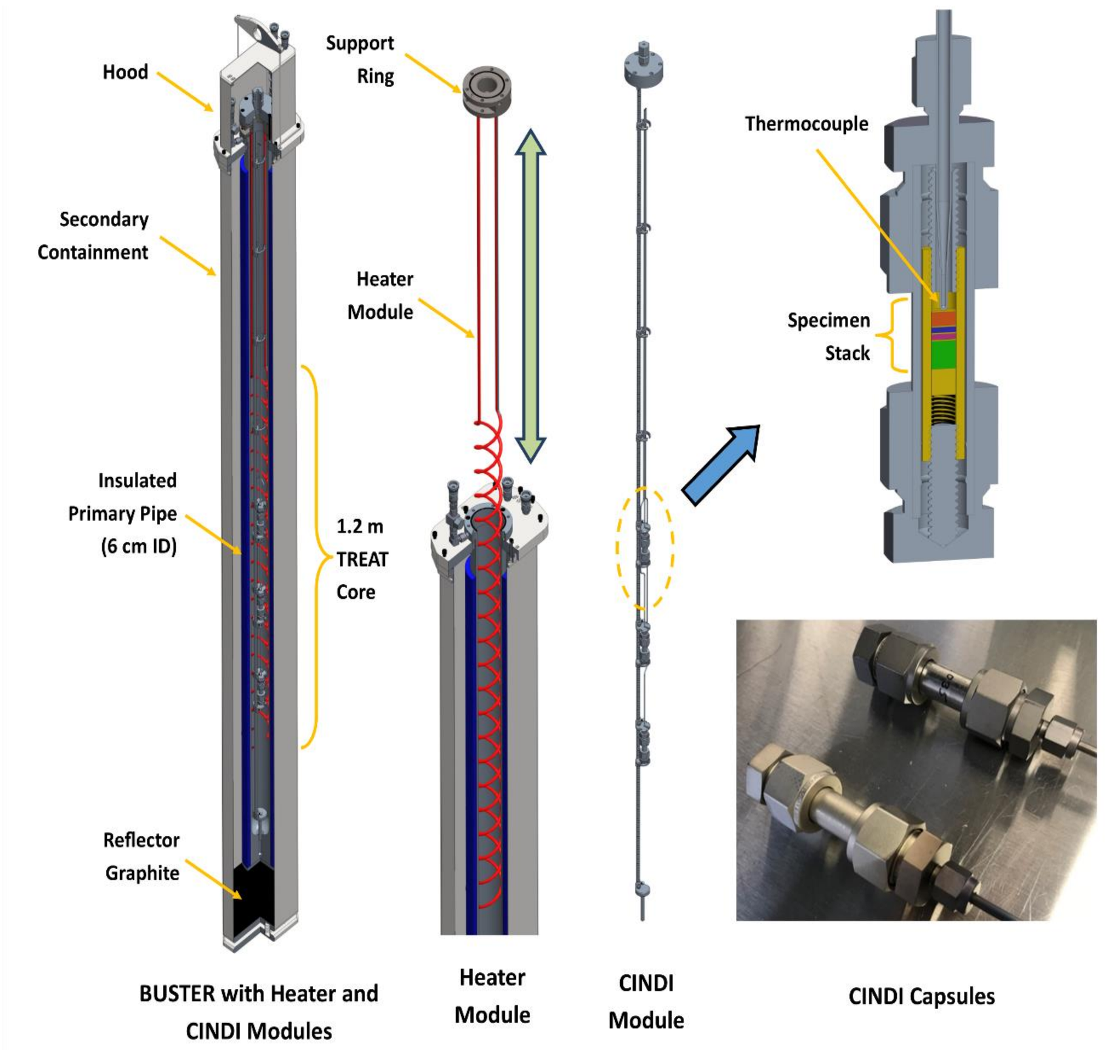


Figure 12. Overview of CINDI and Heater Module Design.

A similar approach to the CINDI design was developed for in-situ measurement of microstructural changes using Resonant Ultrasound Spectroscopy – Laser (RUSL) which infers changes in a specimen's elastic modulus during irradiation (these changes are indicative of grain recrystallization or metallurgic phase changes). A fiber delivers modulated laser energy to the base of a thin specimen supported as a cantilever beam. This excites the first flexural mode of the beam while a second fiber, near the tip of the beam, measures oscillations in light reflected from its surface. Changes in the modulus of elasticity are monitored by exciting the beam and measuring the resonant frequency [5]. The first RUSL irradiation was performed in TREAT in mid-2019 and demonstrated that the same measurement could be made both in-reactor and out-of-reactor on a highly-textured copper specimen where the heater module was used to elevate temperature and cause specimen recrystallization. This effort showed the measurement method to be viable for in-reactor use. The RUSL capsule was suspended from a threaded rod within the heater module and supported by an unsealed disc resting atop the heater module flange (nominal containment was not required since the specimen was unfueled). Minor modifications to the RUSL design are under development for future irradiations focused toward fission-assisted phase transformation behavior in metal fuel alloys. See Figure 13 for a representation of the RUSL design.

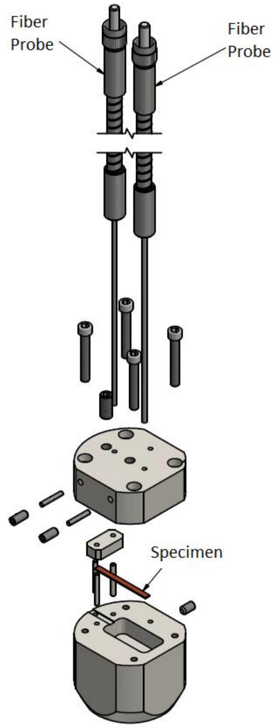
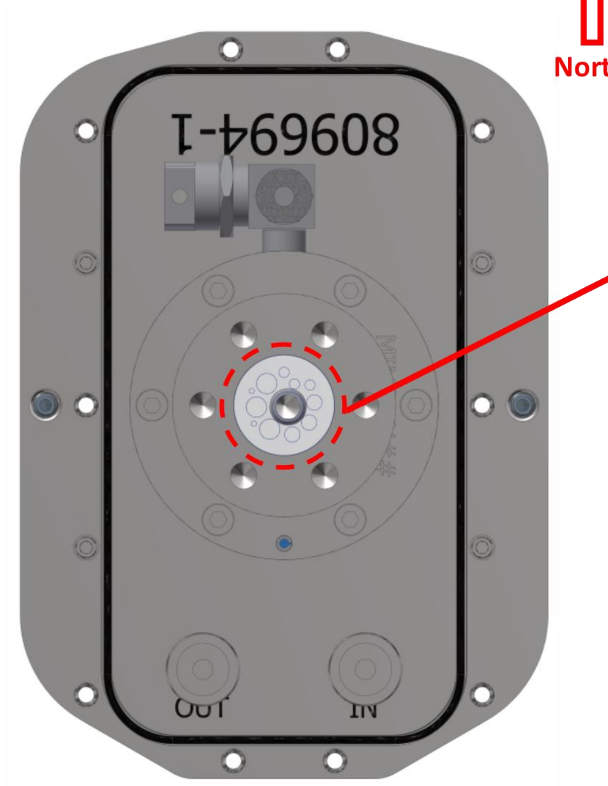
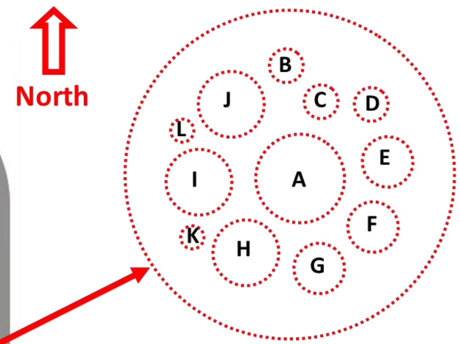


Figure 13. Exploded View of RUSL Capsule.

7. MIMIC-N

The Modular Instrumentation and Material Irradiation Capability (MIMIC) series of irradiations enable testing of sensors and measurement methods in a nuclear environment. MIMIC is paired with analysis strategies that dramatically simplify experiment safety analysis for most sensor materials by populating the nuclear reaction rates for practically every material (for which there is nuclear cross section data) in a way that can be scaled by reactor power/energy to find limiting parameters. The reaction rates that support this type of experiment safety analysis can be found in reference [3]. This strategy supports an ongoing series of irradiations for neutron sensors (referred to as MIMIC-N), where a cluster of 12 aluminum alloy guide tubes enable various sensors to be irradiated, including activation-wire dosimetry (using TREAT's standard dosimeter holder), self-powered neutron detectors, micro-pocket fission detectors, small fission chambers, and TCs. A larger aluminum structural tube surrounds these sensors and supports a thick titanium sleeve. This sleeve is designed to give similar reactivity worth as the M-SERTTA capsule and, hence, serves as its neutronic equivalent dummy for mandatory trial transients. This strategy gives a multi-sensor measurement of neutronic conditions for transients performed on fueled capsule. This capsule simulator is replaceable with sleeves of differing lengths, thicknesses, or materials for matching reactivity worth to other future MARCH modules. See Figure 14 and Figure 15 for a top view of the sensor locations and overview of the MIMIC-N module, respectively.





Position	Nominal Inner	Nominal Inner
A	7.75	0.305
B	3.25	0.128
C	3.25	0.128
D	3.25	0.128
E	4.85	0.191
F	4.85	0.191
G	4.85	0.191
H	6.43	0.253
I	6.43	0.253
J	6.43	0.253
K	1.68	0.066
L	1.68	0.066

Figure 14: MIMIC-N Sensor Guide Tube Diameters.

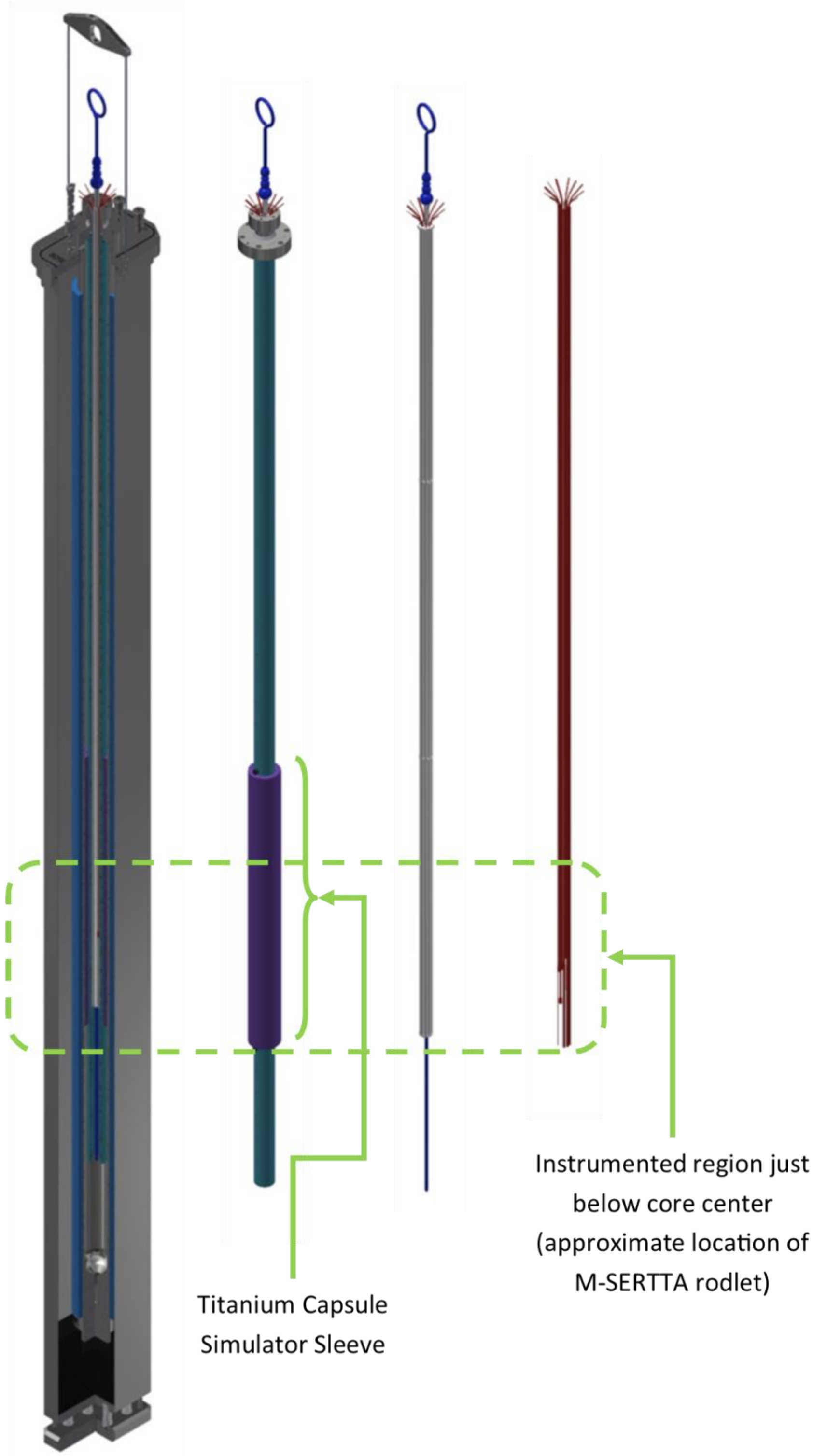


Figure 15. MIMIN-N Module Overview.

8. THOR

The Temperature Heat-sink Overpower Response (THOR) module uses a solid metal heat sink bonded to fuel rods with sodium for time-dependent shaping of fuel temperature histories. The heat sink material can be selected from a few metals with different thermal diffusivities (e.g., titanium, stainless steel, nickel 200) to affect different heat transfer coefficients from the specimen. When used in concert with TREAT's remarkable transient shaping capabilities, THOR tests can approximate the heat transfer conditions and specimen temperature response of practically any reactor system during the heat-up phase of postulated transients. THOR irradiations naturally have high relevance to Sodium Fast Reactors (SFR) and other liquid-metal cooled fuel systems, but can also be useful for testing any specimen type where cladding/chemical interactions are specifically targeted (e.g., pulse testing of LWR for fuel/cladding mechanical interaction where the complication of water boiling otherwise complicates data interpretation). DOE-funded irradiation campaigns are planned for first irradiations with advanced SFR metal fuels in THOR starting in 2020. Another recently awarded NSUF project also plans to use the THOR design with irradiations starting in 2021, where oscillation of transient power in the time domain and phase response of temperature instrumentation will be used to determine radial thermal conductivity of irradiated fuels. Other advanced fuel development projects are considering the use of THOR for SFR oxide fuels and power to melt studies of enhanced thermal conductivity fuel composites.

In THOR, electric heaters elevate the temperature of the heat sink to at least the sodium melting point pre-transient and can be used to elevate the starting temperature further to represent ambient conditions prior to the accident initiation. Several small commercial compression seals surround the lower part of the capsule lid to permit passage of the cable heaters and several radial temperature measurement instruments in the heat sink. A single larger compression seal at the top allows the rodlet to pass through in a small test train with desired instruments for measuring fuel/cladding elongation, rod internal pressure, acoustic detection of cladding failure, and temperature measurements in the fuel centerline, cladding, and sodium annulus. This layout is conducive to reconfiguration of the specimen/instrument package as well as hot cell-based loading when pre-irradiated specimens are used. A small valve and capsule pressure transducer permit inert gas purging and leak testing of the capsule. See Figure 16 for an overview of the THOR capsule with Experiment Breeder Reactor-II (EBR-II) length legacy fuel pins. Axial dimensions of THOR can be scaled to accommodate shorter rods as needed.

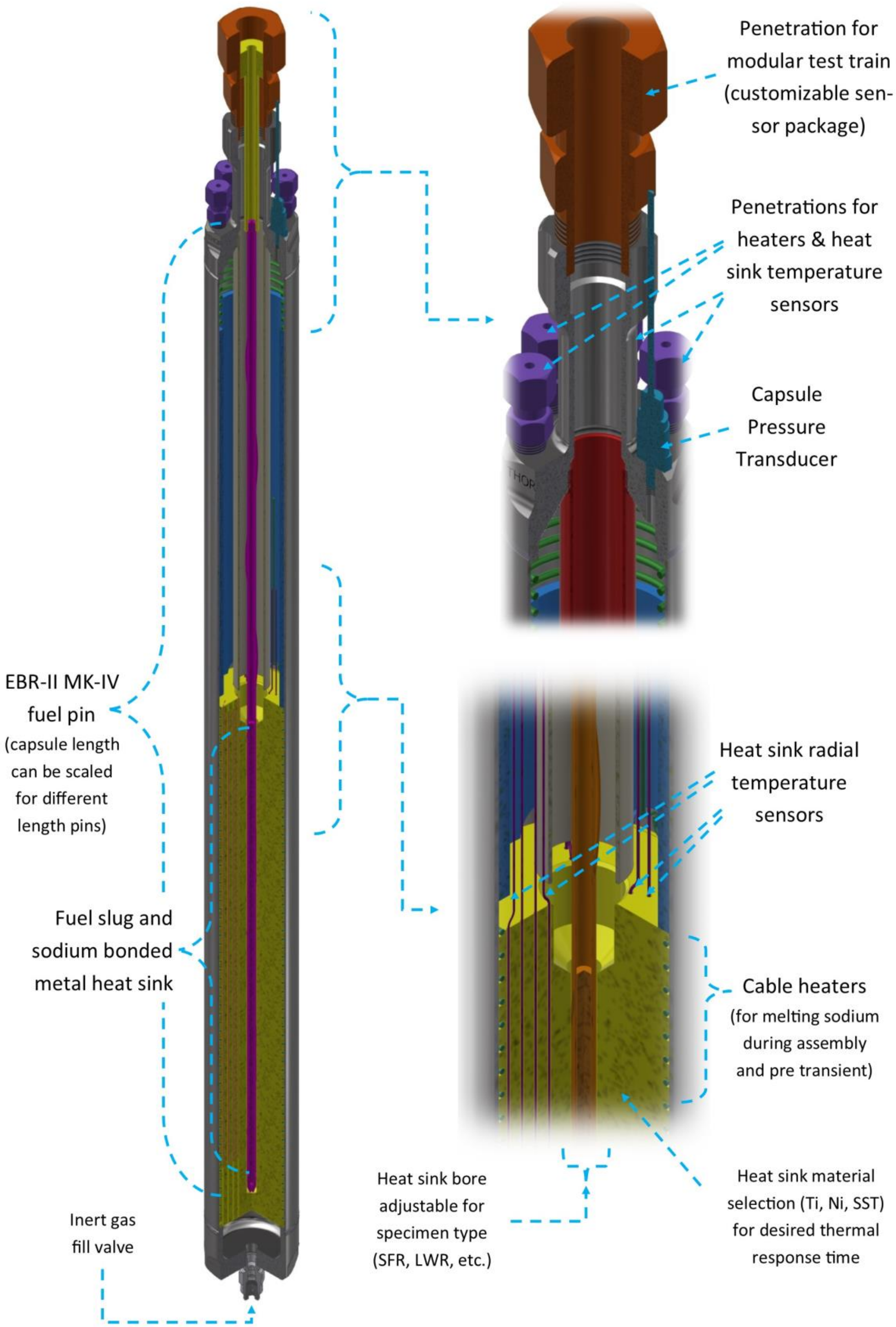


Figure 16. Overview of THOR Capsule.

9. LOCA-SERTTA

The M-SERTTA module is expected to be a highly utilized capability for RIA testing of LWR rodlets and other water-cooled reactor specimens. M-SERTTA transients are designed so that water phase change events (notably, CHF and subsequent rewet/quench) are achieved passively through heat transfer physics. The ability to actively trigger these phase change events, however, can be highly useful for simulated Loss of Coolant Accidents (LOCA) and other conditions of interest. To enable this type of testing in an affordable MARCH-based package, a modification to the SERTTA capsule is envisioned where a large expansion tank is attached to the capsule bottom and an electronically-triggered burst disc rupturing device is used to drive depressurization of the capsule or injection of cold water (depending on the starting pressure and water volume conditions in the capsule and expansion tank). The resulting "LOCA-SERTTA" device requires little modification to the M-SERTTA design for the upper capsule region which will hasten the ability to deploy it. LOCA-SERTTA is presently under investigation to determine whether it is an adequate method for this type of fuel safety research in TREAT or if larger loop-like capabilities (which will not likely fit within the MARCH system) are ultimately needed. See Figure 17 for conceptual renderings of the LOCA-SERTTA module.

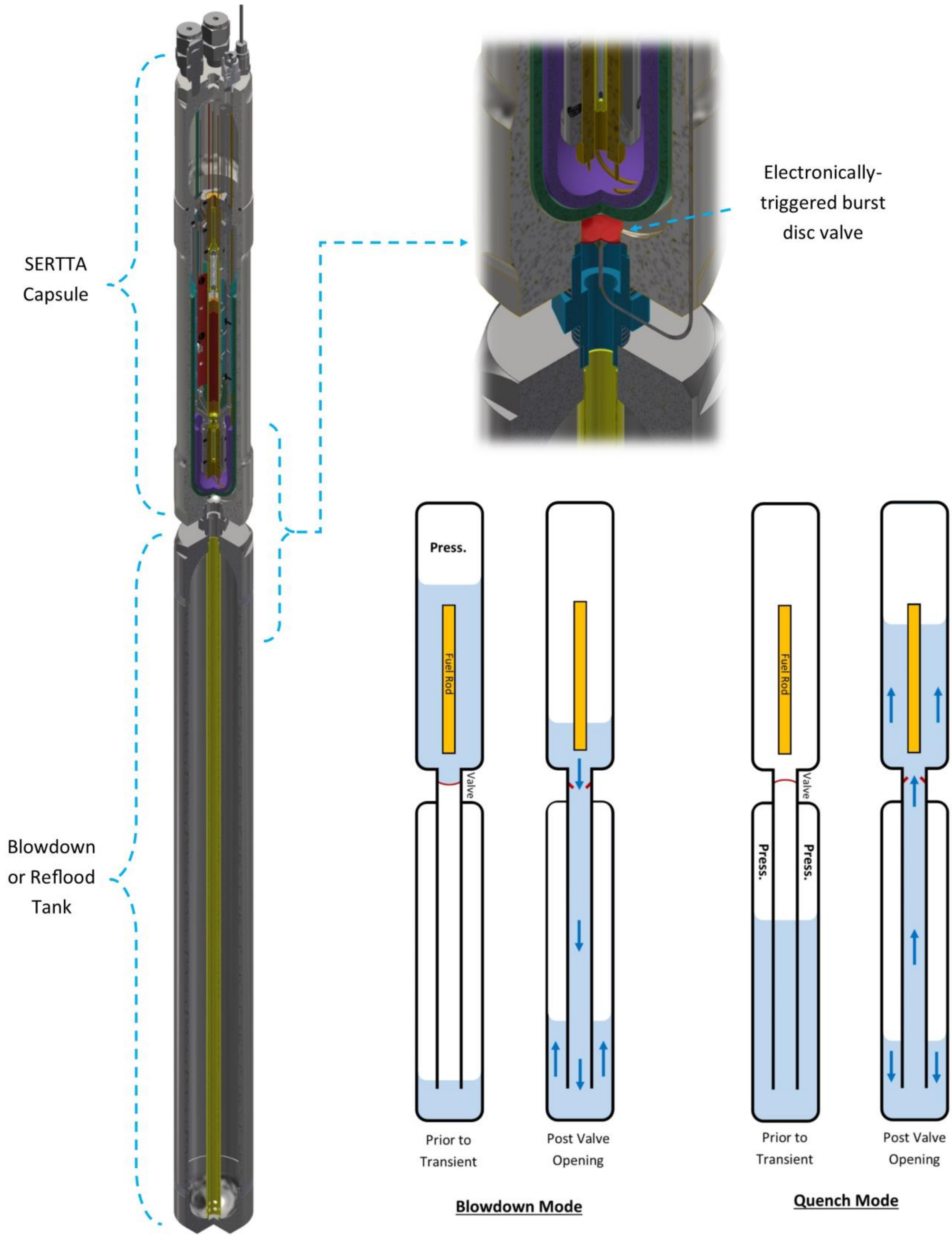


Figure 17. LOCA-SERTTA Design Rendering and Operation Mode Schematic.

10. BIG-BUSTER

While the clever use of compact instrumentation and geometric intricacy, only achievable with additive manufacturing, have enabled a great deal of experimental capability to be housed within BUSTER's primary pipe, it is reasonable to expect that some future experiments will not be able to fit within this envelope, especially when engineering scale fuel and bundle performance are of interest. In these cases, a more classical approach may be used (where the experiment's primary containment and specimen-supporting boundary are one and the same), but the prospect of a larger BUSTER is also considered in order to afford the value of the MARCH system's "capsule in containment" approach to larger test articles. To this end, a neutronics evaluation [6] and conceptual level mechanical design have been performed to show that TREAT is both neutronically and mechanically capable of valuable irradiations in the so-called "Big-BUSTER".

The primary constraint limiting the present BUSTER is the 10 cm width of its rectangular secondary canister which, accounting for clearances, thermal insulation, and primary pipe wall thickness, renders a useable 6 cm diameter for test modules. It is viable to place a Big-BUSTER between four existing graphite half dummies and, making use of the chamfered corners on the adjacent fuel assemblies, create a cylindrical secondary can with 15 cm outer diameter and 10 cm primary pipe useable inner diameter. This concept has a small neutronic penalty and does not require new fuel/dummy assemblies while more than doubling the useable test volume. The primary drawback with the Big-BUSTER is design and fabrication of several small interface items (e.g., storage hole support fixtures, cask alignment sleeves, cask shield ring adapters) which, taken collectively, will require a persistent level of effort to deploy. New design efforts, including structural analysis and core neutronic characterization will also be needed to enable Big-BUSTER deployment. Although no present experiment campaign explicitly requires Big-BUSTER, it should be noted that, approximately one year prior to TREAT's restart, none of the concerned experiment programs intended to use the MARCH system either. The foundational work needed to deploy Big-BUSTER is highly recommended as a forward-looking investment in TREAT's experiment capability suite. See Figure 18 for renderings of the Big-BUSTER concept.

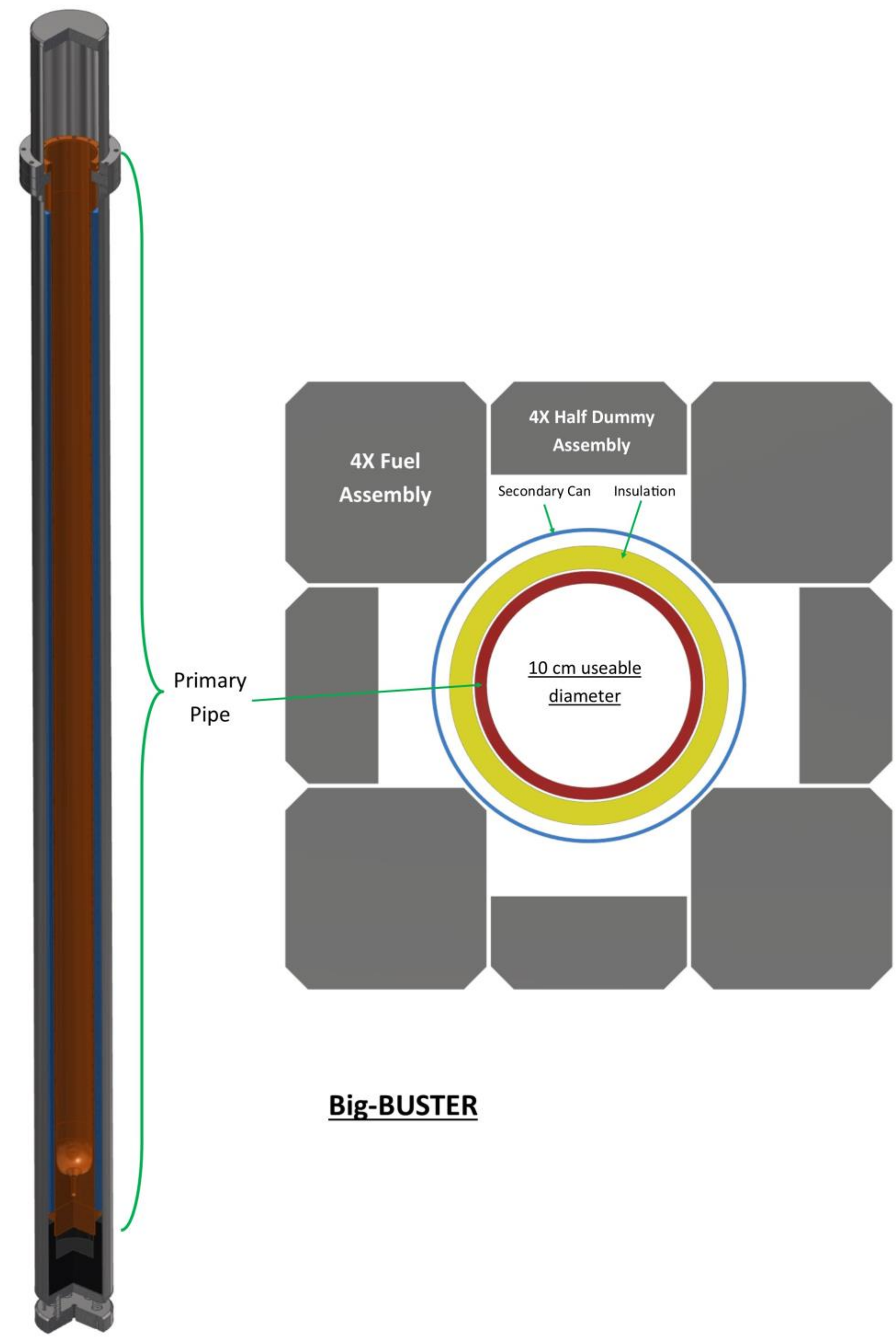


Figure 18. Conceptual Rendering of Big-BUSTER.

11. SUMMARY AND CONCLUSIONS

At the time this report was written, the MARCH modules described herein were in various states of maturity. Table 1 below summarizes the state of these modules and future plans for those not yet fully deployed.

Table 1. Summary of MARCH Module Status and Plans.

Module	Conceptual Design	Final Design & Engineering	Demonstrated in Reactor
BUSTER	Complete	Complete	Complete
SETH	Complete	Complete	Complete
M-SERTTA	Complete	Complete	Fall 2019
CHF-SERTTA	Complete	Complete	Winter 2019
Preirradiated M-SERTTA	Underway	Underway	Fall 2020
SIRIUS-1	Complete	Complete	Complete
Fiberscope	Under evaluation	—	—
Heater Module	Complete	Complete	Complete
CINDI	Complete	Complete	Winter 2019
RUSL	Complete	Complete	Complete
MIMIC-N	Complete	Complete	Complete
THOR	Complete	2020	2020-2021
LOCA-SERTTA	Under evaluation	—	—
Big-BUSTER	Under evaluation	—	—

Development of the MARCH system has and will continue to support and attract experimenters from DOE, industry, and academia to develop experiment-specific modules/adaptations. Through its adaptable design strategy, the MARCH system supports irradiation missions ranging from phenomena identification, screening/scoping, science focused with selected-physics, and semi-integral scale fuel safety research. In this way, the MARCH system enables research capabilities able to provide pioneering data sets for modern model validation, generate phenomena identification data to sharpen fuel research focus, and advance the state of nuclear safety by cultivating broad interest in transient science. The MARCH project is a success story for how a simple and innovative idea can be cultivated under institutional research funds to become a nexus of nuclear science.

12. REFERENCES

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