USERGUIDE

A PRACTICAL GUIDE TO THE TRANSIENT REACTOR TEST FACILITY (TREAT)

Idaho National Laboratory

VISION

Change the world's energy future.

MISSION

Provide state-of-the-art transient irradiation capabilities and apply expertise to the startup and operation of advanced reactors.

VALUES

We will accomplish the TREAT mission through safe and error-free execution, valuing operational excellence, technical rigor, and mastery of requirements.

Contents

1. Introduction of TREAT Reactor

The Transient Reactor Test (TREAT) facility, located at Idaho National Laboratory (INL), is a uranium-fueled, graphite-moderated, air-cooled, thermal-spectrum irradiation test facility specifically designed to evaluate the response of nuclear fuels and structural materials to accident conditions. The reactor is capable of transient power exceeding 18,000 megawatt (MW) depositing over 2,900 megajoule (MJ) of energy, with a negative temperature coefficient of reactivity as a passive safe reactor. From initial criticality in 1959, to being placed in standby in 1994, the reactor had experienced more than 6,000 startups and close to 2,900 transient operations supporting nearly 900 experiments. Until the reactor was placed in standby, the total energy release from the core was just over 2.6 million MJ.

TREAT is the world's most dynamic and flexible transient test reactor available for research and demonstration activities. Originally constructed to test fast-reactor fuels, TREAT's flexible design enables its use for testing of light-water-reactor fuels as well as other exotic special-purpose fuels, such as space reactors. The TREAT facility provides a transformational research platform linking science and engineering capabilities for the advancement of fundamental science and nuclear technology. TREAT directly couples the response of material systems to complex environments experiencing a variety of operational and off-normal transient events anticipated in nuclear reactors. TREAT experiments are performed principally to obtain data on fuel behaviors for predicting postulated accidents. These postulated accidents include loss of coolant flow, loss of coolant, reactivity-initiated power excursions, and other power-cooling mismatch conditions. The experiments will typically simulate severe accident conditions that may include some or all the following phenomena:

- Fuel melting
- Fuel failure
- Fuel vaporization
- Movement of molten cladding and fuel
- Thermal interactions between coolant and molten fuel
- Thermal and chemical reactions between fuel and cladding, cladding and coolant, and fuel and coolant
- Freezing of molten cladding and fuel
- Propagating failure to adjacent fuel pins under conditions ranging from mild upsets to severe accidents.

TREAT's open-core design enables experiment instrumentation and real-time imaging of fuel motion during irradiation, making TREAT an ideal platform for understanding the irradiation response of materials and fuels on a fundamental level. The real-time imaging of fuel motion is achieved by the hodoscope, a system that detects fast neutrons and enables real-time evaluation of the fuel behavior within a test sample. Transient testing is an essential component of the United States and international efforts to develop robust, safer nuclear fuels, for bringing innovative reactor technologies to the market. Figure 1 shows the south view of the reactor.

Figure 1. The Transient Reactor.

It should be emphasized that TREAT should not be used like other steady state materials test reactors running at constant high power accumulating radiation damage for structural materials (often measured in displacement per atom, dpa) or burnups for fuels. While TREAT can apply extremely high power to the test materials or fuels, the power only lasts for a very short period of time, typically on the order of seconds or less than a second; thus the total dpa or burnups are negligible for the tested materials or fuels. For dpa and burnup accumulation, users are encouraged to explore the Advanced Test Reactor (ATR) at INL or similar reactors in other DOE labs.

TREAT was put on standby in 1994. Due to resurging interest in developing innovative nuclear technologies, TREAT was restarted in 2017 and is now a critical fuel and materials safety testbed, supporting all nuclear energy programs.

2. TREAT Reactor Description

2.1 TREAT Reactor and Fuel Systems

The physical arrangement of the TREAT reactor is composed of two primary features: the reactor core and the reactor structure. The reactor core consists of an array of 19 × 19 individually removable fuel and reflector assemblies with overall dimensions approximately 6 × 6 × 9 ft high and is surrounded radially by roughly 2 ft of graphite reflector. The core is once-through air cooled and moderated by graphite in the fuel assemblies and dummy reflector assemblies, with a permanent graphite reflector. A thorough description of the fuel assembly is shown below:

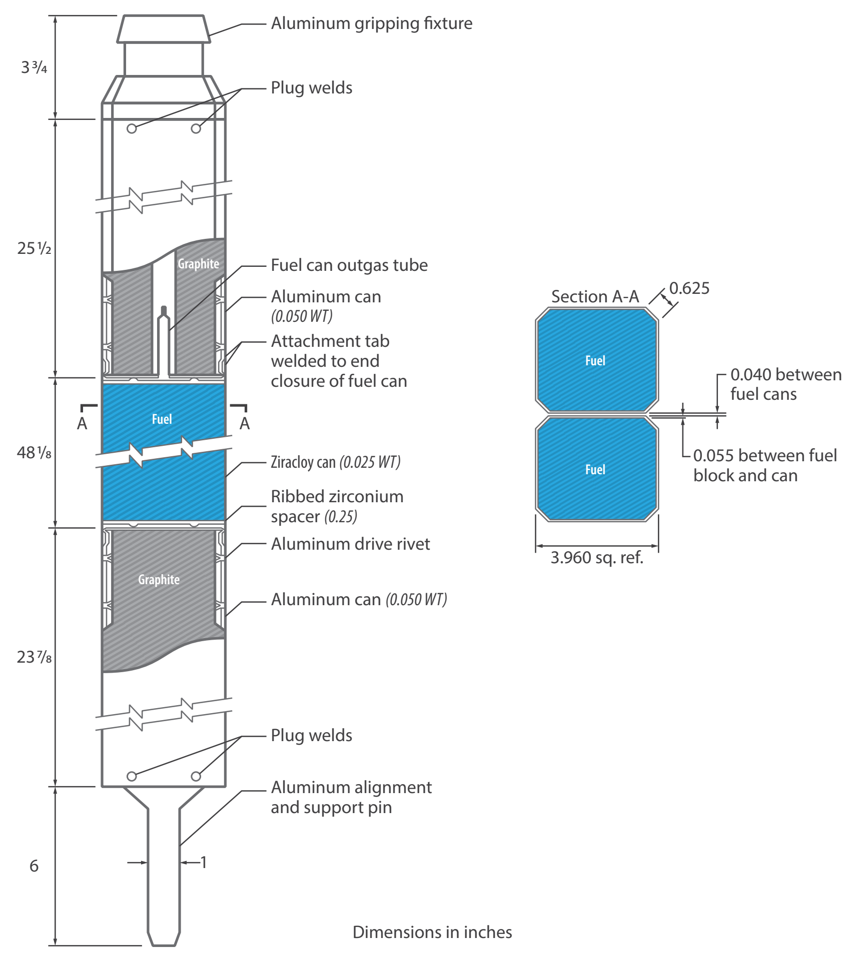


Figure 2. Standard zircaloy-clad TREAT fuel assembly.

The core has a fueled height of 4 ft, with 2 ft of axial graphite reflector above and below. The fuel is a dilute dispersion of highly enriched UO2 particles (10-micron average diameter) in graphite. The carbon-to-uranium (235U) atom ratio is 10,000:1. Experiment facilities containing individual test fuel pins, fuel-pin clusters, or other experiment designs are usually positioned along the core vertical axis at the core radial center to study fuel pin behavior under simulated accident conditions. A row of assemblies with a voided slot 2.75 in. wide, oriented on a radius from core center to the north edge of the core, permits monitoring of test loops by a fast-neutron hodoscope.

The TREAT reactor core is contained in a 3- to 5-ft thick, high-density concrete structure that provides physical support and radiation shielding. The open core design of TREAT also allows for the detailed monitoring of experiments during testing. Below are the typical operating parameters of the TREAT reactor [2,3]:

REACTOR	
Peak neutron flux	~10^{17} $n \cdot cm^{2} \cdot s^{-1}$
Maxiumu neutron fluence	~10^{16} $n \cdot cm^{-2}$
Steady state power limit	120 kw
OPERATING PARAMETERS	
Shaped Transient:	
Energy	<2,900 MJ (core dependent)
Peak power	<10,000 MW (core dependent)
Peak fuel temperature	≤600°C
Peak clad temperature	≤600°C
Minimum reactor period	0.1 sec
Cooling time to 37°C	approx. 5 hours (core dependent)
Natural Burst Transient (Self-Limited Transient Mode):	
Energy	<2,100 MJ (core dependent)
Peak power	<18,000 MW (core dependent)
Peak fuel temperature	≤600°C
Peak clad temperature	≤600°C
Minimum reactor period	0.023 sec
Cooling time to 37°C	approx. 5 hours (core dependent)
COOLANT	Air

Table 1. Operating parameters of the TREAT Reactor.

Major penetrations in this reactor structure are provided for fuel motion, diagnostics instruments (north and south faces), the neutron radiography facility (west face), reactor instrumentation (corners, south, north, and west faces), and the thermal column (east face). The top of the reactor structure includes a Rotating Shield Plug (RSP) located under removable shield blocks that provides access to the reactor core for fuel and experiment handling. The reactor structure below the core includes the grid plate, the lower air plenum for air exiting the core region, and a subpile room housing the control rod drives. The cut view of the TREAT reactor is shown below:

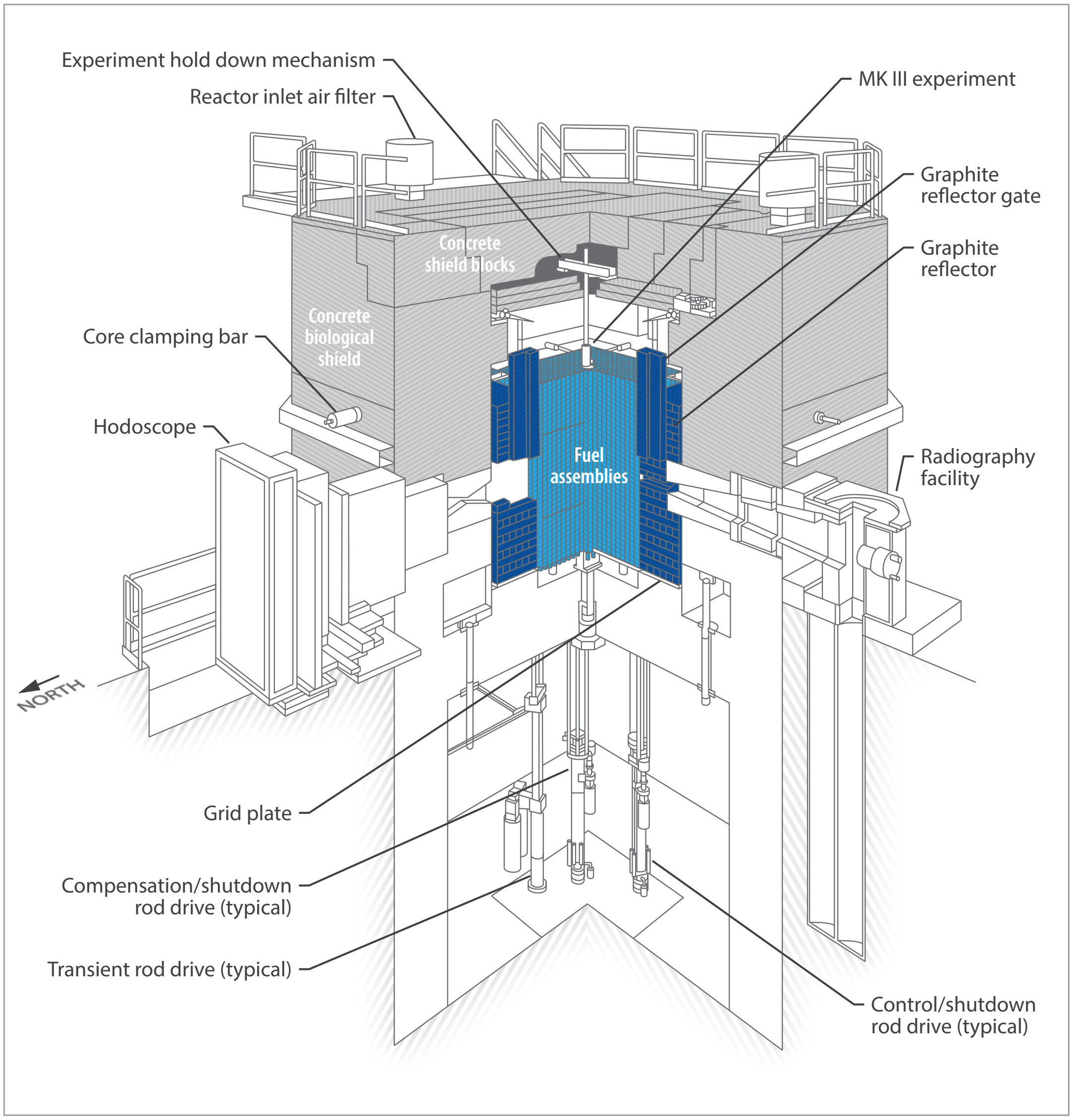


Figure 3. Cut view of TREAT's reactor core.

The TREAT reactor is capable of subjecting experiments to large power transients because the reactor has excess reactivity and is configured with fast-acting-transient control rods. The TREAT reactor uses three independent types of control rods with all control rod drives located below the core. The rods are driven upward to remove their neutron poison elements from the core, downward motion causes neutron poison insertion. The neutron poison element of each of the three types of control rods consists of a 1.75-in.-diameter carbon steel rod filled with B_4C powder that is 60-in. long. Each rod also has a graphite reflector clad in zirconium followed by an upper and lower graphite extension clad in mild steel. The three types of TREAT reactor control rods each serve a specific purpose. First, four compensation/shutdown rods are used to compensate for the total reactivity of an experiment providing fast-acting shutdown. The drives for these rods use a lead screw for rod movement along with a fast acting pneumatically accelerated scram. Each compensation/shutdown rod is driven by a single rod drive. Second, eight control/shutdown rods are the primary means of reactivity control during reactor startup and steady-state operation. There are four control/shutdown rod drives with each drive connected to two control/shutdown rods yoked together. The drives for these rods use a lead screw for rod movement along with a fast-acting pneumatically accelerated scram. Finally, eight transient rods are used for highspeed transient control and travel up to 140 in./s. There are four transient rod drives with each drive connected to two transient rods yoked together. The transient rods are operator controlled during low-speed operation and computer controlled during high-speed transient operation. The transient rods are hydraulically driven in both directions including during reactor scram.

2.2 Concurrent Testing

All the transient experiment assemblies are located in the center of the core, but there are other assemblies housed in small tubes and placed in cooling channels of the reactor where Concurrent Testing (CT) occurs. Cooling channels are located on the corners of the TREAT fuel elements and are formed by a chamber on the edge of each element. CT has been utilized historically for sensors and instrumentation irradiation experiments. The cooling channels were used in the past for CT, but future sensor and instrument irradiation tests shall be conducted at the center of the core similar to other transient experiments, or the K-19 position, which is a second vertical penetration with 6-in. penetration located beneath fuel assembly position. Removal of the plugs from these penetrations and other removable components permits the opening of two penetrations extending from the subpile room to the reactor top.

2.3 Transient Shaping

As mentioned earlier TREAT should not be used to accumulate radiation damage or burnup. Instead, TREAT's primary mission is to conduct various transient tests for evaluation of fuel and materials in accident conditions. The transient tests typically last from tens of milliseconds to a few seconds, and in some cases can last for a few minutes. The accumulated radiation damage or burnup is very small and is considered negligible. TREAT's hydraulically driven transient control rods coupled with the Automatic Reactor Control System (ARCS) permit unrivaled power shaping capability while leveraging the negative temperature feedback for safe self-limiting power excursions. TREAT's transients can be shaped to vary over several orders of magnitude in reactor power, total energy, and transient duration, governed only by the core energy capacity (currently 2,500 MJ). ARCS can interface with experiment diagnostics instruments to allow feedback control and synchronization of experiment boundary conditions (e.g., nuclear and thermal hydraulic). Two major categories of TREAT transients are exponential or peaked bursts (natural) and shaped power bursts (shaped). Exponential bursts are excursions that are temperature limited or rod and temperature limited (clipped); in the latter of which the transient rods are dropped to reduce the length of the transient before the temperature limit is reached or to limit the energy deposited on the tail end of the transient. Shaped power bursts are produced by reactivity insertion or removal at rates required to produce the desired burst shape. TREAT's versatility allows for transient shapes that are applicable for LWRs and advanced reactors. Below is a list of capable power transients as examples.

2.3.1 Steady state power

TREAT can run at steady state up to 120kW for core characterization and instrument calibration, neutron radiography, and pre-irradiation of experiments prior to the transient tests.

2.3.2 "Flattop" (greater than 120 kW) shaped transients

TREAT can run at steady state power at high powers (virtually any power level) for a short duration (time limited by 2500 MJ core energy capacity, typically from a few seconds to several minutes). These so called "flattop" shaped transients can provide fission heating during thermal hydraulic transients in experiment vehicle (e.g., loss of flow), precede ramps, pulses, SCRAM decay, etc. Examples of the power profiles for "flattop" transient are shown in Figure 4 below. The "flattop" transients can be used as pre-conditioning prior transients, are often seen for Loss of Coolant Accident (LOCA) type of tests or reactivity insertion accidents (RIAs), as shown in Figure 5 below [11].

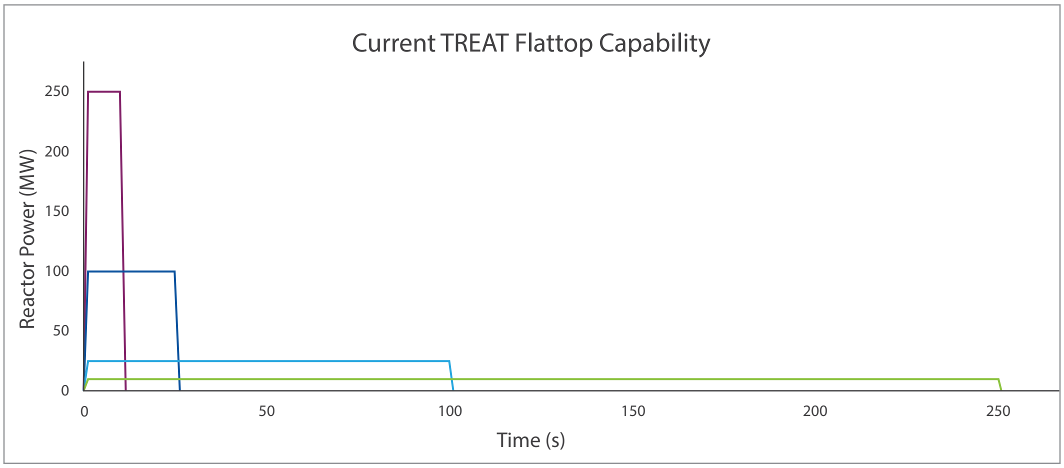


Figure 4. Example of "Flattop" shaped transients.

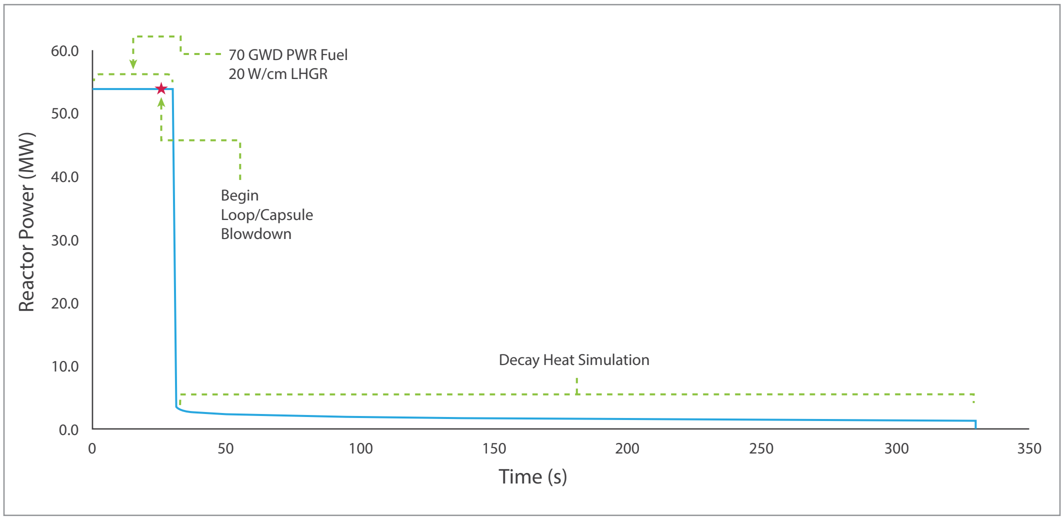


Figure 5. Example of LOCA test with a steady state power "flattop" prior transient.

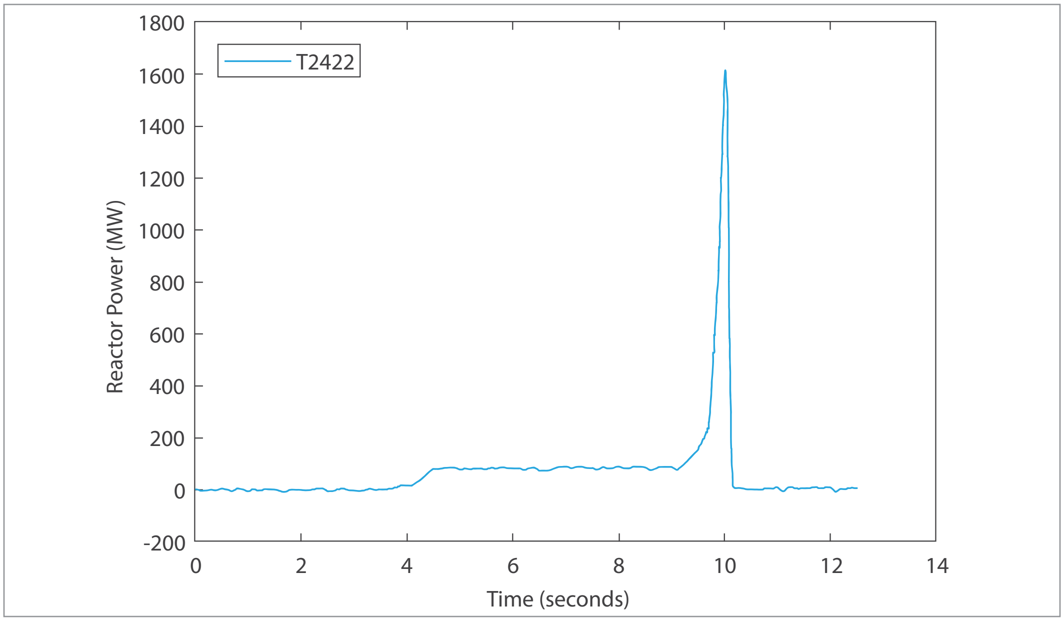


Figure 6. Example of RIA test with a steady state power "flattop" prior transient.

2.3.3 Ramp power insertion transient

TREAT can also simulate power ramp conditions. For example, Figure 7 below shows a ramp power insertion performed on multiple occasions in the TREAT facility, with two transients used as examples. The ramp reactivity insertion provides a controlled insertion of positive reactivity until the desired total energy release is achieved and the transient is terminated. The desired peak power values and the duration of the transients with a ramp reactivity insertion have to fit into the design and safety envelope for TREAT.

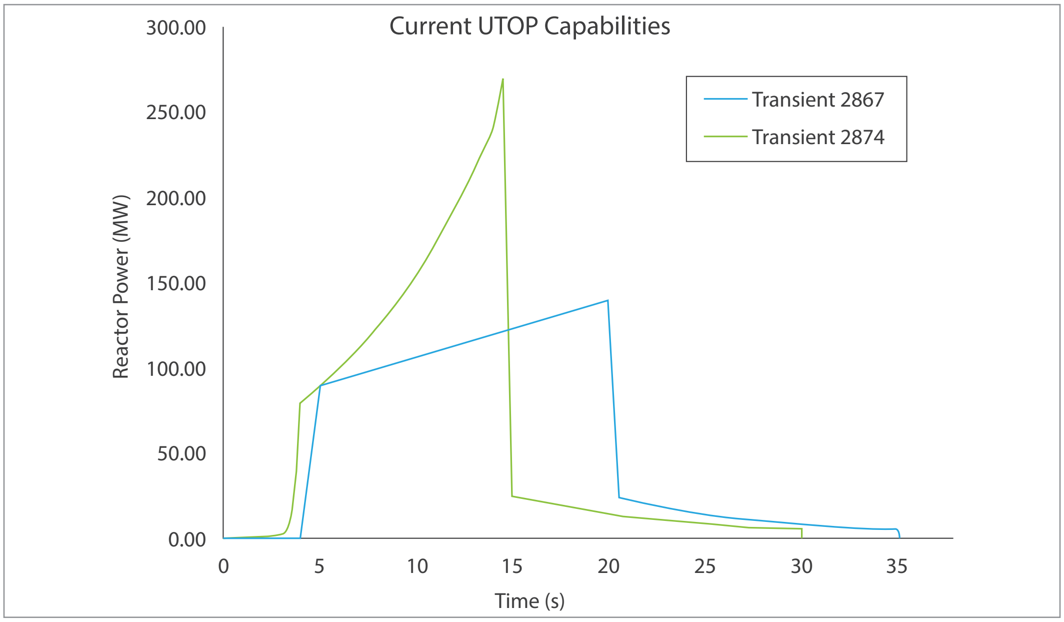


Figure 7. Example of "UTOP" shaped transients.

2.3.4 Other power transients

Another type of transient TREAT simulates is boiling water reactor (BWR) void power instability, as illustrated in Figure 8 below. This is accomplished by transient rod oscillations. Similar transient shapes useful for measuring fuel thermal response properties in-core (e.g., thermal conductivity). The power oscillation capability offers users the flexibility in power maneuver for a variety of in-core experiments, including fuel thermal conductivity measurements without lead cables.

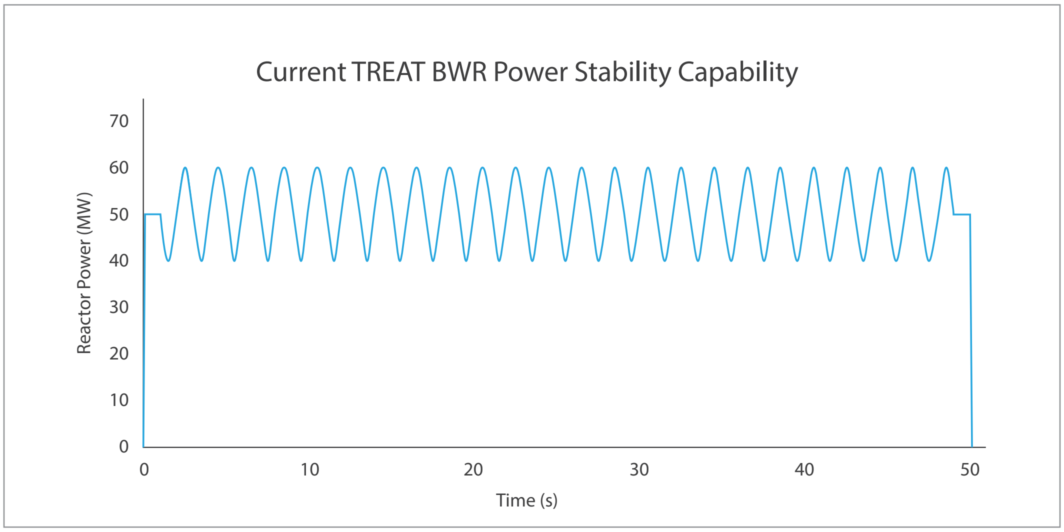


Figure 8. Example of power oscillation transient.

2.3.5 Temperature limited transients with and without "clipping"

A temperature-limited transient is characterized by a rapid introduction (step change) in positive reactivity, resulting in a rapid increase in reactor power followed by a decrease due to the negative feedback in TREAT associated with increased temperature. Once the desired total energy release was achieved for each transient, the transient was terminated. This is the most common type of transient test simulating reactivity insertion accidents (RIA). RIA is a design basis accident for LWRs that can happen due to the rapid ejection of the control rods from the nuclear reactor's core, resulting in a prompt increase of the fission rate density. The increased fission rate, even for a short period of time, causes a rapid temperature increase and thermal expansion of the fuel. The rapid thermal expansion of the fuel closes the gap between the fuel and the cladding (or both could be already in contact for previously irradiated fuel) and imposes a complex mechanical strain to the cladding that may lead to fuel failures.

For certain transients, the full width at half-maximum (FWHM) needs to be controlled or further narrowed compared to a temperature limited transient. This is currently accomplished by control rod movement by adding more negative reactivity to the core, called "clipping". Figure 9 below shows examples of clipped transients in comparison to unclipped temperature limited transients. The FWHM can be reduced from hundreds of milliseconds to sub-hundred milliseconds.

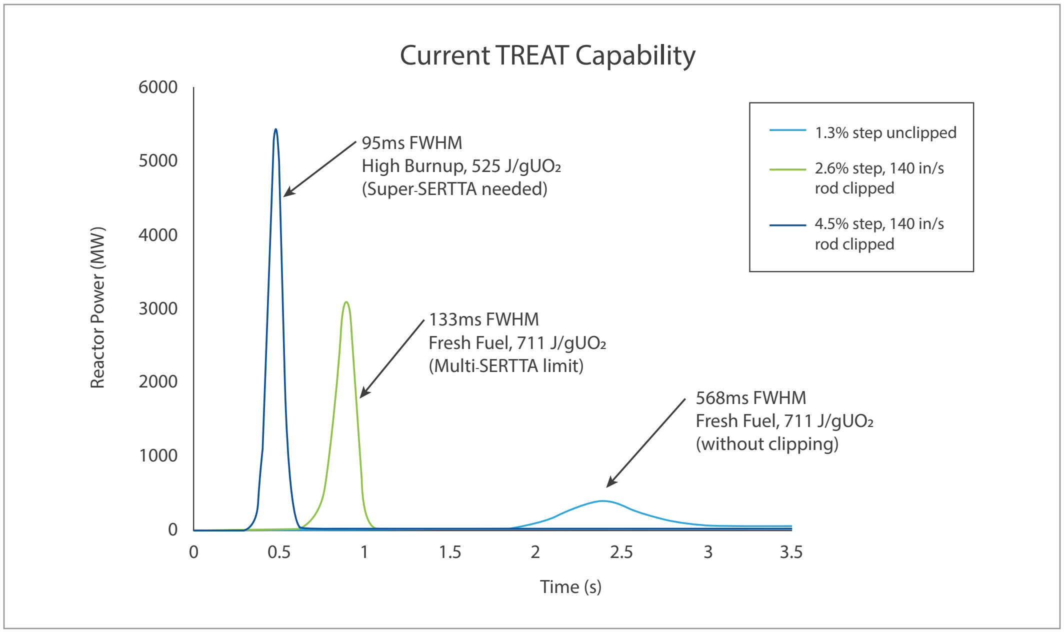


Figure 9. Examples of temperature limited transients with and without clipping.

For RIA in LWRs, the estimated maximum enthalpy increases ranges from 80 to 450 J/gUO_2 and the estimated FWHM ranges from 25 to 75 ms. To achieve such narrow FWHM ranges, a new capability called Helium-3 Enhanced Negative Reactivity System (HENRI) is under development. The HENRI system can rapidly inject helium-3 gas into the core during transient tests to further narrow down the FWHM to meet LWR RIA conditions, as shown in Figure 10 below. This new capability is expected to become available in 2025.

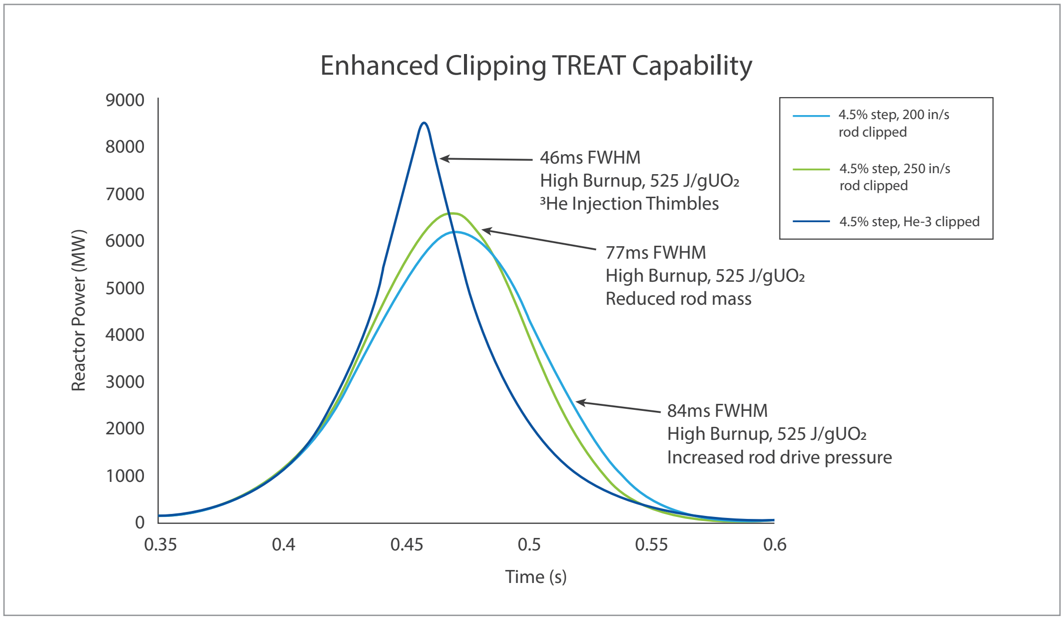


Figure 10. Examples of enhanced clipping transients enabled by HENRI system in comparison to other systems.

3. Overview of the Process for Experiment Insertion

Over the past six decades, TREAT has been utilized to its full potential by major DOE nuclear energy (NE) programs for fuel safety tests. Virtually every nuclear reactor technology today has benefited from experiments conducted at TREAT, from the historical sodium fast reactor fuels development to the current accident tolerant fuel (ATF) development for LWRs under the Advanced Fuel Campaign (AFC) program. Users can reach out to the TREAT program manager and technical lead for additional information on access to TREAT via DOE NE direct programs.

Other DOE programs such as the Nuclear Science User Facility (NSUF) program and Gateway for Accelerated Innovation in Nuclear (GAIN) program, offer users access to TREAT at no cost via a competitive proposal process. The proposal process is the same used to request access to ATR at INL, and users can refer to the ATR user guide following the proposal process for access to TREAT. Potential users can reach out to the NSUF and GAIN program offices or TREAT program manager and technical lead for additional information.

4. TREAT Experiment Configurations

TREAT experiments are housed in an experiment assembly called "Big-BUSTER", as shown in Figure 11. The Big-BUSTER is an enlarged version of the Broad Use Specimen Transient Experiment Rig (BUSTER) used in the TREAT facility to allow irradiation of larger test articles. The main purpose of Big-BUSTER is to support mechanical interfaces and neutronic conditions for test articles. It also provides a safety containment function for the hazards associated with irradiation experiments and is used as a container for transporting highly-radioactive test articles between TREAT and hot cells.

Optional heater modules can be placed within Big-BUSTER for elevated temperature testing. Experiment capsules and modules can be placed within Big-BUSTER for various testing purposes. While not credited as a safety containment, these capsule modules function as hermetic containers to control radiologic contamination during irradiation and shipping. Capsules that are made from low-activation materials can be easily extracted when Big-BUSTER is placed in shielded storage holes. When combined with small specimen sizes and brief irradiation durations, these capsules can typically be extracted and shipped for post irradiation examinations (PIE) within weeks of irradiation in facilities with minimal shielding (e.g., gloveboxes).

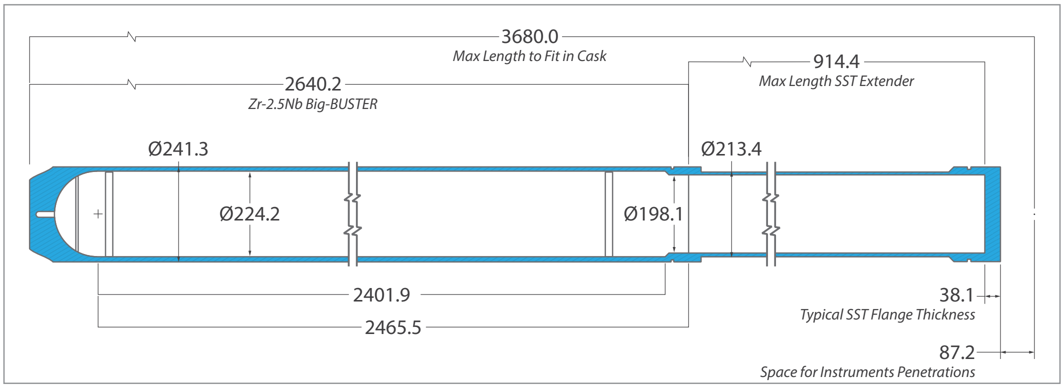


Figure 11. Illustration of "Big-BUSTER" experiment assembly.

The TREAT experiments can be categorized into six testbeds as shown in Figure 12 in the chart below, including Light Water Reactors (LWRs), Sodium Fast Reactors (SFRs), Advanced Gas Coolant Reactor (AGRs), Space Nuclear Propulsion (SNP), Instrumentation and Sensors (I&S), and national security (NS).

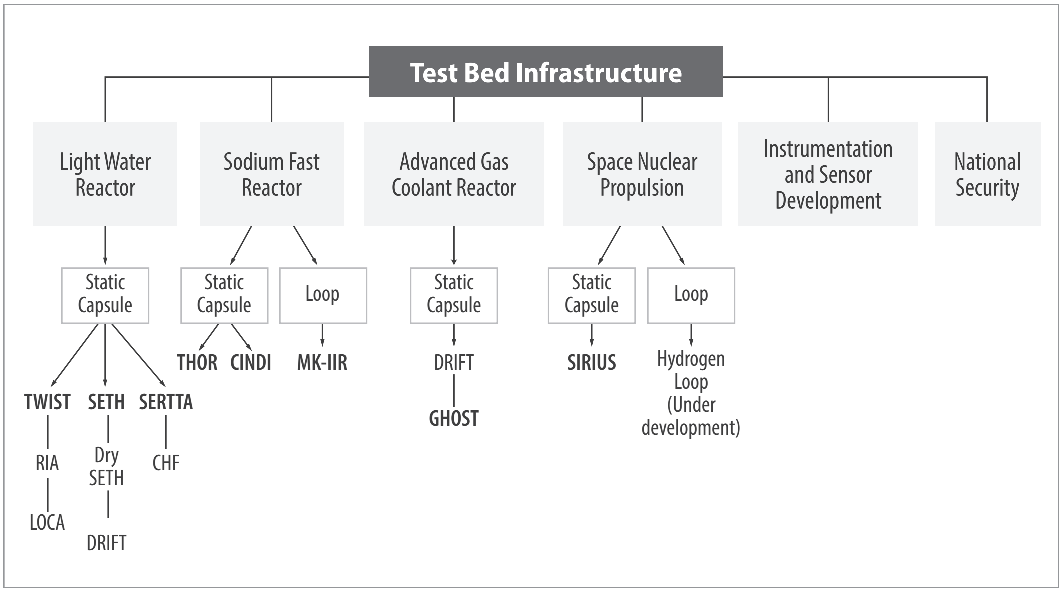


Figure 12. TREAT experiments and test beds.

Each experiment design is organized based on its usage of being either a static capsule or a flow loop, as summarized below.

4.1 Light Water Reactors (LWR) Testbed

The LWR testbed consists of several experiment designs used to determine the LWR fuel safety margins in overpower conditions such as RIA and under cooling conditions such as LOCA, as well as other Anticipated Operational Occurrences (AOOs). The experiments can be conducted in dry capsule conditions or pressurized water capsules. A flowing water loop is being considered as a future capability pending programmatic needs.

4.1.1 Separate Effects Test Holder (SETH)

SETH is a larger static capsule suitable for irradiating small power-reactor rodlets (10 cm or less fuel length), compacts, extrusion, plates, etc. SETH-based tests leverage low-cost consumable components, conventional compression instrument seals, and a predictable specimen environment such as inert gases for affordable concept screening, separate-effects, and phenomena-identification fuel irradiations. SETH is normally conducted in dry conditions, but aqueous test conditions can also be accommodated. A standardized SETH capsule is illustrated in Figure 13.

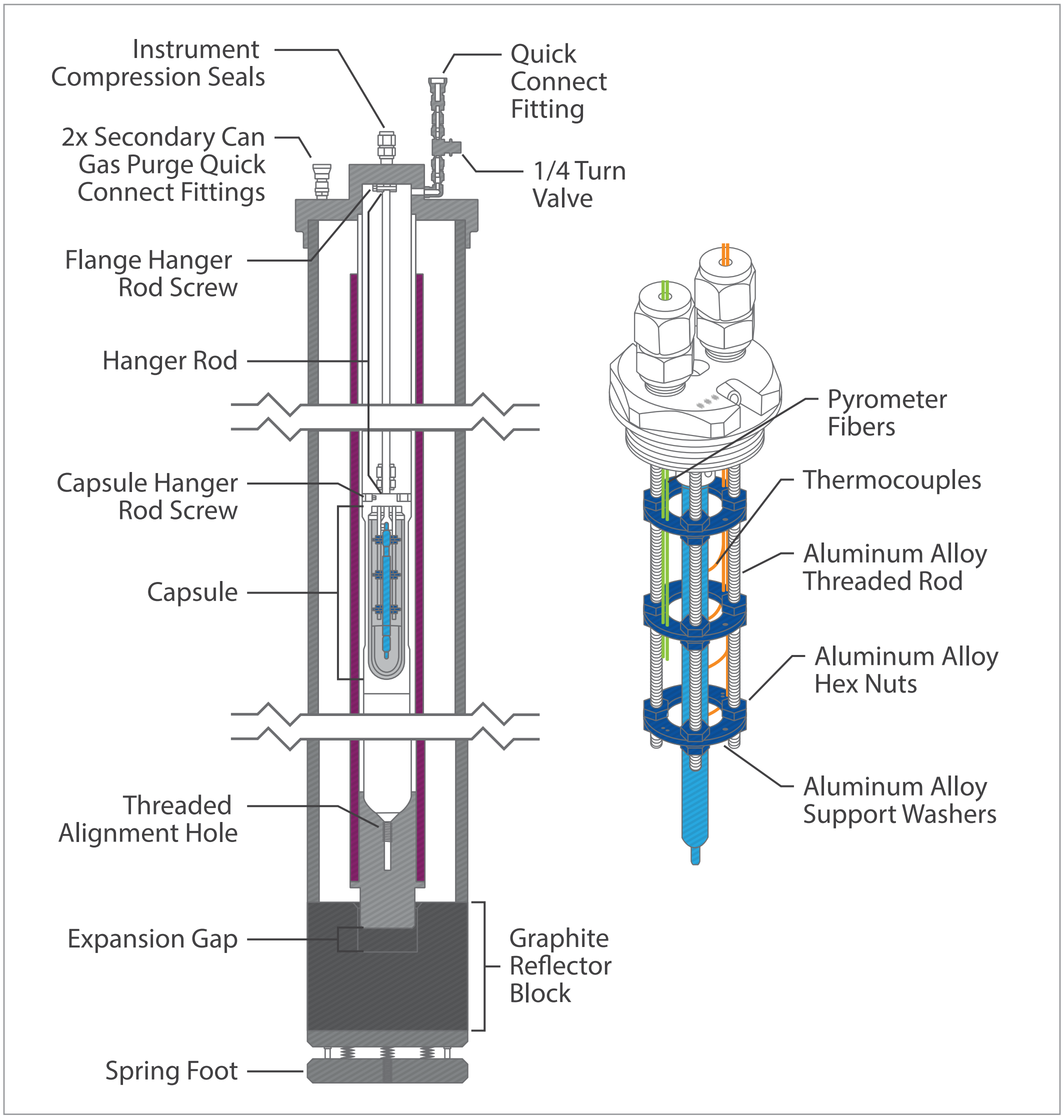


Figure 13. Example of SETH assembly and capsule design rendering [28].

It is worth mentioning that one of the specialized SETH assemblies, which is the Dry In-Pile Fracture Test (DRIFT) capsule, consists of a thick, annular, alloy 316 Stainless Steel cylinder that serves as a heat sink. The experiments employ a heat sink to radially remove heat from the fuel in a manner that simulates the effect of coolant in an operating LWR. The DRIFT capsule is located on the inside of the SETH assembly, as illustrated in Figure 14. More detailed information on the experiment design and application is available from reference [29].

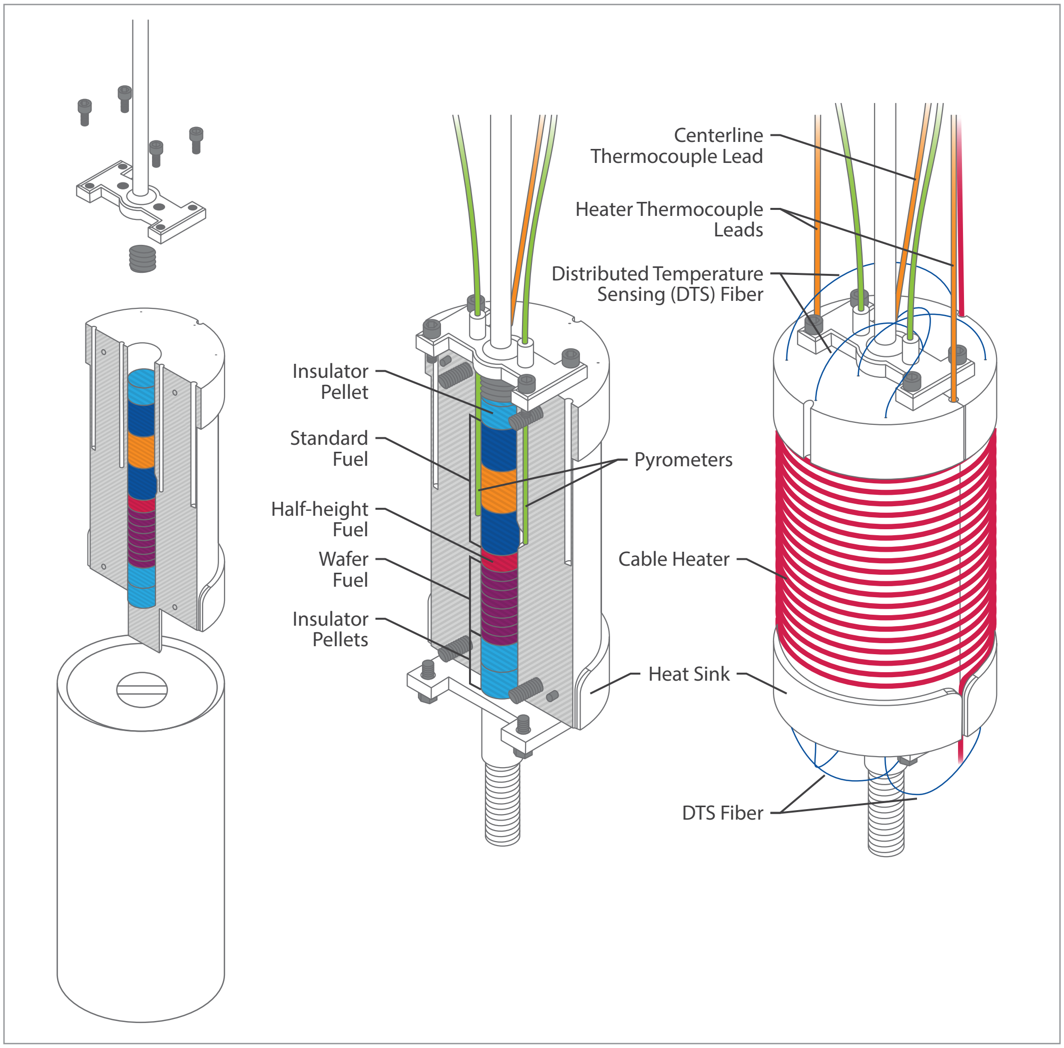


Figure 14. Example of the DRIFT assembly and capsule rendering [29].

4.1.2 The Static Environment Rodlet Transient Test Apparatus (SERTTA)

The SERTTA assembly is a static capsule consisting of a small water-filled capsule housed within a larger containment pipe. It enables affordable and high-throughput water-based testing. The capsule can house one rodlet (10 cm or less fuel length) or similar specimen in a water environment. The water can be heated before the transient to achieve elevated temperature and pressure water or steam environments. The SERTTA assembly is outfitted with detectors to indicate environmental pressure and, temperature, fuel cladding temperature, fuel internal pressure, fuel axial expansion, and water phase change. These provide a full suite of fast-response data for evaluating specimen boundary conditions, determining the timing of crucial performance transitions, and comparison to transient fuel performance models. The SERTTA assembly is ideal to perform tests on LWR fuels to simulate reactivity-initiated accidents (RIA) and to determine critical heat flux (CHF) in water environment. At TREAT, a specified amount of energy can be deposited into a representative test specimen to observe the key known physics of an RIA transient. Figure 15 below shows an example of the SERTTA Assembly.

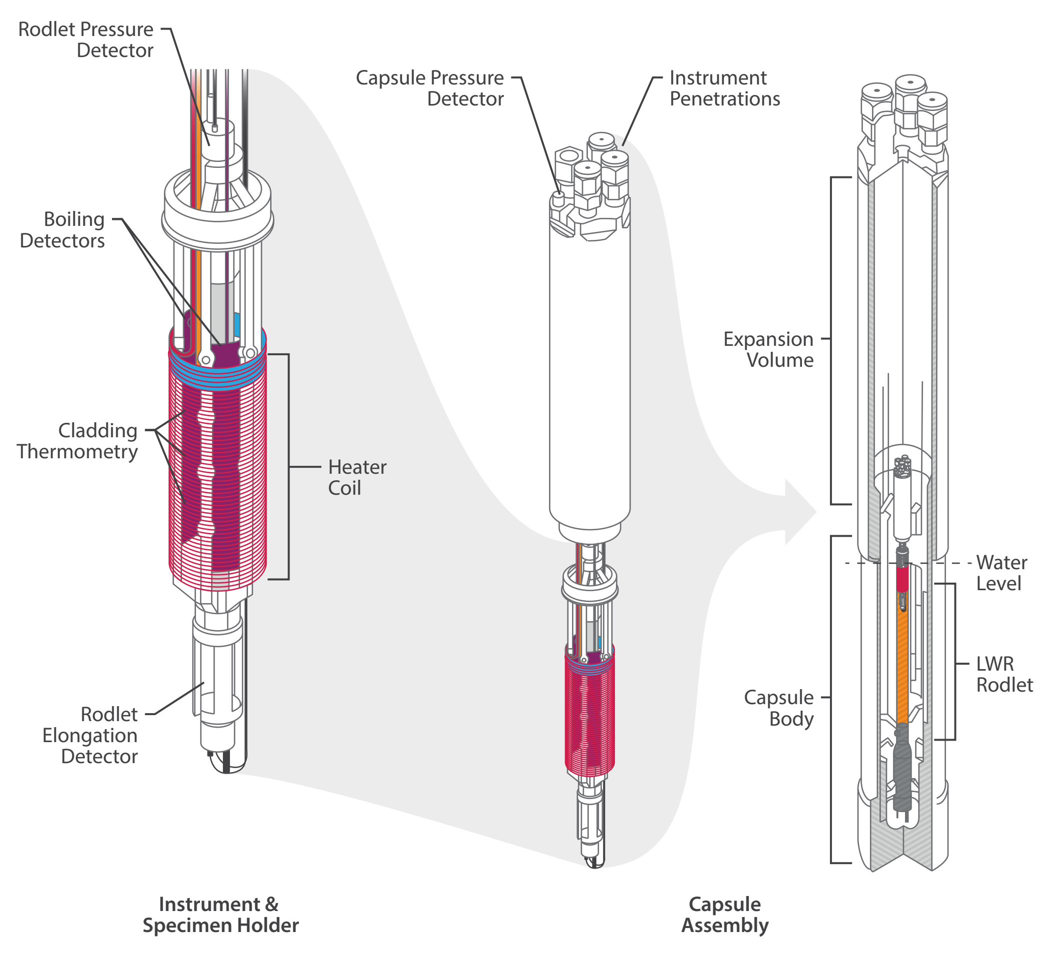


Figure 15. Example of SERTTA assembly.

4.1.3 Transient Water Irradiation System in TREAT (TWIST)

The TWIST assembly is a critical static experiment test vehicle used mainly to support fuel safety research for light water reactor (LWR) type specimens, including accident tolerant fuels (ATF). TWIST is in the SERTTA family of designs offering enhanced capabilities compared to other smaller capsules. TWIST's enhancements include extended energy handling capability, increased compatibility with pre-irradiated specimen data objectives, and an augmented in-situ instrumentation package. This first-generation TWIST vehicle is intended to support irradiations simulating LWR Loss of Coolant Accidents (LOCA), as shown in Figure 16 below.

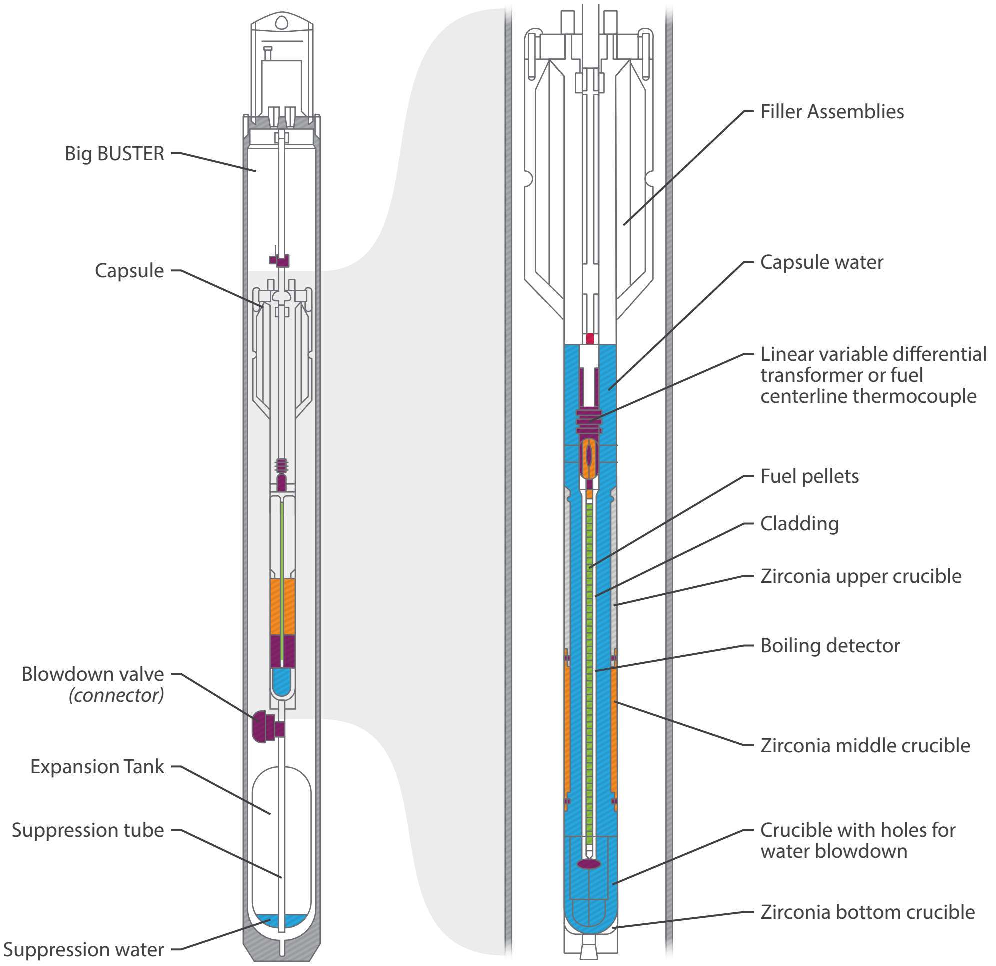


Figure 16. Schematic of LOC-C experiment assembly, and an example of TWIST design.

A flowing water loop experiment assembly is being actively pursued and will be added to the user guide once this capability becomes available.

4.2 Sodium Fast Reactor (SFR) Testbed

Historically, TREAT was mainly used for SFR fuel transient tests. Several sodium-based heat sink tests across three experiment campaigns using mixed oxide (MOX) fuel were executed in the 1960s and 1970s. Most of the more recent historic research in TREAT was dedicated to SFR fuel testing until operation was suspended in 1994. TREAT plays a critical role in determining the safety margins for various SFR fuel designs under transient accidents. SFR testbed can be divided into the static test train called THOR, and sodium loop test train called MK-IIIR loop, as described below.

4.2.1 Temperature Heat-Sink Overpower Response (THOR)

The THOR module is one of the most important static test assemblies that has been designed to test the performance of SFR fuels in an environment simulating transient overpower (TOP) and Loss of Flow (LOF) events in an SFR. The THOR module is a thick-walled capsule in which rodlet type fuel specimens are "bonded" with liquid metal for close thermal transport, an example of THOR assembly is shown in Figure 17. This allows it to serve as a heat sink for longer-shaped transients and other temperature response-shaping strategies. Paired with temperature and elongation sensors, THOR approximates the postulated thermal response of specimens in reactors in a compact and affordable test package.

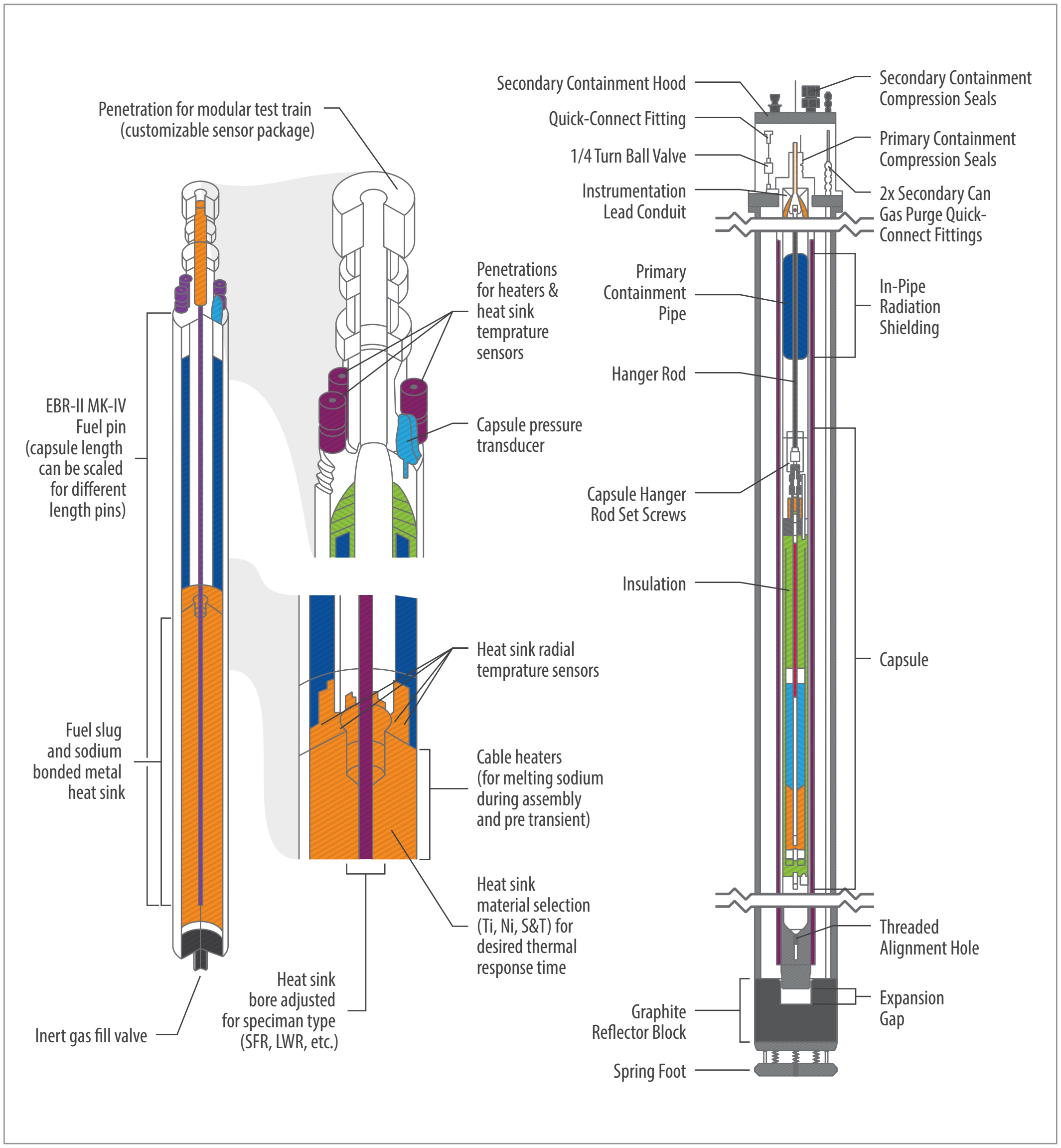


Figure 17. Example of THOR assembly [30].

One variation of the THOR module is called the Characterization-scale Instrumentation Neutron Dose Irradiation (CINDI). An example of a CINDI assembly is shown in Figure 18. The CINDI module enables irradiation of small-scale samples in a well-controlled and temperature monitored environment using an electrical heater module. The CINDI experiments aim to support the development of lower length-scale modeling and fundamental fuel irradiation science. Due to the short duration of irradiation, the effective burnup or radiation damage are very small compared to materials in test reactors such as ATR.

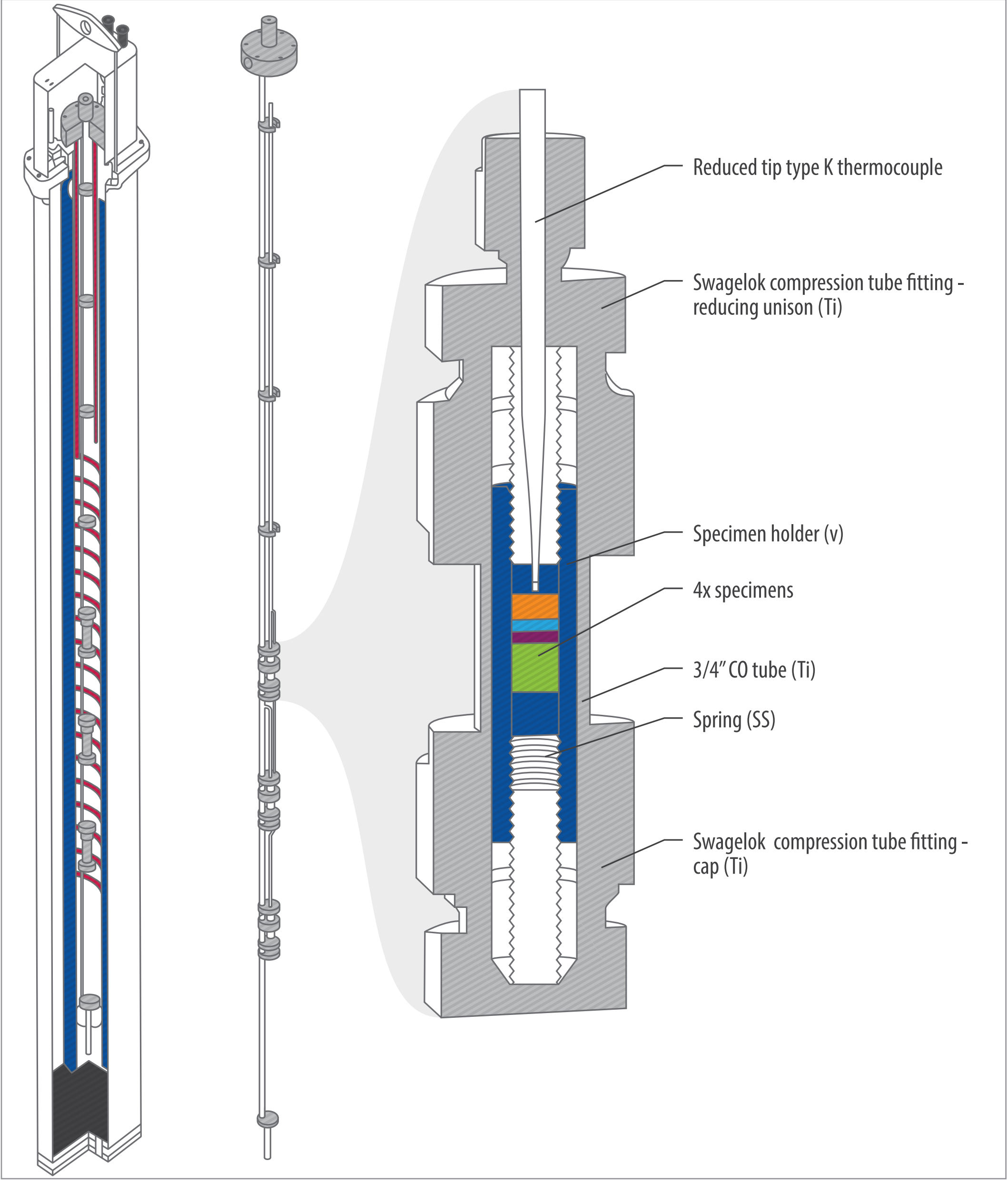


Figure 18. Example of CINDI assembly [31].

4.2.2 MK-IIIR Loop

The MK-IIIR loop is a modern liquid metal loop to test fuels at flowing conditions for advanced liquid metal cooled reactors. The schematic of MK-IIIR Loop is shown in Figure 19. This compact loop, enabled by electromagnetic pumping technology, provides forced convection cooling for a single fuel pin or multiple pins in an individual flow tube. This loop capability allows test trains that are highly instrument-focused, to simultaneously test multiple specimens, or to evaluate bundle scale failure progression, respectively. Modernized instrumentation paired with TREAT's fast neutron hodoscope will provide unparalleled in situ data crucial for the development and licensing of advanced liquid-metal-cooled reactors.

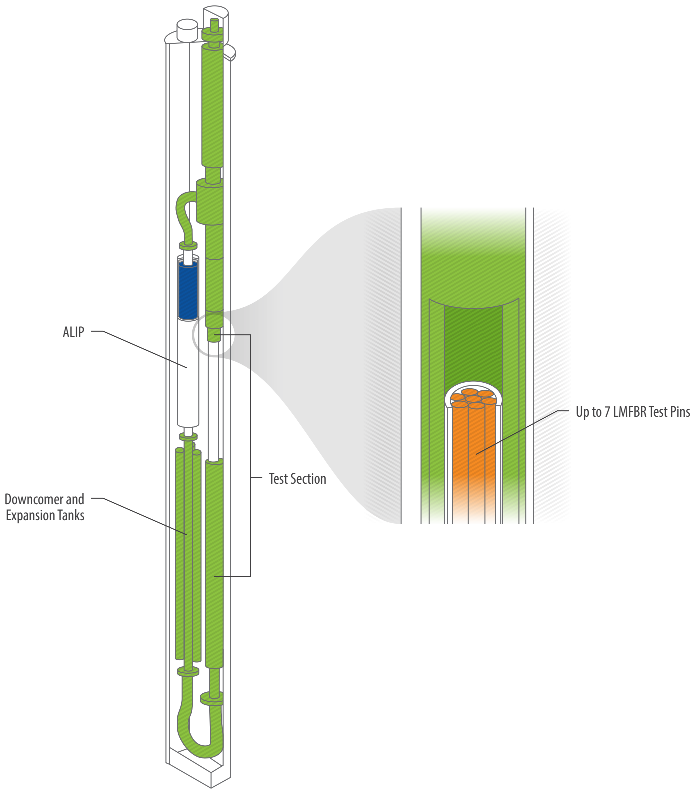


Figure 19. Schematic of MK-IIIR loop.

4.3 Advanced Gas Cool Reactor

For the AGR testbed, a new capsule design called Graphite Heatsink Overpower Safety Test (GHOST) works by the same principle as the THOR capsule described previously, except that it uses graphite as the heat sink with a helium environment and there is a tighter fit between fuel specimens and graphite to simulate the boundary conditions of TRISO fuel compacts in a high-temperature gas cooled reactor. Electrical preheaters enable the GHOST capsule to be heated to prototypic temperature prior to the transient and several thermocouples are included, as illustrated in Figure 20.

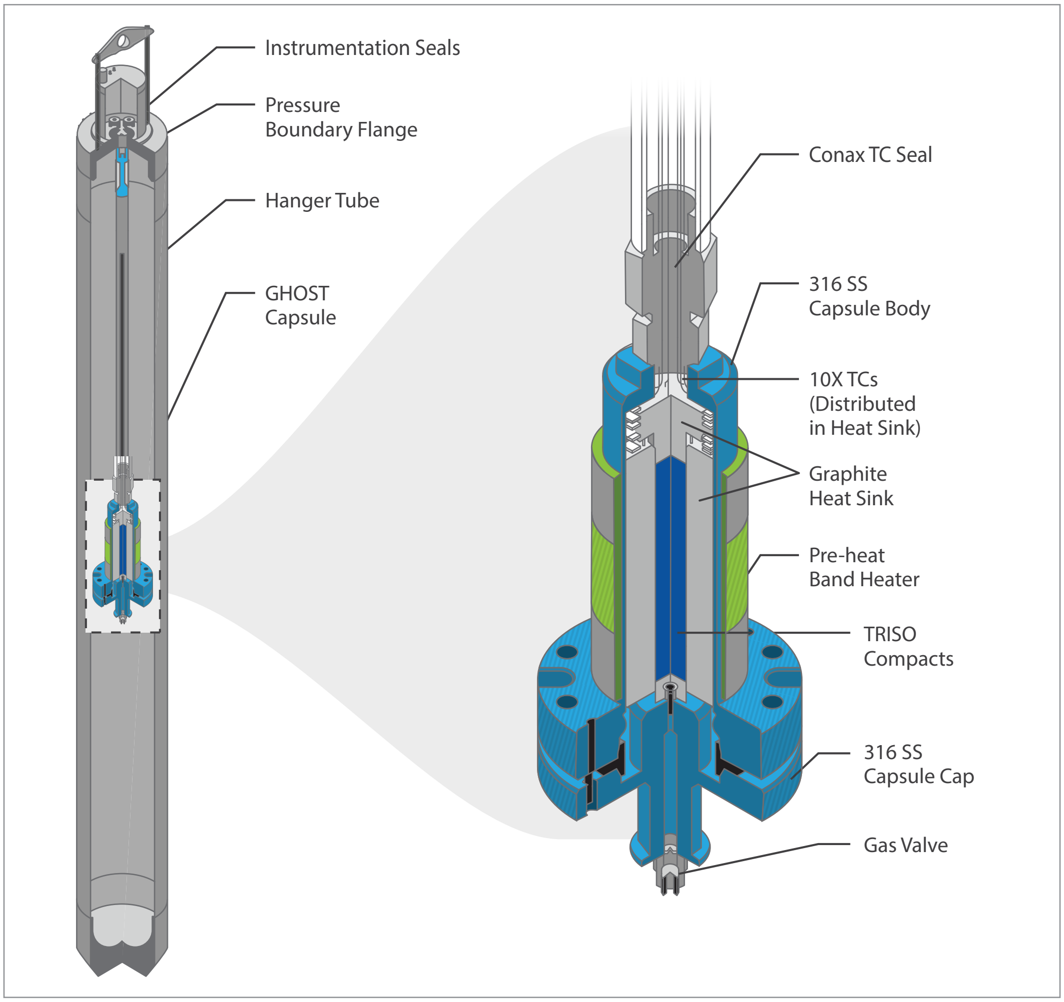


Figure 20. Example of the GHOST assembly for the AGR testbed.

4.4 Space Nuclear Propulsion (SNP) Testbed

The high power and rapid temperature ramping capabilities make TREAT an ideal testbed for SNP fuels due to its extreme operating conditions. A standardized static capsule design called SIRIUS is used for multiple SNP fuel transient experiments in TREAT. A hydrogen flowing loop is installed as a future capability for SNP fuel testing, and this capability will be included in the user guide once it becomes available.

4.4.1 SIRIUS

The SIRIUS assembly is housed in the static test module SETH for examination of the performance of nuclear thermal propulsion (NTP) fuels when subjected to temperature ramp rates that are prototypical of NTP system startup. An example of SIRIUS is shown in Figure 21. The SIRIUS test module can be used to determine the operational startup ramp limits where detrimental performance phenomena are observed, such as cladding ballooning, fuel fragmentation and cracking for a given fuel geometry and material system. It can also facilitate the determination of incipient behaviors such as hydride formation without permitting complete chemical reactions that could result in gross specimen destruction loss.

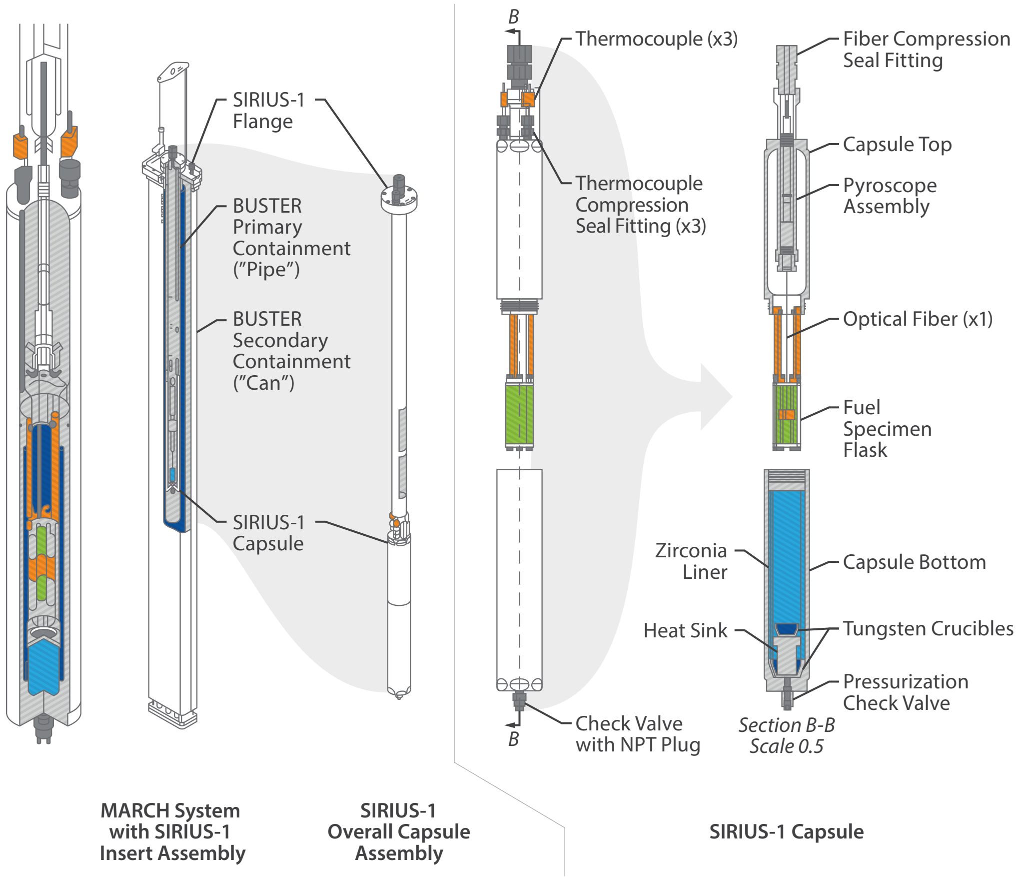
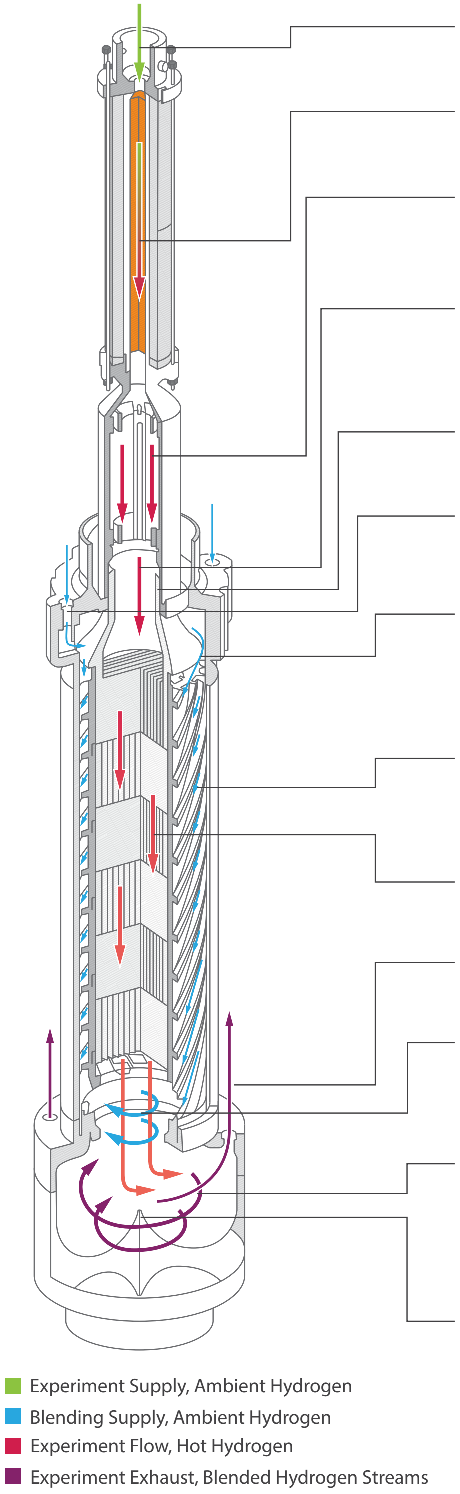


Figure 21. Example of SIRIUS assembly [32].

4.4.2 GH2 System for Experiments

The gaseous hydrogen system currently under construction for experiments in TREAT will be capable of supplying gaseous hydrogen flow of <10 g/s to 200 g/s at a maximum supply pressure of 1000 psig. The system does not pre-heat or pre-cool the hydrogen. Argon is used for purges and valve operation rather than nitrogen to avoid the exposure of irradiated specimen to non-inert gas. A conceptual experiment design called Sirius-4 is illustrated in the figure below.



Experiment H_2 flow enters TAA Cartridge.

Experiment H_2 flows thru 19 flow channels in CERMENT fuel, absorbing thermal energy from the fuel.

Experiment H_2 flows thru the carbon Exposure Cartridge, exposing wafer-shaped specimen to hot H_2

Hot Experiment H_2 flows thru HANC Midflange Insulator to the Heat Sink. The tungsten insulator functions as a chimney insulating the Midflange from the hot hydrogen.

Two rings, function similar to piston rings in an engine, decrease the annular opening between the Midflange insular and

Blending H_2 enters the Midflange plenum.

Blending H_2 fills the Midflange plenum, providing an insulative barrier helping protect the Inconel Midflange from the Midflange insulator as its temperature increases from the hot H_2 flowing inside it.

Blending H_2 flows around the inconel Heat Sink shell. As the Heat Sink and shell increase in temperature during transients, this flowing H_2 insulates and protects HANC, as well as removing heat from the heat sink.

Experiment H_2 flow decreases in temperature as it passes thru the Heat Sink.

Blended H_2 exhausts the mixing plenum.

Blending H_2 swirls around the hot H_2 exiting the Heat Sink, protecting HANC.

Blended H_2, Swirling as it enters the mixing plenum, mixes with the Experiment H_2 flow coming from the Heat Sink. This swirling flow drives adequate mixing and prevents hot spots from forming on the walls of the mixing plenum by ensuring there are no stagnant pockets of gas.

The bottom surface of the Inconel mixing chamber has a convex toroidal geometry that functions to divert the direction of the swirling flow upward to the openings where it exits the mixing chamber.

🟩 Experiment Supply, Ambient Hydrogen
🟦 Blending Supply, Ambient Hydrogen
🟥 Experiment Flow, Hot Hydrogen
🟪 Experiment Exhaust, Blended Hydrogen Streams

Figure 22. Illustration of Sirius-4 experiment assembly

4.5 Instrumentation and Sensors (I&S) Testbed

Historically, newly developed instrumentations and sensors are tested out in TREAT for irradiation performance evaluation via concurrent testing (CT). The CT was housed in small tubes and placed in cooling channels of the reactor. To support future I&C testing, a fuel position called K-19, as shown in the TREAT reactor core diagram in Figure 23, has been identified as the host for future experiments. It is planned that this position will do sensor only irradiation.

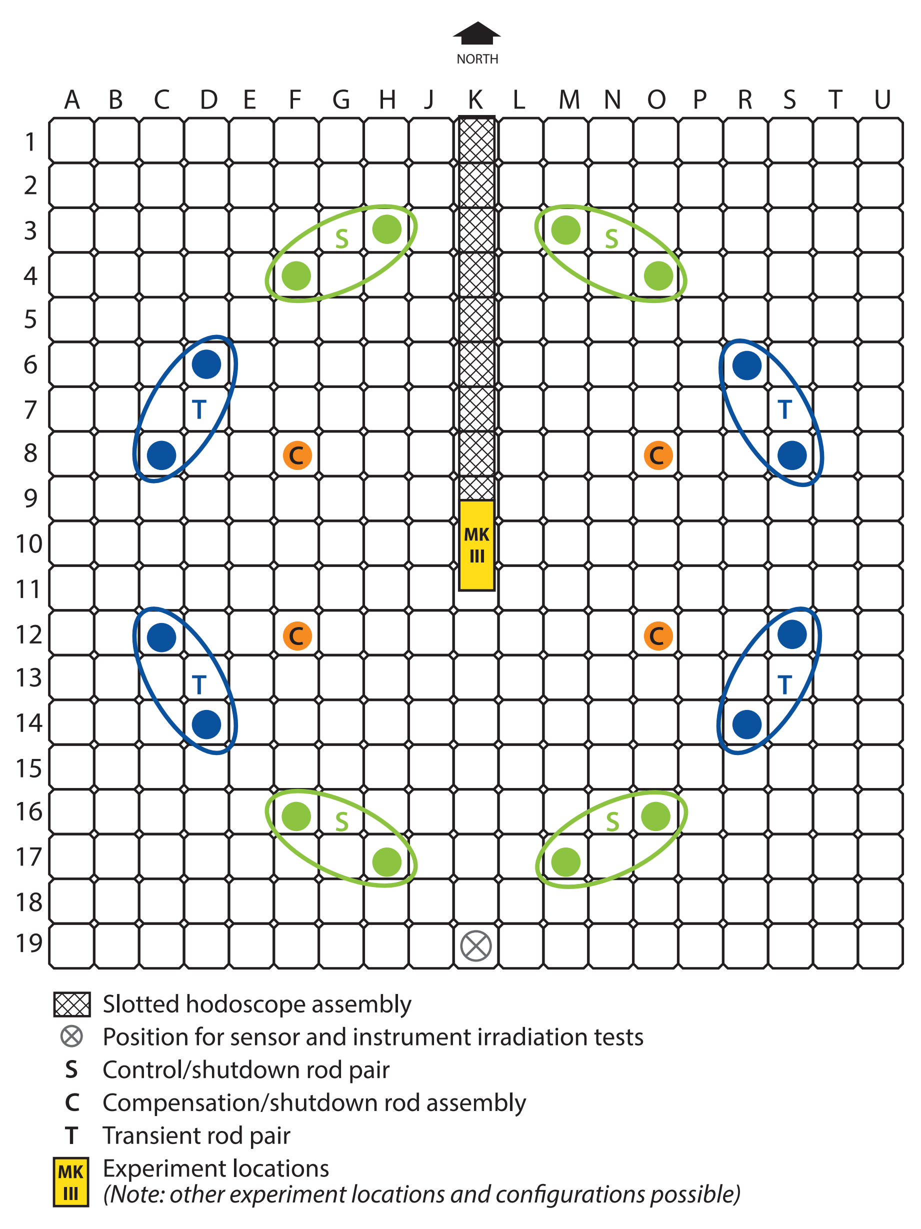


Figure 23. K19 fuel position in TREAT reactor core.

5. Beamline Measurements and In-pile Instrumentation

One of the most powerful tools for TREAT experiments is in-pile instrumentation allowing real-time measurements during experiments to monitor fuel and materials behaviors in accident conditions. Those measurements are critical for conducting research, development, and qualification on nuclear fuels and materials—and in some cases, for creating operation requirements for nuclear reactors.

5.1. Beamline Measurements

5.1.1 Neutron radiography (NR)

Neutron radiography of irradiated nuclear fuel provides more comprehensive information about the internal condition of irradiated nuclear fuel than other non-destructive techniques. The TREAT radiography system is used to perform neutron radiography of fuels, experiments, and other specimens before and after irradiation within the TREAT reactor. Figure 24 shows the neutron radiography facility layout.

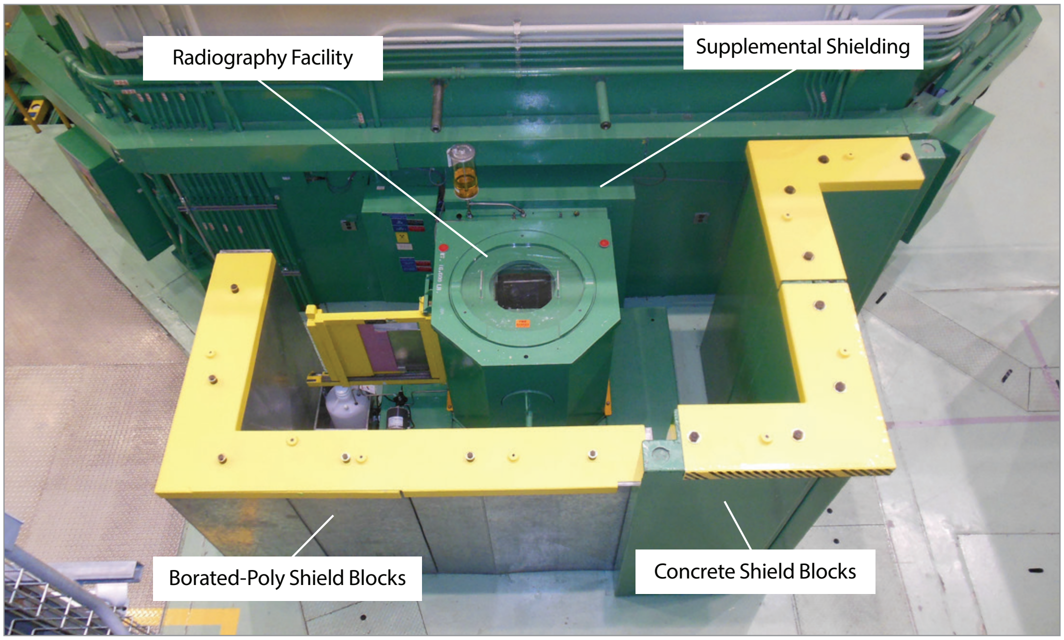


Figure 24. TREAT Neutron radiography facility layout.

At the TREAT NR station, neutron radiographs are acquired using transfer method with dysprosium conversion foils and image plates. This is similar to the process used at the Neutron Radiography (NRAD) Reactor at INL. The system includes the radiography facility where radiography cassettes are initially exposed to the neutron beam and a separate radiography room where radiographs are subsequently processed.

Because TREAT is a transient reactor that can generate a peak power of up to 18,000 MW and high neutron fluxes, a special high speed, flash neutron radiography capability is currently under development. Installation of a flash radiography camera system at TREAT combines high-speed thermal neutron detection with a high-power neutron pulse for high-speed visualization of dynamic phenomena, such as bubble and film formation, which are important to understand events like departure from nucleate boiling (DNB). Supplemental shielding is being developed, installed, and tested to allow for neutrons to pass during a transient. The flash radiography is a future capability that will be available for TREAT users.

5.1.2 X-ray radiography

TREAT is equipped with a portable X-ray source and is able to perform X-ray radiography for experiment vehicles before irradiation. X-ray radiography is another non-destructive exam technique which is useful to verify the location and integration of the fuel and other internal components in a sealed capsule. It can be crucial for certain experiments to verify the as-build conditions and the impact of transportation. X-rays may not be very effective in penetrating dense materials like metals and nuclear fuels, so it is complimentary but not a substitute for neutron radiography.

5.2 In-pile instrumentation

5.2.1 Hodoscope

The hodoscope is a direct-view imaging system and radiation detector that provides time and spatial resolution of fuel motion during transients, and in-place measurement of fuel distribution before and after experiments, shown in Figure 25. It provides a highly sensitive measure of when and where initial fuel system failures occur during transient nuclear events. Full-slotted core loadings allow for cleaner hodoscope measurements with reduced background neutron detections from the reactor, as fueled TREAT assemblies are not placed in the direct path of the hodoscope. In the ongoing transient test program at TREAT, fuel motion surveillance using the fast-neutron hodoscope has been providing time/location/velocity data in a qualitative manner. On-going efforts are being made to offer qualitative mass results using the hodoscope and could become available for future users. Data collected from a hodoscope experiment measuring the response of two fuel pins to a transient is shown in Figure 26. More details of the hodoscope specifications are available in references [20, 21].

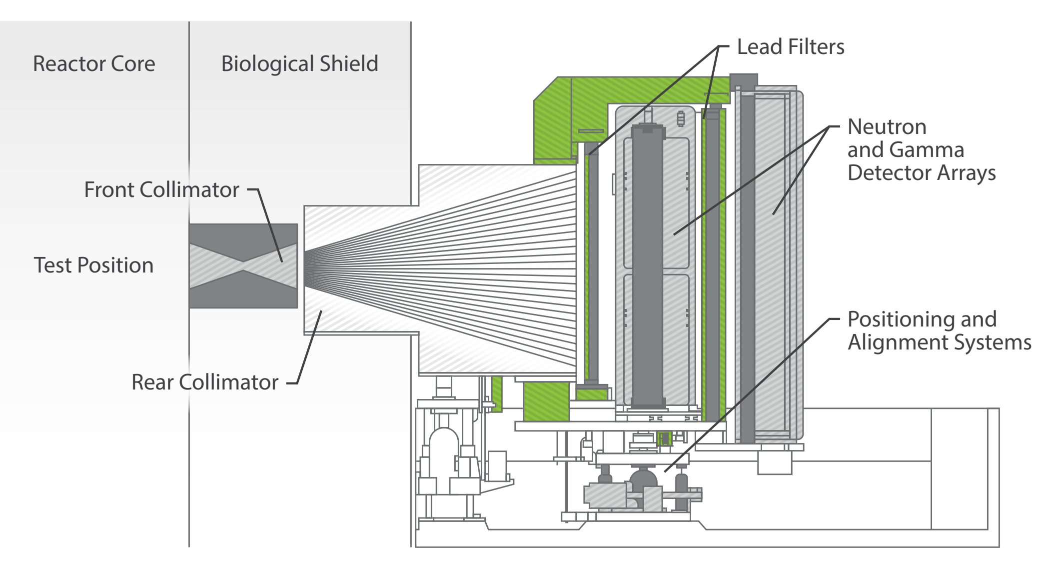


Figure 25. A cross-section drawing of the 1.2-m collimator hodoscope system demonstrating how the components interface with the TREAT reactor.

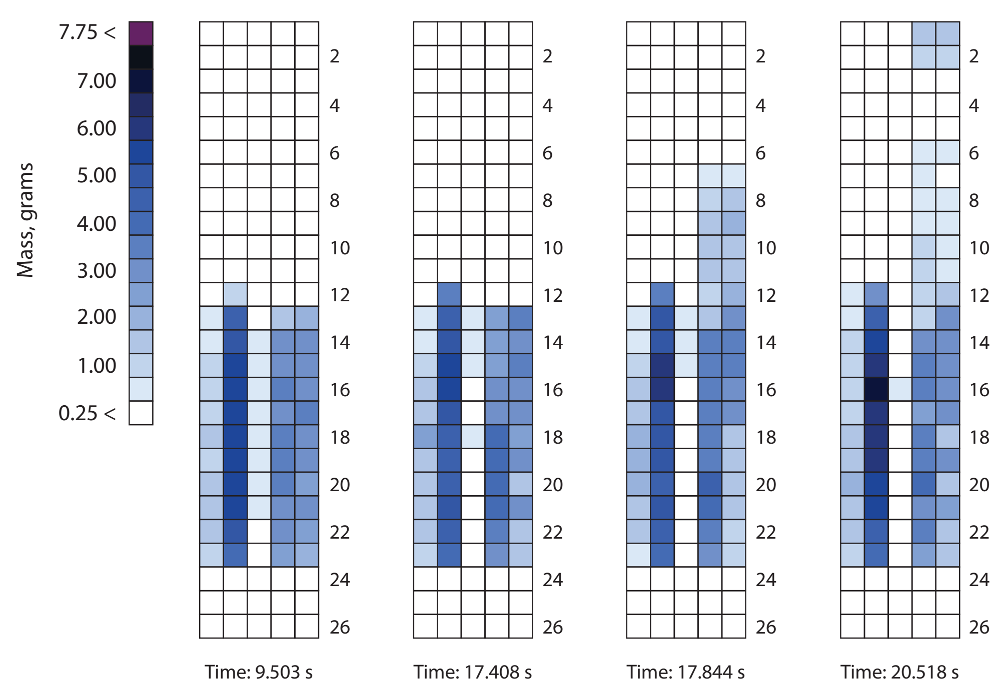


Figure 26. Data from a hodoscope experiment.

5.2.2 Neutron detector (ND)

There are several types of neutron detectors that can be used in an experiment to determine the localized neutron energy, flux, and fluence.

5.2.2.1 Fission chamber neutron detector

Fission chamber neutron detector is a commonly used real-time method for monitoring local neutron flux and is available at TREAT. Fission chambers are built using two electrodes, one has a fissile material deposit that emits fission fragments when placed in a neutron field. These fission fragments produce an instantaneous current pulse between the electrodes that have a polarization voltage applied between them. The resulting pulse is measured via external electronics. The space between the electrodes must have a fill gas to aid detector performance. The outer electrode serves as a boundary between the reactor coolant and the inner materials. The fissile material deposit can be chosen such that the detector is sensitive to either thermal neutrons or fast neutrons. Fission chambers can be operated in three different modes: pulse mode for low power applications that measure the individual pulses, current mode for midrange power applications where pulses are so frequent that they cannot be separated and produce a continuous current, and Campbelling mode for high power applications where the variance of the signal is characterized and correlated to the incident neutron flux. An example of the fission chamber used for TREAT experiments is shown in Figure 27.

Although it is a mutual technology, fission chamber NDs are not commonly used for TREAT experiments. Instead, self powered neutron detectors are more favorable for TREAT experiments, which will be discussed in the next section.

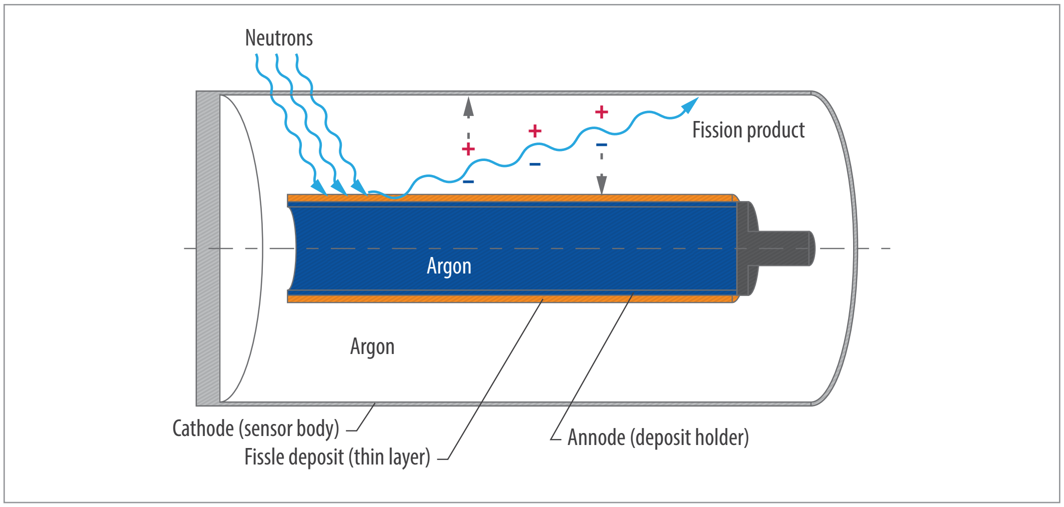


Figure 27. Representative fission chamber and component sketch [33].

5.2.2.2 Self-powered neutron detectors (SPND)

Self-powered neutron detectors (SPND) are a commonly used real-time method for monitoring local neutron flux. SPNDs are built using materials that become radioactive in a neutron field and produce a small current which is correlated to the neutron flux. SPNDs are built around a central electrode, known as an emitter, which is composed of a metal with a relatively high neutron capture cross section. The central electrode is surrounded by an electrical insulator and an outer electrode, known as a collector. The outer electrode serves as a boundary between the reactor coolant and the emitter and insulator. A typical self-powered detector is shown in Figure 28. The current between the emitter and collector is measured via external circuitry. It can take time for the current to build up in the SPND; resulting in a delay time from several seconds to a few minutes before the signal is generated. In addition, if the neutron signal is suddenly changed it will take several minutes for the signal to stabilize. Different emitter materials can be used for SPNDs, such as standard slow-response type rhodium (Rh) and vanadium (V), or fast responsive type gadolinium (Gd) and hafnium (Hf) that are still under development. The Gd type SPND developed in house is becoming a beneficial technology that is available at TREAT to provide fast response for monitoring local neutron fluxes. The prompt-response SPNDs are focused for future TREAT experiments.

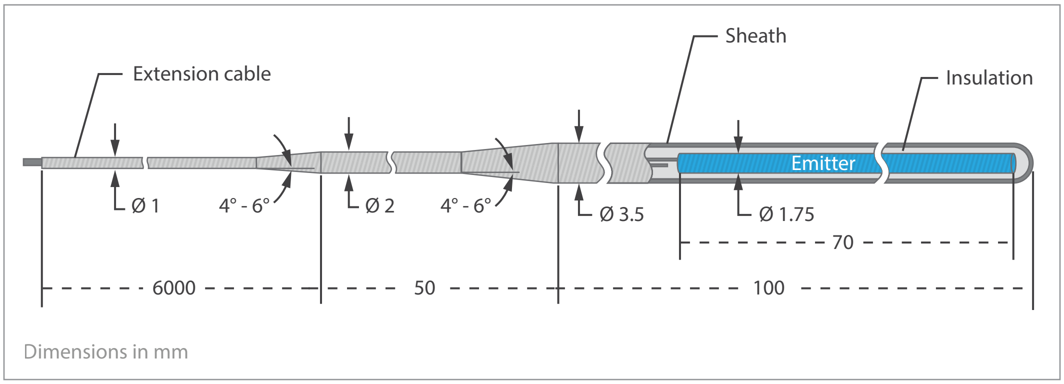


Figure 28. Typical self-powered detector (from Thermocoax).

5.2.2.3 Dosimetry

Standard dosimetry techniques utilize flux wires, disks, and foils to characterize reactor neutron spectra and fluence and fission coupling with understanding reactor-to-specimen power coupling (unit power generated in specimen per unit reactor power). Dosimetry is the most widely used passive method for local neutron activation spectrometry. A flux wire, disk, or foil is simply a material of known composition and purity that is placed in a neutron field. When placed in a neutron field, different elements (and different isotopes of the same element) interact differently with respect to the energy of the incident neutron. When the interaction product is radioactive, the resulting induced activity can be measured and correlated to the integral incident neutron exposure. This measurement and correlation can only be performed after the irradiation is complete and the flux wire or foil is removed from the reactor.

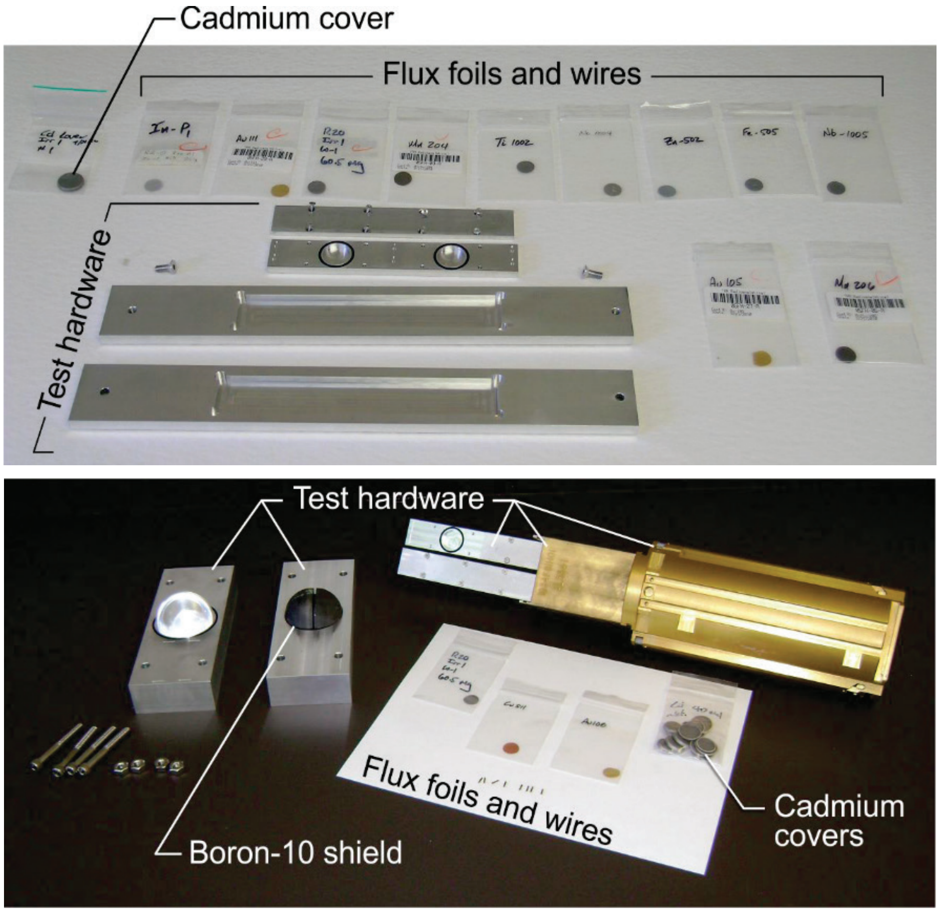


Figure 29. Representative flux wires, flux foils and test hardware used at INL [33].

5.2.2.4 Gamma Thermometer (capability under development)

5.2.2.5 Micro Pocket Fission Detector (MPFD)

MPFD technology utilizes the same concept as coaxial fission chambers, but with a different geometry using parallel plate electrodes instead of coaxial cylinders, as shown in Figure 30. This design is known as a parallel plate fission chamber. However, the MPFD design is distinguished from other fission chambers because their signal is not based on the full energy deposition in the electrode gap from the fission products. This departure from conventional fission chamber design and operating characteristics allows the MPFD technology to have a much smaller chamber size with a much lower fill gas pressure. The MPFD design has excellent discrimination characteristics because the energy deposited by the fission products is much greater than other types of background radiation interactions in the detector. Another benefit is that the small size allows them to have a faster response time. Thus, the smaller MPFD design has the potential to achieve higher count rates than conventional fission chamber designs. The construction materials chosen for the MPFD technology includes temperature and radiation resistant ceramics. All of these characteristics make the MPFD technology well-suited to survive the harsh conditions present in TREAT experiments.

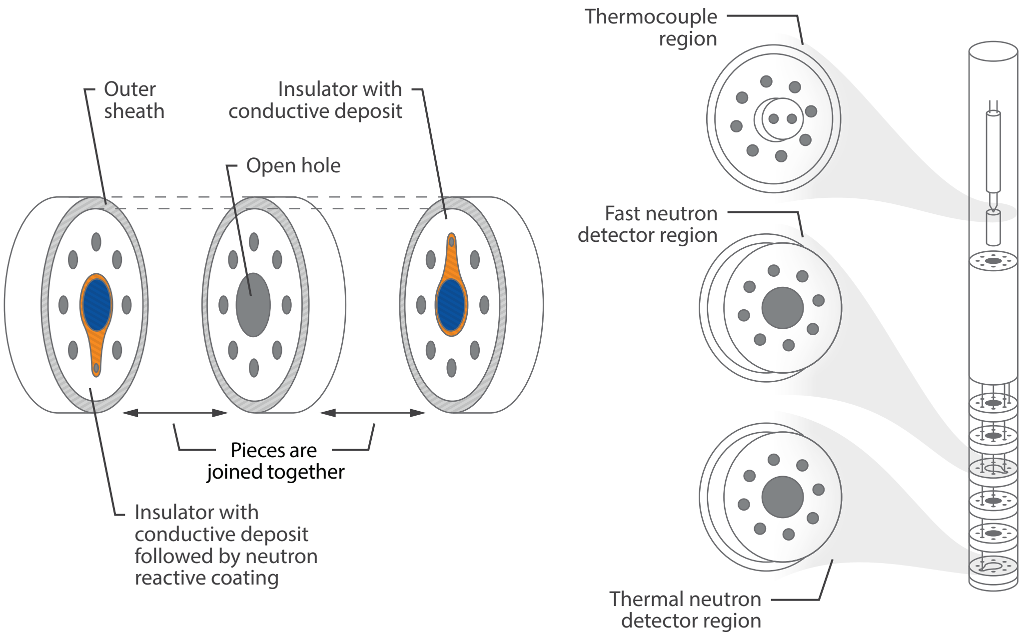


Figure 30. Round geometry MPFD design suitable for TREAT experiments and illustration of test assemblies.

5.2.3 Temperature measurement

Temperature measurement capabilities for TREAT experiments include state-of-the-art approaches utilizing a variety of thermocouple configurations for cladding temperature measurements and next generation approaches using fiber optics and ultrasonics.

5.2.3.1 Thermocouples

Thermocouples are the general standard in-pile thermometry tool. They have been used for measurements supporting experiment operation to measure coolant condition and temperature in various locations across a nuclear fuel system, including outer and inner cladding and internal fuel temperatures. There are several types of thermal couples used in TREAT experiments, such as type C, type K, and type R. Type C thermocouples with HFO_2 insulation and Mo-Re sheaths to measure fuel centerline temperature and specially developed zirconium sheathed thermocouples for cladding surface temperature measurement. These thermocouples were uniquely optimized for application to nuclear fuel rods in prototypic environments. Type K sheathed thermocouples with 1-mm diameter are typically used for experiments with attachment to flow tube hardware near specimens (not directly on specimens).

5.2.3.2 Infrared (IR) Pyrometry

IR pyrometry offers non-contact, high-temperature, and fast time response capability for temperature measurement on cladding surfaces. There is effectively no theoretical temperature limit for pyrometry measurements, and existing systems beyond the melting point of uranium dioxide (2865°C). This measurement capability has strong advantages for the accident condition testing in TREAT where specimen temperatures can reach extreme temperatures, which are accessible to few measurement techniques. A pyrometer is used to measure cladding temperature with time resolution adequate for RIA with minimal impact to cladding. An image from the out-of-pile testing of the pyrometer optical line can be seen in Figure 31 below. Table 2 presents a comparison of important figures of merit for thermocouple and pyrometer measurements currently used for experiments at the TREAT facility. These values are generalized for comparison purposes, and caveats may exist in some cases.

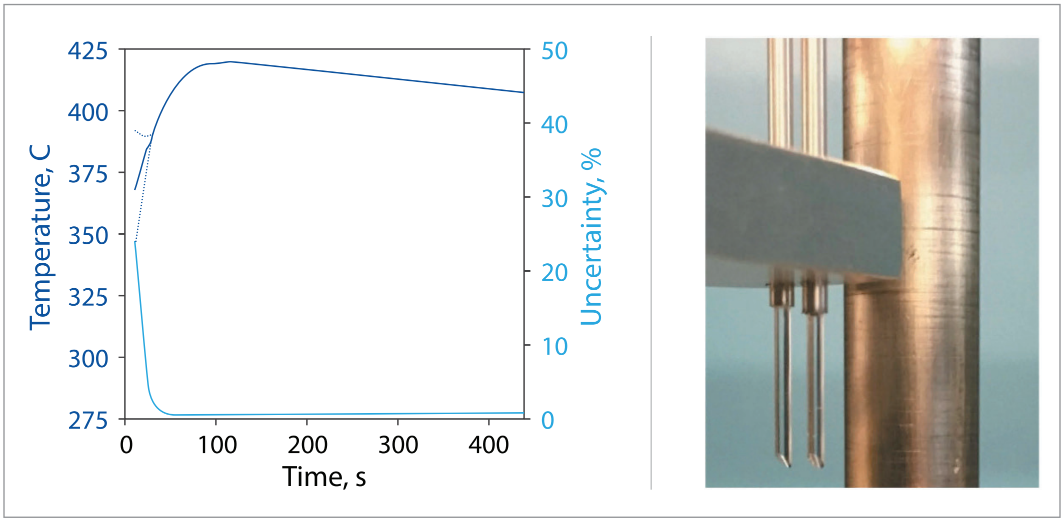


Figure 31. Image of the distal end of the optical line for the fiber optic–based infrared pyrometer aimed at a surrogate fuel rod [1].

	Thermocouple	***Infrared Pyrometer (current capability)***
Minimum time response (ms)	*100 (approximate for 6 mil wire bare junction)*	*5*
Device uncertainty (ΔK)	*2 for T < 1700 K* *4.5 for T < 2600K*	*<5*
Fin Effect (ΔK)	*150 K*	*Not applicable*
Maximum Temperature (K)	*2600 (Type C)*	*3300*

Table 2. Performance comparison of temperature measurement techniques used in TREAT Experiments [1].

5.2.3.3 Distributed Temperature Sensor (DTS)

Distributed temperature sensing DTS systems are optoelectronic devices which measure temperatures by means of optical fibers functioning as linear sensors. Temperatures are recorded along the optical sensor cable, not at points, but as a continuous profile. A high accuracy of temperature determination is achieved over great distances. Typically, the DTS systems can locate the temperature to a spatial resolution of 1 mm with accuracy of 2.8°C at a resolution of 0.1°C.

5.2.3.4 Ultrasonic Thermometry

Ultrasonic thermometry has the potential to improve upon temperature sensors currently used for in-pile fuel temperature measurements. It enables distributed temperature measurements up to 3000°C demonstrating the reliability of magneto strictive material transducers under irradiation. The ultrasonic thermometer is currently under development with research focused on waveguide design optimization and unfolding signal response of distributed measurements. The figure below shows an example of the ultrasonic thermometer which will be irradiated in the BR-2 reactor in Belgium. Similar sensors can be used for TREAT experiments.

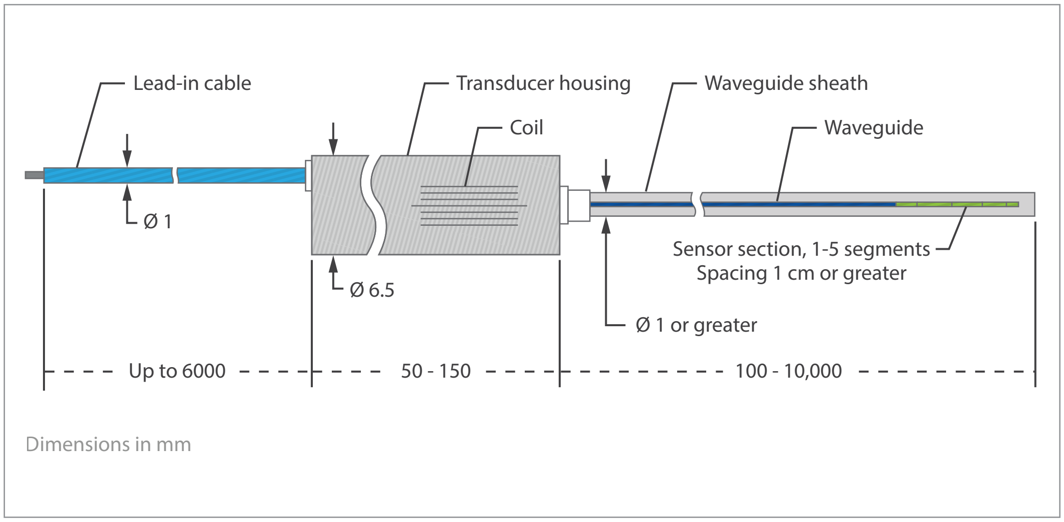


Figure 32. An example of ultrasonic thermometer used in one of irradiation experiments at BR-2 reactor in Belgium.

5.2.4 Dimensional Measurement

5.2.4.1 Linear Variable Differential Transducers (LVDT)

LVDT-based sensors are electromechanical transducers which converts the mechanical movement of a specimen into an electrical output in a simple and reliable manner, as shown in Figure 33. They have been proven to be versatile instruments with a long history of in-pile applications [22]. TREAT utilizes LVDTs integrated directly into fuel and cladding elongation measurements.

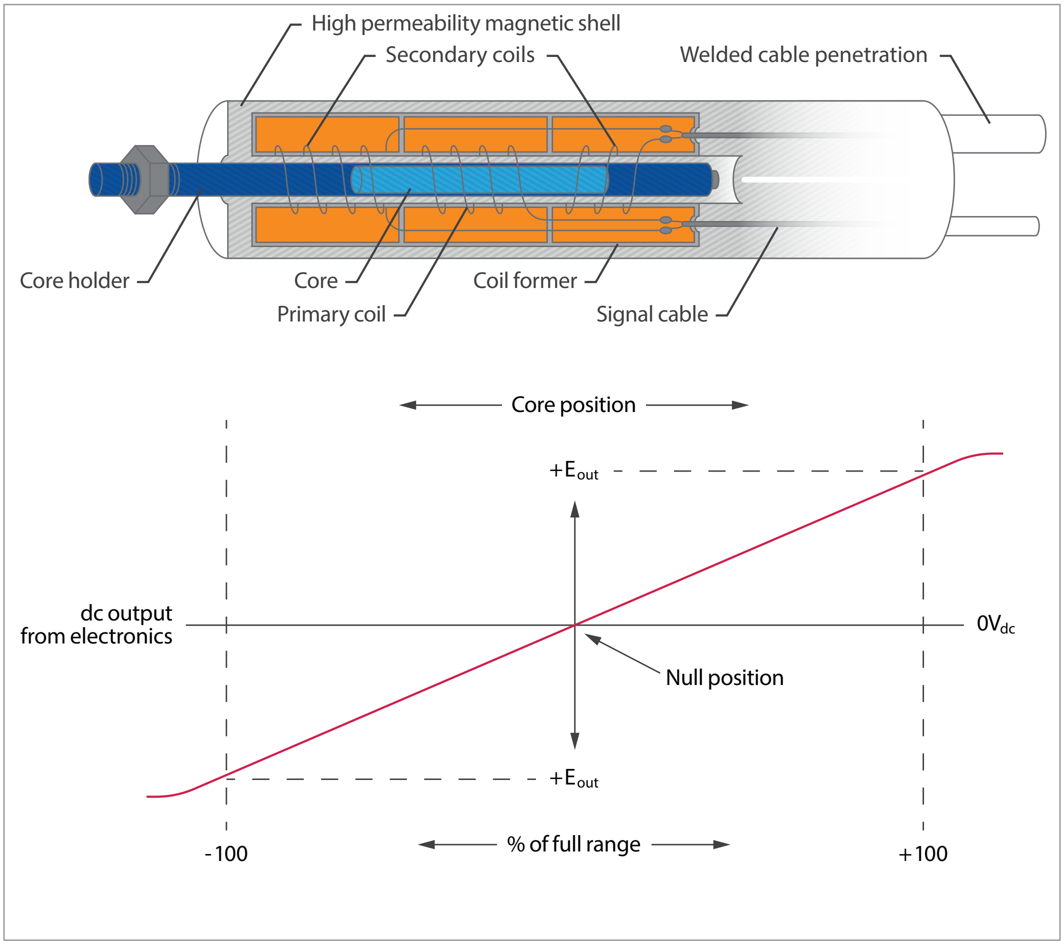


Figure 33. Cross section of basic LVDT design and displacement/electrical output curve.

5.2.4.2 Fiber Optical Sensor for Distributive Strain and Displacement Measurement

The optical fibers are not only capable of measuring temperature as described in Subsection 5.2.3, but can also measure strains cross the fiber for Distributive Strain Measurement. The technique employs a Rayleigh optical frequency domain reflectometry technology, which measures strain at a spatial resolution of 0.65 mm along the length of a standard optical fiber.

The fiber optical sensor can also be used to measure displacement, including fuel elongation. Fiber-optic elongation sensor used in TREAT is based on Fabry-Perot interferometry, as shown in the Figure 34.

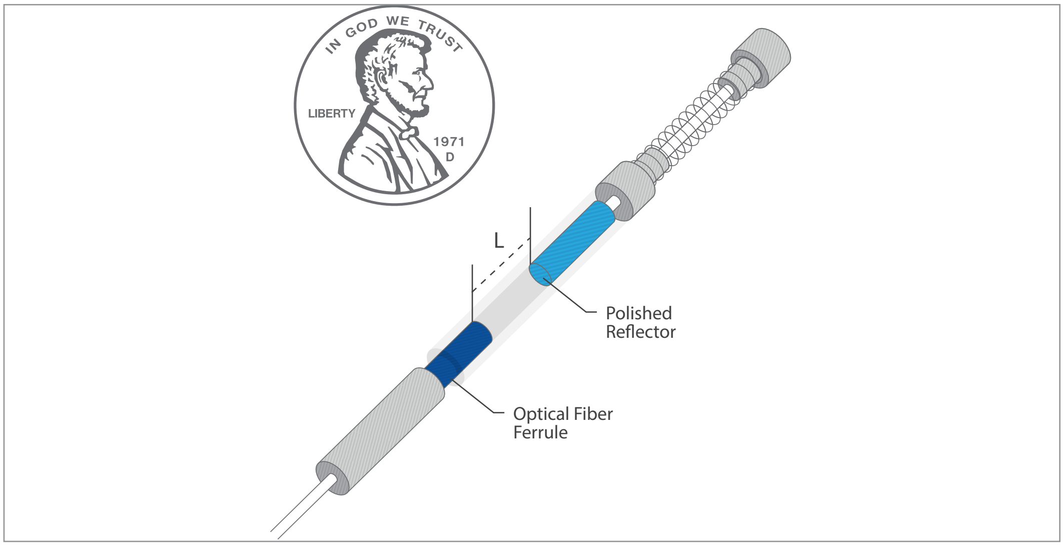


Figure 34. Photograph and rendering of displacement sensor.

5.2.5 Pressure Measurement

5.2.5.1 Pressure Transducers

Pressure transducers, based on a variety of transduction principles, are typically used to measure test specimen environment pressure as well as fuel rod plenum pressure to assess transient fission gas release. A wide variety of pressure transducers have been used over many decades. Frequently, commercial transducers have shown sensitivity to transient irradiation fields requiring experiment designs that place the sensor out of the high flux region of the experiment and/ or the addition of shielding materials around the sensor. Some designs have shown minimal influence from transient irradiation effects with an excellent response rate and a variety of measurement ranges [23]. TREAT has implemented several types of pressure sensors that are robust and reliable for use in experiments.

5.2.5.2 LVDT Bellows

LVDT bellows can also be used to indirectly measure the fuel rod plenum pressure, which was an approach developed and often used in the Halden Reactor Projects, as shown in Figure 35 [24].

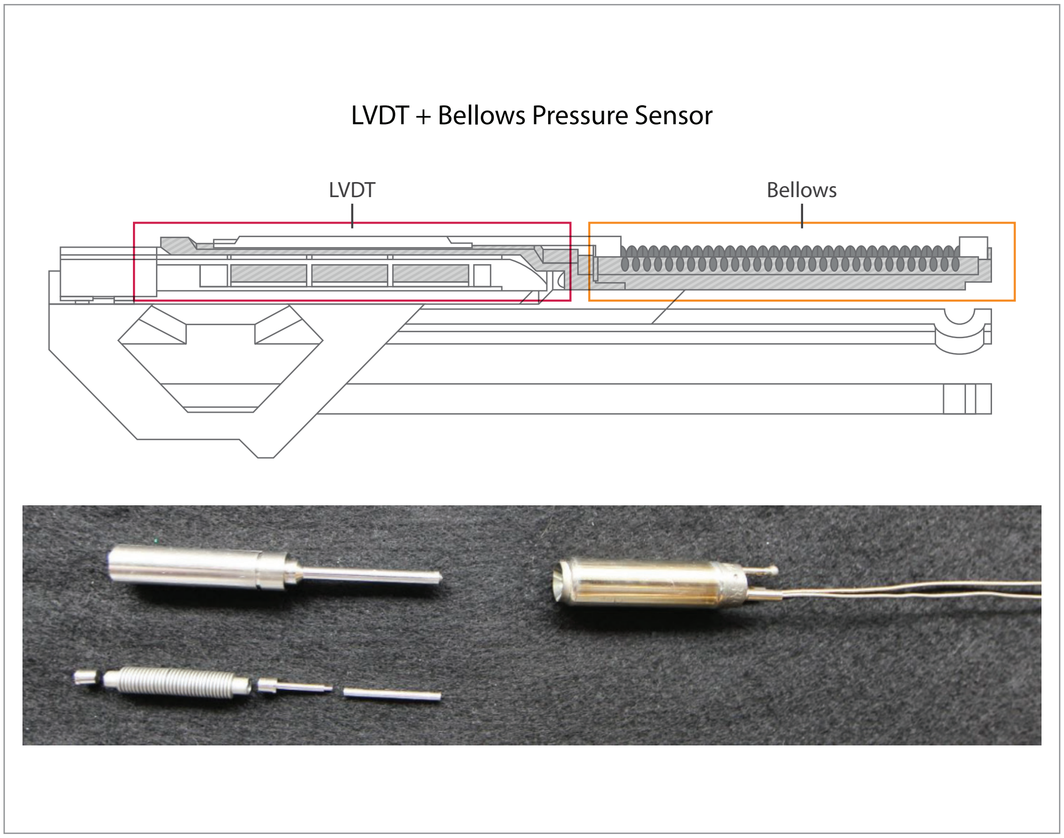


Figure 35. LVDT bellow and pressure sensor components.

5.2.5.3 Optical Fiber Pressure Sensor

The optical fiber pressure sensor is an extrinsic Fabry-Petrot pressure sensor which can withstand high operating temperature and irradiation field [34]. Extrinsic Fabry-Perot sensors utilize the interference of light between two reflecting surfaces. In this design, the ends of the fiber and diaphragm serve as the reflective surfaces. This design minimizes the impact of radiation effects, since it is based on an interferometric measurement instead of a magnitude measurement. The diaphragm deflects (toward the fiber) due to external pressure on the sensor. The diaphragm's thickness and diameter are the main parameters used to modify the pressure range of the sensor. The pressure sensor can be fabricated from stainless steel 304 and 316 which provide corrosion resistance and robust high temperature performance. These stainless steels were used for the ferrule, sensor body, diaphragm, protective tube, and lead-out capillary tube. A single mode optical fiber is used in the sensor. For higher radiation tolerance, a pure silica core with an F-doped cladding is recommended. For low-dose applications, the material composition of the glass is less important. For high-temperature applications, the fiber coating should be considered. The most common optical fiber coatings include acrylate, polyimide, and metal (mainly aluminum, copper, and gold). An example of fiber optic pressure sensor is shown in Figure 36.

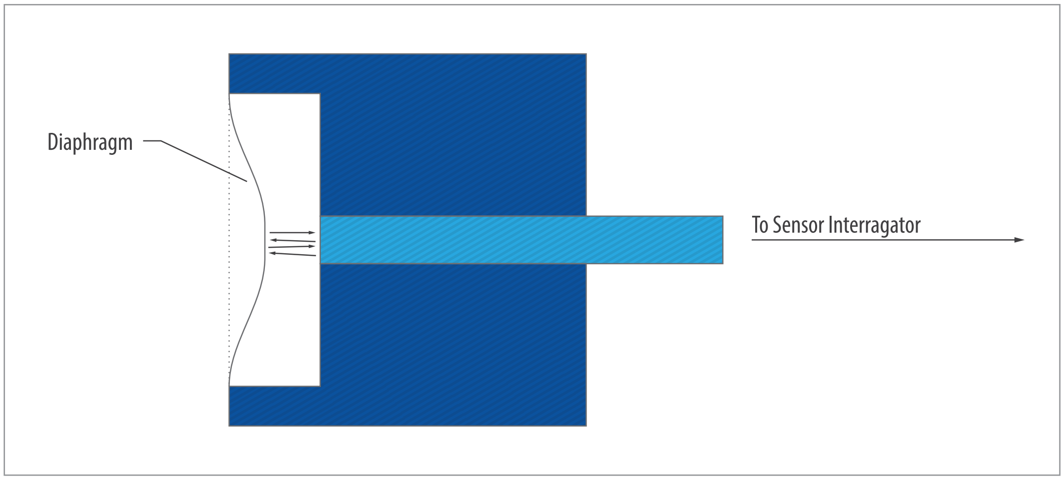


Figure 36. Sensor diagram showing the overall working concept for an extrinsic fiber optic Fabry-Perot pressure sensor.

5.2.6 Coolant Phase Change by Electro Impedance (Boiling Detector)

For water-based tests, a high-speed electrical-impedance based boiling detector has been developed [25]. This instrument measures the electrical impedance between two electrodes that surround a fission heated fuel rod in a water capsule in the TREAT facility. The impedance is a function of the capacitance between the two plates, which is dependent on the permittivity of the material between the plates. The relative permittivity of water and steam significantly differs resulting in good measurement sensitivity to the presence of steam in water. Shown below is the cross section of the sensor. The top of the sensor shown as the "pickup electrode" is the representation of the boiling test design for the in-pile fuel testing. The bottom of the sensor shown as the "driver electrode" is the representation of the coated detector electrode plate used for measurements in liquid water to 300°C. The boiling detector is especially important to understand the heat transfer between fuel cladding and the surrounding coolant under transient scenarios involving critical heat flux (CHF) and departure from nucleate boiling (DNB) [26]. This device is also being used as a semi-quantitative water level sensor in the TWIST design.

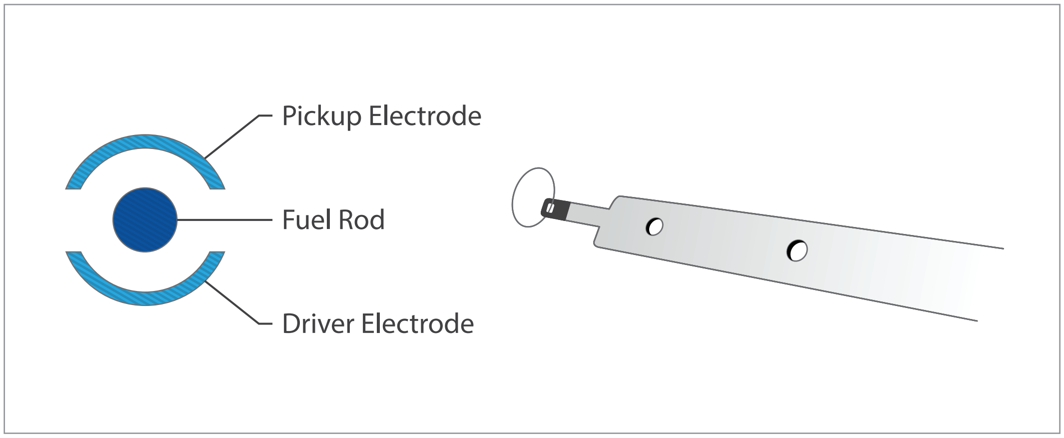


Figure 37. Cross section of electro impedance sensor.

5.2.7 Loop Flow Measurement

Flowmeters have been deployed in both LWR and SFR transient testing experiments. Many devices, based on a variety of operating principles, are available commercially. Turbine flowmeters are commonly used in loop-type applications. Unique permanent magnet flowmeters were used in the sodium loops in TREAT for SFR testing [27].

5.2.8 Fuel Failure Detection

Capturing and understanding fuel failure are crucial for transient experiments. Various sensors and measurement techniques described previously can be used for detecting fuel failures during the transient tests and are summarized and re-emphasized here.

5.2.8.1 Acoustic Emissions Detection

Acoustic detection has been used to provide data relating to the timing of specific events of interest including boiling, fuel-coolant interaction, cladding rupture, etc. The acoustic sensors are readily available for TREAT experiments.

5.2.8.2 Pressure Measurement

As previously described, pressure of the experiment systems such as the rod internal pressure in a test fuel rod or assembly, can be measured using pressure sensors, LVDTs, and fiber optic pressure sensors. The rod internal pressure changes while the rod has significant dimensional changes or even burst, so pressure is a good indication of rod failures.

5.2.8.3 Fission product detection systems

Late in its operational history TREAT incorporated an experimental system that detected gamma emission from fission products in the upper cover gas region of the experiment vehicle. This capability is currently not available at TREAT but could be made available to the users when there is a critical need to restore this capability.

5.2.8.4 In-pile high-speed videography

In-pile videography can be used to directly image the behavior of nuclear fuel under transient conditions. High-speed video has provided invaluable information on fuel motion and coolant voiding behaviors. TREAT has two penetrations that can deploy special video systems to monitor detailed fuel behaviors under power transients. One of the penetrations is used for the hodoscope, the other one is unused but can be made available by demand.

5.2.8.5 Hodoscope

The hodoscope was described in an earlier section as an NDE technique to monitor fuel movement during transient tests and is a crucial tool to understand fuel behaviors and failures in accidents, such as fuel relocation and disposal in LOCA.

6. Available Support Services, Equipment, and Specialized Facilities

The supporting equipment and facilities are subject to change because experiment programs conducted at the TREAT facility are constantly being updated to meet specific needs. The general TREAT Experiment Supporting Facilities are shown in Figure 38 and described in the following sections.

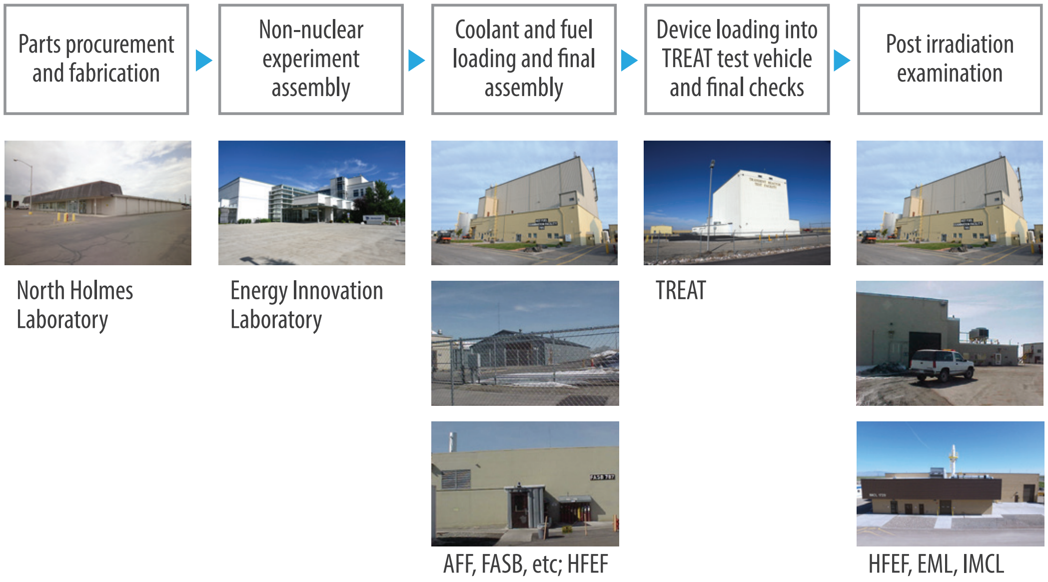


Figure 38. TREAT experiment supporting facilities.

6.1 Procurement and Fabrication

TREAT experiment parts can be procured and fabricated at qualified supplier sites, such as North Holmes Laboratory (NHL) at INL site.

6.2 Non-nuclear Experiment Assembly

The non-nuclear experiment assembly can be put together under the INL quality assurance program at the Measurement Science Laboratories located at the Energy Innovation Laboratory (EIL), including the test modules and sensors [7,8].

6.3 Fuel Loading and Final Assembly

The experiment assembly is loaded with fresh fuels at one of the fuel fabrication facilities at the Materials and Fuel Complex (MFC), such as the Advanced Fuel Facility (AFF) [10], the Fuel and Applied Science Building (FASB) [11], and the Experimental Fuels Facility (EFF) [12]. AFF features a range of material handling and fuel fabrication capabilities used for advanced manufacturing processes, such as spark plasma sintering (SPS), laser welding, and 3-D printing. AFF has radiological space where uranium nuclear fuel is routinely handled. FASB is a radiological facility housing small hot cells, gloveboxes, hoods, and a variety of equipment supporting fueling irradiation experiment assemblies for ATR and TREAT. EFF houses a wide range of fuel fabrication and material handling capabilities, including uranium and uranium alloy casting and extrusion, processing uranium metal and ceramics at all enrichments, fabrication and handling of alloys and powders, and a machine shop with radiological and non-radiological areas. These fresh fuel facilities are used for the final assembly of TREAT experiments with fuel loading, and can perform all required quality checks including dimensional measurement, leak test, non-destructive examinations such as x-rays, etc. The experimental assembly that requires fueling with irradiated fuels will be handled at the large argon filled hotcell Hot Fuel Examination Facility (HFEF) and transferred between TREAT and hot cells using the specialized, shielded transfer cask HFEF-15.

6.4 Post Irradiation Examination (PIE)

After TREAT transient tests, the experiments are left in TREAT storage holes to cool until they are safe to be transferred to the PIE facilities for further examination. The TREAT experiments can be transferred to one or all the PIE facilities at MFC including the HFEF [9], the Irradiated Materials Characterization Laboratory (IMCL) [14], and the Electron Microscopy Laboratory (EML) [13].

HFEF is a national research asset with the largest inert atmosphere hot cell dedicated to nuclear materials research in the U.S. It provides the ability to remotely handle and perform detailed nondestructive and destructive examination of highly irradiated fuel and material samples. Its argon-atmosphere hot cell, labs and special equipment handle a variety of fuel forms, including tiny particles, four-foot research reactor plates and full-sized commercial rods. The routine PIE activities at HFEF include visual exams, neutron radiography at the NRAD reactor, fission gas analysis in fuel rods (GASR), dimension measurements, precision gamma scan (PGS), optical microscopy, radiochemical analysis, mechanical tests, etc. TREAT experiments requiring irradiated fuel and materials handling activities are assembled in HFEF, such as the TWIST for irradiated LWR fuel LOCA test and MK-IIIR for irradiated metallic fuel in sodium loop tests.

IMCL focuses on microstructural, microchemical, and micromechanical analysis, and thermophysical characterization of irradiated nuclear fuels and materials. IMCL's unique design incorporates advanced characterization instruments that are sensitive to vibration, temperature, and electromagnetic interference from modular radiological shielding and confinement systems. The shielded instruments allow characterization of highly radioactive fuels and materials at the micro, nano, and atomic levels, the varying scales at which irradiation damage processes occur.

EML is a classified laboratory dedicated to the materials chemical, thermal, and microstructural characterization, primarily using electron and optical microscopy tools. It contains a shielded glovebox and several fume hoods for TREAT experiment disassembly and sample preparation for electron microscopy.

The fact sheets for the facilities listed above are available in references [7-14].

7. Begin Your Journey

Prospective experimenters interested in TREAT may contact the current TREAT program manager and TREAT technical lead at treat@inl.gov. Approval by the Irradiation Work Acceptance Executive Committee at INL is required for all TREAT experiments. The TREAT program manager and technical lead will assist external users in the approval process. For general questions about nuclear materials irradiation tests, contact the Nuclear Fuels and Materials division at irradiationtesting@inl.gov.

Various funding opportunities are available from DOE for external users, including the NSUF program, GAIN voucher program, as well as NRIC.

For university researchers using TREAT through the Nuclear Science User Facilities program, visit nsuf.inl.gov or email nsuf@inl.gov for the latest information.

For industry developers of advanced reactors seeking TREAT access through a Nuclear Energy voucher, contact the Gateway for Accelerated Innovation in Nuclear at gain@inl.gov or visit gain.inl.gov.

The National Reactor Innovation Center (NRIC) is a national DOE program charged with aiding developers committed to demonstrating advanced reactors. Questions about assistance through NRIC can be sent to nric@inl.gov or visit nric.inl.gov for more information.

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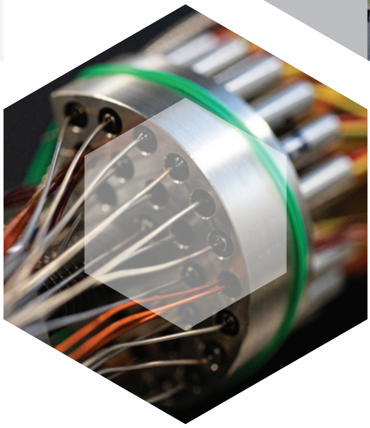
9. Figures and Tables

Figures

Tables



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