TREAT Core Instrumentation Plan

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David Carpenter and Lin-wen Hu
MIT Nuclear Reactor Laboratory

Introduction

The Transient Reactor Test (TREAT) Facility at Idaho National Laboratory is currently undergoing preparation for restart; the facility has been in a shutdown condition since 1994. TREAT first became operational in 1959 and had one major upgrade in 1988. However, many of the reactor systems retain their original design and components. [1] In support of the restart project, investigations are taking place into the refurbishment and upgrade of TREAT systems with modern technology. This work investigates possible modifications to the reactor's instrumentation that takes advantage of new sensor and data acquisition technology. New instruments may expand the measurement capabilities of the facility with extended ranges, faster response times, higher precision, better spatial resolution, and more thorough data logging. This instrumentation is intended to supplement the currently installed sensors, although they may eventually supplant the original components.

Review of TREAT Core Design

The TREAT reactor core design is modular, consisting of a regular 19x19 grid of square assemblies. These assemblies come in a variety of configurations including several variations of fueled assembles, graphite reflector assemblies, and assemblies with open slots to permit viewing from one of the side mid-plane access holes. In addition to these existing standard assemblies, custom designs created to accommodate in-core experiments may be placed in essentially any position within the core. Around the perimeter of this grid is a fixed graphite reflector region, which is in turn surrounded by high-density concrete biological shielding. [2] Above the core is a steel shield plug over the upper plenum where air coolant is drawn into the structure. The upper core structure consists of clamping bars along each edge of the core that secure the assemblies together in a self-supporting grid. At the bottom of the core the assemblies sit in a steel grid plate over the lower outlet air plenum; high-density concrete forms a break between the reactor cavity and the sub-reactor control rod drive mechanism room.

There is extremely limited instrumentation inside the core region. The 14 six-inch diameter "instrument holes" shown in Figure 1 are used for ion chambers and proportional counters to monitor the neutron flux. These penetrations extend only up to the edge of the permanent graphite reflector. Within the core there is only temperature instrumentation; there are six types of thermocouple instrumented assemblies (see Figure 2 for an example) with K-type thermocouples attached in various locations within fuel blocks, graphite reflector, and outer zirconium surfaces. The instrumentation is designed around two main operating regimes: steady-state and transient. Steady-state operation extends up to 80-100 kW, which represents the heat removal capacity of the forced-air cooling system. While this system is not required during transient operation and is normally deactivated before a test is performed, during calibration it is needed to stabilize the pile temperatures. At source range, TREAT has boron proportional counters located in similar positions to the ion chambers to monitor the approach to criticality. During a transient test, ion chambers are used to monitor power and period as the reactor control system carries out pre-programed control element movements.

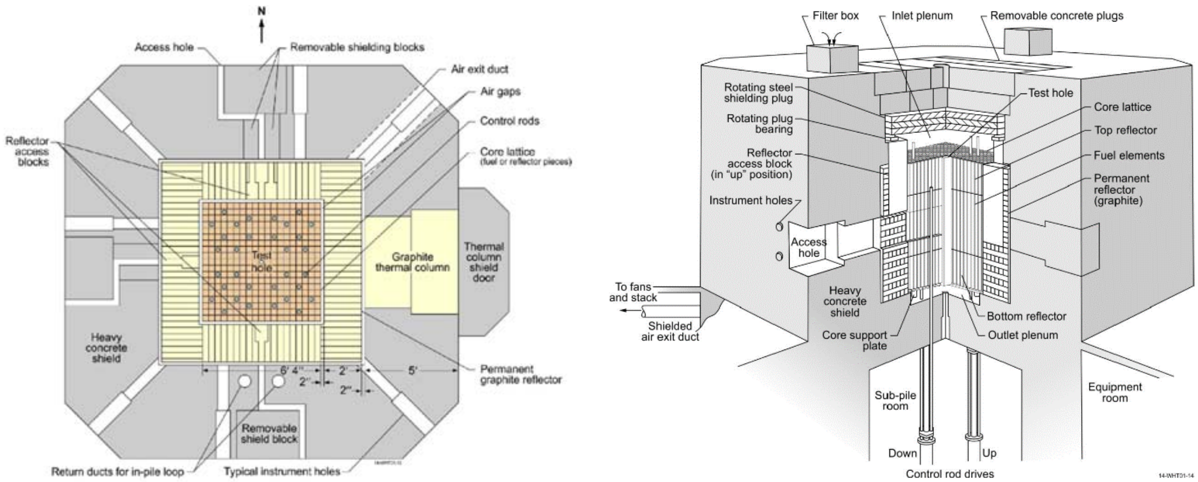

Figure 1. Plan and side vies of the TREAT core. (Bess and DeHart, 2015)

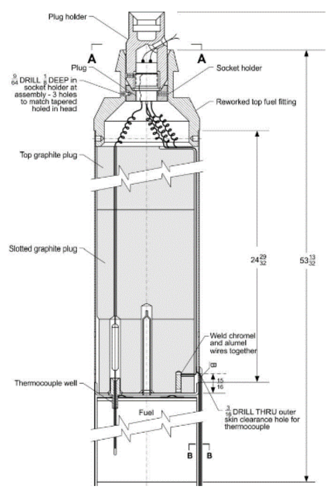

Figure 2. Example of a thermocouple-instrumented TREAT fuel element with both fuel meat and skin attachments. (Bess and DeHart, 2015)

The primary experiment location is at the center of the core, where partial or full elements can be removed, and the facility is aligned with the large access ports on each face of the reactor and its axial centerline. A second similar position is available 36 inches south of the central one. Historically the central location has been used for large experiments, and it is the planned location for the capsule-based SERTTA and TWERL water loop facilities currently being designed by INL. Instrumentation for this position can be run along air channels above or below the core to penetrations in the top shield, and (with additional modifications) through channels directly above and below the core centerline (Figure 3). Additional opportunities for in-core instrumentation exist adjacent to the central position (in the partial assemblies that are required to maintain core stiffness) and in reflector assemblies, especially in the outer region of the core.

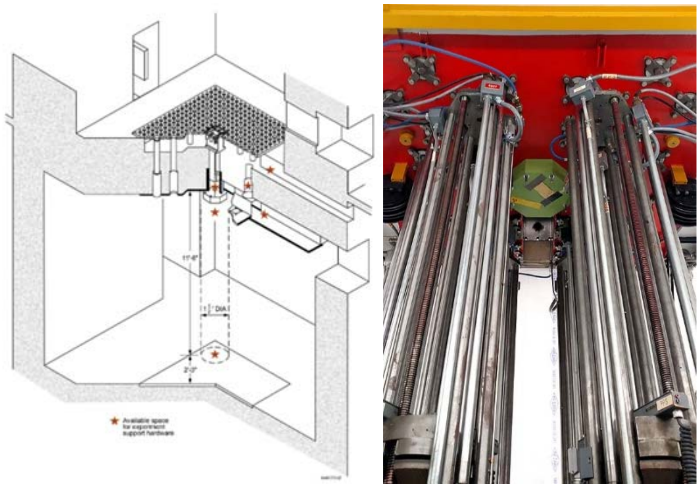

Figure 3. Locations for instrumentation and lead-outs in the lower plenum (Bess and DeHart, 2015) (left), and photo of central penetration plug from control rod drive space.

Outside of the core there are four large access ports on each face of the reactor (Figure 4), two of which have dedicated facilities (neutron hodoscope and radiography station). These positions, as well as the smaller instrumentation tubes and a periscope port to the upper plenum, offer the possibility of additional locations for measurements and sensor tests in a lower flux environment with substantially more space for equipment and relatively easy access. In the past these have been used for high- and low-speed imaging with neutrons and gammas, as well as photography.

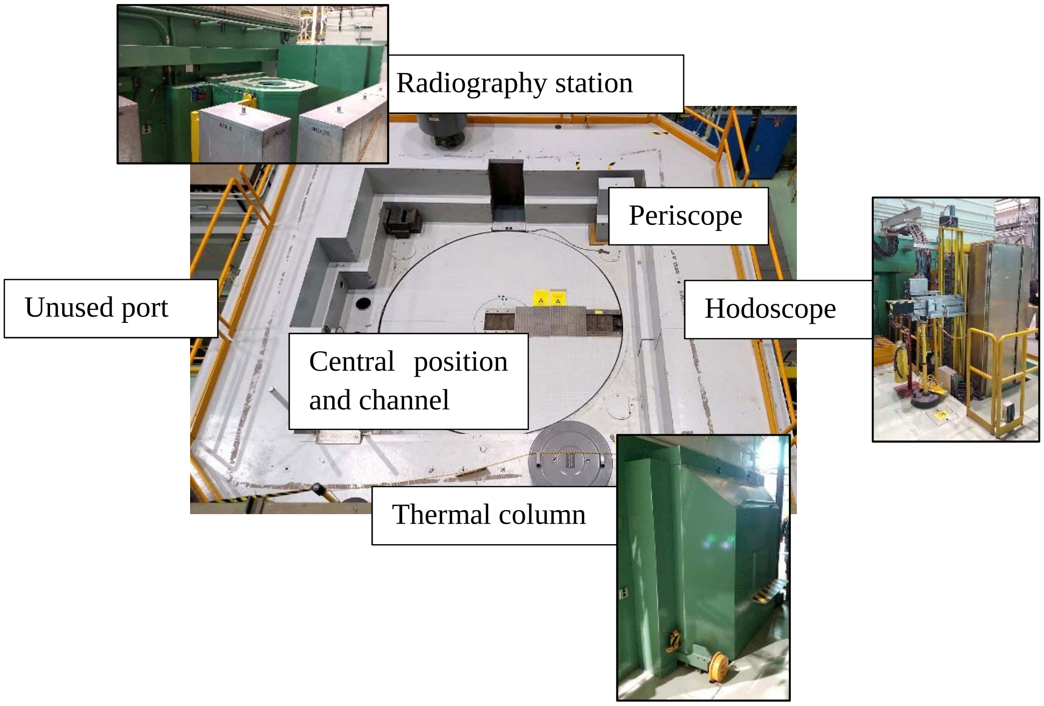

Figure 4. Views of major port facilities and their locations.

As an air-cooled reactor in a filtered, but only lightly conditioned, confinement TREAT is designed to be tolerant of the mild atmospheric conditions of the region. The materials of the core are primarily “nuclear grade” CP-2 graphite, Al-1100 aluminum, Zr-3 zirconium, and a variety of mild steels and brass. The fuel and reflectors are CP-2 graphite and a uranium-carbon mixture. The design of the fuel and reflector assemblies promotes low thermal gradients in the core during steady-state operation and a large thermal mass to heat during transients.

Core Parameter Monitoring

TREAT can operate up to 100 kW steady-state power and 18 GW in transient pulse mode, which presents a wide range of conditions for potential instrumentation. For operation of the reactor the critical parameters are reactor power and temperature. These are easiest to determine during steady-state operation when thermal equilibrium has been established in core. The reactor power can then be determined based upon a heat balance (where the flow rate and inlet/outlet temperatures of the air coolant are known, along with the air thermophysical properties and an estimate of heat losses to the structure). The original configuration of the TREAT reactor has all of the neutron detectors located well outside of the core region in the horizontal instrumentation ports, which terminate at the edge of the permanent graphite reflector. With the power determined through the heat balance, the position and gain of these detectors can be adjusted to give the desired range of readings – some optimized for steady-state and other for high-power transient conditions.

These neutron flux measurements then form the primary means of feedback for controlling the reactor, as well as inferring the neutron flux in the experimental facilities. These detectors are also used to determine the reactivity worth of control elements during physics testing. The relation of neutron flux within the core to that of the detectors is made by a power coupling factor (PCF). [3] Tests are conducted by inserting previously-calibrated fission chambers and self-powered detectors into the central experiment position to measure core power directly, and comparing the results to measurements made at the standard external detectors to determine a general PCF. During normal operations, the PCF is determined for each experimental facility design during the steady-state calibration using information from activation wires/foils placed within the core and then removed from the reactor and analyzed to determine total fluence. This can be repeated with foils irradiated during transients for post-test comparison and estimation of PCF at higher powers and temperatures.

Monitoring core temperatures is also critical to reactor safety, however this is limited in practical usefulness for control due to the larger time constants involved in heat transfer. TREAT was designed with thermocouple-instrumented assemblies to monitor both fuel meat and cladding temperatures. This is useful during steady-state operation but does not respond fast enough during pulsed operation when temperature limits might be challenged. Instead, based upon the steady-state conditions the peak allowable energy deposition is calculated and this informs the permissible transient program.

Other parameters besides neutron flux and temperature may be of interest to reactor operations. The gamma flux will generally follow the neutron flux and responds nearly instantaneously to changes in reactor power. Additionally, it is not attenuated as severely as neutrons by the graphite reflector, which makes it less sensitive to changes in the fuel and reflector arrangement. Geometric changes to the fuel elements are also important, and the strain of the elements could be measured in order to capture phenomena such as swelling and bowing.

Performance Requirements

The requirements for temperature monitoring during TREAT operation are relatively mild; temperatures within the reactor fuel elements are not expected to exceed 600°C during normal operations. [4] This performance can be met by the capabilities of standard commercial type-K (Ni-Cr/Ni-alumel) thermocouples with a range from -270 to 1260°C. Temperature measurements are most critical during steady-state operation for safety and calibration, and at the start of a reactor transient to ensure that the core is at the expected initial conditions. [5] While there is an over-temperature scram function in the automatic control system, in practice TREAT does not depend on temperature measurements for control during transient operations as the short rise times are better handled by neutronics instrumentation; thermal conduction into a sensor would be slow in comparison. The precise response time of the thermocouple depends upon the size of the joint and the thermal contact to the object being measured. Subjected to transient heating, small junctions respond faster but are less reliable, and good contact is difficult to establish and maintain. Experimental reports note the “transient” thermocouples, designed to respond faster to temperature changes, were also likely to fail during experiments. Because they are built in to the assemblies, failed thermocouples have not been replaced. [6]

The nominal maximum steady-state power for TREAT of 100 kW gives a total flux of 1.45×10^{12} n/cm^2-s within the core. The peak transient power of approximately 18,000 MW equates to a total flux of 2.6×10^{17} n/cm^2-s. This five order of magnitude difference in fluxes presents a challenge to the neutron detector setup in the reactor – sensors should be choosen with appropriate range and predictable response curves (i.e.

output with respect to incident neutron and gamma flux and temperature). When considering temporal behavior, the minimum TREAT period is estimated to be 35 ms, while historical detector electronics allowed period measurements to 2 ms. [2] Because the output from these detectors is a current and not individual pulses, detector response time, and subsequent calculation of power and period, is primarily driven by the electronics. The ion chambers used in TREAT are described as parallel-plate boron-coated (both gamma compensated for steady-state and un-compensated for transients are used). This type of detector is described as having a five- to eight-decade possible measurement range. [2, 7]

While the current instrumentation relied on for reactor operations is outside of the core where neutron and gamma fluxes and temperatures are lower, it is hoped that new instrumentation will be able to be installed within the core, where proximity to the experimental facilities and enhanced spatial resolution will improve the ability to monitor and characterize the operation of the reactor.

Selection of Instrumentation

In considering augmenting the current TREAT instrumentation with sensors that may be able to operate in-core, a wide variety of active measurement technologies are of interest. Passive flux and temperature monitors should be used, but this report is concerned with sensors that can provide immediate feedback to monitoring and control systems. For neutron flux measurement, the first sensors to consider are advancements on the existing ion and fission chambers. Ion chambers were the traditional technology of choice for near-core measurement, but are limited by the need for a large chamber volume for the gas media. New ion chambers that are sensitive to either neutrons or gammas are available, but because of their size and relative sensitivity to thermal stresses have not seen as much development for transient reactors. [8]

One technology of particular interest is Micro-Pocket Fission Detectors (MPFD), which are a miniaturized parallel plate-type fission chamber first developed at Kansas State University. [9] These chambers aim to allow measurement in high-flux environments with higher fluence limits and smaller footprint than other types of detectors. [10] It has been possible to construct MPFDs with sub-millimeter diameter electrodes, allowing for very compact designs such as that shown in Figure 5. By varying the composition of the fissile layer, for instance ^{235}U or ^{232}Th, the MPFD can also be made more sensitive to fast or thermal neutrons, providing spectral information in addition to flux.

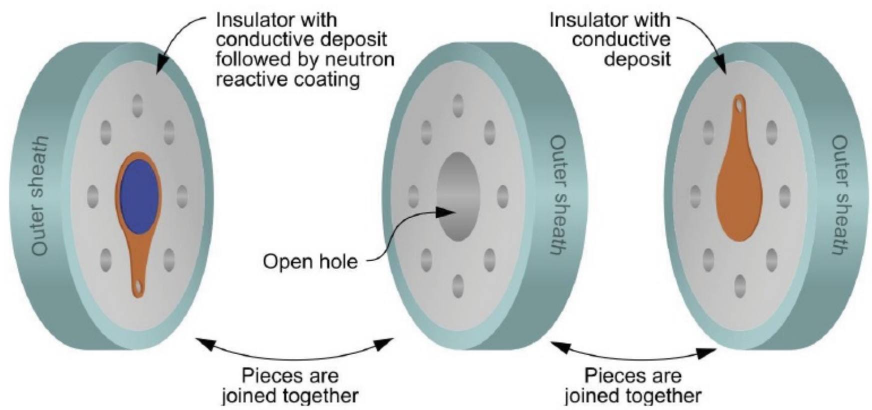

Figure 5. MPFD design (Unruh, 2012)

Other types of miniaturized fission chambers are also available, such as coaxial cylindrical probes being developed by the French Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA). In collaboration with Photonis France S.A.S., CEA have developed commercially-available gas-filled fission chamber probes down to 1.5 mm diameter with quoted ranges up to $5x10^{14}$ n/cm^2-s at 350°C. With this design there are concerns about the survivability of the sensor – the welds are prone to failure (leading to loss of gas hermeticity) and the fissile deposits have de-bonded during transient pulsing. However, it may be suitable for low-energy TREAT transients or placement in the reflector region.

Self-powered neutron and gamma detectors (SPDs) are another technology that is available commercially in a miniaturized form. The traditional problem with these detectors is the slow response time compared to ion or fission chambers as they rely on the activation and subsequent radioactive decay of the emitter, usually on the order of seconds. [12] SPDs have also been designed using "prompt" emitters, such as hafnium and gadolinium, that would be more suitable for use in a transient reactor. In fact, prototype prompt SPDs have been tested in TREAT previously. [13] These sensors have shown promising performance, but are susceptible to both gamma interference, changes in response with temperature, and degradation due to burnup. Going forward, all three of these technologies – MPFDs, miniaturized fission probes, and SPDs, could be used in TREAT depending on the desired conditions.

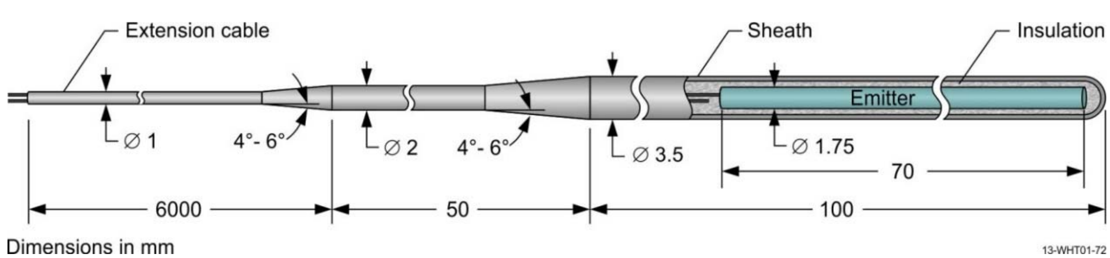

Figure 6. Typical self-powered detector (from Thermocoax).

While temperature measurements have typically been of secondary concern to neutron flux in TREAT operations, new technologies may provide more localized and faster responding measurements that increase their relevance. Modern thermocouple technology is similar to that found in the current TREAT instrumented assemblies, with some reduction in the diameter of cable and junction that can be reliably manufactured. However, the limitations of thermocouples (reliable contact, speed of conduction, size of junction) still make them primarily useful for only steady-state measurements. Several other types of sensors may be able to overcome some of these limitations.

Infrared (IR) pyrometry and intrinsic fiber-optic strain sensing are both being actively pursued. IR pyrometers are commercially available, and use a fiber waveguide to direct the interrogation of a free surface. Traditionally optical-grade fibers have performed poorly in high radiation environments, but the low fluence of a single TREAT irradiation and ability to focus on narrow wavelengths may allow the cable to survive an experimental campaign if it can avoid mechanical damage. This pyrometer would provide a fast reading of the temperature, but limits applicability to directly accessible surfaces of the core. The non-contact nature of the measurement, however, may have significant advantages for certain applications, especially in retro-fitting this sensor to existing elements. With the addition of an active laser reflectometer the emissivity of the surface can also be continuously monitored, improving the accuracy of the temperature measurement as the condition of the material changes.

Fiber strain measurements instead use the fiber itself to gather data by measuring the reflections of waves from defects placed along its length. This can in theory allow down to millimeter-resolution of changes in strain along the entire length of the fiber, allowing either strain or temperature to be inferred. This provides an attractive spatial density of measurements with a single instrument, but it is dependent on maintaining good thermal and mechanical contact over the area of interest.

Calibration Requirements

Detectors will need to be evaluated depending on their construction and position in order to determine the expected neutron and gamma flux, neutron fluence, and temperature range for a given experiment so that their electronics and data acquisition systems can be prepared appropriately. Those neutron detectors with lower activation could be tested in other facilities first, such as was done previously with SPDs in the NRAD reactor at INL [13], in order to establish approximate flux/response curves and aid with initial positioning of the detectors. Temperature probes can also be evaluated over the expected operating regime prior to installation in TREAT.

The absolute calibration available for the neutron flux instrumentation is the thermal power balance of the reactor at steady-state as discussed previously. [3] This is a standard requirement for reactors, and it is assumed that TREAT will continue to operate according to this procedure. Establishing the detector response at 80-100 kW, followed by determining the power coupling between the ex-core detectors and the flux in the central experiment position provides a good baseline at low power. Comparison against activation foils and simulations will still be required to estimate detector response during high power transients, as even with new instrumentation it would not be possible to establish a thermal equilibrium above the primary air cooling capacity of the reactor.

Modern electronics and modeling will allow better evaluation of the uncertainties in the flux and temperature measurements, especially when considering propagation of uncertainties from components of the steady-state thermal balance and impurities/microstructure of the fuel assemblies and experiment vehicle. [14] Additionally, the stability of the detectors against the greater thermal stresses and radiation damage present in-core will need to be evaluated with integrated tests in order to determine an appropriate schedule for re-assessment of function and recalibration. In part this may be tied to the experiment schedule, and whether detectors will be recalibrated with sufficient regularity if done as each new facility is installed in the reactor.

Modern data acquisition equipment will permit retaining much more detailed records on reactor conditions, detector placement, calibration records, and data from reactor operations than currently exists from any previous TREAT operation. This will enable better linkage of experimental data and the provenance of the instrumentation that recorded that data; such information is currently lacking, compounded by previous limitations in the frequency and total capacity of data that could be collected during a single transient program. New data acquisitions systems will permit focusing on not just key neutronics instruments, but detailed analysis of all flux and temperature histories.

Location of Instrumentation

The existing ion chambers and proportional counters are expected to remain in the same horizontal instrumentation ports (Figure 1). Additional space is available in these ports for the detectors, and indeed for the most direct comparison it may be desirable to shadow existing detectors with newer models in order to get an initial relative calibration between the pair. There are four other large and accessible ex-core positions for instrumentation – the upper and lower plena, and the two large radial access ports not occupied by the hodoscope and neutron radiography stations. With the focus on miniaturization, any of the sensors discussed in this report could be positioned in these locations with pathways for cable lead-outs from the sensors to the support electronics.

Within the core there are many different options, and when selecting locations a few guidelines are considered: (1) minimize changes to the configuration of the core; (2) do not require any new type, or physical modification, of an existing element; (3) minimize possible interference with the configuration and operation of experiments. The TREAT core is highly re-configurable, but generally changes to the layout and fuel loading are made only as to accommodate the experiment in the central position. The most practical way to install new instrumentation within the core but outside of the central experiment facility is to create a standalone fixture that can attach to or rest inside of an existing access space.

There are three main areas where such access already exists. In Figure 7 it can be noted that for some experiments not all possible control element positions are used. These unused positions may still contain fueled or dummy vertical access hole assemblies (Figure 8) which can easily accommodate instrumentation inserted down to any axial position. This options provides the largest volume for new in-core instrumentation; the smallest cross section within those assembles is 1.77 inches diameter, and a majority is over 2.5 inches diameter. However, the positions are inflexible and are generally not proximal to the experiment.

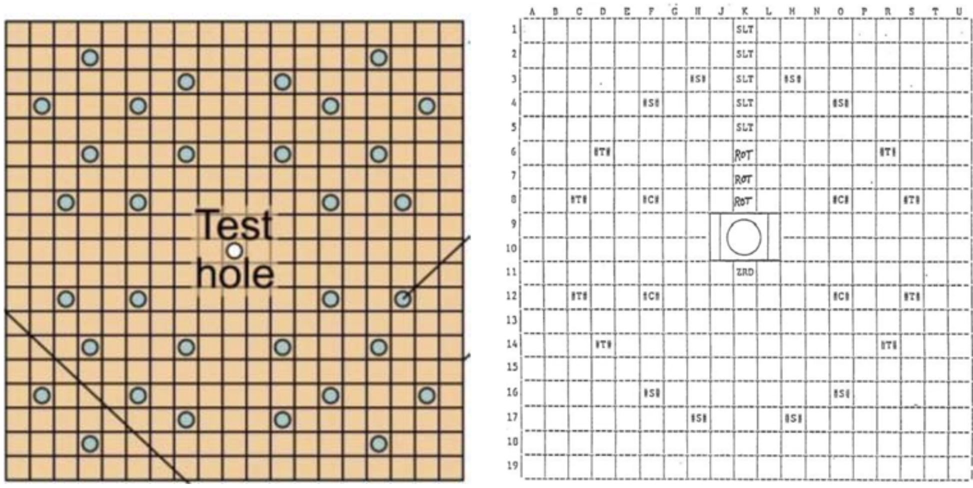

Figure 7. Expanded view of the TREAT core (left) and typical loading for a transient test (right). (Bess and DeHart, 2015)

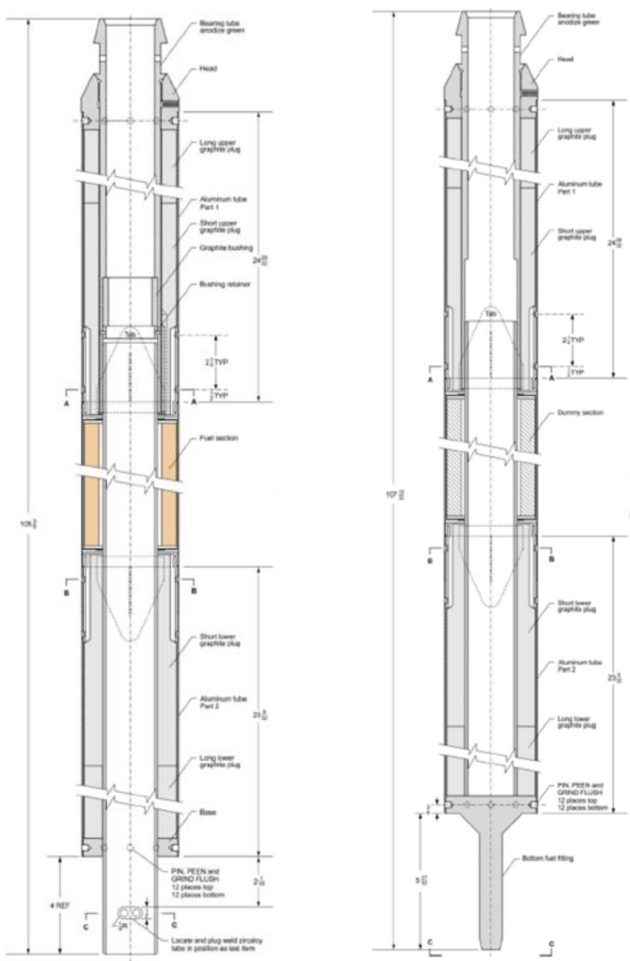

Figure 8. TREAT vertical access hole fuel (left) and dummy (right) assemblies. (Bess and DeHart, 2015)

The next largest positions available are the partial elements located around the central test position. The partial graphite assemblies shown in green in Figure 9 are customized to fit around the shape of the experimental facility is being used. These positions are convenient as they may need to be modified anyway for the experiment, and they are immediately adjacent to the experiment, allowing placement of sensors as close as possible to the test section. Conversely, their unusual shapes and proximity to the test section may restrict the ability to access them or run cabling, and they may need to be replaced with additional frequency as test sections are modified.

The third option is use of the air coolant channels between assemblies. These channels, as shown in white in Figure 9, are 5/8-inch square and offer the most flexibility with regards to general radial position within the core, though not as close to the test section as the partial width assemblies. Blockage of a few coolant channels will likely have minimal impact on the reactor, as forced cooling is generally not used during transient operations. These also offer limited access to the faces of the adjacent assemblies, which further limits the size of sensor that may be employed.

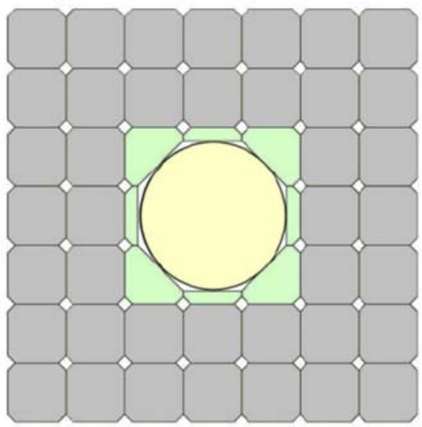

Figure 9. View of TREAT central experiment position and partial graphite assemblies. (Beasley, 2015)

Summary

The existing general neutronics and temperature instrumentation of the TREAT reactor has been described, along with the expected conditions and requirements for its operation. A variety of new sensor technologies has been introduced and considered for applicability in the reactor, and especially for positions within the core. New devices such as MPFDs and fiber optic probes may enable real-time, local measurement of flux and temperature with reliability and spatial resolution around the TREAT experimental positions that was previously not possible. This enhanced capability benefits general the reactor operations as well as the experimentalists and modelers by giving a more complete reconstruction of the in-core environment during steady-state and transient operation.

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