A study of a Helium-3 Injection System at TREAT

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Since restart of the TREAT facility, many programs have been looking at ways they can use the cores' flexible design and large energy deposition, which can be injected on a millisecond timescale, for various fuels and fuel accident research. One such program is looking at ways in which TREAT may be able to provide prototypic pulses for studies of Light Water Reactor (LWR) Reactivity Initiated Accidents (RIAs). To achieve desired RIA testing, pulse widths should be in the magnitude of 25 to 75 ms. TREAT, to date, has only been able to achieve a pulse width of roughly 92 ms through the insertion of eight boron carbide filled transient rods which travel up to 140 inches per second over a 40-in stroke. A modular helium-3 injection system is being studied and designed to modify the core to generate desired prototypic pulses for RIA nuclear fuels testing.

1. Introduction

The Transient Reactor Test (TREAT) Facility has been deemed an optimal place for Light Water Reactor (LWR) Reactivity Initiated Accident (RIAs) fuels testing to be performed. The only problem is that to date it has only been able to produce pulse widths in the 90-ish millisecond range, while studies show that pulse widths for Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) need pulse widths in the timeframe of 25-75 milliseconds. In order to configure TREAT's modular core to reduce the pulse width, a new "clipping" system is needed to reduce reactivity quicker than the current performance of the transient rods. A system using helium-3 gas, a high neutron absorbing material, is being developed for insertion into the TREAT core in order to reduce the pulse widths. With the addition of this system, TREAT will add capability that can subject PWR and BWR fuels to RIA accident conditions better than any research reactor in operation today.

2. Background

2.1. TREAT Overview

TREAT is a graphite moderated reactor that is cooled by flowing air through the core. The core is a 19 by 19 array made up of 4 inch by 4 inch fuel elements, with a ratio of U^{235} to carbon atoms of 1-10,000. The core is very modular allowing for fuel elements being able to be removed to allow for experiments of many shapes and sizes. Since restart only fuel elements in the center location have been removed to allow for such experiments. The Minimal Activation Retrievable Capsule Holder Broad Use Specimen Transient Experiment Rig (MARCH-BUSTER) vehicle cores removed two fuel elements and Big BUSTER cores, anticipated to be reconfigured in late FY 2023, will remove 9 fuel elements but will add additional moderation around a large cylindrical vehicle to interface with the square core. TREAT can supply shaped or pulse type transients designed to expose nuclear fuels to accident type conditions. The reactor can supply approximately 2100 MJ of energy in a pulse transient while energy deposition for shaped transients are dependent on the transient design. Figure 1 and Figure 2 show examples of possible transients performed at TREAT, pulse type and shaped. [1]

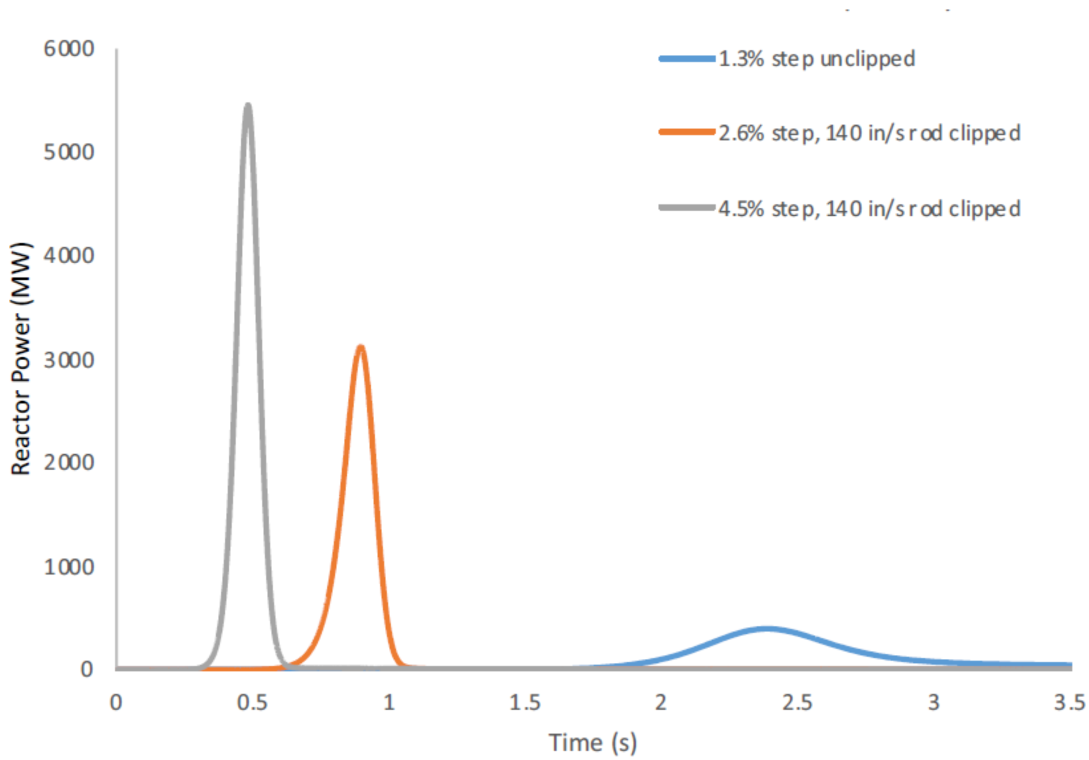

Figure 1: Examples of exponential pulses at TREAT. [1]

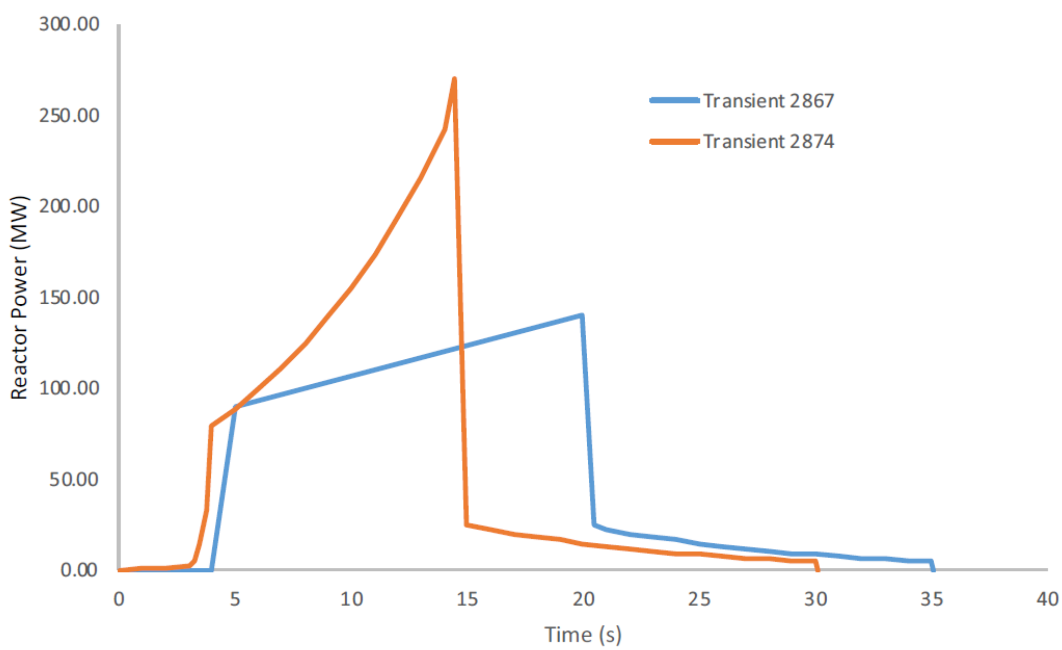

Figure 2: Example of shaped pulses at TREAT. [1]

To control these transients, there are 20 control rods. Eight of the rods are control/shutdown rods, four are compensation/shutdown rods, and eight are transient rods. The control/shutdown rods are used to bring the TREAT core critical and maintain it at power while positioning the transient rods for the prescribed transient. The compensation/shutdown rods are typically out of the core during operation. The transient rods are positioned based on the desired transient prescription and do the majority of the work to achieve the power profiles in the core. Due to the nature of the core operation, providing large amounts of energy in a short amount of time, control of the shaped or pulse transients are done with an automated system known as the Automatic Reactor Control System (ARCS). This computer system is capable of providing an infinite number of transient shapes with the only limit being the reactivity available in the rods. Table 1 shows a table of the characteristics of the control rods. [1]

Table 1: Control rod characteristics of TREAT [1]

Type	**Nominal Reactivity Worth (Core 1469)** [3]	**Effective Length** [2]	**Velocity**	
			Reactivity Insertion [3]	**Reactivity Removal (Clip/Scram)** [3]
Control/Shutdown Rods	0.088 Δk/k	58 in.	20 in./min.	300 in./sec.
Compensation/Shutdown Rods	0.069 Δk/k	58 in.	20 in./min.	300 in./sec.
Transient Rods	0.085 Δk/k	40 in.	Adjustable (0-140 in./sec.)	140 in./sec

Based on improved modeling capabilities, analysts have been able to predict RIA phenomena and what is needed to be reproduced in test reactors. Based on this modeling PWR RIA pulse widths should be in the 25-65 ms range and BWR RIA pulse widths should be in the 45-75 ms range. A study performed in 1998 suggested that TREAT could produce a pulse width in the 71 ms range. However, a trial transient was performed at TREAT in 2019, after restart, which showed in reality TREAT's smallest pulse width that could be achieve was approximately 90 ± 3 ms. This lead to the need for a modification to the core in order to be able to achieve pulse widths to support RIA fuels testing. [1]

2.2. TREAT Pulse Width Reduction Overview

An extensive parametric study was done in 2019 as part of an INL Laboratory Directed Research and Development (LDRD) to determine the best way in which TREAT may be able to reduce the pulse width from approximately 90 seconds to those desired for RIA testing. The study looked at increasing the rod speeds of the existing TREAT transient rods, adding injectable boron pistons, or the use of gaseous helium-3. In addition to these mechanical modifications the study also investigated what occurs when the reactivity insertion is modified. The study showed that while modifying the transient rod speeds could achieve pulse widths suitable for BWR RIA testing, it was not sufficient for PWR RIA pulse widths, in addition stopping the rod motion at the end of their travel was going to be an additional challenge. The study suggested that the boron piston would need to travel at approximately 8,000 inches per second to achieve the desired results and any device needed to decelerate such force was going to be one use components causing additional strain on operations. The final outcome from the study was a helium-3 injection system could be used to achieve the desired clipping of TREAT pulses. The helium-3 study also mentioned that the helium-3 system would need to clip at a rate of -5% Δk/k reactivity in 5 milliseconds to achieve the shortest pulse widths desired. [4] Figure 3 shows the comparison of the increased transient rod speeds and use of a helium-3 injection system compared to the BWR and PWR pulse width ranges. [3] It should be noted that the PWR RIA pulse widths for the lower range are difficult to hit even with the helium-3 system but provides a larger range of pulse widths than the transient rod speed increases.

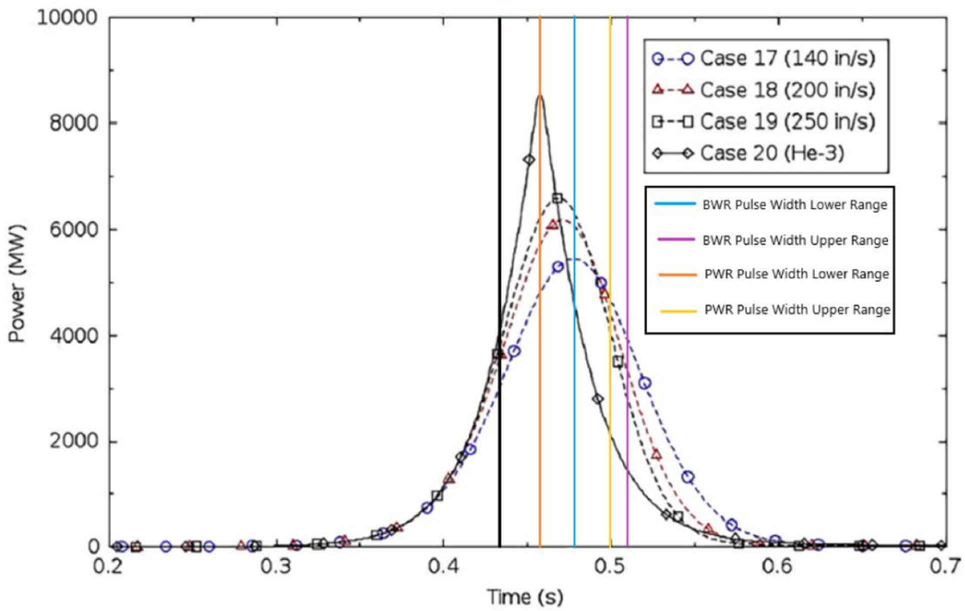

Figure 3: Pulse widths of clipping techniques compared to desired LWR pulse width ranges. [1]

3. Helium-3 System Design

Based on the study performed in 2019, TREAT engineering started to design a helium-3 system for use in the reactor. This system is known as the Helium-3 Negative Reactivity Insertion (HENRI) system. The HENRI system consists of four in-core modules and a recovery system. The in-core module contains three components: driver tank, transfer line, and gas thimble. The modules and recovery system are described in detail below.

3.1. HENRI Design

Figure 4 is a computer-generated rendering of the current HENRI in-core module design.

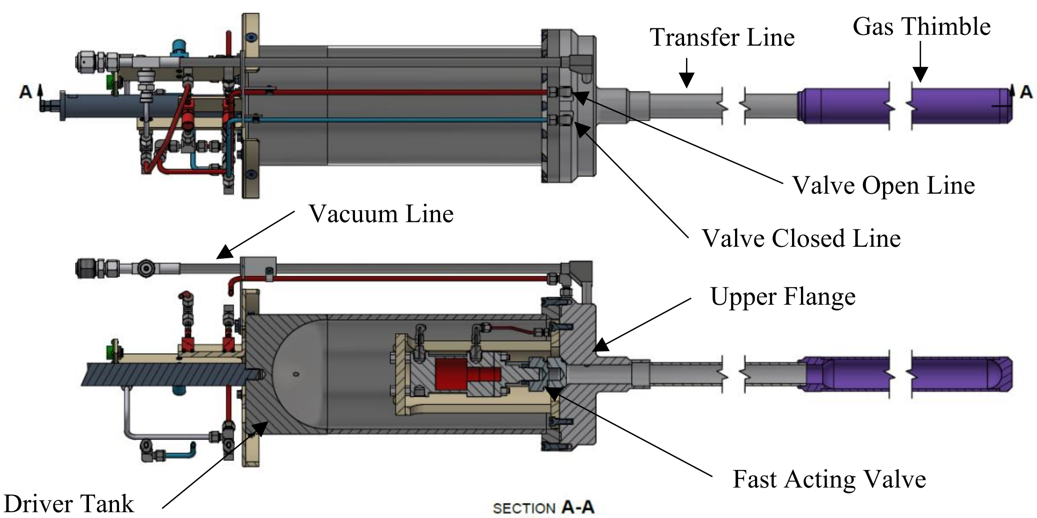

Figure 4: CAD model of HENRI

The gas thimble is a nominal 1.5-inch schedule 40 pipe size that is fabricated from Zirconium-2.5Niobium (Zr-2.5Nb). The gas thimble is approximately six feet in length which extends from the top of the active core region to the bottom of the TREAT core. The gas thimble is sized to fit inside control rod fuel assemblies that have an inner diameter of two inches. This was done to avoid having to fabricate new fuel assemblies or moderator assemblies for this project. The gas thimble is where all the neutron absorption will occur during flow of the helium-3 gas.

The next section of the module is the transfer line. The transfer line connects the driver tank to the gas thimble. The transfer line is a nominal one-inch schedule 40 pipe size that is made of Zr-2.5Nb and is approximately two feet in length. The transfer line contains an upper flange as well which connects the driver tank and has the mating features for the fast-acting valve. The flange also contains a pair of o-rings to allow access to the valve, if needed, for maintenance. Out of the flange is a vacuum line connection which allows for the connection of a vacuum pump to evacuate any helium-3 in the gas thimble prior to reactor start-up and valve actuation. In addition to the vacuum line, there is also connection points for opening and closing the fast-acting valve.

The final component of the HENRI module is the driver tank. The driver tank holds the high-pressure helium-3 during reactor operations, prior to valve actuation. The driver tank is a nominal six-inch schedule 40 stainless steel pipe with a top head and flange welded to it. The driver tank holds approximately six liters of gas. Inside the driver tank is the fast-acting valve which contains the gas in the driver tank until actuated to release the helium-3 into the rest of the system. At the top of the driver tank are all the solenoid valves needed to operate the fast-acting valve. In addition, a supply line delivers gas into the top of the driver tank. At the top of the driver tank, not shown in Figure 4, will be a shroud to protect the gas lines from damage during various operations at TREAT. Figure 5 shows a schematic of the entire gas system.

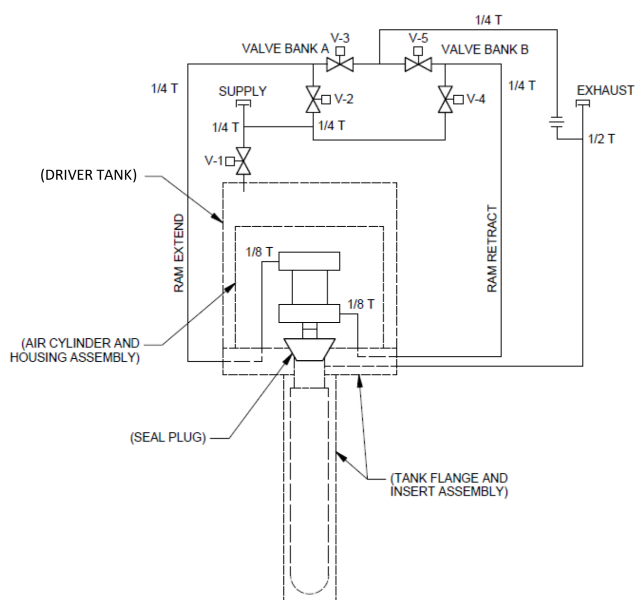

Figure 5: P&ID of HENRI in-core module valving and gas lines.

3.2. Recovery Skid Design

In addition to the in-core module discussed above, there is a recovery skid that is also part of the system. The recovery skid will house the supply gas to the modules, the vacuum pump for the system, as well as a purification system to remove impurities to ensure greater than 99% helium.

The system will have a low-pressure storage buffer tank where the helium-3 gas will be stored while not in use to reduce leakage potential. Two compressors will be used, one at the end of the vacuum pump to ensure gas reaches the low-pressure storage and a larger one that is capable of pressurizing the low-pressure gas back to operational pressures. There are valves throughout the system to isolate the in-core modules from the recovery skid to allow for alternate design pressures between the two systems. The recovery system will have the capability to be operated locally using a local HMI and remotely in the TREAT control room. Figure 6 shows a P&ID drawing for the recovery system skid and the components of the system.

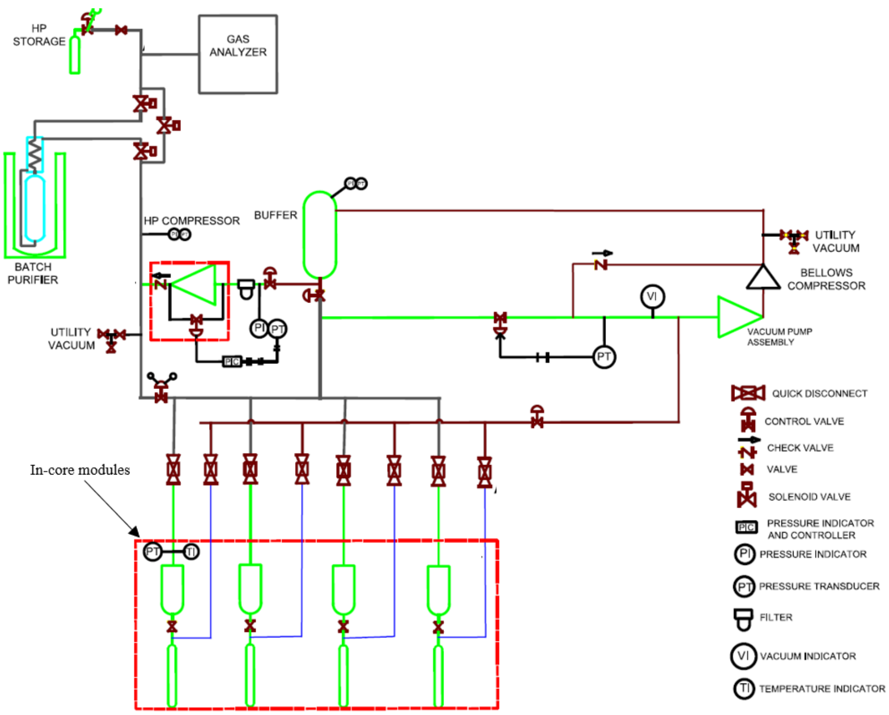

Figure 6: P&ID of entire HENRI system including recovery skid

3.3. Core Configuration

Based on reactor kinetics modeling of the system, to achieve the desired -5% Δk/k reactivity in 5 milliseconds, 4 modules would need to be placed into the core. This also ensured a more symmetrical radial flux profile throughout the core as well. The locations chosen were the M14, M6 and H14, H6 locations which are additional locations for control rods and support the use of control rod fuel assemblies and the length of the HENRI in-core modules. Figure 7 shows a computer-generated core with the HENRI modules "installed" in the locations discussed above. [1]

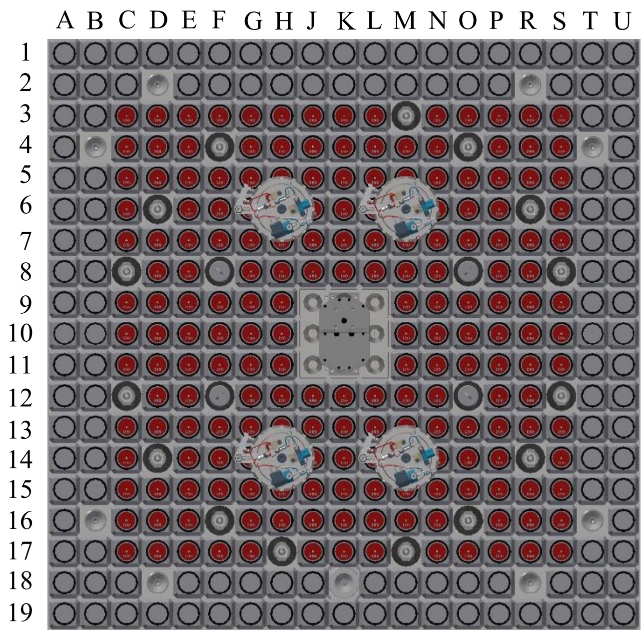

Figure 7: Core layout with HENRI installed.

3.4. HENRI Operation

At a high level, the operation of the HENRI system during transient operation will be simple. During the pre-transient phase the vacuum pump will operate ensuring any leaked helium-3 goes to the low pressure storage buffer tank. While the vacuum is running, the HENRI fast acting valve will be closed, or at least verified to be closed and the recovery system will fill the driver tank to approximately 250 psig, based on reactor kinetics evaluations. [1] During the actual transient phase, the HENRI fast acting valves will open at a desired time in the transient releasing the helium-3 into the gas thimble section. Post transient actions will occur many hours after the transient due to the extensive heating that occurs in the helium-3 during the absorption of neutrons. In this phase, the system will vacuum out the modules and process the helium-3 through the gas purification system.

4. Current Work

Besides design work, the HENRI in-core modules are currently being evaluated. Final reactor kinetics modeling and heat generation rate tallies are being performed using Monte-Carlo N-Particle (MCNP). This information is fed to a thermal hydraulic model using RELAP5 to generate the expected pressure and temperatures within the system. The cases being ran for the thermal hydraulic modeling are the nominal case, in which all 4 HENRI modules release gas at the same time, and an accident case, in which only one HENRI module in the highest flux location fires and the others remain filled with a vacuum. Abaqus is then used to perform structural analysis on the system to meet American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code requirements for both cases.

Initial evaluation of the design presented in this paper indicated that the thermal gradient between the inner gas thimble wall and outer gas thimble wall, ~1500°F and ~230°F respectively, was too great and caused extreme bending stresses on the gas thimble during the accident case. As a result, a design change to add an extremely tight tolerance Zr-2.5Nb tube within the gas thimble was done to absorb some of the heat. Final results have not been completed to date, but back of the envelope calculations suggest this should be sufficient to reduce the stresses enough to be within stress limits of the system.

Other work that is currently being done is the integration of the system into ARCS. Due to the number of valves and the timing in which some of these valves need to occur, the delays in the electronic signals to and from HENRI are being evaluated. Since the negative reactivity needs to occur in the five-millisecond timeframe, it is important that the signal delay be known as this will impact when the signal is actually sent to the fast-acting valves to initiate. The gas dynamics and neutron absorption within the HENRI modules occurs in approximately 2.5-3 ms. [1] If the signal delay is greater than 2-3 milliseconds, the signal may be required to be sent prior to the transient even being initiated which has potential error precursors associated with it.

5. Future Work

Once analysis comes back satisfactorily for the HENRI system, the next step is to fabricate and assemble the HENRI in-core modules and recovery skid. The fabrication is expected to take a minimum of 18 months based on ability to receive the Zr-2.5Nb materials. In parallel to that of fabrication and assembly, safety documentation will need to be performed to ensure safe operation in the core. This may be performed through the Unreviewed Safety Question (USQ) process or the Experiment Safety Analysis (ESA). Once it is fabricated and deemed safe for reactor operations, the TREAT core will be characterized with these in the locations specified above. During this characterization it is anticipated that operation of the system will be done to validate performance of the system and to fine tune any timing that may be needed.

6. Conclusion

References

[1] C. Race, “Narrowing Pulse Widths Using Helium-3 at the Transient Reactor Test Facility (TREAT) – An Evaluation of the Helium-3 Negative Reactivity Injection (HENRI) System,” 2022

[2] Argonne National Laboratory, "TREAT Baseline Description Document," 1992.

[3] Idaho National Laboratory, "Transient Reactor Test (TREAT) Facility FSAR. SAR-420," 2022.

[4] J. D. Bess, N. E. Woolstenhulme, C. B. Davis, L. M. Dusanter, C. D. Folsom, J. R. Parry, T. H. Shorthill and H. Zhao, "Narrowing transient testing pulse widths to enhance LWR RIA experiment design in the TREAT facility," Annals of Nuclear Energy, vol. 124, pp. 548-571, 2019.