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THOR-aLEU Report

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CONTENTS

FIGURES

TABLES

aLEU-THOR

1. EXPERIMENT DESCRIPTION AND OBJECTIVES

The advanced low enriched uranium (aLEU)-THOR experiment vehicle is designed to irradiate fresh fuel rodlet specimens containing UO_2 (uranium dioxide) in the Temperature Heat-sink Overpower Response (THOR) capsule. The goal of the experiments are to compare the behaviors of standard UO_2 pellets to an aLEU concept in which molybdenum (Mo) foils separate UO_2 wafers increasing the thermal conductivity of the fuel. This experiment is designed to be conducted in the Transient Reactor Test facility (TREAT) using the Minimal Activation Retrievable Capsule Holder (MARCH) irradiation system. The goal of these experiments is to assess the effect of thermally conductive inserts in UO_2 by measuring their net effect on radial thermal conductivity using transient nuclear heating and then to determine their power-to-melt threshold in transient overpower ramps.

The objective of the aLEU-THOR fuels experiment is to determine the viability and study the performance of UO_2 fuel pellets employing newly upgraded TREAT capability. A novel transient measurement technique will be used with the THOR capsule, which has a solid heat sink to generate the transient temperature gradient for conductivity measurement.

2. SCOPE OF WORK ACCOMPLISHED

2.1 Design

2.1.1 Overview of Design

The design of the aLEU-THOR capsule includes a fuel rodlet which contains three distinct fueled regions each isolated from one another with an insulator pellet to avoid axial heat transfer between the fuel regions. Each fueled region is aligned with at least two temperature sensors contained within the surrounding iron heat sink that are close enough to measure the temperature difference and estimate the thermal transport time. The fuel regions have the same radial dimensions as those used in pressurized water reactors, with zirconium alloy cladding and at least 10 cm of fueled length. The experiment is able to test both standard UO_2 pellets and thin UO_2 discs with thermal inserts. The heat sink temperature is measured with minimal disturbance to the rodlets and the heat sink during the transient. The THOR capsule is compatible with the MARCH irradiation system and allows for glovebox assembly for fresh fuel specimens.

The sandwich fuel design consists of alternating discs of UO_2 and Mo, which improve the radial thermal conductivity compared to the baseline fuel of solid UO_2 pellets. This reduces the fuel centerline temperature and the radial temperature gradients thus reducing pellet fracturing due to thermal stresses and increases the power-to-melt margin (aLEU-THOR). The THOR capsule has a thick wall heat sink with sodium bond to the rod, which provides similar benefits as UO_2-DRIFT for the fuel pellets. The aLEU application is intended for water-cooled reactors, but the THOR heat sink with sodium bond simulates the heat transfer well and avoids the complications of water voiding. The three fueled region rodlet consists of two variants of aLEU sandwich fuel which contain different thicknesses of the Mo and UO_2 discs and a baseline UO_2 fuel for comparison. The Mo fraction is 5 vol% in the fuel, which has negligible impact on the neutronics. The pellets are obtained from Framatome with a specific enrichment for optimizing the test performance.

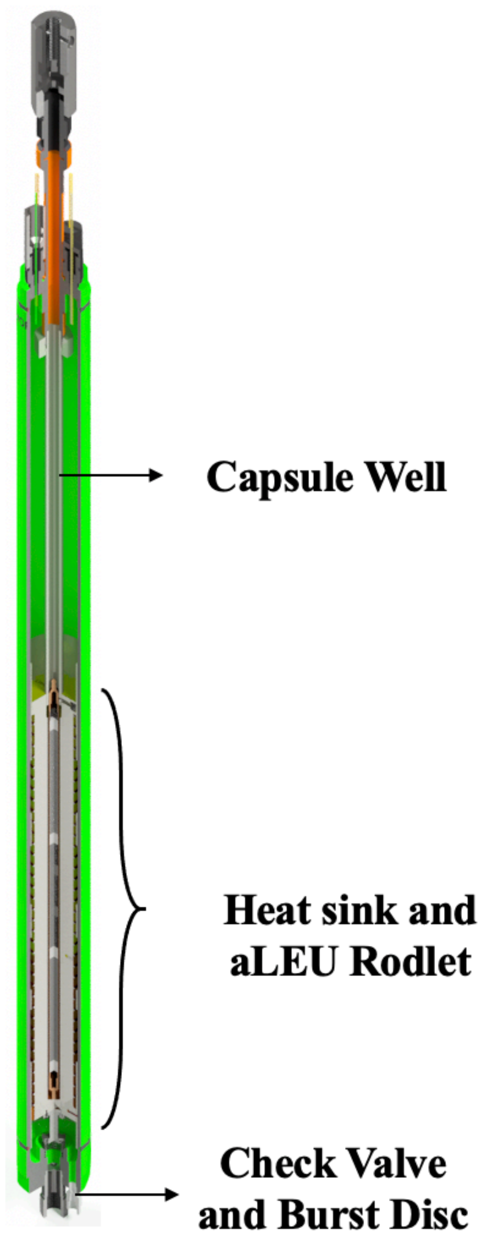


Figure 1. aLEU-THOR.

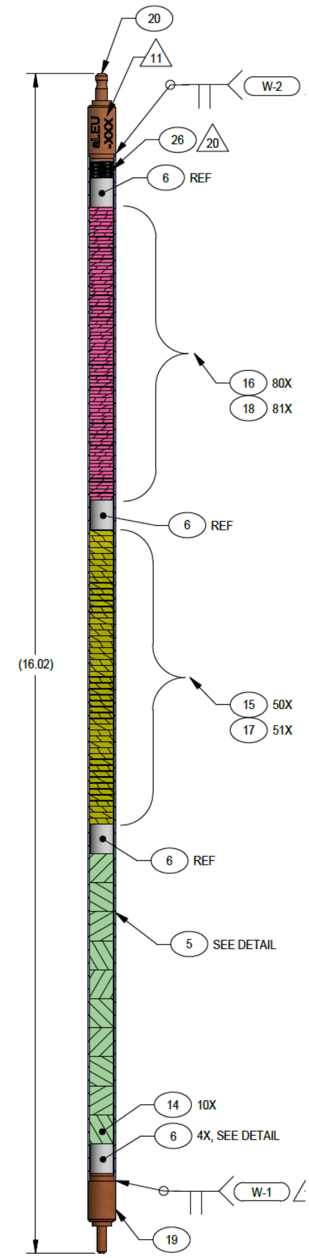
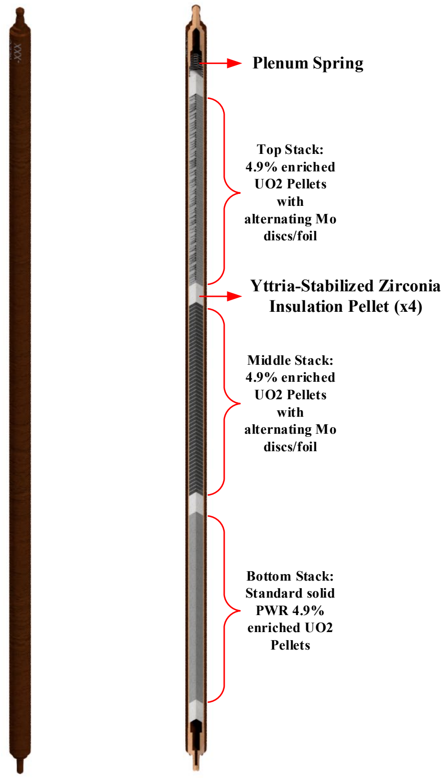


Figure 2. aLEU THOR Specimen stack.

2.1.2 Specimen Details (corresponding to Figure 2)

- 3x Fresh 4.9% enriched UO_2 pellet stacks, 10 cm each
- Top Stack: 1 pellet = 8x 1.19 mm UO_2, 7x 71.2 µm Molybdenum Foil
- Middle Stack: 1 pellet = 5x 1.9 mm UO_2, 4x 125 µm Molybdenum Foil
- Bottom Stack: 10x Standard UO_2 Pellets.



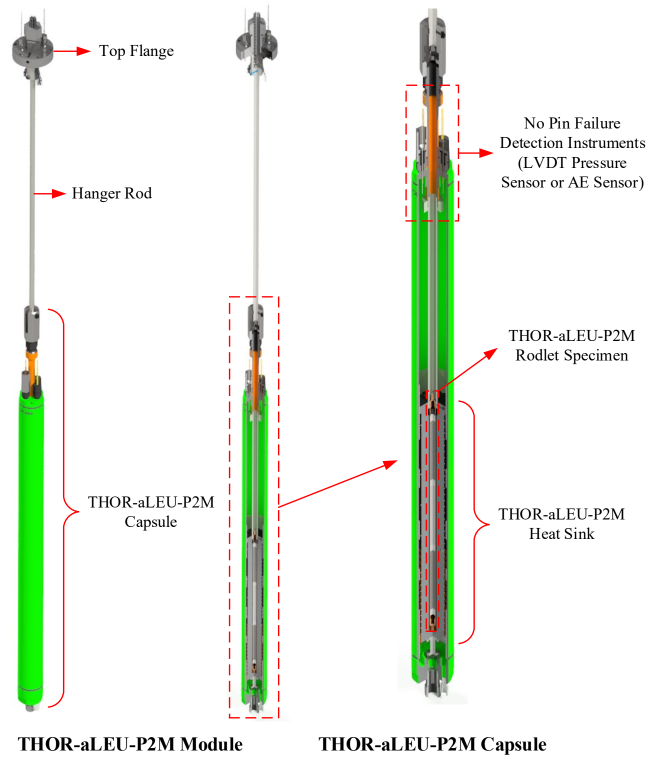
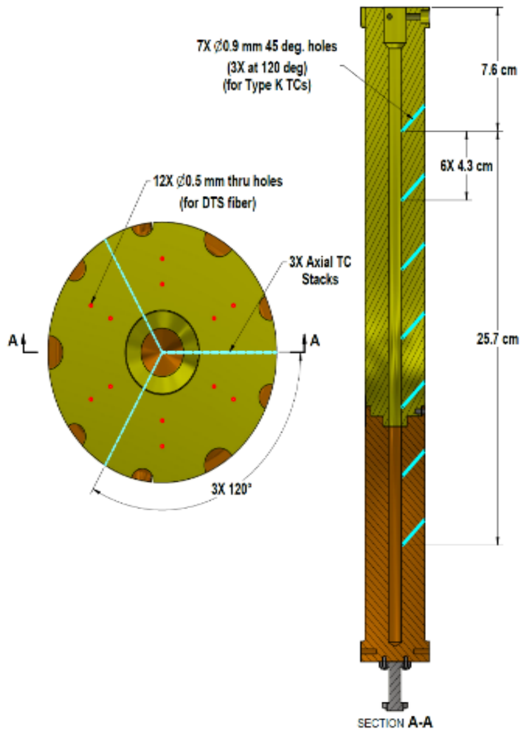


Figure 3. aLEU-THOR Specimen Stack.

Figure 4. aLEU-THOR Module and Capsule.

2.1.3 Heat Sink

The heat sink is a metal block made from Armco Grade 2 iron with holes drilled along its length to accommodate thermocouples and a distributed temperature sensing fiber. The thermocouples are type K, which can measure temperatures up to 1260°C. The distributed temperature sensing fiber is a single-mode optical fiber that can measure temperature profiles along its length using Raman scattering. The heat source is a cable heater that can deliver up to 1000 W of power at 208V. The cable heater is wrapped around the heat sink and insulated with ceramic fiber seen below.



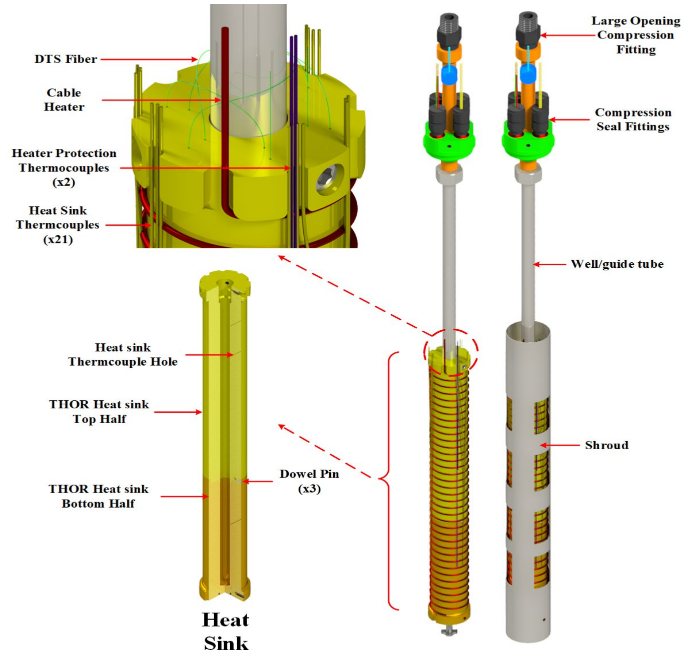


Figure 5. Heat Sink Model 1

Figure 6. Heat Sink Model 2

2.1.4 Capsule

The capsule consists of a cylindrical capsule made of annealed Inconel-625, which is welded shut on a Test Train Assembly Facility (TTAF) lathe welder. The capsule has a diameter of 1.1 cm (0.43 in.) and a length of 114 cm (44.8 in.). The capsule contains sodium, with a volume of 21 g. The capsule is equipped with a Type 5 small LVDT to measure the displacement of the capsule during the experiment.

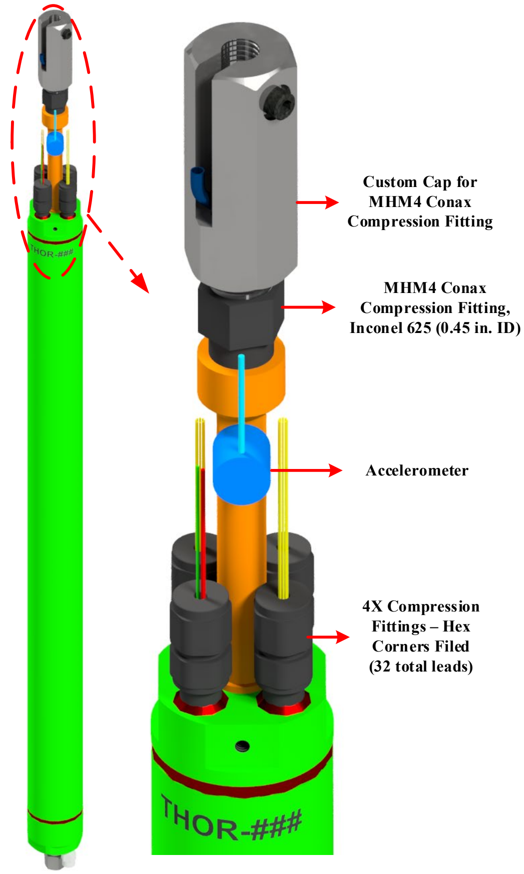


Figure 7. aLEU-THOR top assembly.

2.2 Analysis

The aLEU-THOR experiment consists of a single capsule and will undergo two transients. Table 1 provides an overview of the parameters associated with each of the transients. Additional details of the aLEU-THOR-B transient are provided in Table 2, and a plotted representation of this transient power profile is shown in Figure 1.

The first transient, aLEU-THOR-A, is intended to confirm power coupling through in-situ calorimetry using temperature measurements in the capsule. The second transient, aLEU-THOR-B, is the primary programmatic transient reaching high power conditions in the test specimen.

Table 1. Final targeted transient operating parameters.

Experiment ID	**Step Insertion (% Δk/k)**	**Reactor Energy Target (MJ)**	**Clipped/ Unclipped**	**Test Purpose**
aLEU-THOR-A	1.2	250	Clipped	Calorimetry
aLEU-THOR-B	--------------See Table 7. MURA Summary.-------------			Programmatic

Table 2. Final detailed targeted transient operating parameters for aLEU-THOR-B.

Segment	Start Time (sec)	Power (MW)	Type
1	0	0	1.12% Δk/k
2	3.00	5	1.12 % Δk/k
3	3.94	400	Ramp
4	6.21	428.5	Rod Stop
5	14.35	N/A*	Clip

*Power during rod stop is not a targetable parameter as rod motion would be required to adjust the power history. An estimation of power during the rod stop is shown in Figure 8.

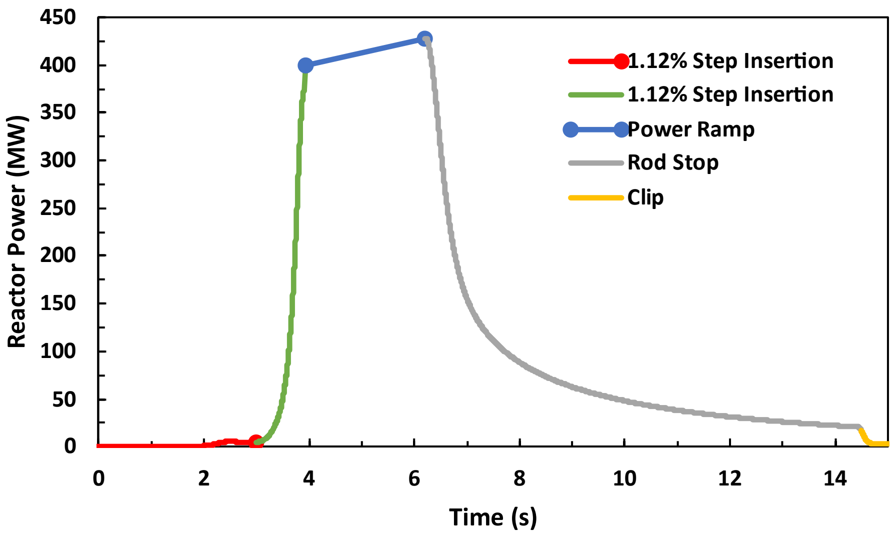


Figure 8. Plotted representation of targeted power transient for aLEU-THOR-B.

The design of the aLEU-THOR-B transient consists of an initial power rise raising the temperature of the fuel to typical light water reactor fuel temperatures. This is done quickly so that substantial heat up of the heat sink due to conduction from the fuel does not occur. The next segment of the transient is a linear power ramp. In this segment, the rate at which energy is deposited into the fuel is faster than it can conduct out to the heat sink. This further raises the temperature of the fuel. However, the rate at which heat can conduct out of the aLEU sandwich fuel segments of the rod is greater than that of the baseline UO_2 segment. By the end of this segment, the goal is to substantially melt the centerline of the baseline UO_2 fuel, while the aLEU sandwich fuel segments remain solid.

The radial temperature profile of the three fuel segments as predicted by RELAP5-3D simulation at the end of the power ramp segment are shown in Figure 9. The simulation results predict that approximately 40% of the baseline UO_2 will reach the melting temperature of 3120 K while the peak temperatures in the aLEU sandwich fuel segments are approximately 2900 K, well below the melting temperature.

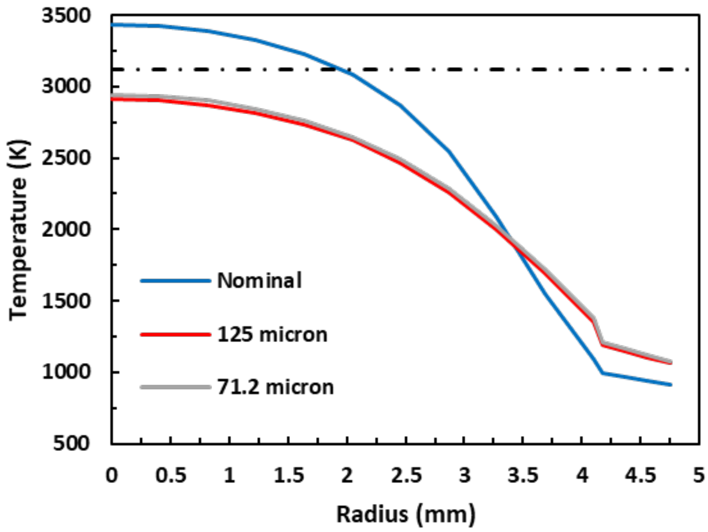


Figure 9. Radial Temperature Profile Predicted by Relap-3D.

2.2.1 Neutronics Analysis

The aLEU-P2M fuel assembly was simulated using the MCNP code in the TREAT full-slot core configuration. The control rod positions were calculated to achieve a steady state condition with a constant power level. The MCNP model included the detailed geometry and material composition of the fuel assembly, the control rods, and the surrounding reflector.

Table 3. Control rod positions determined for steady state.

Experiment Temp	Core Temp	Operational State	Control Rod Position [in (cm)]
160°C	20°C	Steady State	27.22 (69.1388)
600°C	20°C	Steady State	27.22 (69.1388)

The MCNP simulation was ran at experiment temperatures of 160°C and 600°C. Each of the three fueled regions were modeled explicitly. The lower section has full size pellets, the middle section has 1.9 mm UO_2 and 125 µm Mo, and the upper section has 1.19 mm UO_2 and 71.2 µm Mo. The model assumes steady-state at a TREAT core temperature of 20°C and rods out at 260°C. TREAT-to-specimen coupling factors (CFs) were computed for the fuel and the structural materials in the experiment.

Table 4. CFs for fuel and HGRs for structural parts.

Configuration	Stack Location	Operational State	Tally Type	Average CF [W/g-MW]
Programmatic 160°C	Lower	Steady State	F4	9.95E-01
Programmatic 160°C	Lower	Rods Out	F4	1.07E+00
Programmatic 160°C	Middle	Steady State	F4	1.02E+00

Configuration	Stack Location	Operational State	Tally Type	Average CF [W/g-MW]
Programmatic 160°C	Middle	Rods Out	F4	1.13E+00
Programmatic 160°C	Upper	Steady State	F4	1.02E+00
Programmatic 160°C	Upper	Rods Out	F4	1.13E+00
Programmatic 600°C	Lower	Steady State	F4	9.76E-01
Programmatic 600°C	Lower	Rods Out	F4	1.06E+00
Programmatic 600°C	Middle	Steady State	F4	9.97E-01
Programmatic 600°C	Middle	Rods Out	F4	1.11E+00
Programmatic 600°C	Upper	Steady State	F4	1.01E+00
Programmatic 600°C	Upper	Rods Out	F4	1.14E+00

2.2.2 Thermal Analysis

A thermal analysis was performed to ensure that under planned experiment conditions, the aLEU-THOR experiment does not threaten capsule integrity. Temperatures and pressures from this analysis were used as inputs to structural analysis of experiment. The analysis was ran at both the planned experiment starting temperature of 280°C and MCNP predicted CFs as well as a more conservative case in which the starting temperature was 310°C and the MCNP predicted CFs were increased by 25%.

Table 5. Thermal Analysis Summary.

Experiment	Transient	Heater Temperature	
		°F	°C
THOR-aLEU-P2M	Service Level A	536	280
	Service Level A (Increased CF)	590	310

Experiment	Transient	Capsule		BUSTER	
		°C °F	psig	°C °F	psig
THOR-aLEU-P2M	Service Level A (Increased CF)	586 1087	23.6	433 811	17

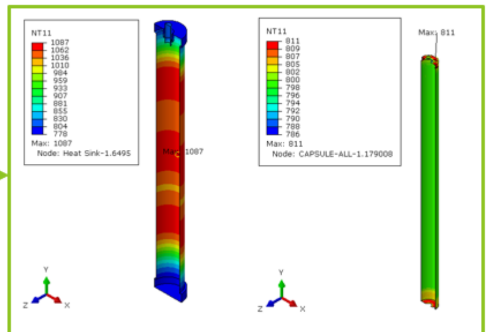


Figure 10. Temperature results and pressure predictions.

2.2.3 Maximum Unplanned Reactivity Addition Analysis

The Maximum Unplanned Reactivity Addition (MURA) for aLEU-THOR was also analyzed to ensure the experiment remained within its rated containment capacity. The MURA as dictated by the TREAT facility safety requirements is an accident scenario where the transient does not go as planned and the amount of energy and energy deposition rate is much greater than planned. This analysis consisted of two parts: a high-pressure event in the first minute and a high temperature event after the first minute. The high-pressure event happens right after the transient starts as this is when pressurization within the capsule due to fuel/sodium vaporization would occur. The highest temperatures within the capsule and the containment pipe known as the Broad Use Specimen Transient Experiment Rig (BUSTER), however, occur later on once all the energy has been deposited.

Table 6. Final Pressure and Temperatures.

Experiment	Transient	Capsule Temperature	Capsule Pressure	BUSTER Main Pipe Temperature	BUSTER Main Pipe Pressure
aLEU	MURA-1: High Pressure Event	650.9 K	16.7 MPa	583.7 K	5.87 MPa
aLEU	MURA-2: High Temperature Event	708.3 K	1.055 MPa	706.3 K	0.192 MPa

2.2.4 Structural Analysis

The THOR aLEU capsule complies with the nuclear safety standards for TREAT that are specified in SAR-420 and TS-420. The experiment is assessed, and the peak pressure and temperature values do not exceed the design limits based on the MURA. The experiment design has a valve to fill the enclosed volume with an inert gas. This valve and its plug are able to withstand the expected internal pressure from

THOR transients as calculated by the relevant thermal and structural ECARs. The experiment and its containment satisfy the acceptance criteria for different service level conditions as defined in the applicable structural analyses.

The ASME Section III Evaluation defines four Service Levels for the design and analysis of nuclear components. These are Level A, B, C and D, corresponding to normal, upset, emergency and faulted conditions, respectively. The type of evaluation required, and the allowable stresses vary depending on the Service Level.

The loads that affect the structural integrity of nuclear components include internal pressure and temperature gradients. These loads are determined by the most severe transient scenarios that the component may experience. For example, the Most Energic Expected Transient (MEET) is a Level A condition that involves a rapid increase in power and temperature. The Maximum Unplanned Reactivity Accident (MURA) is usually a Level D condition that involves a sudden insertion of reactivity and a spike in pressure. However, since BUSTER does not have a pressure relief device, the MURA is treated as a Design Condition. The BUSTER conditions are used for the structural analysis of the component.

Table 7. MURA Summary.

Event	ASME Service Level	Internal pressure	Material Temperature	Temperature Gradient	Number of cycles
MEET	Design-1	17 psi	779°F (main pipe) 250°F (top flange)	--------	Not applicable
MURA-1	Design-2	294 psi	391°F (main pipe) 250°F (top flange)	---------	1000[d]
MURA-2	Design-3	16.8 psi	1020°F [a] (main pipe) 250°F (top flange)	---------	
MEET	Level A	17 psi	-------	From thermal analysis	
(a) As this temperature is over 800°F, the high temperature section of the ASME Code (Sec. III, NH) must be used.					

2.3 Fabrication

2.3.1 Top Flange Weldment

The flange weldment at the top of the THOR-aLEU module forms the BUSTER primary containment and is considered and credited with serving an ASME BPVC Section III pressure containment function. As such, the material procured for fabrication was ASME Section III material. After fabrication a liquid penetrant examination was performed on each component to verify no material flaws. After assembly and welding of the flanges, the weldments were examined both visually and with liquid penetrant to verify no flaws occurred during welding. The flanges were then helium leak tested with an acceptable leak rate not to exceed 1×10^{-6} STD CC/SEC. One of the as-built flange weldments is pictured in Figure 11.

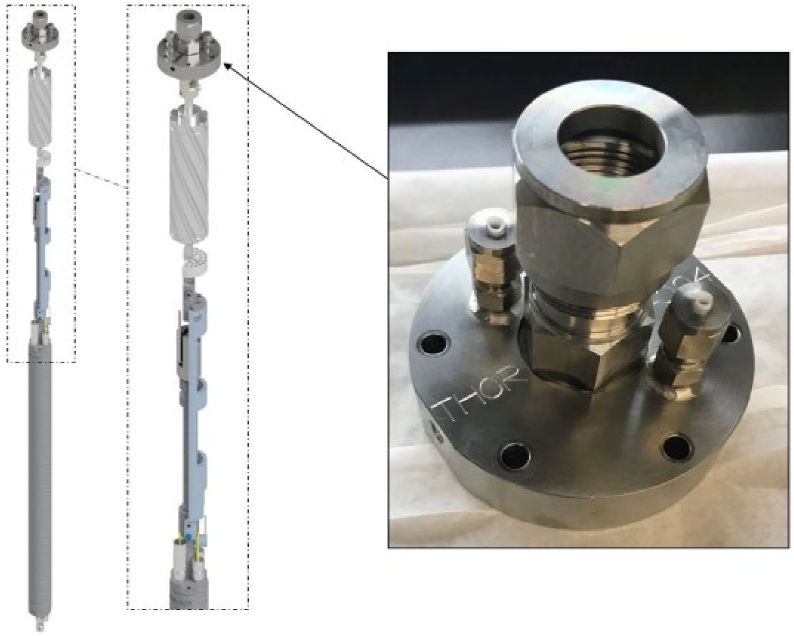


Figure 11. As-built top flange weldment and pictorial description in the THOR assembly.

2.3.2 Additional Module Components

The other primary components of the upper hanger have been fabricated, inspected and are ready for assembly. Figure 10 shows the well extensions and compression seal fittings, which sit at the top of the capsule, and provide the capsule seal after rodlet insertion.

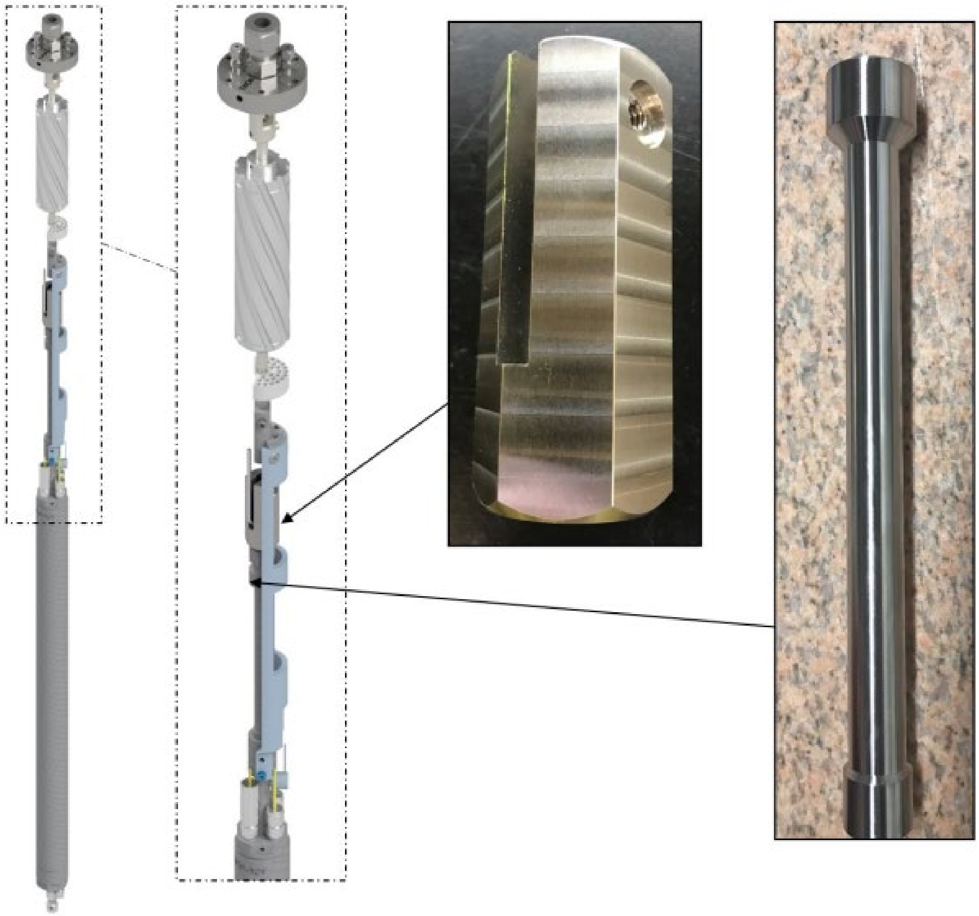


Figure 12. Fabrication well extension and compression seal fitting and pictorial description in the THOR assembly.

2.3.3 Capsule Body

The capsule components, fabricated from Inconel 625, were constructed at the INL. After fabrication, dimensional inspection on the diameters was completed prior to welding. Dimensional inspection reports of the lower capsule components are included in Appendix B. Figure 12 shows one each of the capsule components. The lower capsule assemblies have been welded and visual examinations have been completed on the welds. The capsule upper caps will be assembled and welded to the lower capsule assembly during the experiment final assembly process.

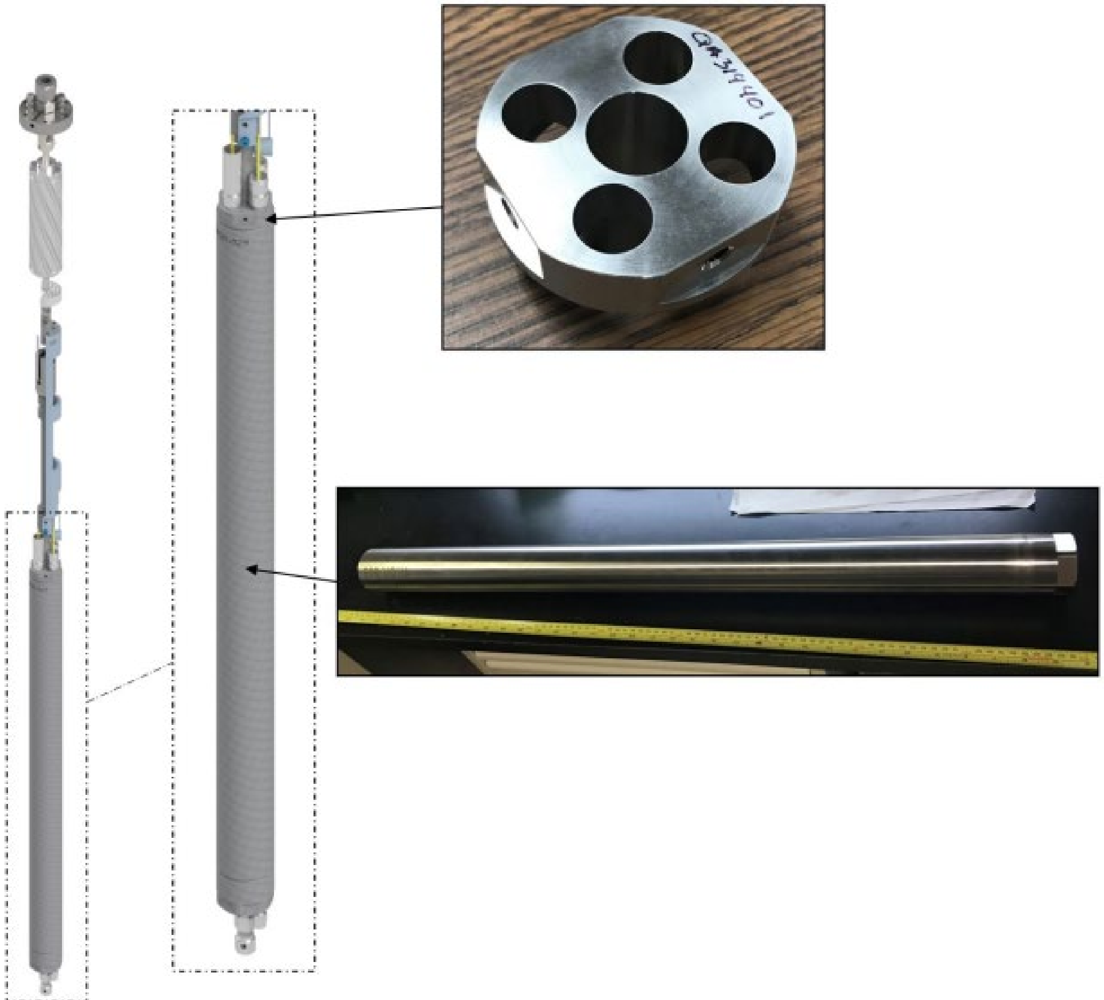


Figure 13. Fabricated capsule ready for final assembly and pictorial description in the THOR assembly.

2.3.4 Heat Sink

Figure 14 shows the three aLEU heat sink assembly components fabricated out of Armco Grade 2 Iron (high purity iron). These components will be match drilled and pinned together as part of the final experiment assembly process. The heat sink components were machined at INL, with the twelve 0.5 mm through holes made via electrical discharge machining hole popping by an outside vendor with specialized expertise.

Figure 14. Fabricated iron heat sink components and pictorial description in the THOR assembly.

2.3.5 Insert Assembly Components

Figure 15 shows the additional primary insert assembly components. The long heat sink sleeve, shown on the right, is fabricated from titanium and provides a cover over the instrumentation that surrounds the heat sink assembly. The short capsule well provides an extension of the heat sink assembly that houses the rodlet.

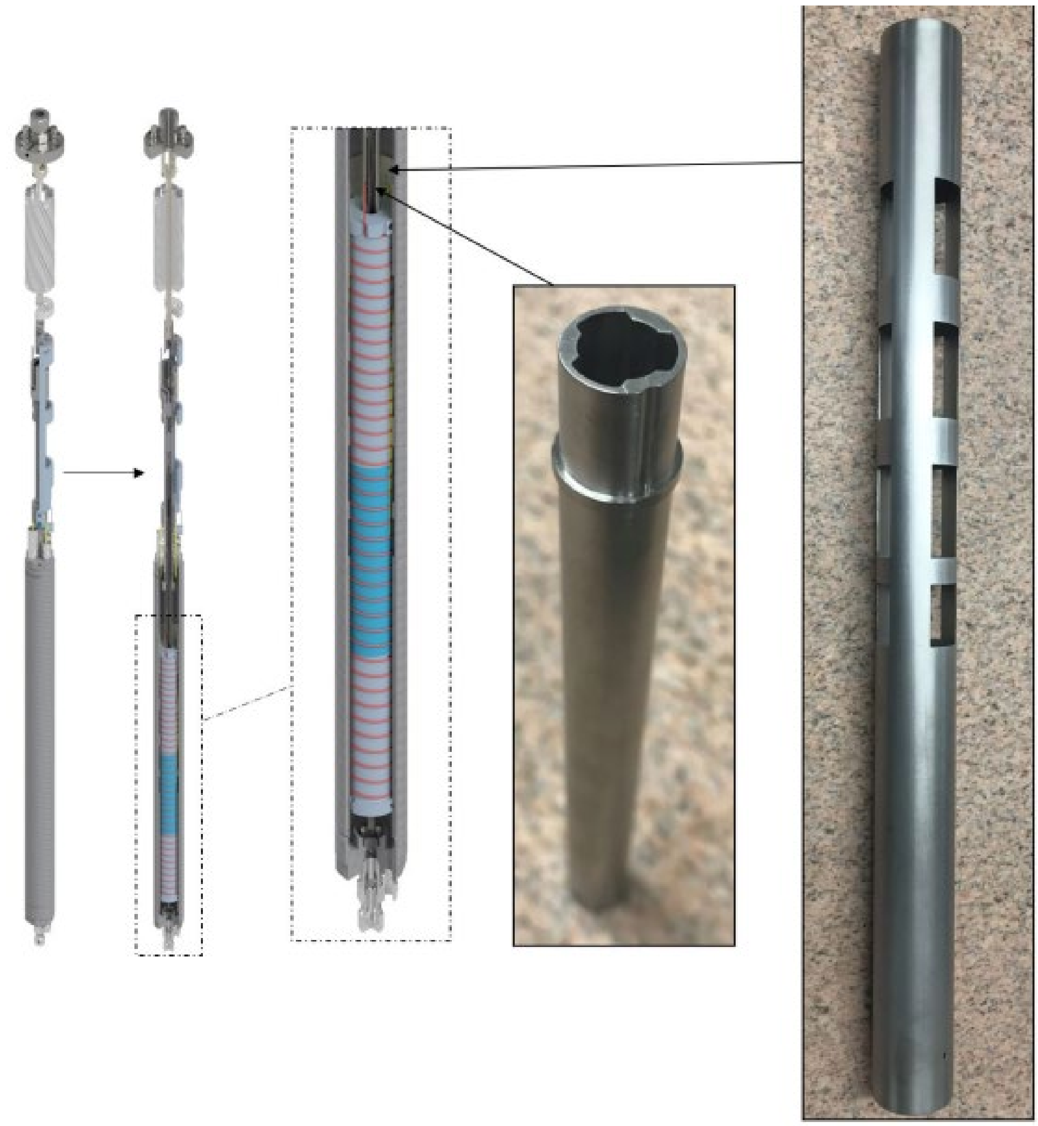


Figure 15. Fabricated short capsule well and long heat sing sleeve and pictorial description in the THOR assembly.

2.4 Assembly

The fuel is surrounded by 21 thermocouples that measure the temperature at different axial levels. A fiber optic cable that acts as a distributed temperature sensor is inserted through the heat sink to capture the radial temperature profile. A pressure sensor or an elongation sensor is used to measure the fuel-cladding mechanical interaction. An acoustic emission sensor is attached to the cladding to detect any rupture events. A cable heater is wrapped around the heat sink to provide a steady-state heat flux to the fuel before the transient. Two additional thermocouples are used to protect the heater from overheating.

The capsule sodium assembly is performed in the Pyro-chemistry Glovebox (PCG) in the Fuels and Applied Science Building (FASB). The capsule is transferred from the hardware assembly area to the glovebox using a rigging system. The capsule is then filled with solid sodium cylinders that are rolled to a diameter of about 0.25 inches. The sodium is melted and solidified inside the capsule and its height is checked with a gauge to ensure proper loading. See figures below.

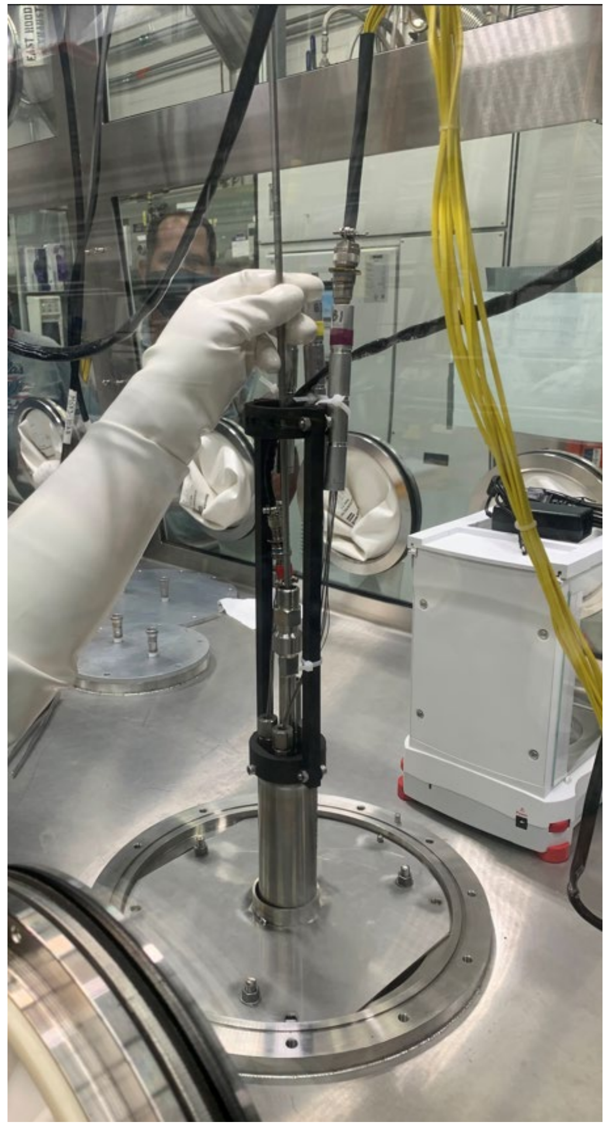


Figure 16. THOR-aLEU Instrument Assembled. Figure 17. THOR-aLEU pin and sodium loaded.

3. THOR EXPERIMENT ISSUES THAT AFFECT THOR-aLEU

3.1 Sodium Leak

To fabricate small holes along each segment of the heat sink for the DTS fiber, a two-piece heat sink design was used for the aLEU-THOR experiment. A metallic knife edge crush gasket was placed between the two heat sink faces and they were joined together. Testing of the multiple piece heat sink design and the crush gasket seal was performed as part of the experiment design process. The testing showed that the crush gaskets performed as expected and sodium did not leak out at the interface of the two heat sink pieces. Heat sinks made from both iron and although testing gave confidence to the multiple heat sink design, a different experiment, also utilizing the THOR experiment vehicle, known as MOXTOP faced a problem which has been interpreted as sodium leaking out at the interface of heat sink pieces. During sodium of the MOXTOP-2 experiment sodium got stuck in the well above the heat sink. The sodium was then cooled and hardened in the heat sink. The level gauge showed that some sodium had escaped from the heat sink. More sodium was added to the MOXTOP-2 capsule, but it also leaked. The same issue was found in the MOXTOP-1 capsule. When it was discovered that both MOXTOP experiment capsules experienced sodium leaking out of the heat sink, the aLEU-THOR capsule was fully assembled and waiting to be irradiated in TREAT. However, with no way to readily verify that the sodium remained within the heat sink of the already assembled aLEU-THOR capsule and the observed sodium leaking in the MOXTOP experiments, the decision to pause irradiation of the aLEU-THOR capsule was made.

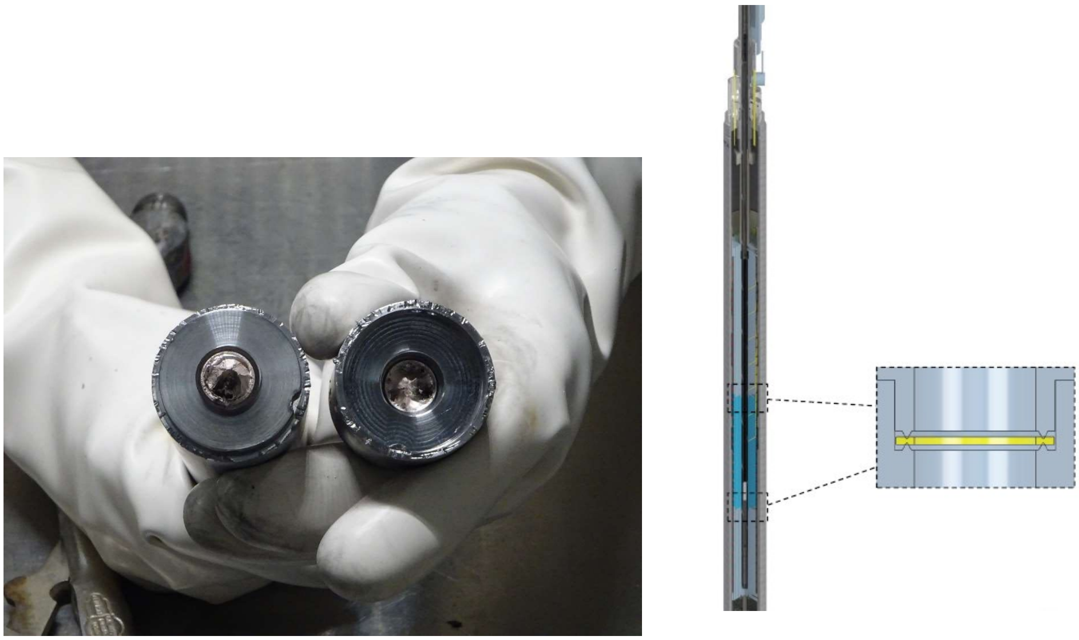


Figure 18. Crush gasket testing with the iron heat sink.

Other experiments which utilize the THOR capsule have updated the design of the heat sink so that it is a single piece containing a gun drilled hole for the test specimen. This design modification loses the DTS fiber instrumentation capability; however, it ensures that sodium will remain within the heat sink. This puts the aLEU-THOR experiment in a unique position where resumption of the experiment campaign could be achieved at a low cost. This could be done by leveraging the single piece heat sink design proven by other THOR experiments.