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TEX-HEU: Integral Experiment Execution of Thermal/Epithermal eXperiments using Highly Enriched Uranium with Polyethylene

IER-297 CED-3b Report

Jesse Norris, Catherine Percher, Anthony Nelson, William Zywiec, and David Heinrichs

External Audience (Unlimited)

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Disclaimer

Acknowledgements

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Executive Summary

This report documents the experimental critical configurations and measurements for IER-297, Thermal/Epithermal eXperiments (TEX) using highly enriched uranium (HEU) fuel, moderated and reflected by polyethylene. These experiments establish the baseline TEX-HEU configurations spanning thermal, intermediate, and fast fission energy regimes.

The experiment campaign was completed in FY2020 at the National Critical Experiments Research Center at the Nevada National Security Site. The campaign produced six documented critical configurations (0”, ⅛” A, ⅛” B, ¼”, ½”, and 1½”) and one reproducibility measurement (⅛” R). Table 1 summarizes these seven experiments along with their period and calculated reactivity, in order of execution.

Table 1: Summary of experiment reactivities and timeline of operations.

Experiment	Dates	Period (s)	Reactivity (¢)
¼”	Feb. 25 – Feb. 27	100.02 – 106.49	9.41 – 9.89
⅛” A	Mar. 2 – Mar. 4	22.11 – 23.53	26.11 – 27.02
⅛” B		187.40 – 200.67	5.57 – 5.90
½”	Mar. 5 – Mar. 11	51.19 – 53.96	15.57 – 16.14
1½”	Mar. 11 – Mar. 12 May 20 – May 26	60.45 – 66.41	13.45 – 14.38
0”	May 27 – June 1	265.73 – 287.00	3.91 – 4.19
⅛” R	June 2	39.87 – 41.28	18.62 – 19.11

The Comet General Purpose Critical Assembly Machine was used to conduct the TEX-HEU experiments. The HEU fuel consists of U(93+) plates, collectively known as the “Jemima” plates. Each experiment consisted of an alternating stack of these HEU plates with or without polyethylene moderator plates. By varying the thicknesses of the polyethylene plates, the neutron spectrum of the experiment could be fine-tuned to a specific fission energy regime. The experiments were reflected by 1” of polyethylene consisting of a bottom and top plate and outer reflector rings to surround the HEU and polyethylene plates. The fine reactivity control of the system was provided by the thickness of the top reflector plate, which could be varied in increments of ⅟₃₂”.

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Section 1

Introduction

Intermediate energy range critical benchmarks are an established data need by the international criticality safety community. The goal of the Nuclear Criticality Safety Program's (NCSP) Thermal/Epithermal eXperiments (TEX) Program is to address these recognized nuclear data need. This is done by executing experiments with NCSP fissile material assets that can be used to create critical assemblies that span a wide range of fission energies: from the thermal (below 0.625 eV), through the intermediate (0.625 eV to 100 keV), to the fast energy range (above 100 keV). An additional goal of the TEX Program is to design critical assemblies that can be easily modified to include various high priority materials (diluents) identified by the international criticality safety and nuclear data communities. IER-297 is the second design in the TEX Program, focusing on assemblies of highly enriched uranium (HEU) fuel with polyethylene moderator (TEX-HEU). The first diluent planned to be investigated with TEX-HEU is hafnium (TEX-HEU-Hf), which is a strong neutron absorber important for marine propulsion applications.

In FY2018, Lawrence Livermore National Laboratory completed the final design for TEX-HEU and TEX-HEU-Hf[1]. The TEX-HEU baseline experiments were completed in FY2020 at the National Critical Experiments Research Center (NCERC) at the Nevada National Security Site. The TEX-HEU-Hf experiments are scheduled for execution in FY2021.

The Comet General Purpose Critical Assembly Machine was used for the TEX-HEU experiments. Five experiment designs were executed resulting in six critical experiment configurations and one reproducibility measurement. The experiments are designated by their nominal moderator thickness: 0", ⅛", ¼", ½", and 1½".

This report documents the experimental critical configurations and measurements for TEX-HEU. Section 2 describes the components of the vertical lift machine, the TEX-HEU experiment design, and measurement techniques such as the alignment, height, levelness, and temperature. Section 3 describes the benchmark experiment configurations with specific measurements and photos documenting the configurations. Appendix A and Appendix B include the measured part masses, dimensions, and material composition information for the TEX-HEU components. Finally, Appendix C includes design drawings of the additional vertical lift machine parts.

[1] Nelson, A., C. Percher, W. Zywiec, and D. Heinrichs, "IER-297 CED-2: Final Design for Thermal/Epithermal eXperiments with Jemima Plates with Polyethylene and Hafnium," Lawrence Livermore National Laboratory (2017).

Section 2

Equipment Description

2.1 Vertical Lift Machine

The Comet General Purpose Critical Assembly Machine is a vertical lift machine (VLM) used to remotely assemble a critical experiment. As shown in Figure 1, Comet consists of the surrounding structure, stationary platform, and movable platen. For TEX-HEU, additional parts were affixed to Comet: an experiment platform, affixed to the stationary platform, and a lower adapter, extending the movable platen. The following sections describe these additional parts along with the design drawings in Appendix C.

During assembly, roughly half of the experiment is built on the experiment platform with the other half on the lower adapter. During operation, the movable platen is extended vertically to bring the two halves of the experiment into contact. Once fully assembled, the two halves are only separated by a thin aluminum membrane.

The additional parts for TEX-HEU were weighed prior to adding them to Comet. The weights are reported in Table 2 and were measured with a Mettler Toledo SB16001 High Capacity Precision Balance under the NCERC Calibration Program (Cal No. 012708). The calibration for this balance was certified on May 2, 2019 and is valid through May 2, 2020. These measurements were taken on February 24, 2020. The manufacturer of the SB16001 reports a maximum capacity of 16,100 grams, precision of 0.1 grams, and linearity of 0.3 grams[2]. The Part IDs reported in Table 2 refer to the design drawings in Appendix C.

Table 2: Additional TEX-HEU parts used on Comet.

Part		Part ID	Mass (g)
Alignment Plate		128Y1720901	1123.0
Membrane		128Y1720910	2396.1
Lower Adapter	Adapter Plate	128Y1720900-03	5014.7
	Adapter Extension	128Y1720916	8365.3
Experiment Platform	Interface Plate	128Y1720909	See note 3.
	Standoffs	128Y1720908-01	633.8 634.4 634.0 635.0

[2] Mettler Toledo SB Precision Balance Operating Instruction, Section 6, Technical data and optional equipment. Retrieved on September 1, 2020, available at https://www.mt.com/us/en/home/library/operating-instructions/laboratory-weighing/SB_BA_0.html. Archived on November 30, 2020, available at https://web.archive.org/web/20201130221822/https://www.mt.com/dam/mt_ext_files/Editorial/Generic/3/SB_BA_Editorial-Generic_1165556464133_files/sb-ba-e-11780774a.pdf.

[3] The interface plate was not weighed with the other parts on February 24, 2020, due to its large size. This part will be weighed in the future.

Figure 1: Comet General Purpose Critical Assembly Machine with additional TEX-HEU parts.

2.1.1 Experiment Platform

The experiment platform holds the upper half of the experiment, shown in Figure 2. The platform consists of an interface plate and four standoffs. The interface plate is a 28” x 28” x 0.5” AL 6061-T651 plate with a 19” diameter hole through its center. The standoffs are 12” long AL 6061-T6 cylinders with a 1.25” diameter. These standoffs affix the experiment platform to the stationary platform of Comet.

The membrane is placed on top of the hole in the interface plate, allowing the movable platen to lift the lower half of the experiment as it comes into contact with the upper half of the experiment through the membrane. The interface plate includes four pegs to hold the membrane and alignment plate in place.

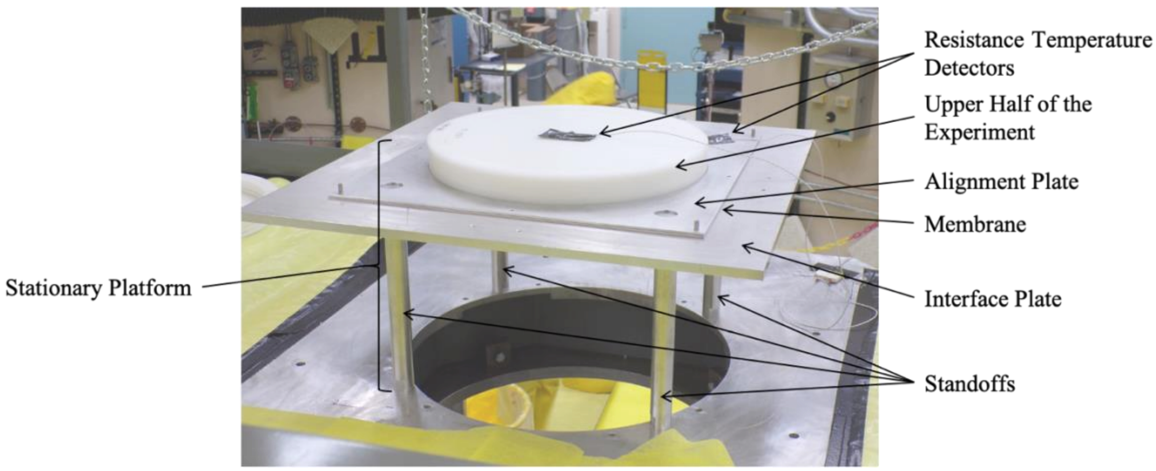

Figure 2: Experiment platform, alignment plate, and membrane on the stationary platform of Comet.

2.1.2 Lower Adapter

The lower adapter holds the lower half of the experiment, shown in Figure 3. This lower adapter consists of a cylindrical adapter plate and an adapter extension which affixes the lower adapter to the movable platen of Comet. The cylindrical adapter plate has a 0.53” thickness and 18.5” outer diameter. This plate features a 17.15” inner diameter with an additional 0.47” lip height, to hold the 17.1” diameter reflector. The adapter extension is an 8” tall annular cylinder with a wall thickness of 0.25” and a 12” outer diameter. This extension includes a 2.5” wide and 0.5” thick top and bottom lip to affix it to the adapter plate and the platen. Both components of the lower adapter are AL 6061-T6.

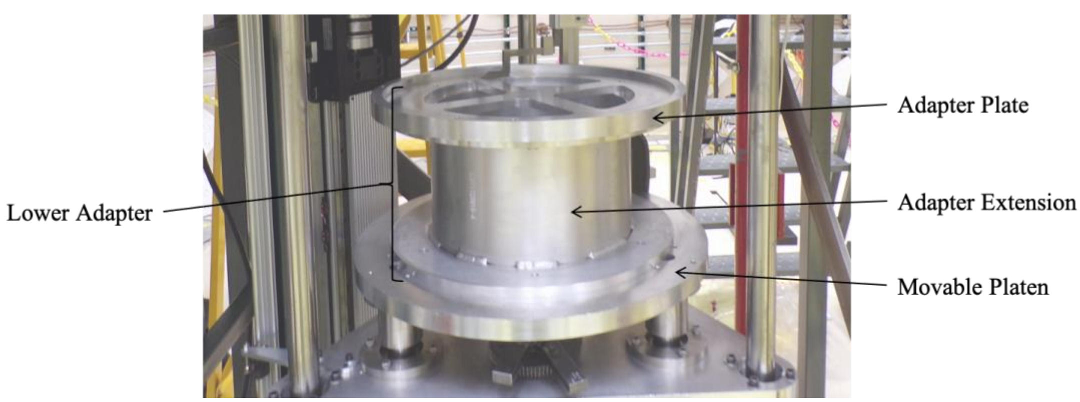

Figure 3: Lower adapter on the movable platen of Comet.

2.1.3 Membrane and Alignment Plate

The membrane and alignment plate are both 21” x 21” x 0.125” AL 6061-T6 plates. The alignment plate has a 17.150” diameter hole through its center, to accommodate the 17.1” reflector rings. These plates are set on top of the interface plate of the experiment platform using the four pegs. These pegs allow the plates to be lifted as the VLM brings the two halves of the experiment into contact. The membrane and alignment plate are shown together in Figure 4 and Figure 6 with the membrane by itself in Figure 5.

The upper half of the experiment is assembled on top of the membrane where the alignment plate is used to align the experiment. This alignment ensures that even though the two halves of the experiment are assembled separately on the VLM they will be in alignment when they are brought together. Prior to the final reactivity measurement for the experiment, the alignment plate is removed, leaving only the membrane in place for the benchmark configuration.

There are four additional 1.155” holes through the alignment plate. These holes allow the fastener between the interface plate and the standoffs to be manipulated while the alignment plate is in place, as shown in Figure 25. Adjusting the position of the interface plate allows the alignment between the upper and lower halves of the experiment to be fined-tuned, as described in Section 2.3.

Figure 4: Membrane and alignment plate on the experiment platform.

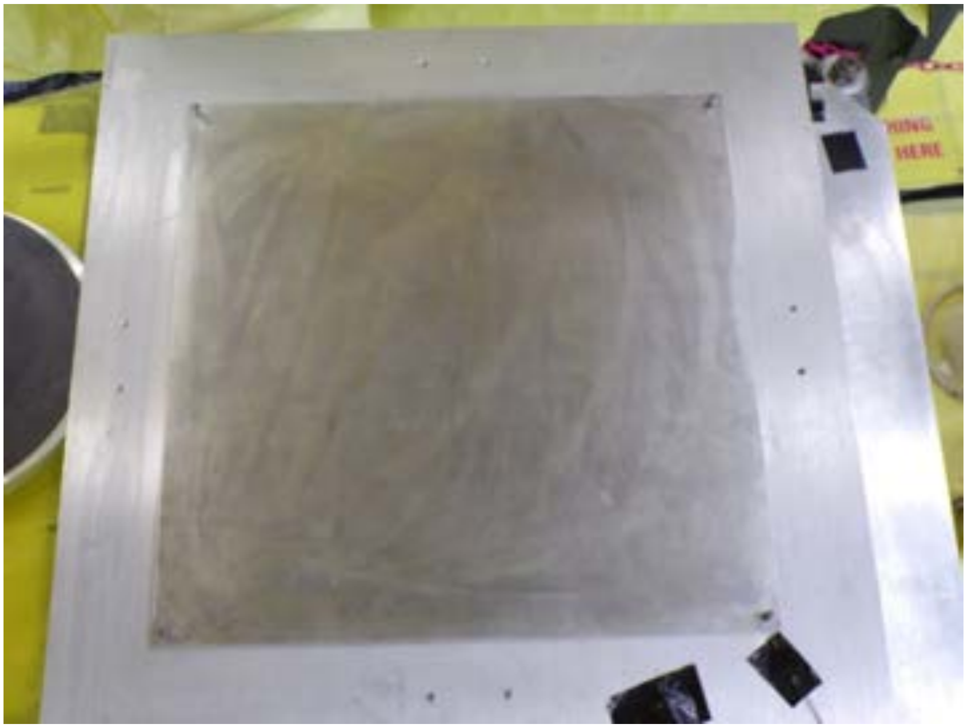

Figure 5: Membrane on the experiment platform.

Figure 6: Alignment plate being place on top of membrane on the experiment platform.

2.2 Experiment Design

The experiment design involves of a stack of 15” HEU plates surrounded by a 1” reflector. The experiment is split roughly in half on Comet, with the upper half on the stationary platform and lower half on the movable platen. A cutaway of the experiment design on the VLM is shown in Figure 7, with the parts of the experiment and VLM defined.

The plate stack consists of the HEU plates with and without interspersed polyethylene plates. By including, and then varying the thicknesses of, the interspersed polyethylene plates, the neutron spectrum of the experiment can be fine-tuned to a specific fission energy regime. The reflector consists of three types of polyethylene parts: a base plate, stacking rings, and a top plate. The reflector base sits in the plate of the lower adapter. The stacking rings surround the HEU and polyethylene plate stack to provide 1” of reflection on the sides. The top reflector plate sits on top of the plate stack and is used as the fine reactivity control in the design. This top reflector may be added to or removed from in increments of as little as ⅓₂” by using combinations of the polyethylene reflector and moderator plates.

Appendix A provides the measured masses and dimensions of all the parts used in the TEX-HEU experiment configuration.

2.2.1 Highly Enriched Uranium Plates

The highly enriched uranium plates are 0.118” thick, 15” outer diameter U(93+) plates, collectively known as the “Jemima” plates. These plates are either solid or annular cylinders with an inner annulus of 2.5”, 6”, or 10”. The annulus removes some of the HEU mass resulting in lower and higher mass plate variants. Each of these four variants are shown in Figure 8, Figure 9, Figure 10, and Figure 11.

These plates have a long history in many critical experiments executed by Los Alamos National Laboratory. The “early Aunt Jemima experiments” between 1952 and 1954 used similar U(93.4) plates[4]. However, these plates were 0.800 cm thick with a 10.50” outer diameter and inner 0.875” annulus. The earliest usage of HEU plates similar to those in TEX-HEU are the later “extension of the earlier Jemima experiments” in 1956, which are 3 mm thick U(93.4) plates with a 15” outer diameter[5]. Since then, these HEU plates have been used in the Big Ten experiments in the 1970s[6], the first three Zeus experiments in 1999-2002[7,8,9], and the Nb-1Zr experiment in 2004[10].

The mass and average thickness of all HEU plates used in these experiments are reported in Appendix A. The average thickness was based on three independent measurements of each plate, using a caliper. There were no instruments available to accurately measure the outer or annuli diameters of the plates.

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[4] B. Krohn et al., “The Early Jemima Experiments: Bare Cylindrical Configurations of Enriched and Natural Uranium,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, IEU-MET-FAST-001 (1995).

[5] R. Kidman et al., “Natural Uranium Reflected Assembly of Enriched and Natural Uranium Plates,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, IEU-MET-FAST-002 (1995).

[6] J. Sapir et al., “Big Ten: A Large, Mixed-Uranium-Metal Cylindrical Core with 10% Average ^{235}U Enrichment, Surrounded by a Thick ^{238}U Reflector,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, IEU-MET-FAST-007 (2011).

[7] R. Mosteller et al., “The Initial Set of Zeus Experiments: Intermediate-Spectrum Critical Assemblies with a Graphite-HEU Core Surrounded by a Copper Reflector,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, HEU-MET-INTER-006, (2004).

[8] R. Mosteller et al., “The Unmoderated Zeus Experiments: A Cylindrical HEU Core Surrounded by a Copper Reflector,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, HEU-MET-FAST-073, (2005).

[9] D. Hayes et al., “Zeus: Fast-Spectrum Critical Assemblies with an Iron-HEU Core Surrounded by a Copper Reflector,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, HEU-MET-FAST-072, (2006).

[10] D. Loaiza et al., “Niobium – 1wt.% Zirconium Moderated by Polyethylene and Fueled with Highly Enriched Uranium,” *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, HEU-MET-FAST-047, (2006).

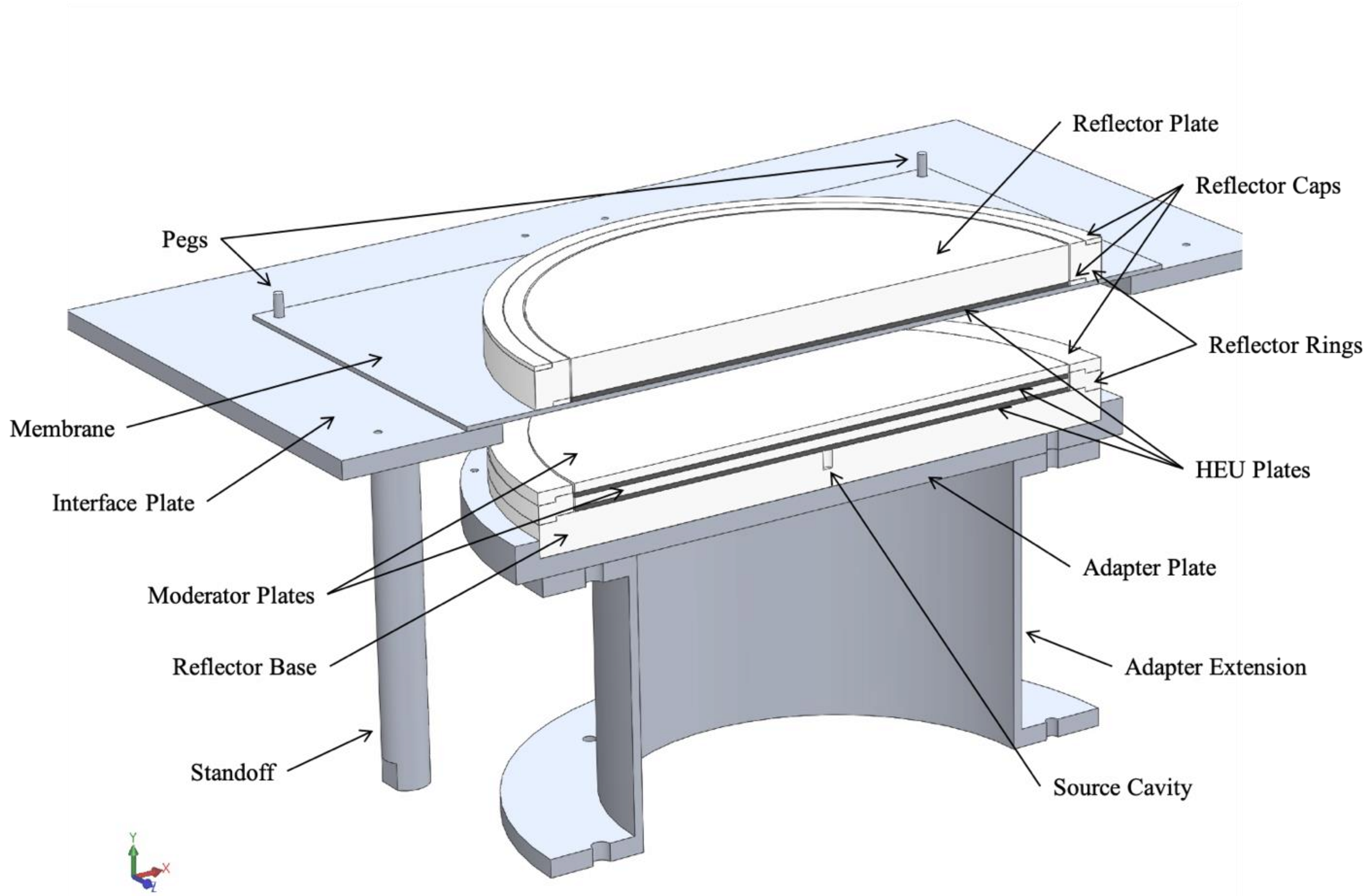

Figure 7: Experiment design cutaway diagram.

Figure 8: HEU plate (11147).

Figure 9: Mass measurement of HEU plate with 2.5" annulus (10464).

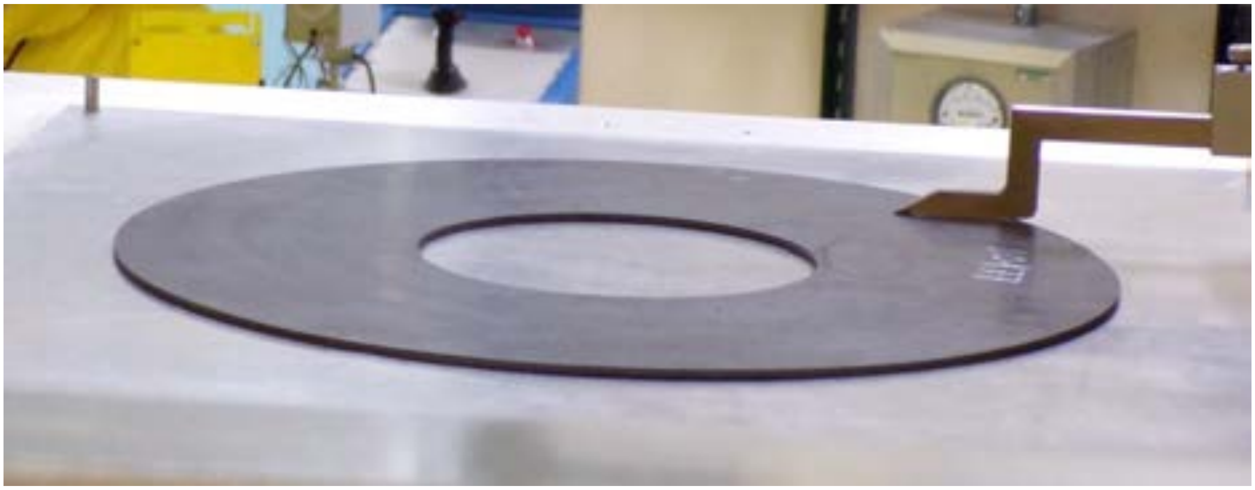

Figure 10: HEU plate with 6” annulus (10477).

Figure 11: Mass measurement of HEU plate with 10” annulus (10479).

2.2.1.1 Aluminum Inserts

The inserts are 0.125" thick AL 6061 disks which come in three diameters[11]: 2.4", 5.9", and 9.9". These inserts were placed within the annuli of the HEU plates to prevent any sagging of the polyethylene moderator and reflector plates due to weight. To ensure the fit, the inserts are nominally 0.1" smaller in diameter than the corresponding HEU plate annuli.

Experiment photos of these inserts are shown in Figure 12 and Figure 13. The mass and dimensions for all inserts used in these experiments are included in Appendix A. An elemental analysis of impurities can be found in Appendix B.

Figure 12: Insert for an HEU plate with a 2.5" annulus.

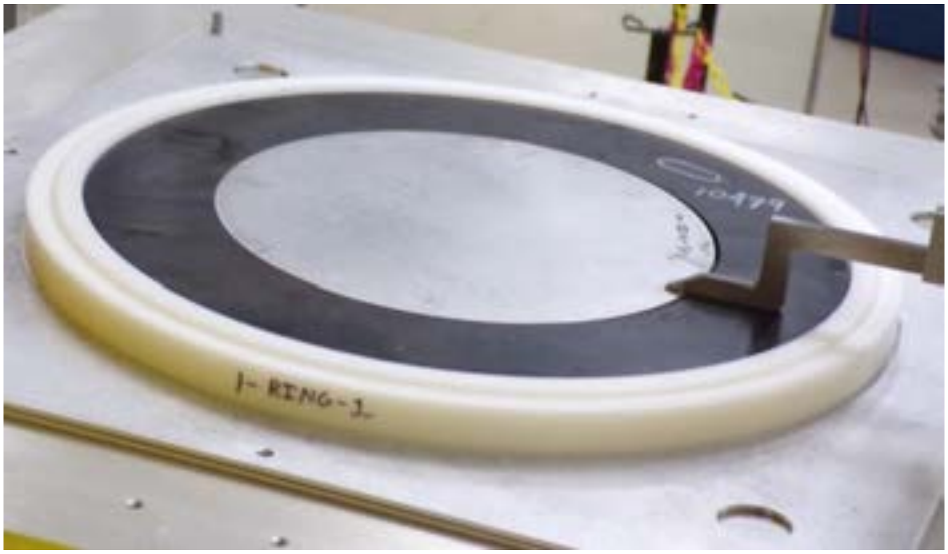

Figure 13: Insert for an HEU plate with a 10" annulus.

[11] The inserts were originally to be made of AL 1100, but the final parts were made of AL 6061.

2.2.2 Polyethylene Parts

The polyethylene parts are all high-density polyethylene (HDPE)[12]. The mass and dimensions for all HDPE parts used in these experiments are included with Appendix A. An elemental analysis of impurities can be found in Appendix B.

2.2.2.1 Moderator and Reflector Plates

The moderator and reflector plates are 15" diameter plates with varying thicknesses. The moderator plates are interspersed with the HEU plates and come in four thicknesses: ⅛", ¼", ½", and 1½". The reflector plates are used as the top reflector and come in three thicknesses: 1⁄32", 1⁄16", and 1". The moderator plates were also used in the top reflector to aid in the fine reactivity control for the 0", ¼", and ½" experiments (see Figure 77). The use of the moderator plates allowed reflector thicknesses less than 1" or greater than 1 3⁄32".

Experiment photos of the moderator and reflector plates are shown in Figure 14 and Figure 15.

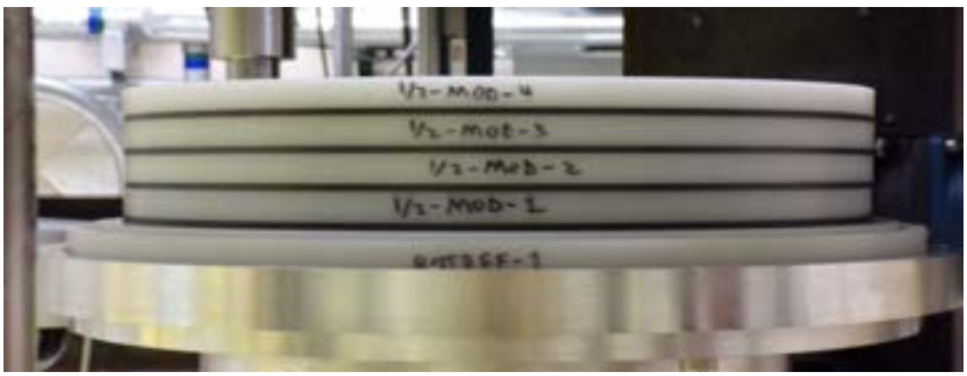

Figure 14: Moderator plates used in the lower half of the ¼" experiment.

Figure 15: Moderator and reflector plates used in the upper half of the 1½" experiment.

[12] The density of this polyethylene will be better characterized through gas pycnometry.

2.2.2.2 Reflector Rings

The reflector rings are 17.1” outer diameter and 15.1” inner diameter annular cylinders which come in four thicknesses: ¼”, ½”, 1”, and 3”. The rings stack around the HEU, moderator, and reflector plates to provide 1” of reflection around the configuration. They are designed to interlock, using step joints, which keep the rings in alignment as they are stacked. Figure 16 shows how the interlocking step joints stack with the reflector rings and caps. On the lower half of the experiment, the bottom reflector ring interlocks with the reflector base. On the upper half of the experiment, the bottom reflector ring sits on a bottom reflector cap.

Experiment photos of the reflector base are shown in Figure 17 and Figure 18.

2.2.2.3 Reflector Caps

There are two different types of reflector caps: one type used for fine height adjustment on the top of the reflector rings and the other type used to provide a base for the first reflector ring on the upper half of the experiment. The reflector caps allow the ring reflector to be brought to within ⅓₂” of the top reflector height. The bottom reflector caps provide the base for the reflector rings on the upper half of the experiment, making the reflector ring flush with the membrane.

The reflector caps are 15.1” inner diameter, 16.1” step diameter, and 17.1” outer diameter rings with a ⅛” base thickness and additional step thickness. There are 8 step thicknesses: 0”, 1/32”, 1/16”, 3/32”, ⅛”, 5/32”, 3/16”, and 7/32”. They are identified by the *Y-CAP-X* part identification, where *Y* is the step thickness and *X* is a unique integer. The bottom reflector cap is a ⅛” thick ring with a 15.1” inner diameter and 16.1” outer diameter. It is denoted with the *0-BOTCAP-X* part identification, where *X* is a unique integer. The bottom reflector cap and the reflector cap with 0” step thickness are zero-height caps, meaning they sit within the step joint of the reflector ring without adding additional height (as shown in Figure 16).

Experiment photos of the reflector base are shown in Figure 19, Figure 20, and Figure 21.

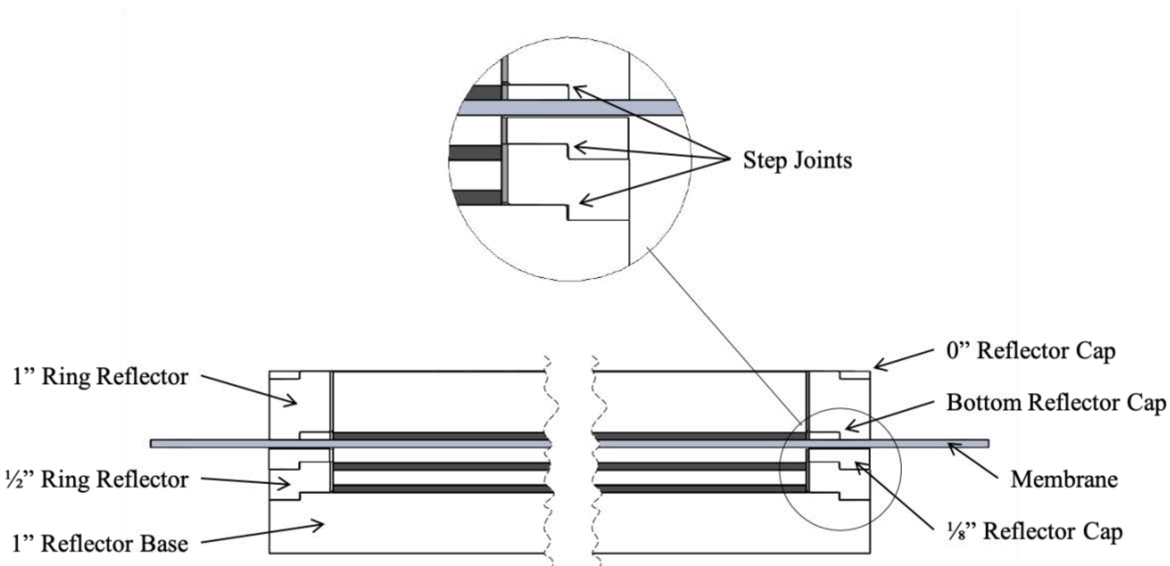

Figure 16: Reflector ring and cap design diagram.

Figure 17: Experimenter holding a 1" reflector ring (1-RING-5).

Figure 18: Reflector ring around the upper half of an experiment.

Figure 19: Experiment holding a bottom reflector cap (0-BOTCAP-1).

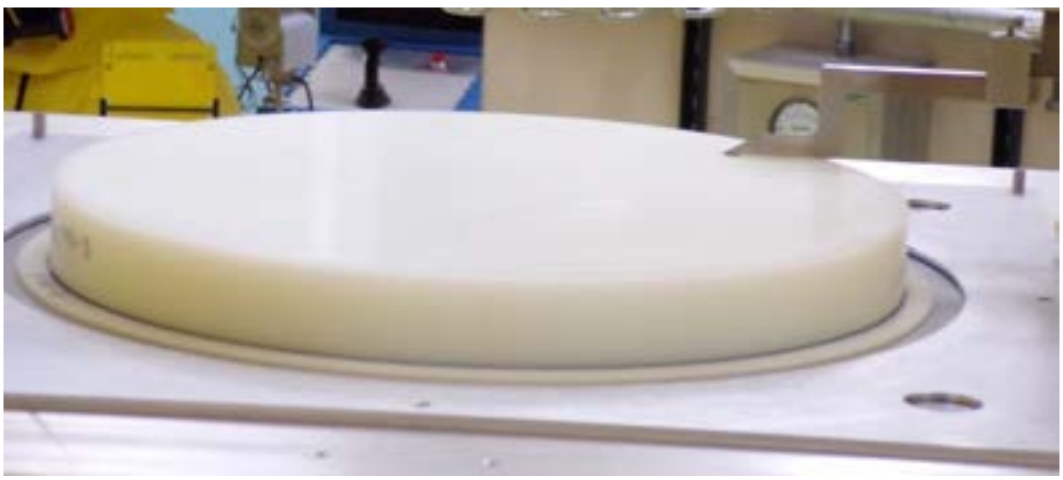

Figure 20: Bottom reflector cap around the base of the upper half of an experiment.

Figure 21: Reflector ring before and after adding the reflector cap.

2.2.2.4 Reflector Base

The reflector base is a 1” thick plate with a 17.1” diameter and outer step joint. It provides the foundation for the HEU plates and the ring reflectors on the lower half of the experiment. The reflector base sits in the plate on the lower adapter on Comet, held in place by the lip of the plate. The center of the base has a small cavity to hold the neutron source during the approach to critical.

Experiment photos of the reflector base are shown in Figure 22 and Figure 23.

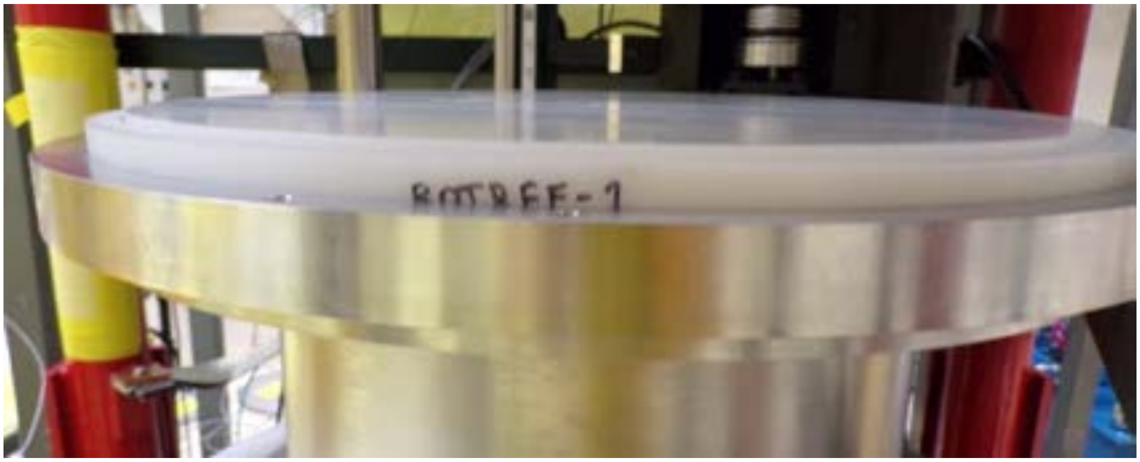

Figure 22: Reflector base in the adapter plate of the lower adapter.

Figure 23: Top-down view of the reflector base, showing the neutron source cavity.

2.3 Alignment

2.3.1 Comet Alignment

Comet holds the two halves of the experiment configuration as they are brought together. The upper half of the experiment sits on top of the membrane and is centered using the alignment plate. The lower half of the experiment sits in the adapter plate on the lower adapter.

Figure 24 and Figure 25 show how the alignment between the lower half and upper half of the experiment is achieved using the alignment plate. On the upper platform of Comet, the alignment plate centers the upper half of the experiment directly over the lower half of the experiment. This alignment plate sits on top of the membrane while setting the experiment up and is then removed prior to final execution.

With the reflector rings lifted through the alignment plate, as shown in Figure 25, a feeler gauge was used to measure the space around the circumference of the reflector and the alignment plate. This measurement informs the potential offset between the upper and lower halves of the experiment once they are brought together. The reflector ring part number was 1-RING-1 (dimensions included in Appendix A). When 1-RING-1 was roughly centered within the alignment plate, the feeler gauge measured between 25 and 30 mils as it was moved around the gap, reported in Table 3.

Figure 26 shows the bottom reflector sitting within the plate on the lower adapter. The lip of the adapter plate holds the reflector base in place. A feeler gauge was used to measure the gap around the reflector base and the lip of the adapter plate. The bottom reflector part number was BOTREF-1 (dimensions included in Appendix A). When BOTREF-1 was roughly centered within the lip of the pedestal, the feeler gauge measured between 5 and 20 mils as it was moved through the gap, reported in Table 3.

Table 3: Measured gaps around the VLM alignment plate and adapter plate.

Measured Gap	Feeler Gauge Measurement (mils)
Around alignment plate and 1-RING-1	25 to 30
Around adapter plate lip and BOTREF-1	5 to 20

2.3.2 Experiment Alignment

The VLM ensured the alignment between the exterior reflector rings of the upper and lower halves of the experiment. However, there was no way to measure or ensure the alignment of the interior HEU plate and moderator plate stack within the reflector rings. For some degree of uniformity, the plate stack was pushed to one side of the reflector rings as shown in Figure 28 and Figure 29. This interior alignment was performed with a tool as shown in Figure 27 and Figure 32. Pushing the interior HEU plate and moderator plate stack to one side resulted in a gap on the other side of the stack as shown in Figure 30 and Figure 31.

Finally, the vertical alignment of the reflector rings was ensured using two T-squares. The T-squares were aligned using the lip of the adapter plate for the lower half of the experiment, as shown in Figure 32. The T-squares were aligned with an alignment bracket (shown in Appendix C) for the upper half of the experiment, as shown in Figure 33, Figure 34, and Figure 35.

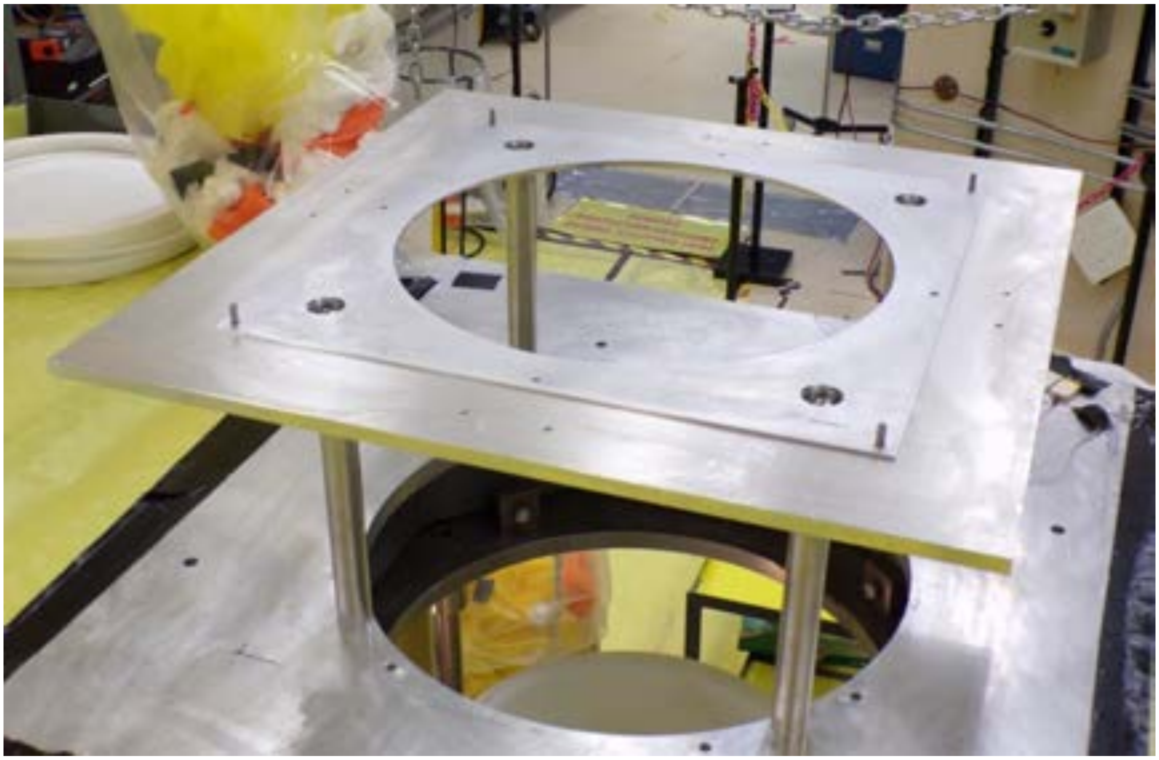

Figure 24: Experiment platform with the alignment plate by itself.

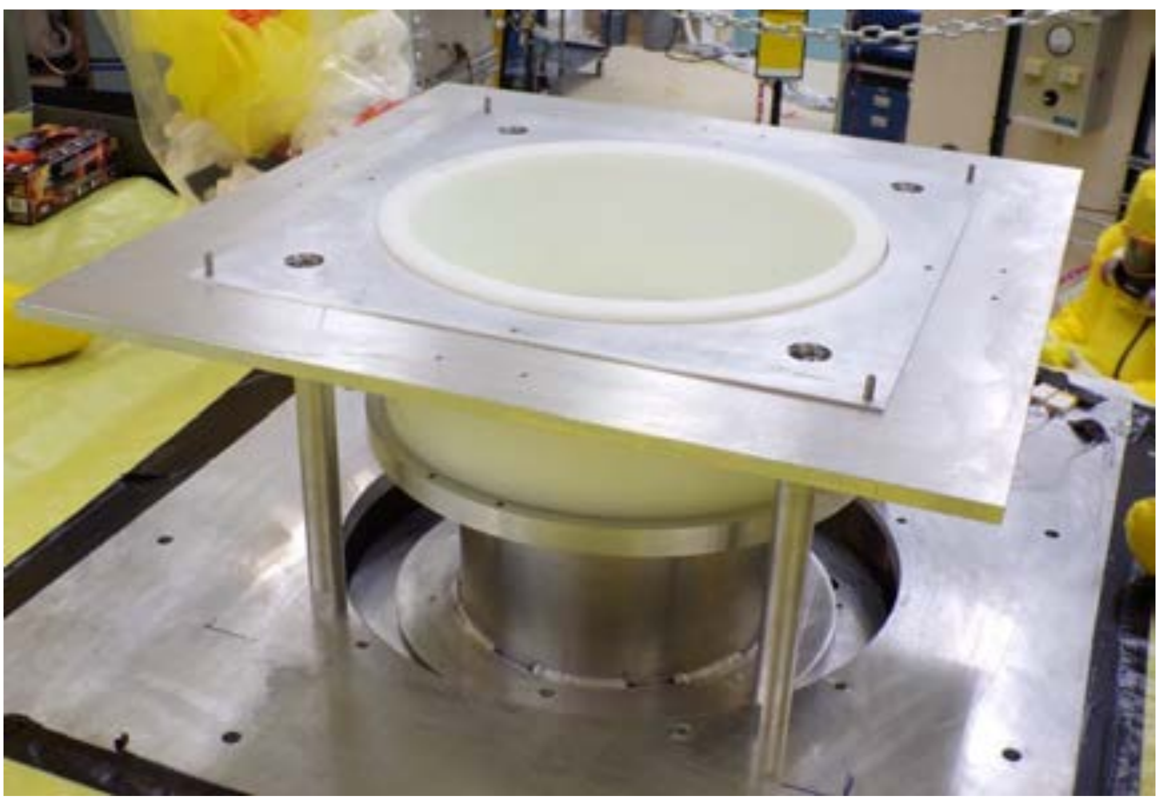

Figure 25: Reflector ring lifted through the alignment plate on Comet.

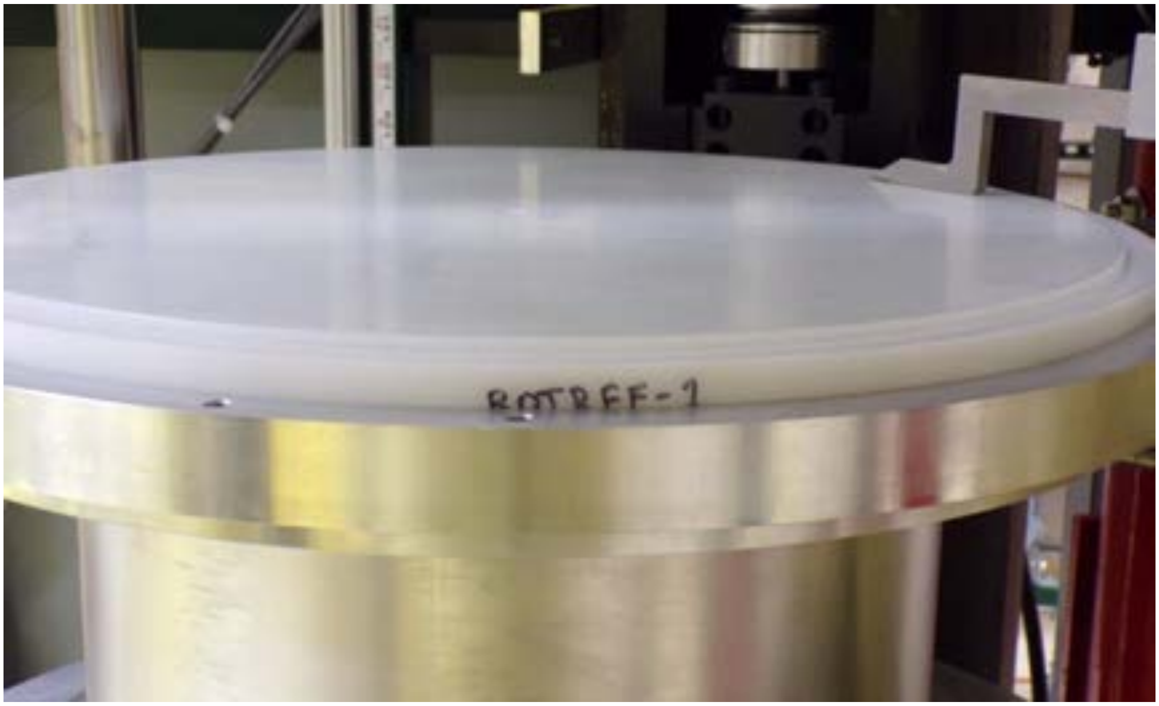

Figure 26: Reflector base in the adapter plate on the lower adapter.

Figure 27: HEU and moderator plate stack alignment within the reflector rings, showing an operator using a tool to push the stack to one side of the reflector rings.

Figure 28: Insert in an HEU plate with a 2.5” annulus, showing the insert pushed to the same side as the plate.

Figure 29: Two sides of the same HEU plate, the left shows the plate pushed towards the inside of the reflector ring leaving a gap on the right.

Figure 30: Gap between the reflector rings and the plate stack.

Figure 31: Close-up of the gap between the reflector rings and plate stack.

Figure 32: Operators using a T-square to align the first reflector ring with the bottom reflector and a tool to push the stack to one side of the reflector rings.

Figure 33: T-squares in the alignment brackets on the upper half of the experiment.

Figure 34: Operator using a T-square for final alignment of the reflector rings.

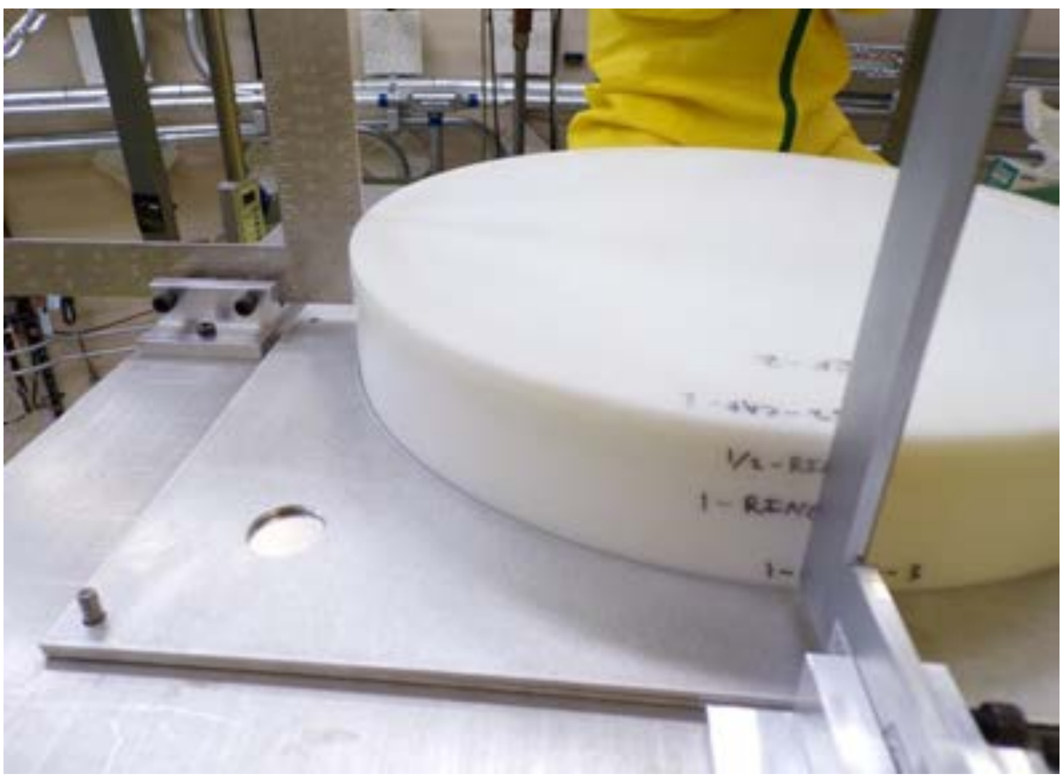

Figure 35: Close-up of the T-squares in the alignment brackets.

2.4 Height Measurements

The need for highly accurate height measurements was determined during the design phase of this experiment. To perform such measurements a Westward Electronic Height Gauge (Model No. 2YND5) was procured. This instrument has a reported resolution and indication variability of 0.0005” (0.01 mm)[13]. The manufacturer’s report indication accuracy is listed in Table 4.

Table 4: Westward Electronic Height Gauge indication accuracy, as reported by the manufacturer.

Height Range	Accuracy
0” - 12”	± 0.04 mm
12” - 18"	± 0.06 mm
18” - 24"	± 0.07 mm

The gauge was new from the manufacturer prior to first use for this experiment. At the time of experiment, the height gauge was not on any institutional calibration program. There were also no calibrated gauge blocks available to test the height gauge prior to use. Since the TEX-HEU experiment campaign, the height gauge has become part of the NCERC Calibration Program and passed all checks .

For measurements, the height gauge was clamped to the VLM, as shown in Figure 36 and Figure 37. On the experiment platform, the height gauge was clamped to the interface plate and zeroed at the membrane. On the lower adapter, the height gauge was clamped to the platen and zeroed at the base of the adapter plate. Once the height gauge was clamped and zeroed, the upper half or lower half of the experiment configuration were assembled, and a height measurement was taken for each HEU plate and moderator plate in the stack.

When the experiment configuration was completely assembled, additional measurements from three new positions were taken of the overall height of the plate stack and separately of the reflector stack. For the upper half of the experiment, these measurements were again zeroed at the membrane, as shown in Figure 38. For the lower half of the experiment, these measurements had to be zeroed on the lip of the adapter plate since the experiment covered the base of the adapter plate, as shown in Figure 39. Therefore, the reported overall height measurements of the lower half of the experiments throughout Section 3 must account for the height of the lip on the adapter plate. This height is nominally 0.47” (11.938 mm). Table 5 reports the measured height of this lip, taken during three separate experiments: ½”, ⅛” (which uses the same bottom half for A and B), and ⅛” R.

Table 5: Height measurements of lower adapter plate lip.

Height Measurement (mm)		
½”	⅛”	⅛” R
12.83	12.82	11.87
13.12	12.54	
11.36	12.73	

[13] Westward Electronic Height Gauge Operating Instructions and Parts Manual. Retrieved on September 1, 2020, available at https://www.grainger.com/product/WESTWARD-Electronic-Digital-Digital-2YND5. Archived on November 30, 2020, available at https://web.archive.org/web/20201130221610/https://www.grainger.com/ec/pdf/2YND4_2.PDF.

Figure 36: Height gauge clamped to the interface plate for height measurements of the upper half of the experiment.

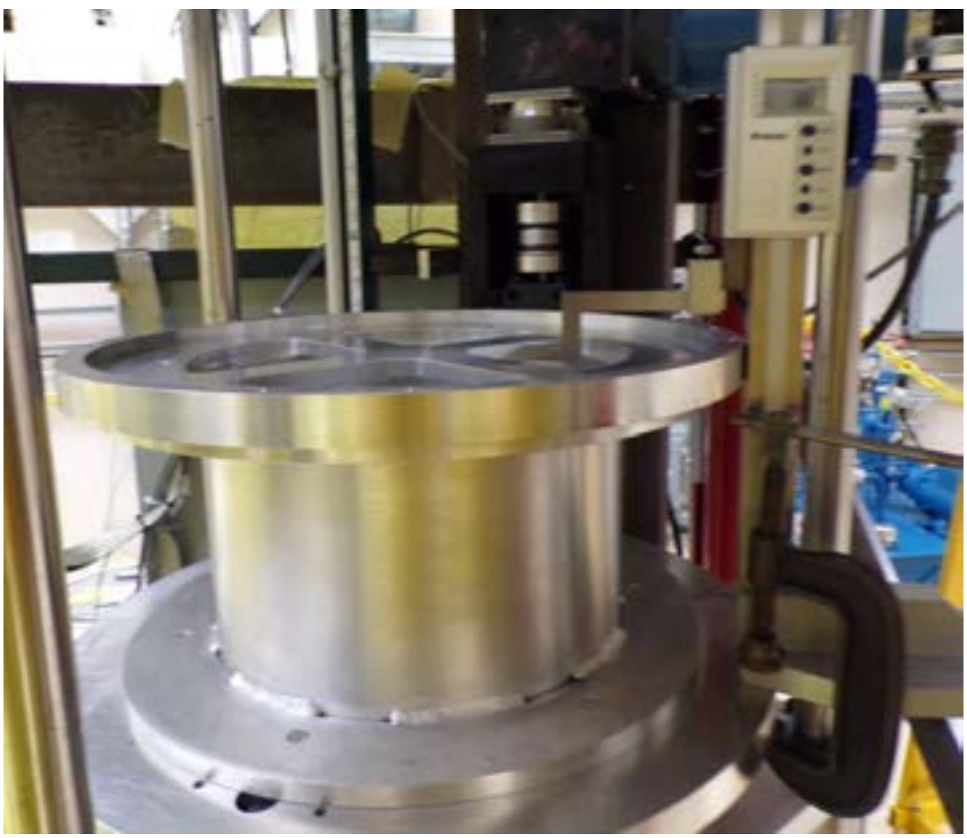

Figure 37: Height gauge clamped to the movable platen for height measurement of the lower half of the experiment, being zeroed at the base of the adapter plate.

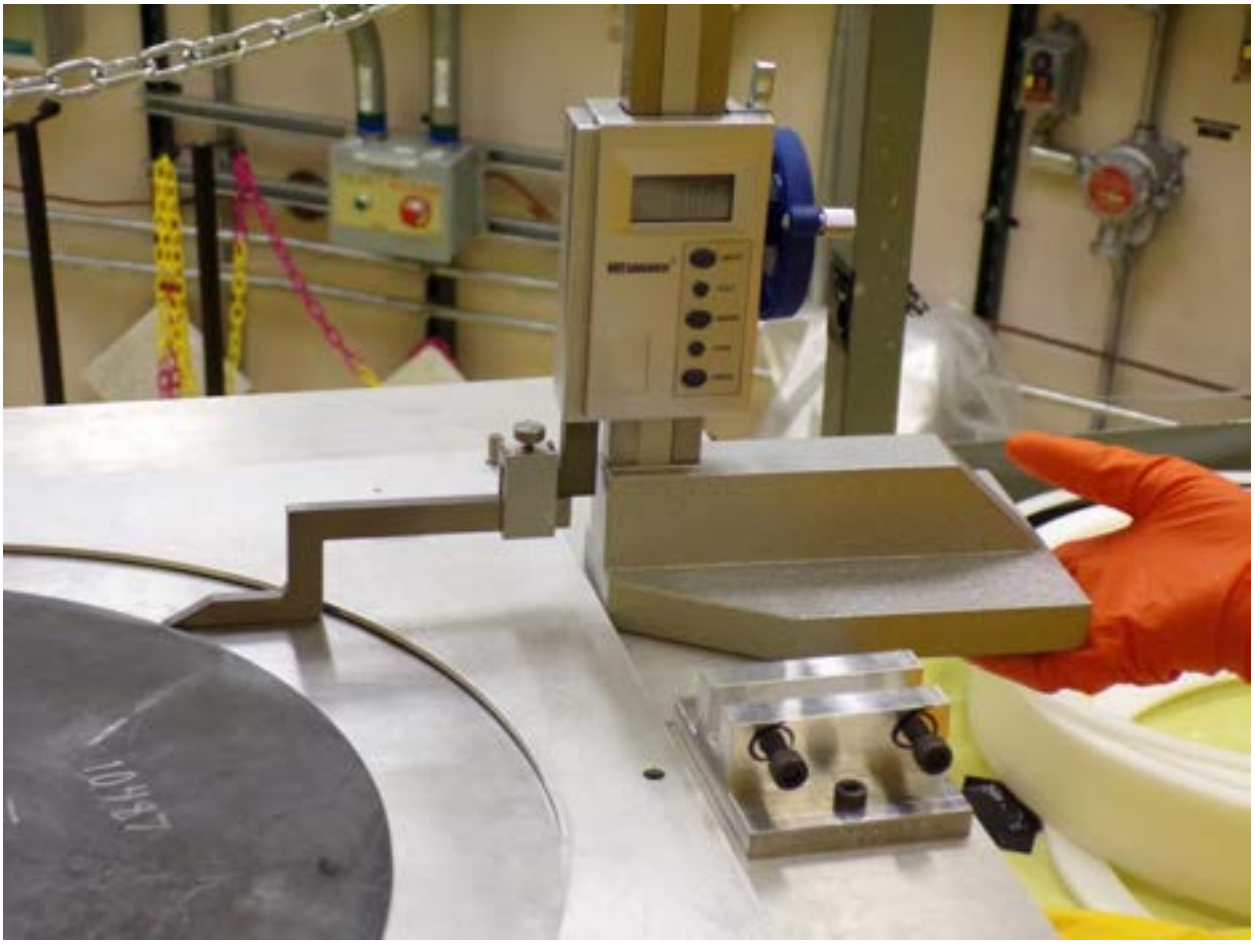

Figure 38: Height gauge being zeroed on the membrane with the alignment plate in place.

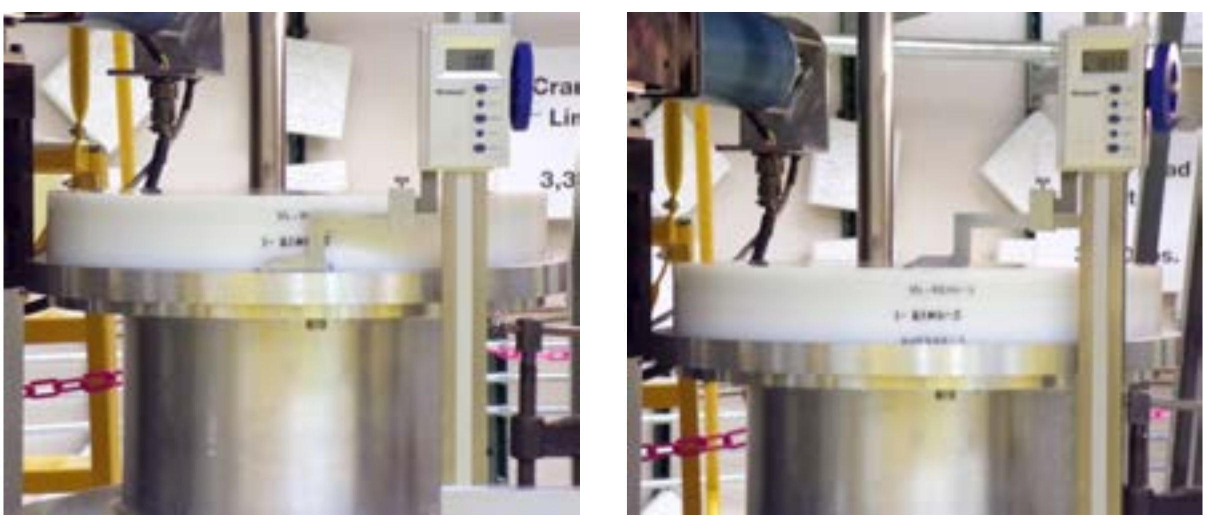

Figure 39: Height gauge measuring the overall stack height of the lower half of the experiment where it must be zeroed on the lip of the lower adapter plate.

2.5 Levelness

Levelness measurements were performed for upper and lower halves of each benchmark experiment. The measurement was performed with both a spirit and digital level. Table 6 reports the levelness measurement from the digital level for each experiment.

Table 6: Levelness measurements reported by the digital level.

<table>
<tr><th rowspan="2">Experiment</th><th colspan="2">Upper Half</th><th colspan="2">Lower Half</th></tr>
<tr><th>N/S</th><th>E/W</th><th>N/S</th><th>E/W</th></tr>
<tr><td>0”</td><td>0.00°</td><td>0.00°</td><td>0.00°</td><td>0.25°</td></tr>
<tr><td>⅛” A</td><td>0.00°</td><td>0.00°</td><td rowspan="2">0.25°</td><td rowspan="2">0.00°</td></tr>
<tr><td>⅛” B</td><td>0.20°</td><td>0.00°</td></tr>
<tr><td>⅛” R</td><td>0.25°</td><td>0.00°</td><td>0.00°</td><td>0.00°</td></tr>
<tr><td>¼”</td><td>0.20°</td><td>0.00°</td><td>0.20°</td><td>0.00°</td></tr>
<tr><td>½”</td><td>0.00°</td><td>0.00°</td><td>0.00°</td><td>0.00°</td></tr>
<tr><td>1½”</td><td>0.20°</td><td>0.00°</td><td>0.00°</td><td>0.20°</td></tr>
</table>

The digital level is a Fowler Xtra-Value Digi-Level (Model No. 54-422-444-0) under the NCERC calibration program (Cal No. 018011). The calibration for this digital level was certified on February 4, 2020 and is valid through February 4, 2021. These measurements were taken between February 5 and June 2. The manufacturer of the digital level reports a resolution and repeatability of 0.05° and an accuracy of ±0.2°[14].

Figure 40 shows the levelness measurement being performed for the lower half of the ⅛” experiment, using both the spirit level and digital level. Additional levelness measurements are also shown in Figure 46, Figure 47, Figure 54, Figure 55, Figure 58, Figure 75, Figure 76, Figure 90, and Figure 91.

[14] Fowler Xtra-Value Digi-Level 54-422-444-0. Retrieved on September 1, 2020, available at https://www.fowlerprecision.com/Products/Economy-Digi-Level/544224440.html. Archived on January 6, 2018, available at https://web.archive.org/web/20180106181658/https://www.fowlerprecision.com/Products/Economy-Digi-Level/544224440.html.

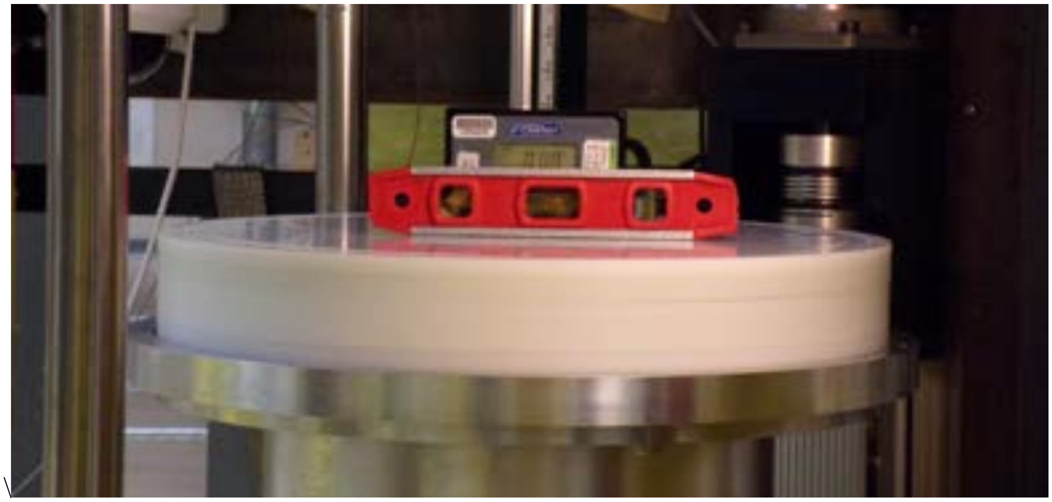

Figure 40: Levelness measurement using the spirit and digital levels.

2.6 Temperature

The temperature of each experiment was measured by placing two resistance temperature detectors (RTD) on the upper half of the experiment, shown in Figure 2. The RTDs were placed on the aluminum membrane which was in direct contact with an HEU plate (RTD #1) and on top of the polyethylene reflector (RTD #2). These RTDs were only put in place during the approach to critical and the initial critical configuration. They were removed during the restack of the experiment prior to the reactivity measurement for the benchmark configuration. In addition to the RTDs on the experiment, there were also measurements of the ambient temperature in the room, which was taken from an RTD mounted on the Comet junction box.

Table 7 reports the temperature measurements from the experiments. There was no measurable departure from the ambient temperature of the room during operation of the critical experiments.

Table 7: Ambient and RTD temperature measurements.

Experiment	RTD #1 (°C)	RTD #2 (°C)	Ambient (°C)
0”	11.4	8.7	11.5
⅛” A ⅛” B	12.3	11.1	11.4
⅛” R	11.5	8.8	11.3
¼”	12.4	11.6	11.6
½”	12.2	8.2	11.7
1½”	11.8	8.8	11.5

Section 3

Experiment Configurations

The following sections list the measured quantities from each benchmark experiment. These quantities include the height of each layer within the stack, the overall height of the stack and the reflector rings measured at three separate positions, the period measurements from all available detectors, and the calculated excess reactivity. In addition to the measured quantities, each section includes a detailed experiment layout with each part labeled and identified. Finally, photographs and descriptions documenting each experiment are included.

The individual layer and overall height measurements are split between the upper half of the experiment on the stationary platform and the lower half of the experiment on the movable platen. These height measurements had to be zeroed at various position as described in Section 2.4.

The separation distance, or membrane lift, is noted at both the point where the two halves of the experiment first come into contact and when the experiment is fully lifted. These reported values are based on the Comet load sensor. As the lower half of the experiment begins to come into contact with the membrane and upper half of the experiment, the load sensor begins to register the increasing weight. When the two halves are in full contact and the movable platen is fully lifting the membrane and upper half of the experiment as well, the load sensor stops increasing. For every experiment, the movable platen is extended to between 0.000” and 0.005” of separation distance. Therefore, the separation distance when the two halves first come into contact and when the membrane begins to lift informs the final distance between the membrane and the interface plate.

There are six benchmark configurations and one reproducibility measurement documented from this experiment. The configurations are identified based on the moderator thickness. For example, the 1” experiment uses 1” thick moderator and the 0” experiment uses no moderator. There are five moderator thicknesses: 0”, ⅛”, ¼”, ½”, and 1½”. The ⅛” experiment includes three configurations: ⅛” A, ⅛” B, and ⅛” R. The ⅛” A and ⅛” B experiments were two benchmark configurations and the ⅛” R experiment was a reproducibility measurement.

3.1 0” Experiment

The 0” experiment began on May 27 and reached first criticality on May 28. The benchmark configuration was documented on June 1 with a calculated excess reactivity of 3.91¢ to 4.19¢. Membrane lift began at 250 mils and ended at 225 mils of separation.

Table 8: Height measurements at each layer of the 0” experiment.

Upper Half	
Part ID	Height (mm)
1/2-MOD-7	50.24
1/4-MOD-5	37.42
1/8-MOD-11	30.86
1/16-REF-1	27.77
1/32-REF-1	26.05
10479 (10-DISK-3)	25.23
10463 (10-DISK-2)	22.34
10457 (6-DISK-4)	18.93
10493 (6-DISK-3)	15.44
10467 (2.5-DISK-7)	12.34
10470 (2.5-DISK-6)	9.04
10475 (2.5-DISK-5)	6.12
10489 (2.5-DISK-4)	2.96

Lower Half	
Part ID	Height (mm) [15]
11017	59.77
11150	56.81
11019	54.14
11147	50.85
11149	47.43
10464 (2.5-DISK-3)	44.18
10487 (2.5-DISK-2)	40.95
10491 (2.5-DISK-1)	37.60
11018 (6-DISK-2)	34.42
10477 (6-DISK-1)	31.03
10472 (10-DISK-1)	27.92
BOTREF-1	25.25

Table 9: Overall height measurements of the 0” experiment, taken from three separate positions.

Upper Half	
Stack Height (mm)	Reflector Height (mm)
50.65	50.81
50.46	50.55
50.66	50.39

Lower Half[16]	
Stack Height (mm)	Reflector Height (mm)
49.60	48.10
49.91	50.36
50.07	50.07

Table 10: Period measurements and calculated excess reactivity for the 0” experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	268.80	4.15	10^{-10}
LC_2	265.73	4.19	10^{-10}
LC_3	272.77	4.09	10^{-10}
SU	287	3.91	-

[15] There was a discrepancy with the initial BOTREF-1 height measurement. Reported values have been adjusted according to discussion in Section 3.1.1.
[16] Must account for additional lower adapter plate lip height, measurements in Table 5.

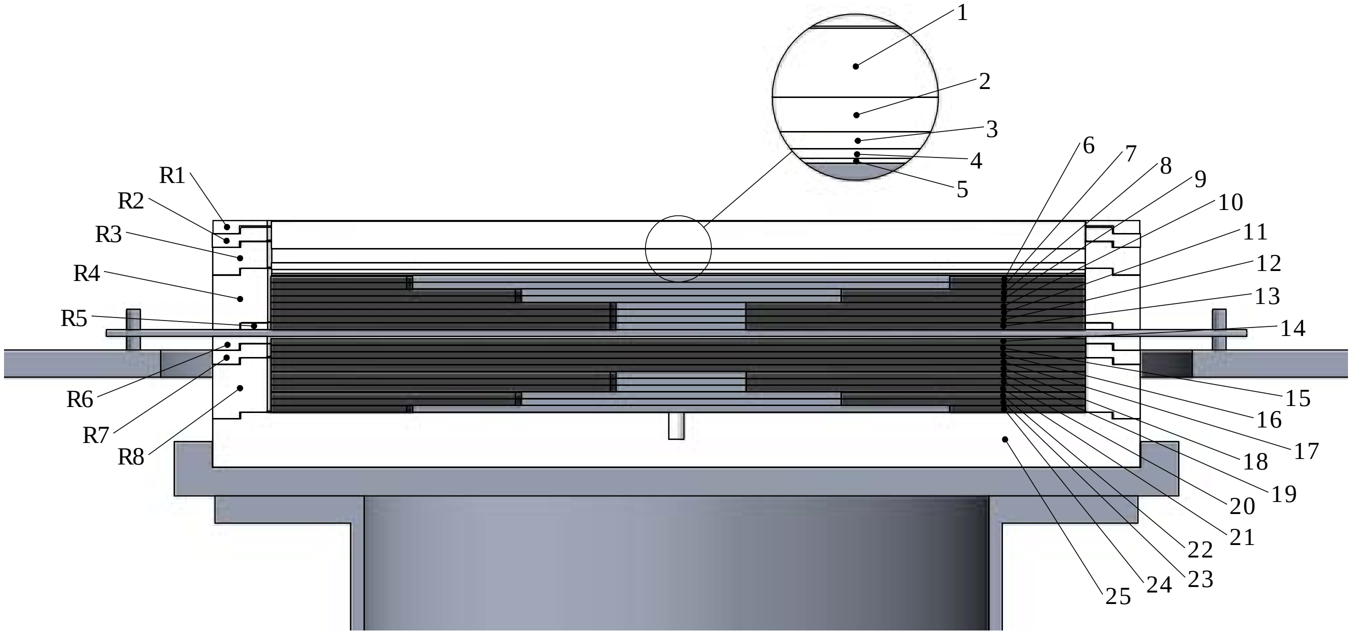

Figure 41: Configuration of the 0” experiment.

Table 11: Part numbers for the 0” experiment.

#	Part ID
1	1/2-MOD-7
2	1/4-MOD-5
3	1/8-MOD-11
4	1/16-REF-1
5	1/32-REF-1
6	10479 (10-DISK-3)
7	10463 (10-DISK-2)
8	10457 (6-DISK-4)
9	10493 (6-DISK-3)

#	Part ID
10	10467 (2.5-DISK-7)
11	10470 (2.5-DISK-6)
12	10475 (2.5-DISK-5)
13	10489 (2.5-DISK-4)
M	Membrane
14	11017
15	11150
16	11019
17	11147

#	Part ID
18	11149
19	10464 (2.5-DISK-3)
20	10487 (2.5-DISK-2)
21	10491 (2.5-DISK-1)
22	11018 (6-DISK-2)
23	10477 (6-DISK-1)
24	10472 (10-DISK-1)
25	BOTREF-1

#	Part ID
R1	3/32-CAP-1
R2	1/4-RING-1
R3	1/2-RING-1
R4	1-RING-1
R5	0-BOTCAP-1
R6	1/8-CAP-3
R7	1/4-RING-2
R8	1-RING-5

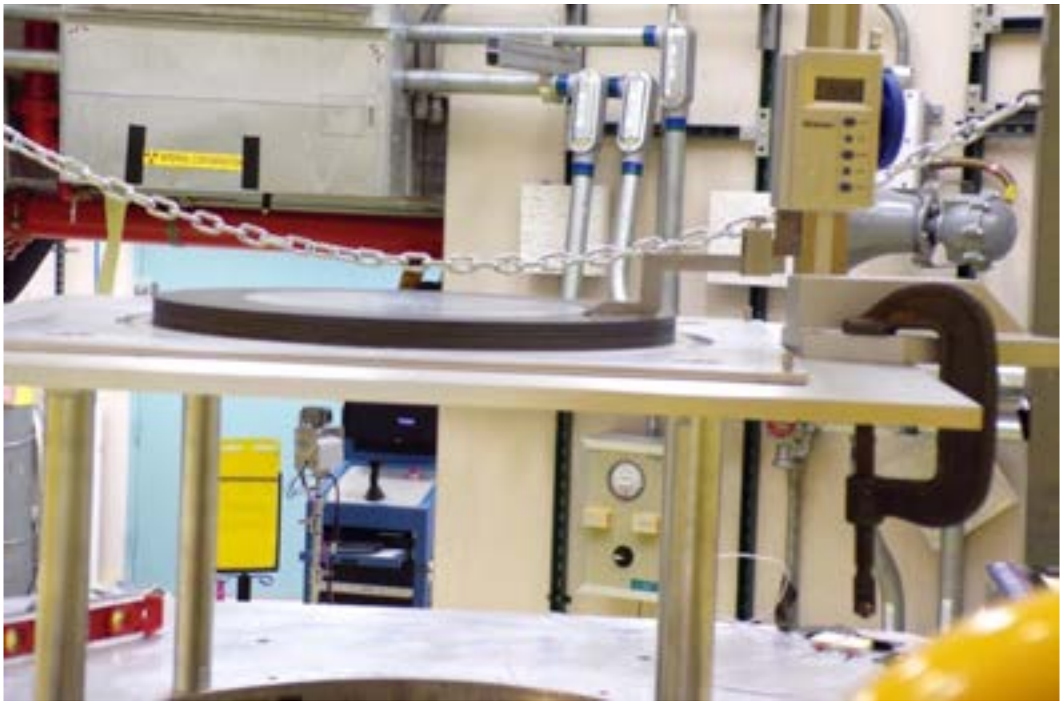

Figure 42: Upper half of the 0” experiment with eight HEU plates on top of the membrane. Prior to adding the reflector rings.

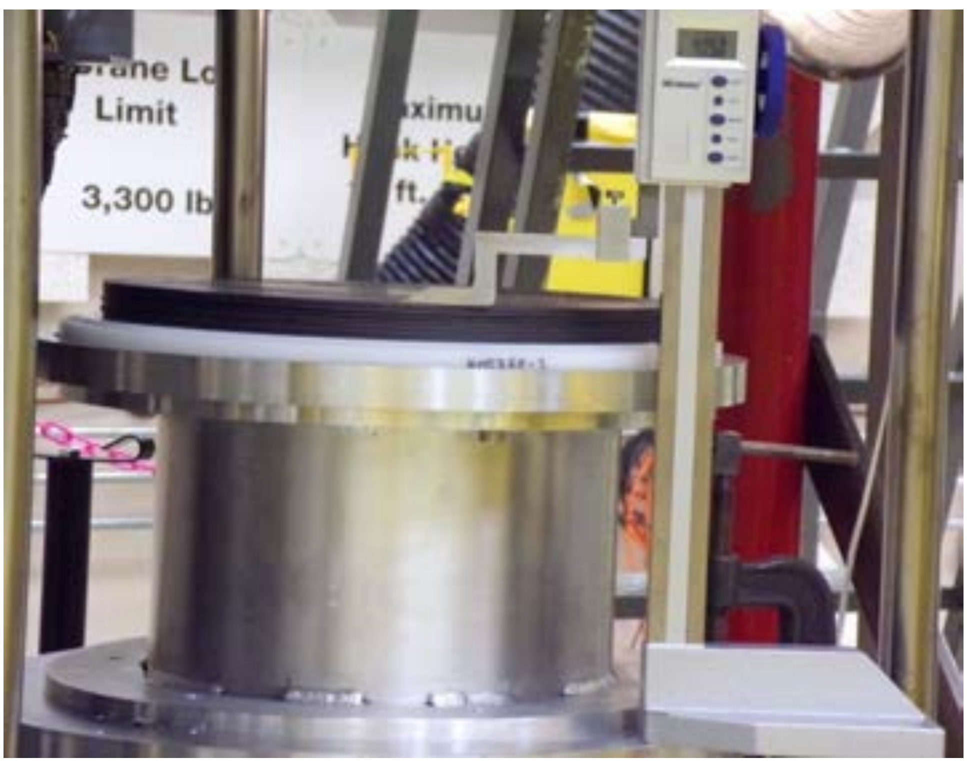

Figure 43: Lower half of the 0” configuration with seven HEU plates and the bottom reflector. Prior to adding the reflector rings.

Figure 44: Complete upper half of the 0" experiment.

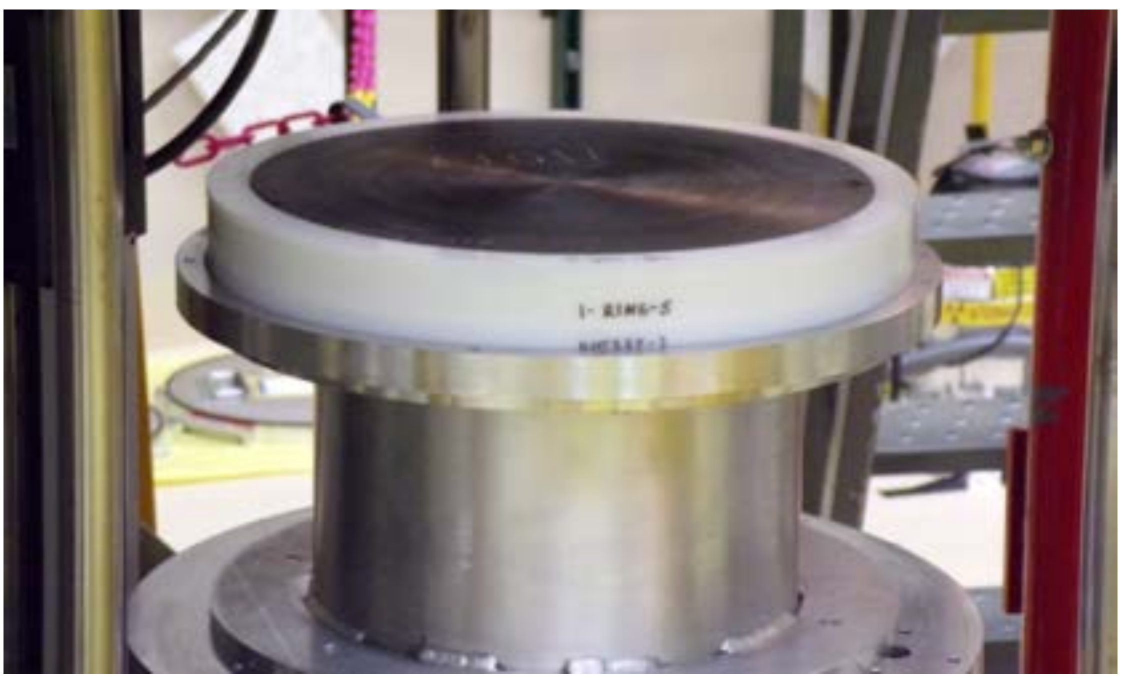

Figure 45: Complete lower half of the 0" experiment.

Figure 46: Levelness measurement for the upper half of the 0” experiment

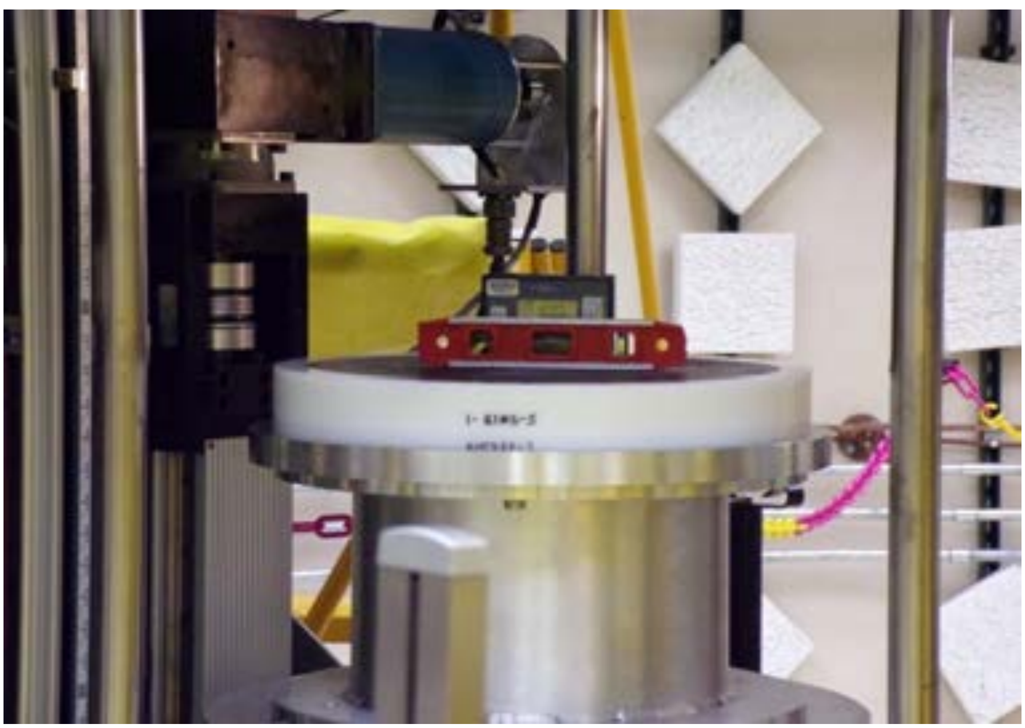

Figure 47: Levelness measurement for the lower half of the 0” experiment.

3.1.1 BOTREF-1 Height Measurement

The height measurement of BOTREF-1 was performed incorrectly during the 0" experiment. This was likely due to the way in which the height gauge was zeroed. The average BOTREF-1 height measurement for the other experiments is 25.06 ± 0.56 mm with an independently measured thickness of 25.9715 ± 0.00254 mm. The measurement taken during this experiment was 18.32 mm.

This discrepancy was noticed during the reactivity measurement of the 0" experiment. Another measurement was taken during the disassembly of the 0" experiment, prior to the ⅛" R reproducibility measurement. The new measurement was 25.25 mm, which is in much better agreement with the prior measurements and the expected thickness of 1".

Since the error is assumed to have occurred during the initial zeroing of the height gauge, the height measurements of the other layers relative to the initial incorrect measurement are assumed to be accurate. This is a safe assumption because the height gauge was only zeroed once while measuring the height of each layer. The corrected heights, using the 25.25 mm measurement for BOTREF-1, are reflected in the parenthesis of Table 8.

3.2 ⅛" Experiments

The ⅛" experiment involves three critical configurations: two benchmark configuration and one reproducibility measurement. The first ⅛" experiment was the ⅛" A configuration. However, the measured period of ⅛" A corresponded to a higher reactivity than desired. The ⅛" B experiment was assembled with a higher HEU mass, by swapping the 11150 HEU plate for the 11147 HEU plate, and reduced top reflector thickness, from 1³⁄₃₂" to 1¹⁄₁₆". These changes sufficiently reduced the measured period of ⅛" B. The lower half of the ⅛" A and ⅛" B experiments is the same and was only assembled and measured once between the two experiments. Since the bulk of the time required for the benchmark configuration was finding the critical point, it was decided that both ⅛" A and ⅛" B would be documented. The ⅛" B experiment was documented first, followed by the ⅛" A experiment.

The reproducibility measurement (⅛" R) was based on the ⅛" B configuration, with different moderator plates and reflector rings. Only the overall heights of the ⅛" R experiment were measured, not the height of each individual layer. This was decided because the ⅛" R experiment serves as a reproducibility measurement of the ⅛" B configuration.

Following the ¼" experiment, it was decided that the three additional height measurements for the overall stack height were unnecessary because that measurement was already performed during the individual layer height measurements. This decision would both save time on the experiment and simply the measurements for the operators. However, after looking more closely at the measurements of the ¼" experiment, it was clear that the height measurement of the final layer was not in good enough agreement with the average of three additional height measurements to deem them unnecessary. Because of this decision, the additional height measurements are not included for the ⅛" A and ⅛" B configurations.

Looking at the measurements of the upper half of the ¼" experiment, the final measurement of the individual layer heights was 73.09 mm while the average of the three additional stack height measurements is 72.44 ± 0.12 mm. While this discrepancy is only around 0.5 mm, it may have resulted from the repeated sliding up and sliding down of the scriber as each layer height is measured and the next layer is put in place. During this assembly process, the height gauge is only zeroed for the first measurement, meaning that it could have lost accuracy by the final measurement.

In the end, it seemed like a poor decision to sacrifice experiment detail for a minor time savings. This decision to not measure the overall stack height at multiple positions only applied to the ⅛" A and ⅛" B experiments before being rectified.

3.2.1 ⅛" A

The ⅛" experiment began on March 2 and reached first criticality on March 3. The ⅛" A benchmark configuration was documented on March 4 with a calculated excess reactivity of 26.11¢ to 27.02¢. During the execution of this experiment, the absolute encoder, which reports the vertical position of the movable platen, began to fail resulting in inserting and removing the movable platen multiple times (see discussion in 3.2.1.1). The membrane lift appeared to be between 0.125" and 0.0625". This lift is based on an observation using the video of the experiment as the absolute encoder was unable to report a value.

Table 12: Height measurements at each layer of the ⅛" A experiment.

Upper Half	
Part ID	Height (mm)
1-REF-2	49.71
1/16-REF-1	24.34
1/32-REF-1	22.46
11149	21.84
1/8-MOD-10	18.41
11019	15.43
1/8-MOD-9	12.08
11017	8.99
1/8-MOD-8	6.19
11150	2.98

Lower Half	
Part ID	Height (mm)
1/8-MOD-7	70.08
10464 (2.5-DISK-7)	67.19
1/8-MOD-6	63.47
10475 (2.5-DISK-6)	60.47
1/8-MOD-5	57.28
10470 (2.5-DISK-5)	54.20
1/8-MOD-4	5096
10489 (2.5-DISK-4)	47.39
1/8-MOD-3	44.28
10491 (2.5-DISK-3)	41.47
1/8-MOD-2	37.70
10467 (2.5-DISK-2)	34.50
1/8-MOD-1	31.58
10487 (2.5-DISK-1)	28.41
BOTREF-1	25.18

Table 13: Reflector ring height measurements for the ⅛" A experiment. The lower half was zeroed at the base of the adapter plate.

Upper Half (mm)
49.45

Lower Half (mm)
69.96

Table 14: Period measurements and calculated excess reactivity for the ⅛" A experiment[17].

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	22.14	27.01	10^{-9}
LC_2	22.68	26.65	10^{-9}
LC_3	22.11	27.02	10^{-9}
SU	23.53	26.11	10,000

[17] The data files containing the detector measurements used to calculate the excess reactivity were lost due to a computer error.

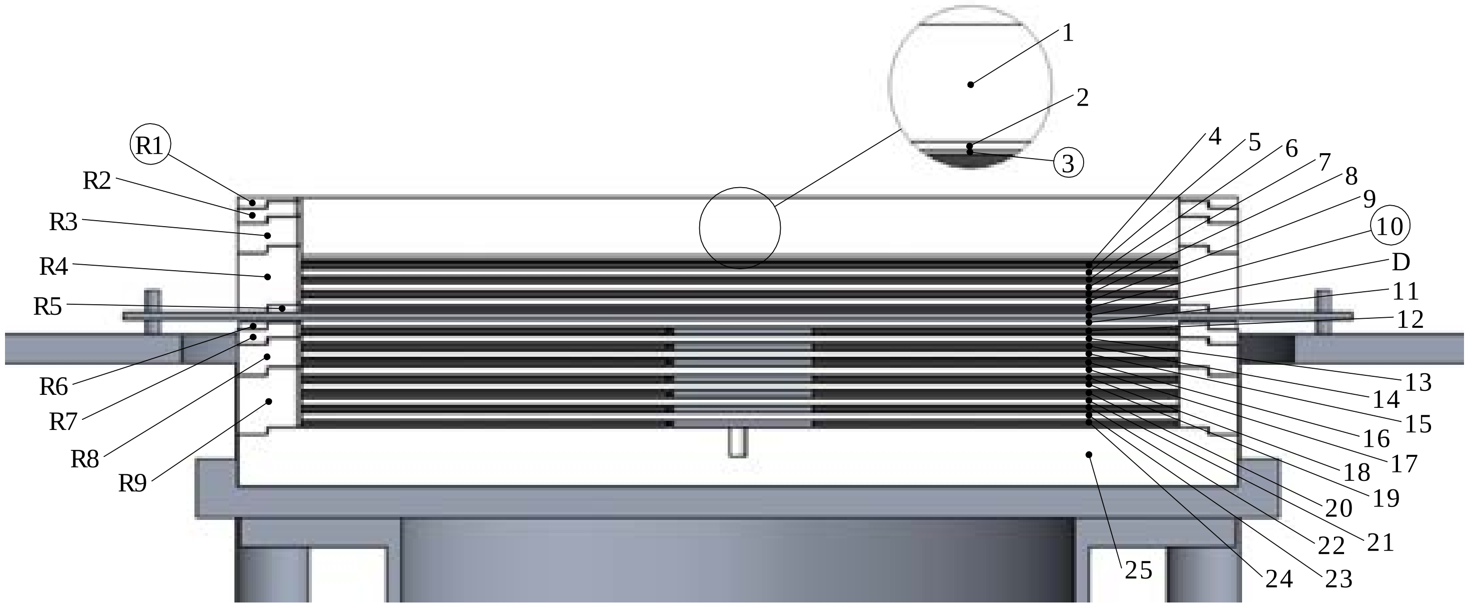

Figure 48: Configuration of the ⅛" A experiment. The circle numbers are the parts that differ from ⅛" B.

Table 15: Part numbers for the ⅛" A experiment. The bolded Part IDs are those that differ from ⅛" B.

#	Part ID	#	Part ID	#	Part ID	#	Part ID
1	1-REF-2	10	**11150**	18	10489 (2.5-DISK-4)	R1	**1/16-CAP-1**
2	1/16-REF-1	D	Membrane	19	1/8-MOD-3	R2	1/4-RING-2
3	**1/32-REF-1**	11	1/8-MOD-7	20	10491 (2.5-DISK-3)	R3	1/2-RING-1
4	11149	12	10464 (2.5-DISK-7)	21	1/8-MOD-2	R4	1-RING-3
5	1/8-MOD-10	13	1/8-MOD-6	22	10467 (2.5-DISK-2)	R5	0-BOTCAP-1
6	11019	14	10475 (2.5-DISK-6)	23	1/8-MOD-1	R6	0-CAP-1
7	1/8-MOD-9	15	1/8-MOD-5	24	10487 (2.5-DISK-1)	R7	1/4-RING-1
8	11017	16	10470 (2.5-DISK-5)	25	BOTREF-1	R8	1/2-RING-3
9	1/8-MOD-8	17	1/8-MOD-4			R9	1-RING-5

3.2.1.1 Absolute Encoder Replacement

On March 4, the absolute encoder of Comet began to fail. This occurred during the ⅛" A experiment, after the successful completion of the ⅛" B experiment. The absolute encoder is the instrument used to report the vertical position of the movable platen on Comet. This vertical position is used to determine the separation distance between the movable platen and the stationary platform. The separation distance is used by both the operators during the approach to critical and the VLM's control system as an aid to the operators to automatically slow the speed of the stepper motor as the separation distance approaches zero. As the encoder began to fail, the control system would not automatically slow the speed of the motor and actually increased the speed.

The operators were able to manually set the speed of the stepper motor. However, by the time the ⅛" A experiment was successfully close it had been inserted and removed multiple times. This could have caused the alignment of the lower stack of moderator and HEU plates against the reflector rings to be lost due to the polyethylene moderator plates in the stack sliding as the platen was inserted and removed. There was no clear indication that the alignment of the lower stack was lost. This had no impact on the upper half of the experiment on the stationary platform.

The Cognizant Systems Engineers that support NCERC were able to successfully replace the absolute encoder the following day. There were no further problems with it for the remainder of the experiments.

3.2.2 ⅛” B

The ⅛” experiment began on March 2 and reached first criticality on March 3. The ⅛” B benchmark configuration was documented on March 4 with a calculated excess reactivity of 5.57¢ to 5.90¢. Membrane lift began at 200 mils and ended at 150 mils of separation.

Table 16: Height measurements at each layer of the ⅛” B experiment.

Upper Half	
Part ID	**Height (mm)**
1-REF-2	48.49
1/16-REF-1	23.14
11149	21.46
1/8-MOD-10	18.05
11019	14.78
1/8-MOD-9	11.89
11017	8.74
1/8-MOD-8	6.08
11147	4.45

Lower Half	
Part ID	**Height (mm)**
1/8-MOD-7	70.08
10464 (2.5-DISK-7)	67.19
1/8-MOD-6	63.47
10475 (2.5-DISK-6)	60.47
1/8-MOD-5	57.28
10470 (2.5-DISK-5)	54.20
1/8-MOD-4	5096
10489 (2.5-DISK-4)	47.39
1/8-MOD-3	44.28
10491 (2.5-DISK-3)	41.47
1/8-MOD-2	37.70
10467 (2.5-DISK-2)	34.50
1/8-MOD-1	31.58
10487 (2.5-DISK-1)	28.41
BOTREF-1	25.18

Table 17: Reflector ring height measurements for the ⅛” B experiment. The lower half was zeroed at the base of the adapter plate.

Upper Half (mm)
48.48

Lower Half (mm)
69.96

Table 18: Period measurements and calculated excess reactivity for the ⅛” B experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	188.21	5.88	10^{-10}
LC_2	188.64	5.87	10^{-10}
LC_3	187.40	5.90	10^{-10}
SU	200.67	5.57	10,000

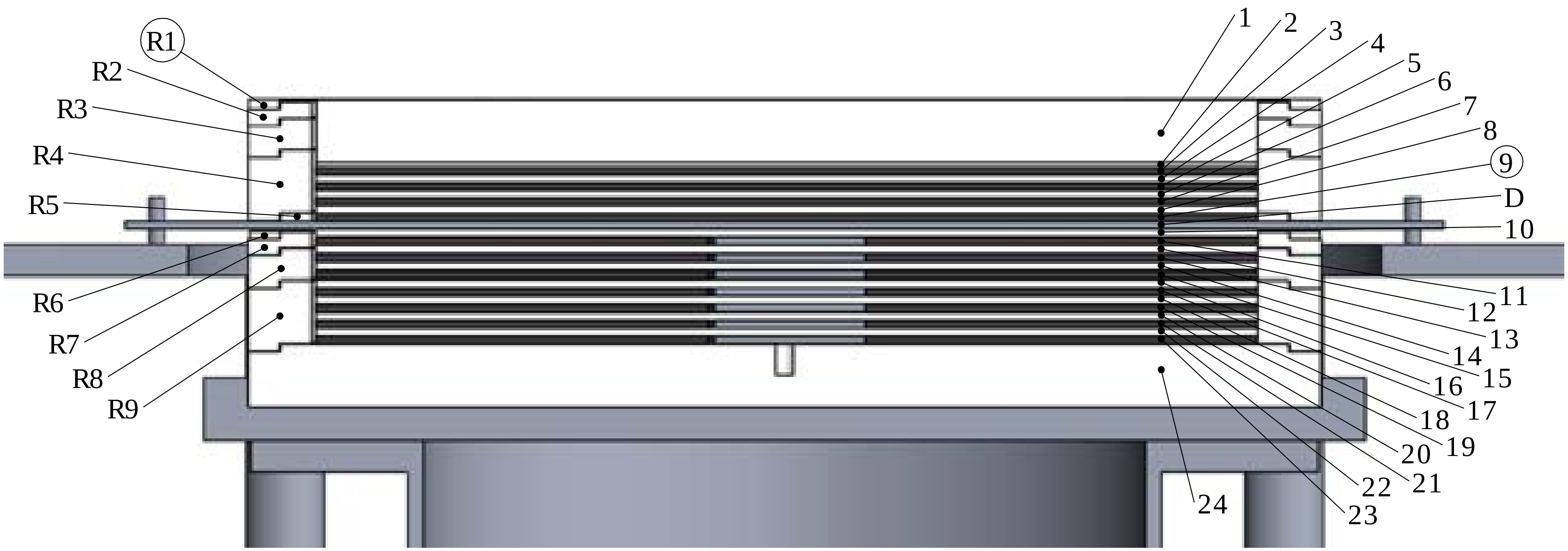

Figure 49: Configuration of the ⅛" B experiment. The circle numbers are the parts that differ from ⅛" A.

Table 19: Part numbers for the ⅛" B experiment. The bolded Part IDs are those that differ from ⅛" A.

#	Part ID	#	Part ID	#	Part ID	#	Part ID
1	1-REF-2	D	Membrane	18	1/8-MOD-3	R1	**1/32-CAP-1**
2	1/16-REF-1	10	1/8-MOD-7	19	10491 (2.5-DISK-3)	R2	1/4-RING-2
3	11149	11	10464 (2.5-DISK-7)	20	1/8-MOD-2	R3	1/2-RING-1
4	1/8-MOD-10	12	1/8-MOD-6	21	10467 (2.5-DISK-2)	R4	1-RING-3
5	11019	13	10475 (2.5-DISK-6)	22	1/8-MOD-1	R5	0-BOTCAP-1
6	1/8-MOD-9	14	1/8-MOD-5	23	10487 (2.5-DISK-1)	R6	0-CAP-1
7	11017	15	10470 (2.5-DISK-5)	24	BOTREF-1	R7	1/4-RING-1
8	1/8-MOD-8	16	1/8-MOD-4			R8	1/2-RING-3
9	**11147**	17	10489 (2.5-DISK-4)			R9	1-RING-5

Figure 50: Height measurement of the first HEU plate on the upper half of the ⅛” B experiment.

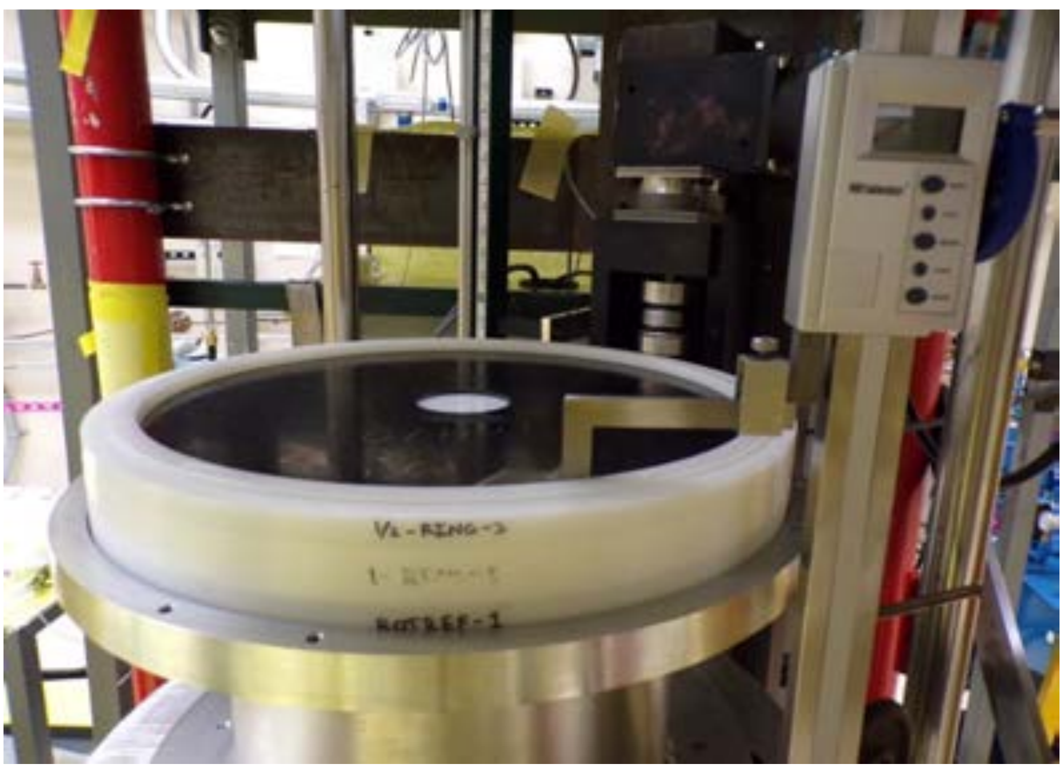

Figure 51: Height measurement of an HEU plate with a 2.5” annulus on the lower half of the ⅛” experiment (used for both ⅛” A and ⅛” B).

Figure 52: Zeroing the height gauge for the overall height measurement of the upper half of the ⅛” A experiment.

Figure 53: Overall height measurement of the lower half of the ⅛” experiment (used by both ⅛” A and ⅛” B).

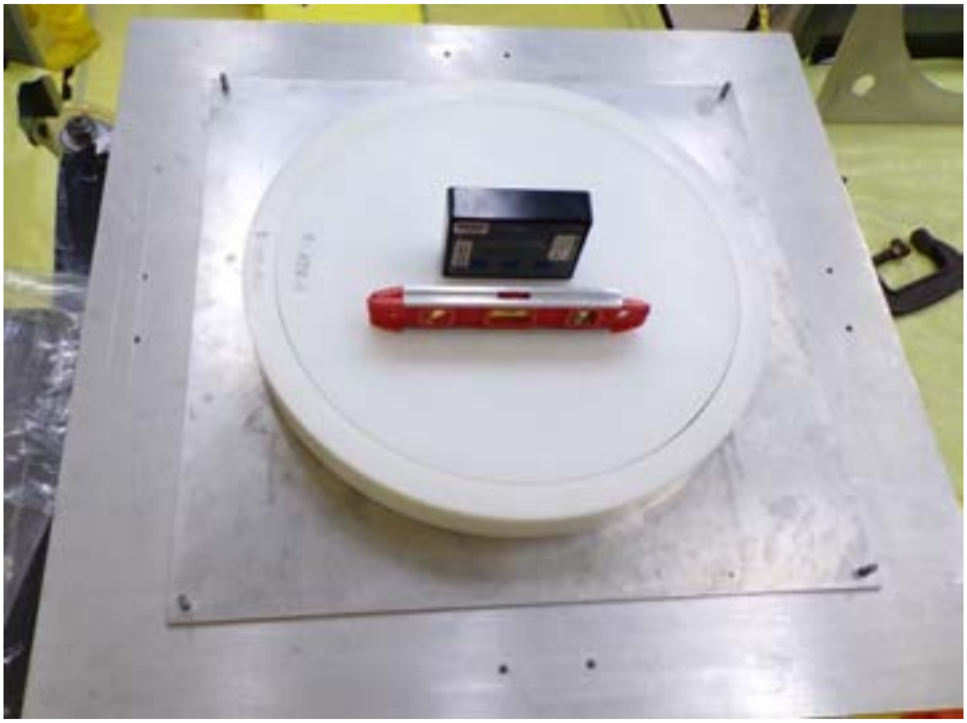

Figure 54: Levelness measurement of the upper half of the ⅛" B experiment.

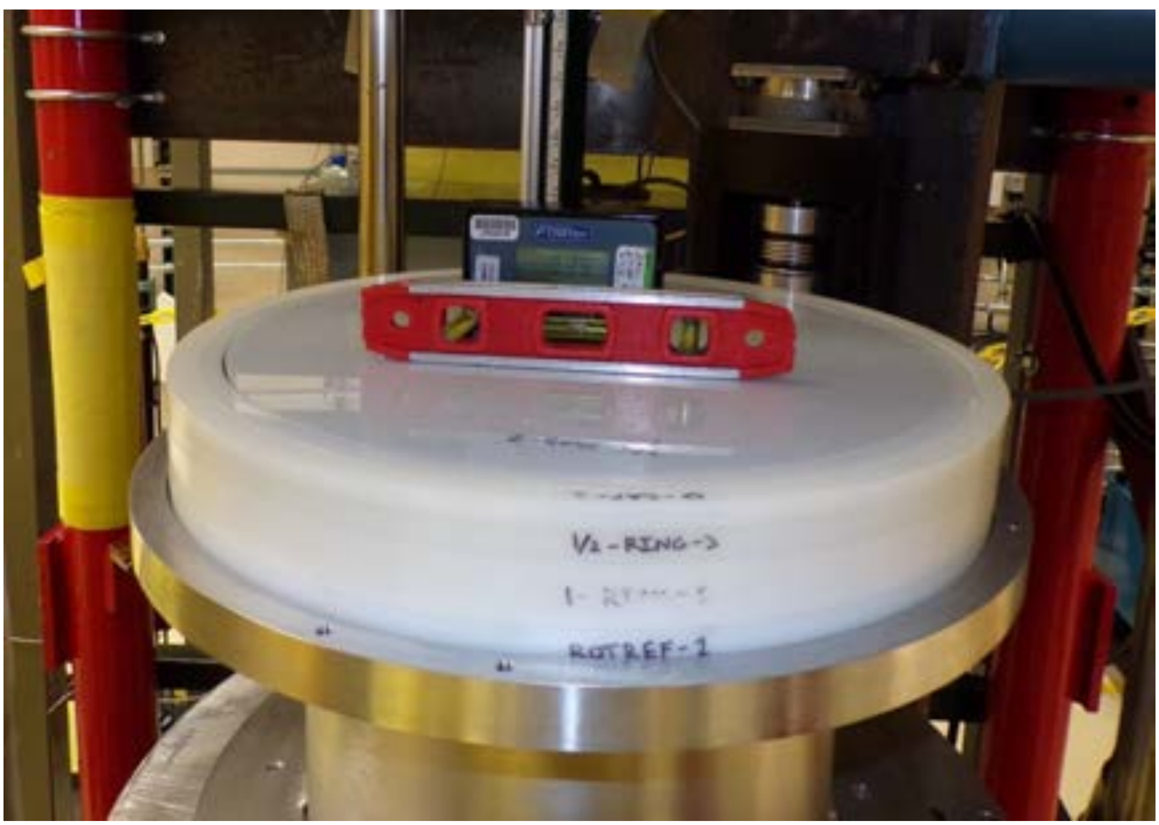

Figure 55: Levelness measurement of the lower half of the ⅛" experiment (used by both ⅛" A and ⅛" B).

3.2.3 ⅛" R

The ⅛" R reproducibility measurement was documented on June 2 with a calculated excess reactivity of 18.62¢ to 19.11¢. Membrane lift began at 250 mils and ended at 200 mils of separation.

Table 20: Overall height measurements of the ⅛" R experiment, taken from three separate positions.

Upper Half	
Stack Height (mm)	Reflector Height (mm)
48.53	48.38
48.87	48.63
48.40	48.32

Lower Half	
Stack Height (mm)	Reflector Height (mm)
58.26	58.13
58.15	58.51
58.36	58.21

Table 21: Period measurements and calculated excess reactivity for the ⅛" R experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	40.10	18.97	10^{-10}
LC_2	39.87	19.04	10^{-10}
LC_3	39.64	19.11	10^{-10}
SU	41.28	18.62	-

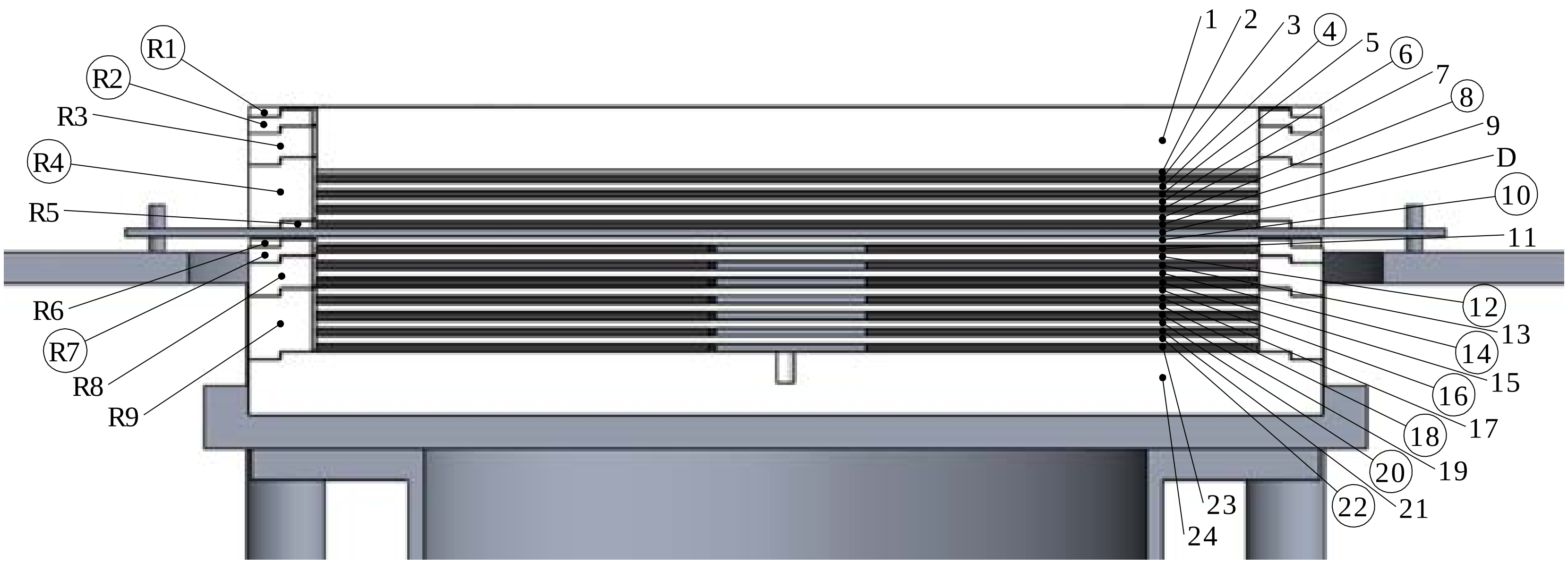

Figure 56: Configuration of the ⅛" R experiment. The circled numbers are the parts that differ from ⅛" B.

Table 22: Part numbers for the ⅛" R experiment. The bolded Part IDs are those that differ from ⅛" B.

#	Part ID
1	1-REF-2
2	1/16-REF-1
3	11149
4	**1/8-MOD-21**
5	11019
6	**1/8-MOD-20**
7	11017
8	**1/8-MOD-19**
9	11147

#	Part ID
D	Membrane
10	**1/8-MOD-18**
11	10464 (2.5-DISK-7)
12	**1/8-MOD-17**
13	10475 (**2.5-DISK-10**)
14	**1/8-MOD-16**
15	10470 (**2.5-DISK-9**)
16	**1/8-MOD-15**
17	10489 (**2.5-DISK-8**)

#	Part ID
18	**1/8-MOD-14**
19	10491 (2.5-DISK-3)
20	**1/8-MOD-13**
21	10467 (2.5-DISK-2)
22	**1/8-MOD-12**
23	10487 (2.5-DISK-1)
24	BOTREF-1

#	Part ID
R1	**1/32-CAP-3**
R2	**1/4-RING-1**
R3	1/2-RING-1
R4	**1-RING-1**
R5	0-BOTCAP-1
R6	0-CAP-1
R7	**1/4-RING-2**
R8	1/2-RING-3
R9	1-RING-5

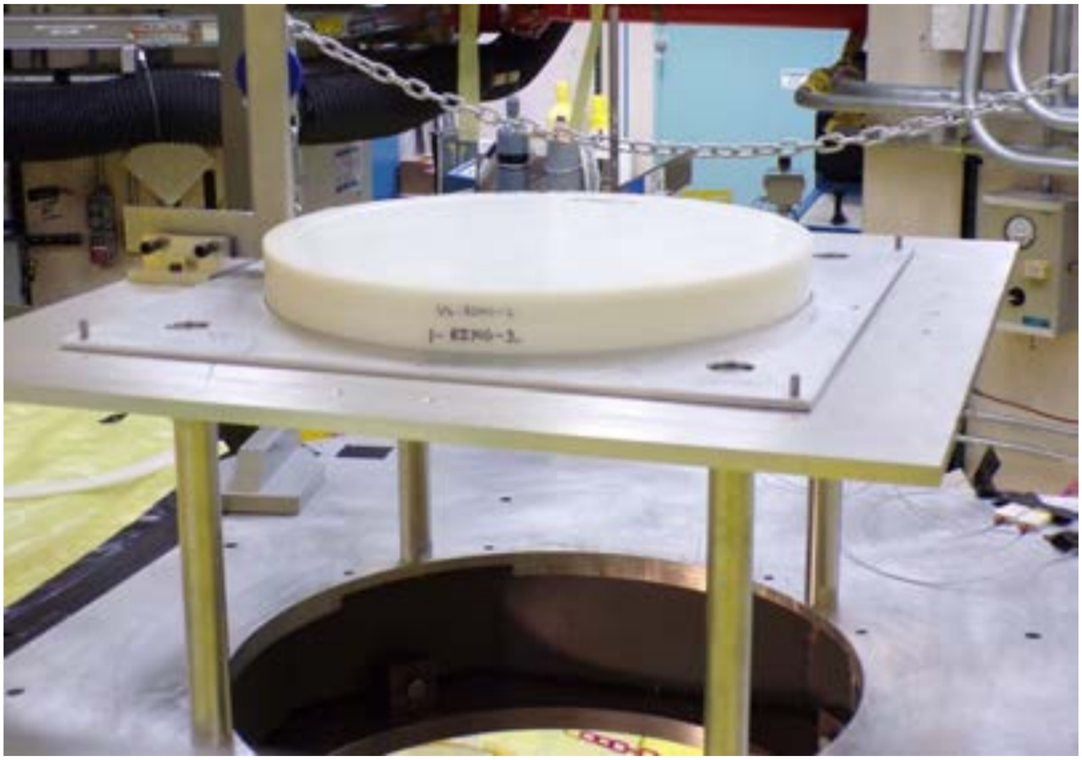

Figure 57: Complete upper half of the ⅛” R experiment.

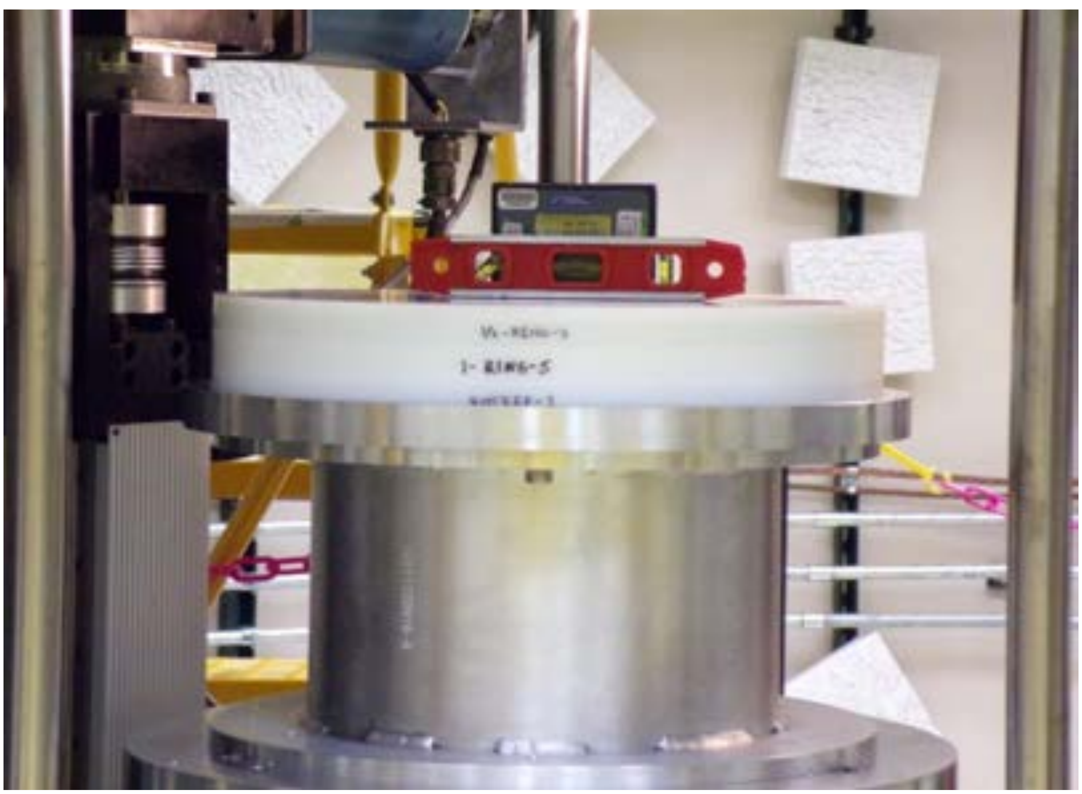

Figure 58: Complete lower half and levelness measurement of the ⅛” R experiment.

3.3 ¼" Experiment

The ¼" experiment began on February 25 and reached first criticality February 27. The benchmark configuration was documented on February 27 with a calculated excess reactivity of 9.41¢ to 9.89¢. The membrane lift was not recorded for this experiment.

Table 23: Height measurements at each layer of the ¼" experiment.

Upper Half	
Part ID	Height (mm)
1-REF-2	73.09
1/8-MOD-1	47.2
1/16-REF-1	44.05
1/32-REF-1	42.60
10470 (2.5-DISK-5)	41.90
1/4-MOD-9	38.70
10489 (2.5-DISK-4)	32.60
1/4-MOD-8	29.20
10491 (2.5-DISK-3)	22.77
1/4-MOD-7	19.42
10467 (2.5-DISK-2)	13.19
1/4-MOD-6	10.09
10487 (2.5-DISK-1)	3.70

Lower Half	
Part ID	Height (mm)
1/4-MOD-3	52.63
11019	46.15
1/4-MOD-2	43.23
11017	36.8
1/4-MOD-1	33.9
11150	27.52
BOTREF-1	24.11

Table 24: Overall height measurements of the ¼" experiment, taken from three separate positions.

Upper Half		Lower Half[18]	
Stack Height (mm)	Reflector Height (mm)	Stack Height (mm)	Reflector Height (mm)
72.27	72.59	42.00	42.28
72.50	71.84	41.46	42.17
72.55	71.77	41.72	42.66

Table 25: Period measurements and calculated excess reactivity for the ¼" experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	100.62	9.84	10^{-10}
LC_2	100.45	9.86	10^{-10}
LC_3	100.02	9.89	10^{-10}
SU	106.49	9.41	10,000

[18] Must account for additional lower adapter plate lip height, measurements in Table 5.

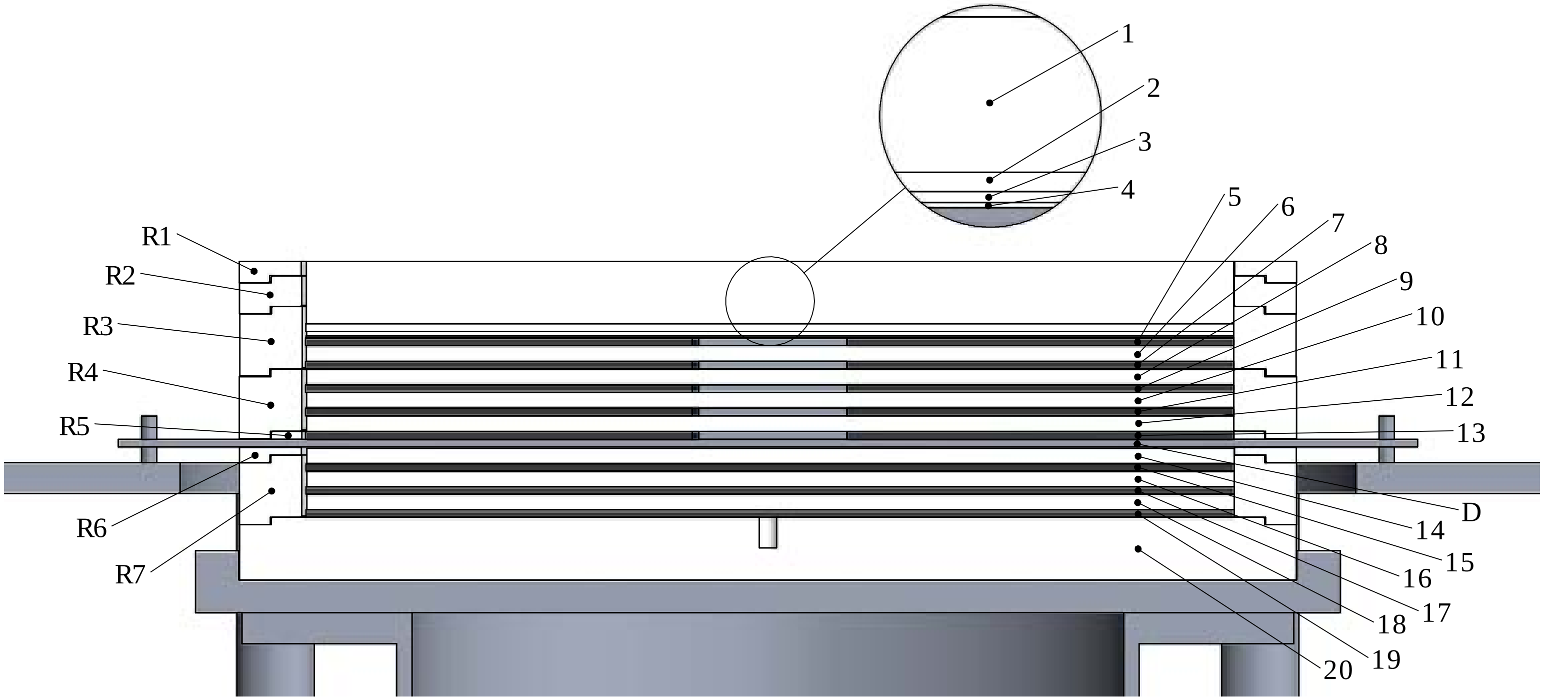

Figure 59: Configuration of the ¼" experiment.

Table 26: Part numbers for the ¼" experiment.

#	Part ID
1	1-REF-2
2	1/8-MOD-1
3	1/16-REF-1
4	1/32-REF-1
5	10470 (2.5-DISK-5)
6	1/4-MOD-9
7	10489 (2.5-DISK-4)

#	Part ID
8	1/4-MOD-8
9	10491 (2.5-DISK-3)
10	1/4-MOD-7
11	10467 (2.5-DISK-2)
12	1/4-MOD-6
13	10487 (2.5-DISK-1)
D	Membrane

#	Part ID
14	1/4-MOD-3
15	11019
16	1/4-MOD-2
17	11017
18	1/4-MOD-1
19	11150
20	BOTREF-1

#	Part ID
R1	7/32-CAP-1
R2	1/2-RING-1
R3	1-RING-4
R4	1-RING-3
R5	0-BOTCAP-1
R6	1/8-CAP-2
R7	1-RING-5

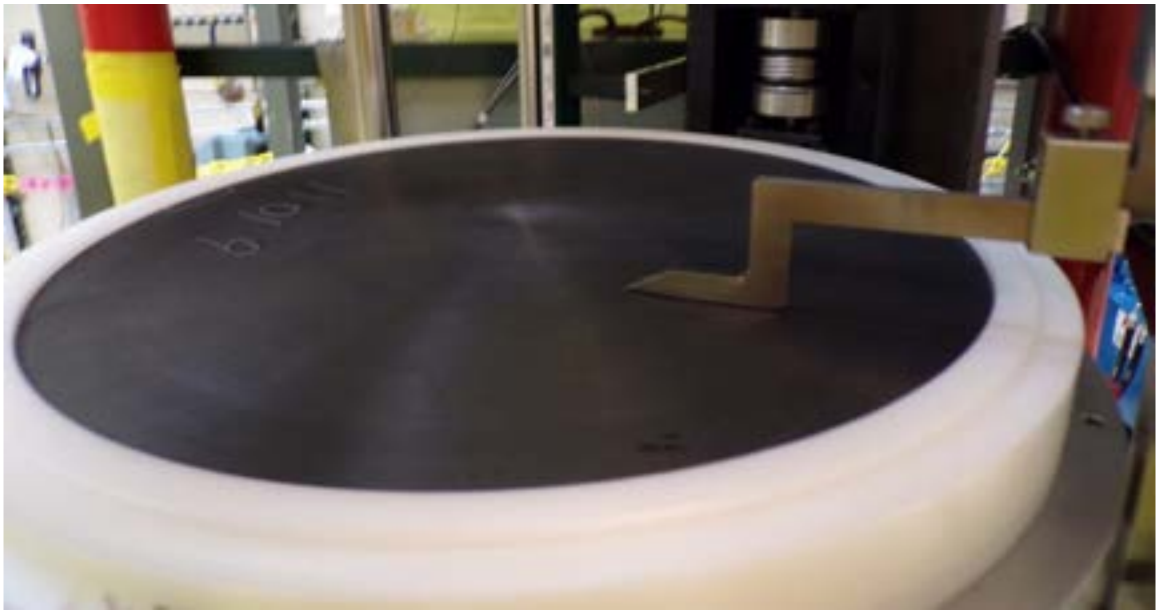

Figure 60: Height measurement of an HEU plate (11019) on the lower half of the ¼” experiment.

Figure 61: Height measurement of an HEU plate (11150) on the lower half of the ¼” experiment.

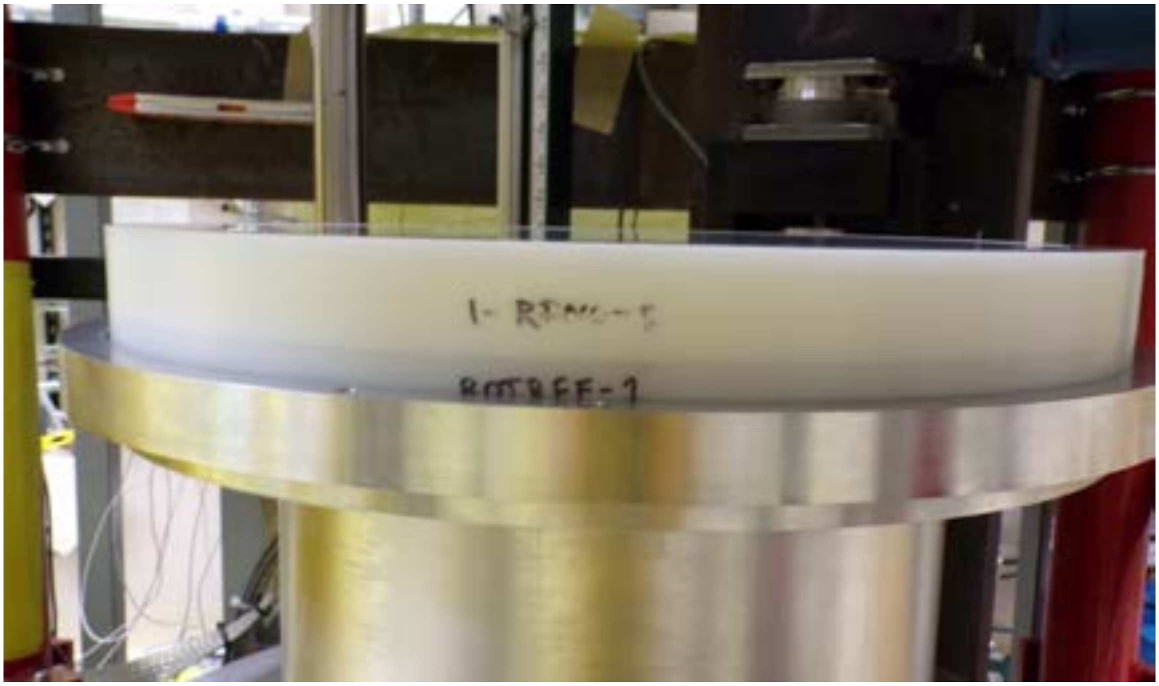

Figure 62: Complete lower half of the ¼” experiment.

Figure 63: Reflector height measurement of the lower half of the ¼” experiment.

Figure 64: First HEU plate for the upper half of the ¼" experiment.

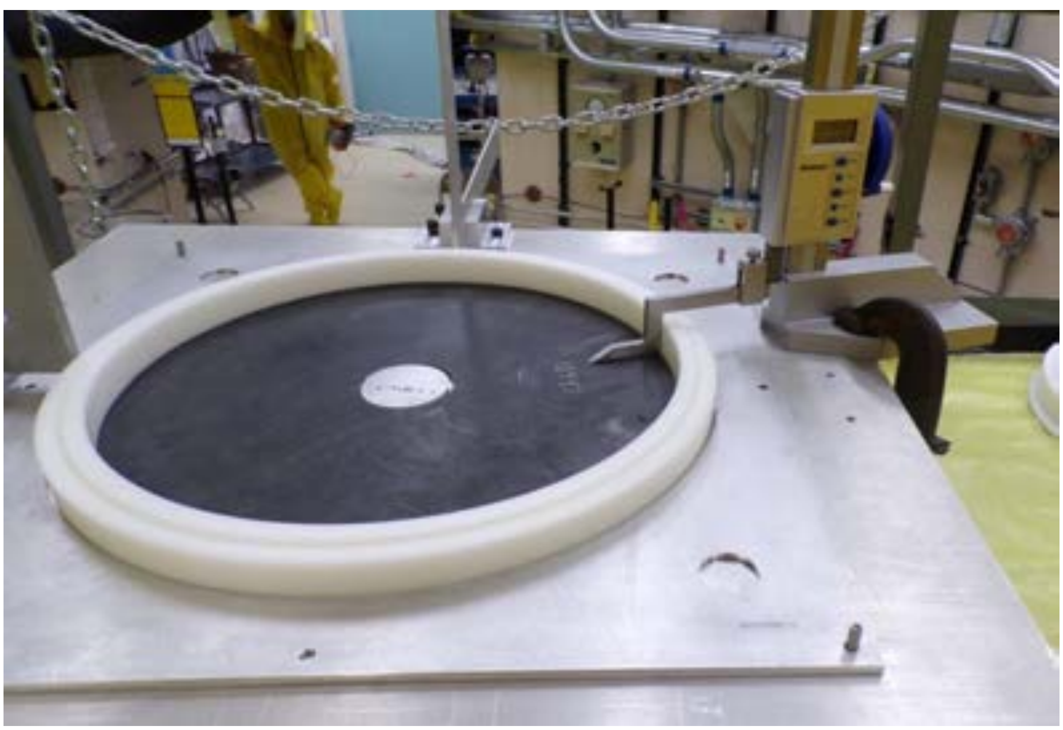

Figure 65: Height measurement of the first HEU plate for the upper half of the ¼" experiment.

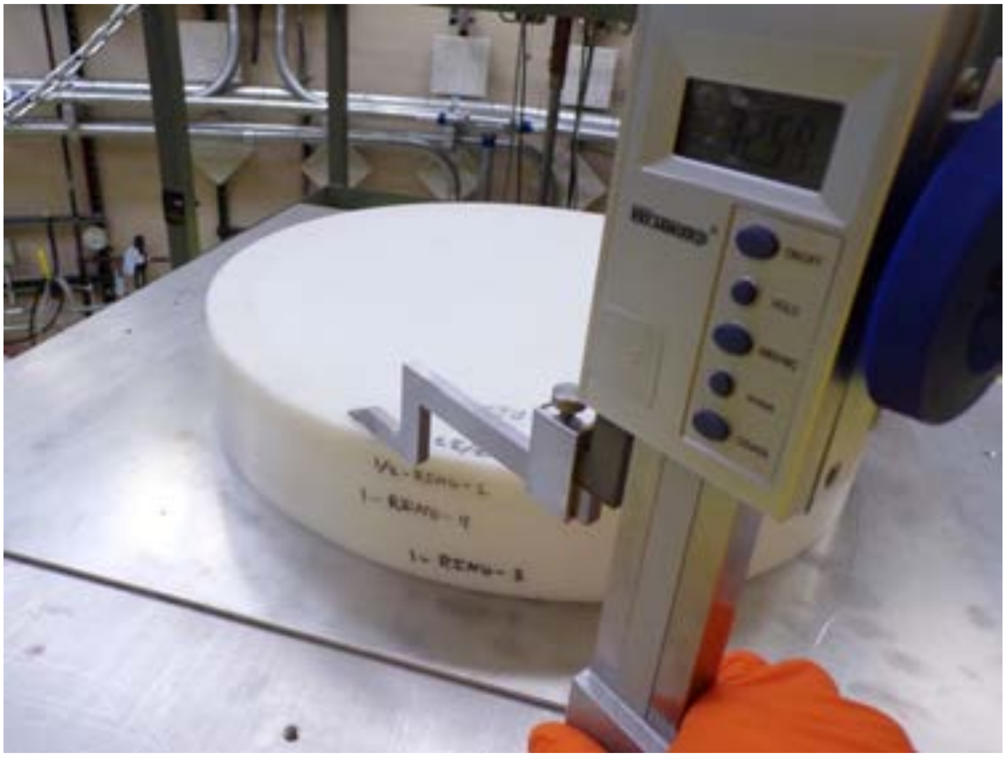

Figure 66: Reflector height measurement of the upper half of the ¼" experiment.

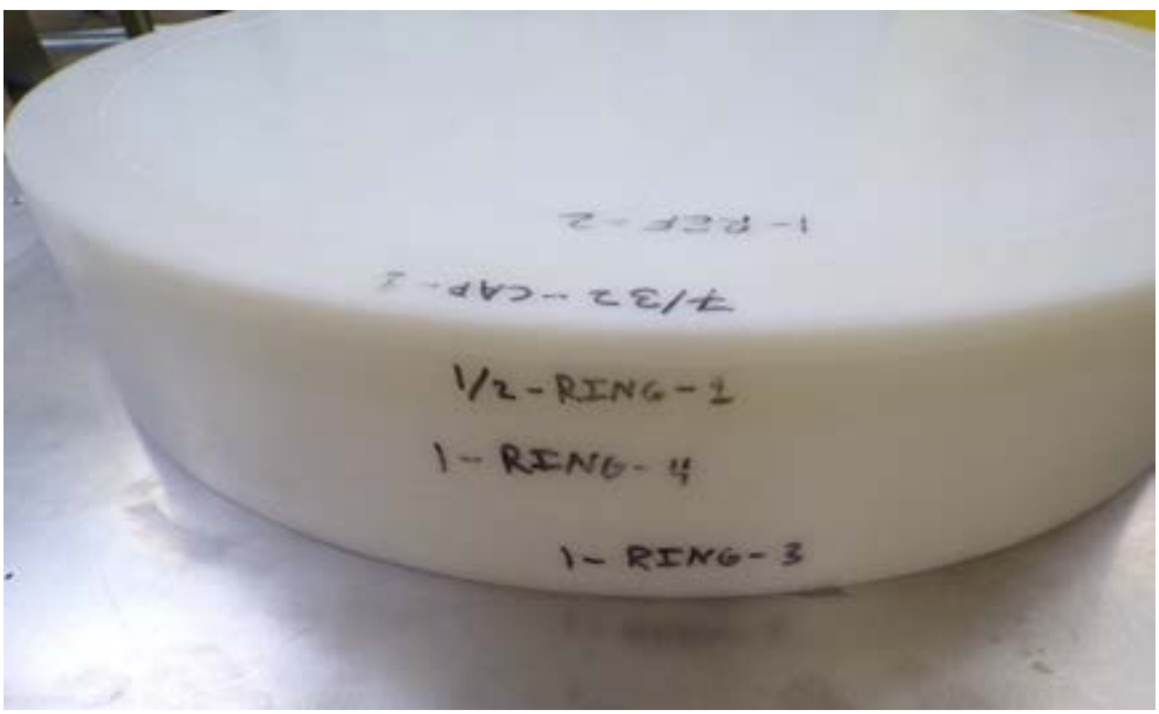

Figure 67: Complete upper half of the ¼" experiment, showing the reflector ring part IDs.

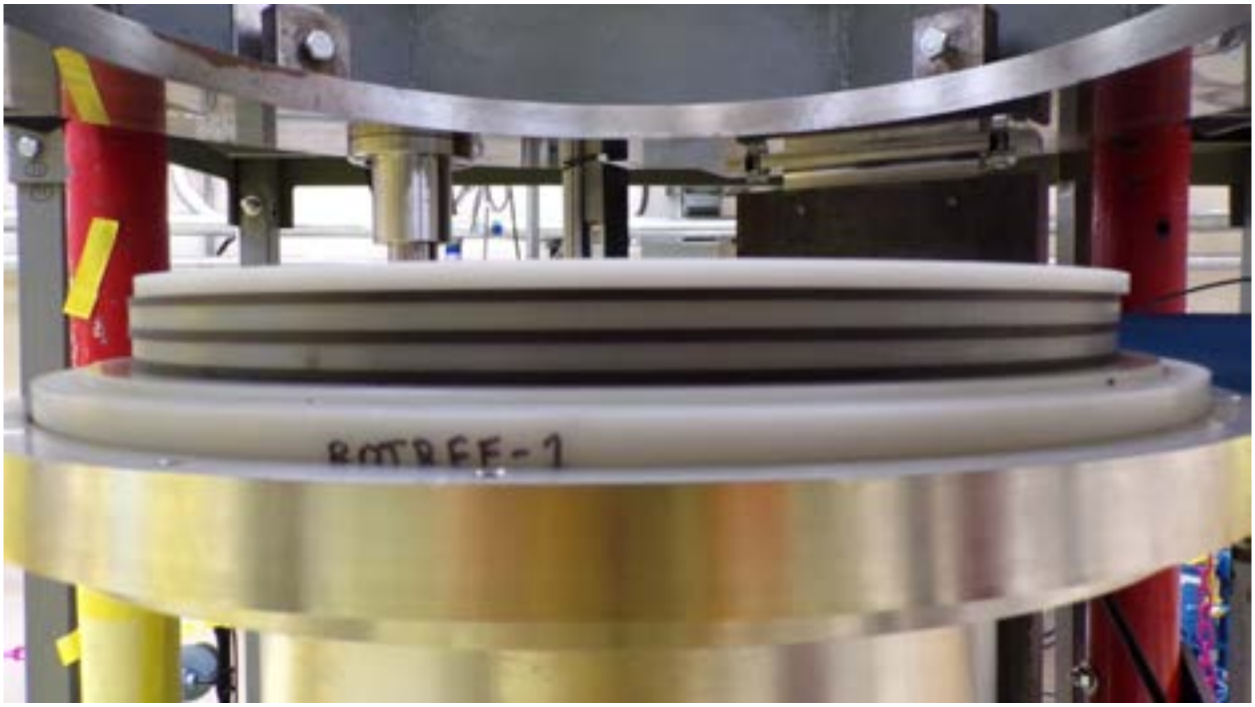

Figure 68: Lower half of the ¼” experiment without reflector rings, which were removed during disassembly.

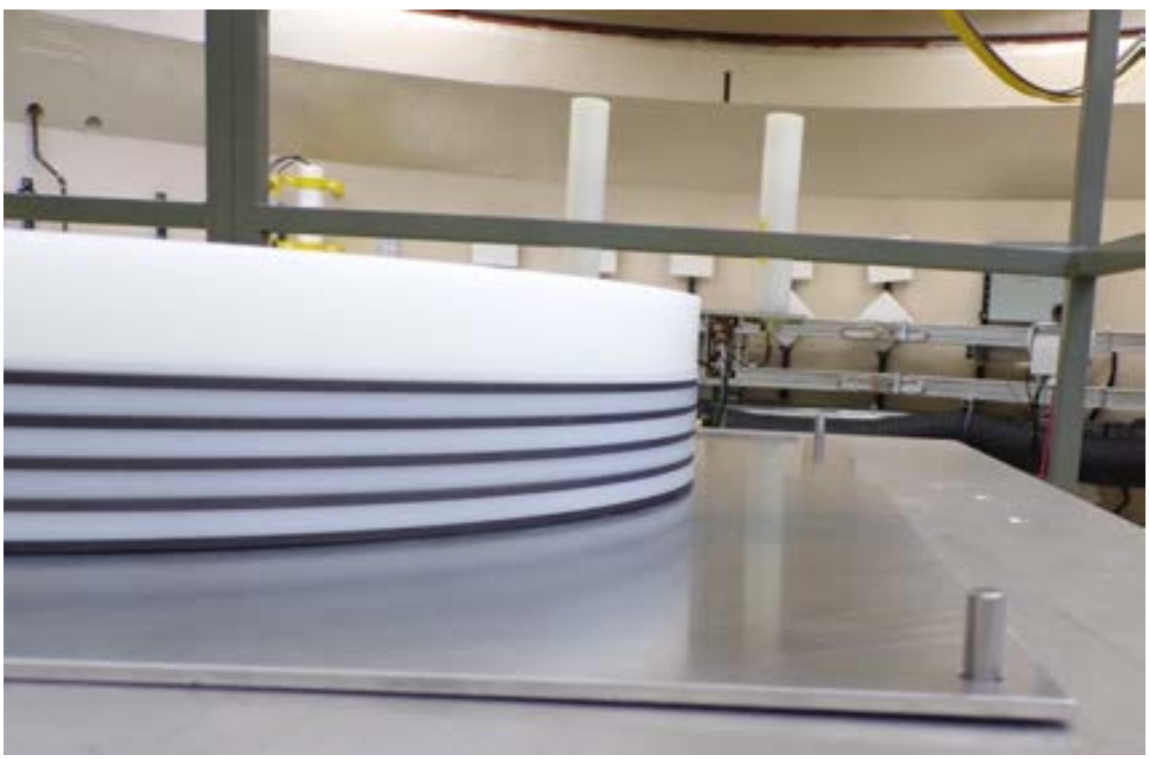

Figure 69: Upper half of the ¼” experiment without reflector rings, which were removed during disassembly.

3.4 ½" Experiment

The ½" experiment began on March 5 and reached first criticality on March 9. The benchmark configuration was documented on March 10 with a calculated excess reactivity of 15.57¢ to 16.14¢. Membrane lift began at 200 mils and ended at 150 mils of separation.

Table 27: Height measurements at each layer of the ½" experiment.

Upper Half	
Part ID	Height (mm)
1-REF-2	45.01
1/2-MOD-6	19.19
1/8-MOD-1	6.60
1/32-REF-1	4.11
11147	3.17

Lower Half	
Part ID	Height (mm)
1/2-MOD-4	89.06
11149	76.32
1/2-MOD-3	73.07
11019	60.91
1/2-MOD-2	57.29
11017	44.65
1/2-MOD-1	41.60
11150	28.92
BOTREF-1	25.48

Table 28: Overall height measurements of the ½" experiment, taken from three separate positions.

Upper Half	
Stack Height (mm)	Reflector Height (mm)
44.69	44.45
44.76	44.05
45.22	44.59

Lower Half[19]	
Stack Height (mm)	Reflector Height (mm)
74.22	75.99
76.62	77.39
75.76	76.57

Table 29: Period measurements and calculated excess reactivity for the ½" experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	51.19	16.14	10^{-9}
LC_2	51.77	16.02	10^{-9}
LC_3	51.36	16.10	10^{-9}
SU	53.96	15.57	100,000

[19] Must account for additional lower adapter plate lip height, measurements in Table 5.

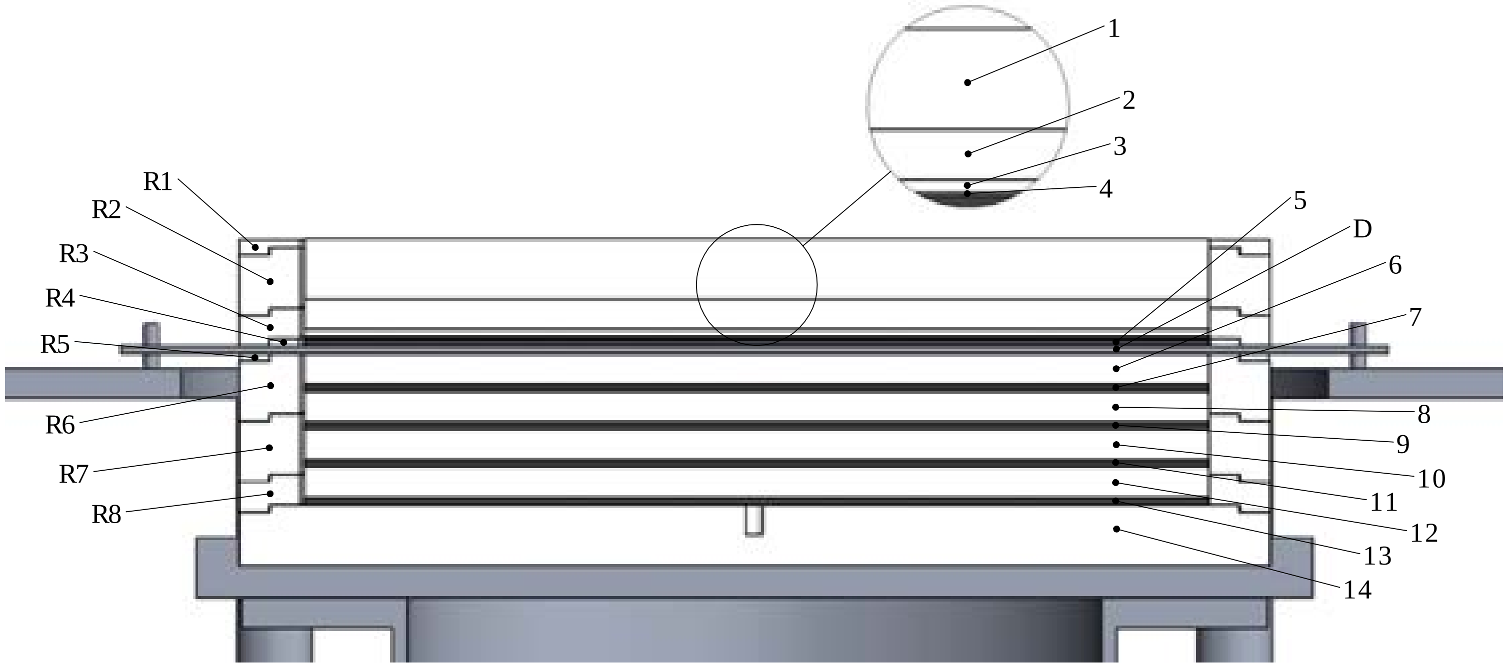

Figure 70: Configuration of the ½" experiment.

Table 30: Part numbers for the ½" experiment.

#	Part ID
1	1-REF-2
2	1/2-MOD-6
3	1/8-MOD-1
4	1/32-REF-1
5	11147
D	Membrane
6	1/2-MOD-4
7	11149

#	Part ID
8	1/2-MOD-3
9	11019
10	1/2-MOD-2
11	11017
12	1/2-MOD-1
13	11150
14	BOTREF-1

#	Part ID
R1	1/8-CAP-1
R2	1-RING-3
R3	1/2-RING-1
R4	0-BOTCAP-1
R5	0-CAP-2
R6	1-RING-1
R7	1-RING-5
R8	1/2-RING-2

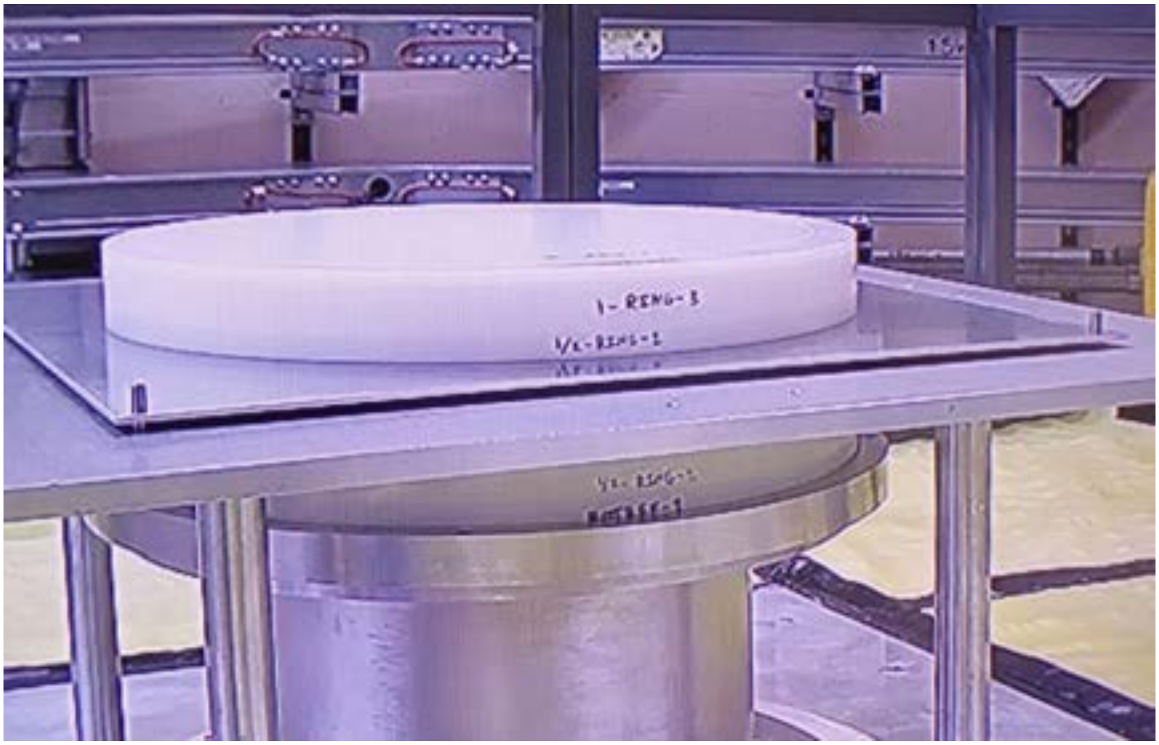

Figure 71: Fully assembled ½” experiment during operation.

Figure 72: Operator performing overall height measurements for the upper half of the ½” experiment.

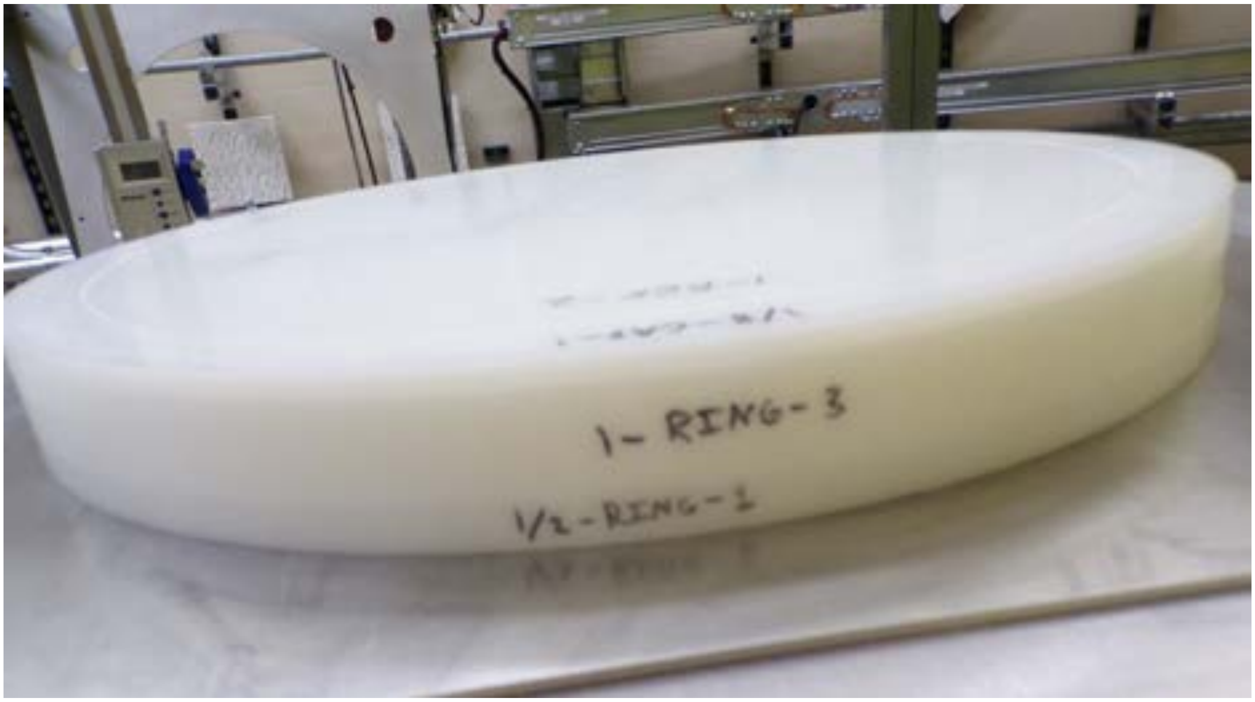

Figure 73: Complete upper half of the ½" configuration, showing the ring reflector part IDs.

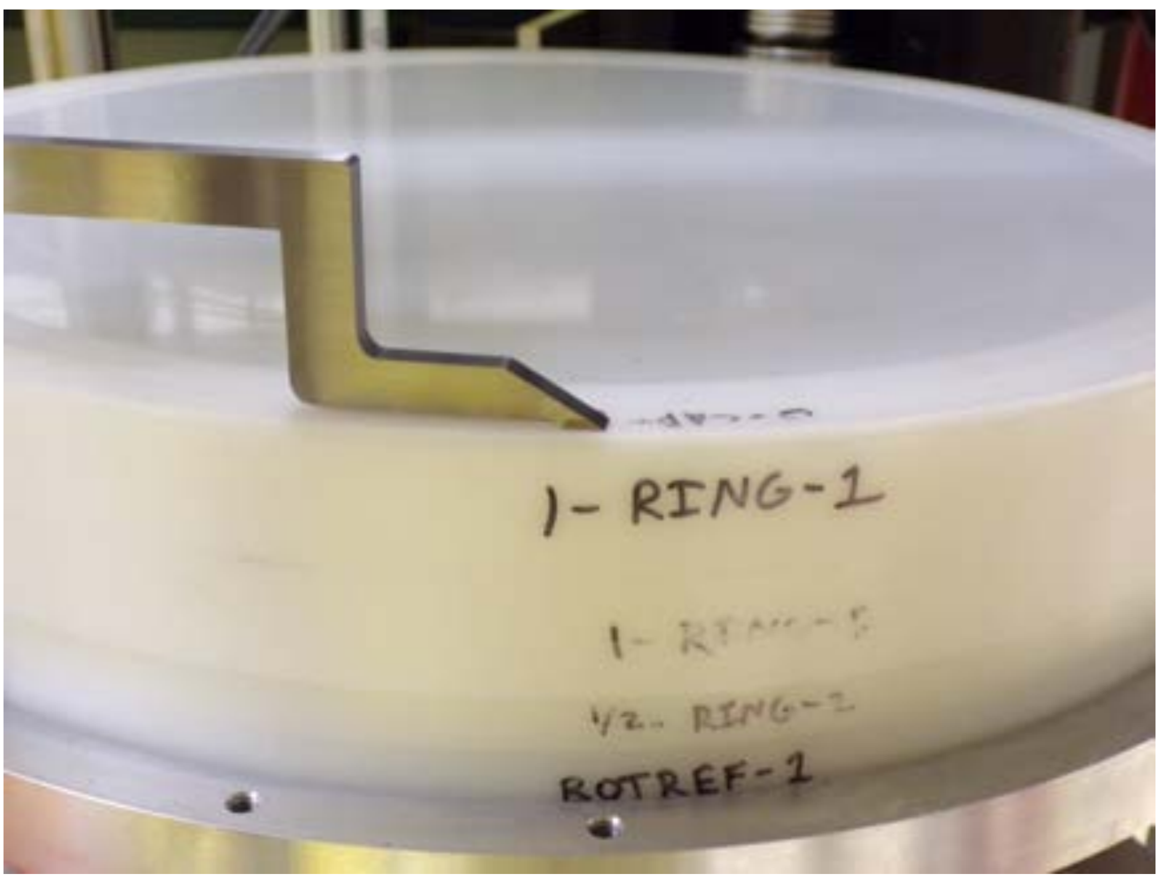

Figure 74: Complete lower half of the ½" configuration, showing the ring reflector part IDs.

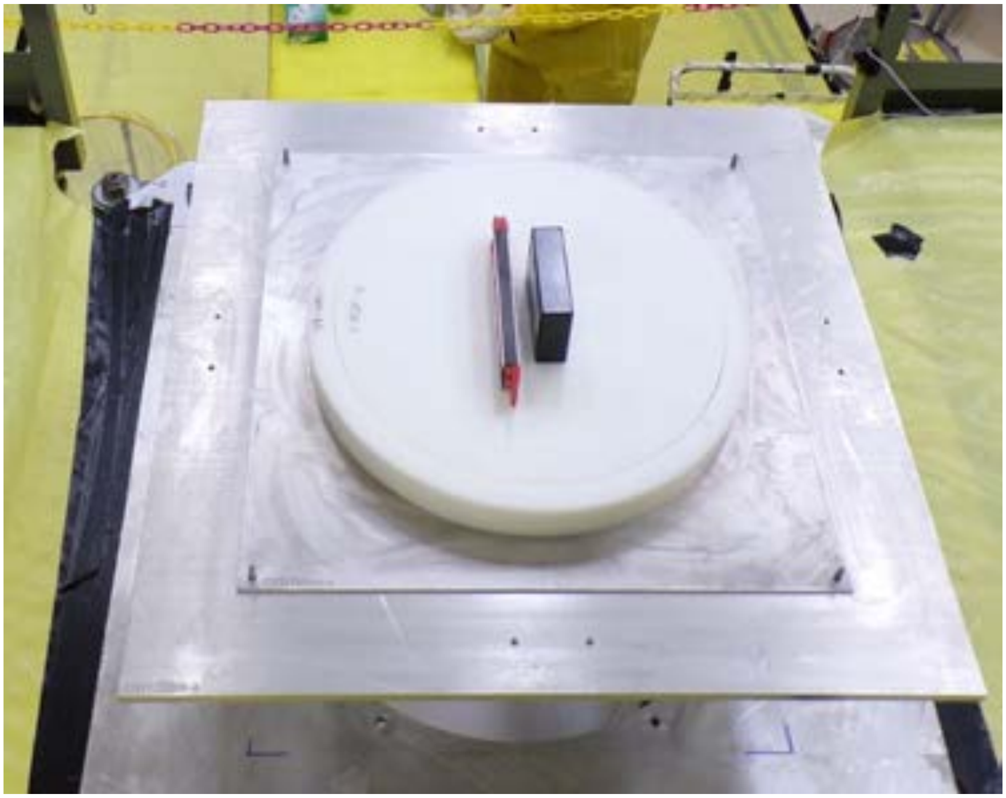

Figure 75: Complete upper half of the ½" configuration.

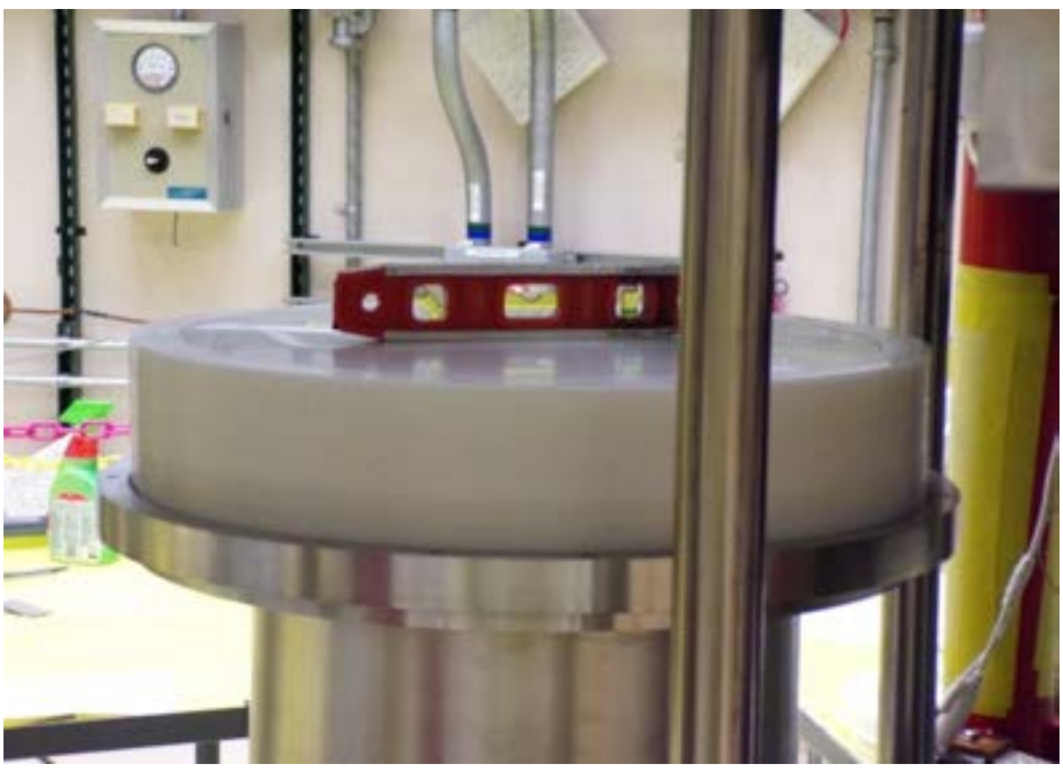

Figure 76: Levelness measurement for the lower half of the ½" configuration.

Figure 77: Upper half of the ½” configuration with ring reflectors removed during disassembly. The 1/2-MOD-6 moderator plate is used as a reflector.

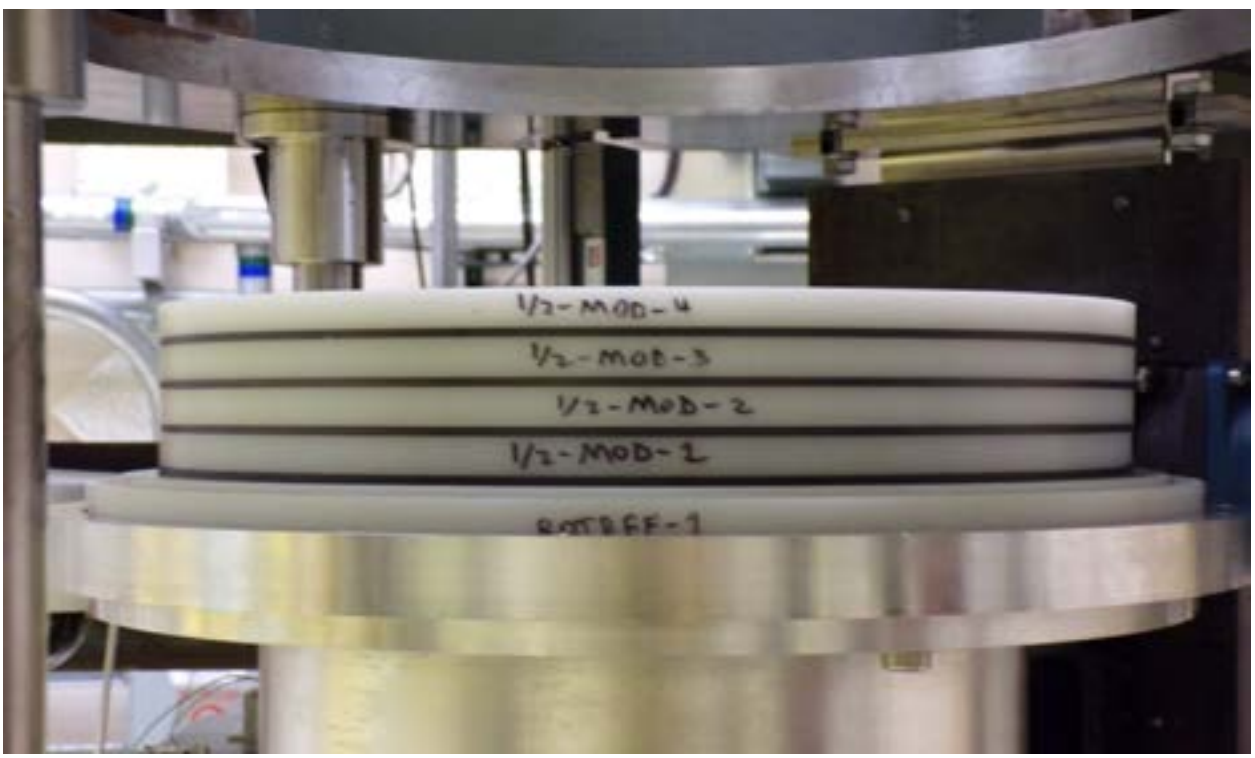

Figure 78: Lower half of the ½” configuration with ring reflectors removed during disassembly, showing all moderator part IDs.

Figure 79: Alignment of the fuel and moderator plates of the upper half of the ½” configuration. The stack is shown without reflector rings, which were removed during disassembly.

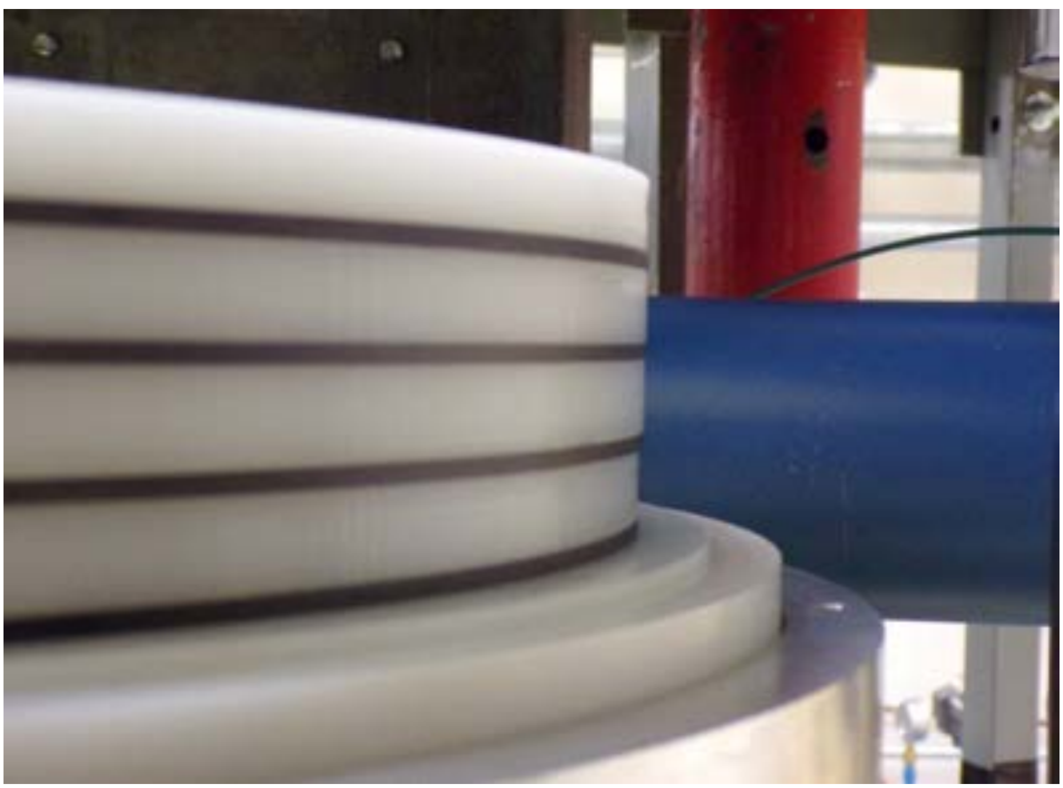

Figure 80: Alignment of the fuel and moderator plates of the lower half of the ½” configuration. The stack is shown without reflector rings, which were removed during disassembly.

3.5 1½" Experiment

The 1½" experiment began on March 12 and reached first criticality on May 26, following a break from the experiment between March 13 and May 20. The benchmark configuration was documented on May 26 with a calculated excess reactivity of 13.45¢ to 14.38¢. Membrane lift began at 200 mils and ended at 175 mils of separation.

Table 31: Height measurements at each layer of the 1½" experiment.

Upper Half	
Part ID	**Height (mm)**
1-REF-2	114.60
1/8-MOD-4	88.69
11017	85.45
1.5-MOD-4	82.56
10457	44.07
1.5-MOD-3	41.25
10477	3.41

Lower Half	
Part ID	**Height (mm)**
1.5-MOD-2	108.40
10493	70.67
1.5-MOD-1	67.57
11147	28.78
BOTREF-1	25.48

Table 32: Overall height measurements of the 1½" experiment, taken from three separate positions.

Upper Half	
Stack Height (mm)	**Reflector Height (mm)**
114.11	114.04
114.67	114.56
114.60	114.83

Lower Half[20]	
Stack Height (mm)	**Reflector Height (mm)**
96.03	96.05
97.04	96.78
96.65	96.98

Table 33: Period measurements and calculated excess reactivity for the 1½" experiment.

Detector	Period (s)	Reactivity (¢)	Scale
LC_1	61.43	14.22	10^{-10}
LC_2	60.45	14.38	10^{-10}
LC_3	61.27	14.25	10^{-10}
SU	66.41	13.45	See note 21.

[20] Must account for additional lower adapter plate lip height, measurements in Table 5.

[21] No scale was noted in the Comet logbook.

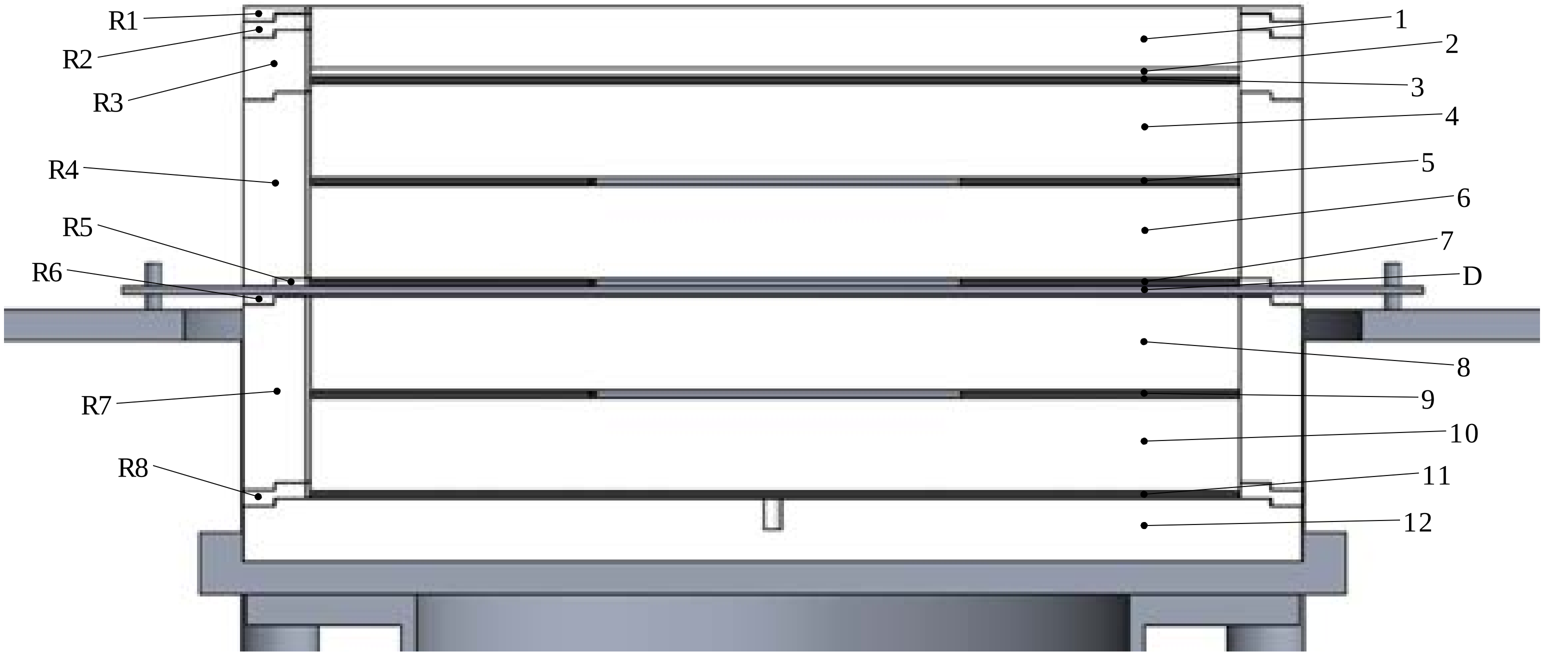

Figure 81: Configuration of the 1½" experiment.

Table 34: Part numbers for the 1½" experiment.

#	Part ID	#	Part ID	#	Part ID
1	1-REF-2	8	1.5-MOD-2	R1	3/32-CAP-1
2	1/8-MOD-1	9	10493 (6-DISK-2)	R2	1/4-RING-2
3	11017	10	1.5-MOD-1	R3	1-RING-1
4	1.5-MOD-4	11	11147	R4	3-RING-5
5	10457 (6-DISK-3)	12	BOTREF-1	R5	0-BOTCAP-1
6	1.5-MOD-3			R6	1/32-CAP-1
7	10477 (6-DISK-1)			R7	3-RING-1
M	Membrane			R8	1/4-RING-1

Figure 82: Fully assembled 1½" configuration during operation.

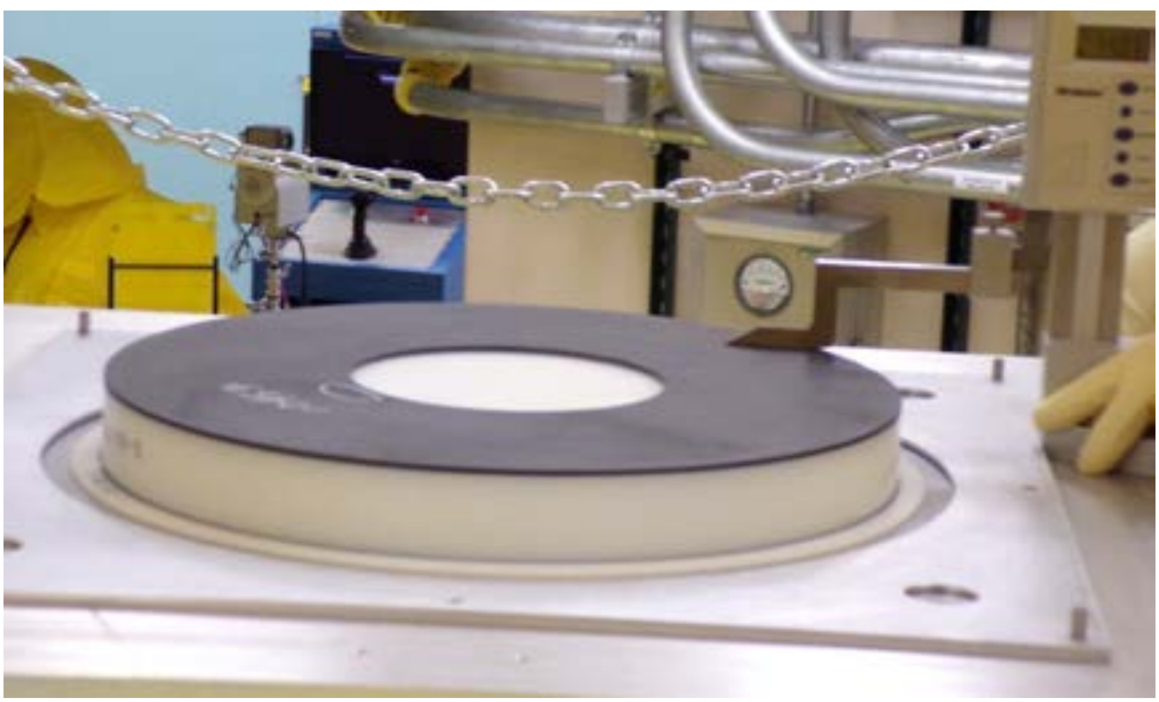

Figure 83: Height measurement of an HEU plate with a 6" annulus on the upper half of the 1½" experiment.

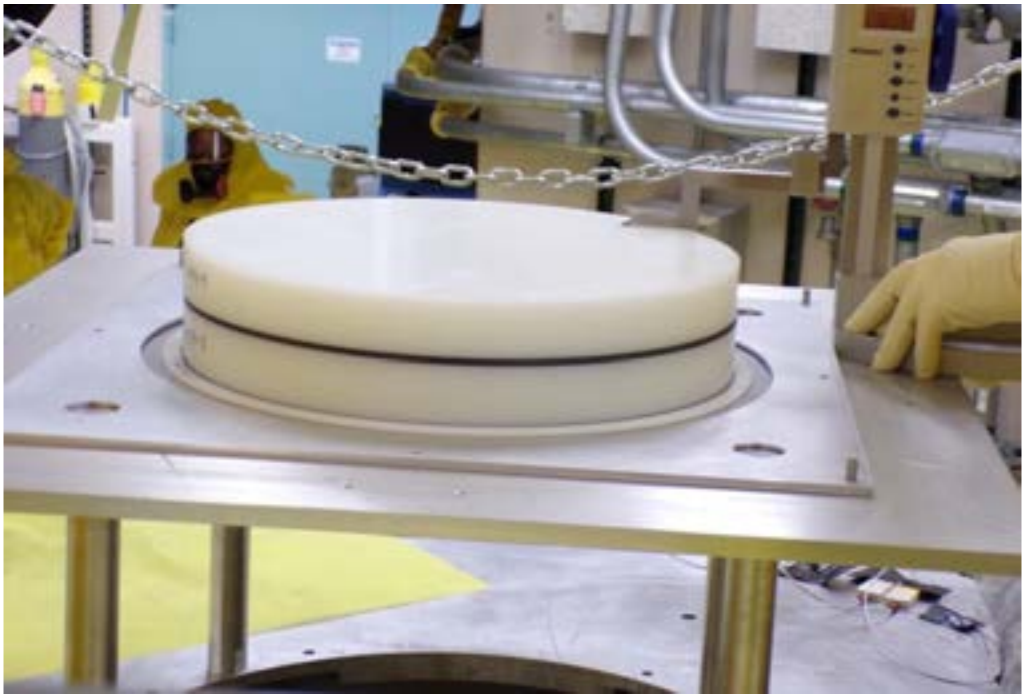

Figure 84: Partial upper half of the 1½” experiment, showing 2 HEU plates and 2 moderator plates along with the alignment plate atop the membrane.

Figure 85: Upper half of the 1½” configuration with ring reflectors around the fuel and moderator stack, but not yet around the top reflectors.

Figure 86: Complete upper half of the 1½" configuration.

Figure 87: Complete lower half of the 1½" configuration.

Figure 88: Upper half of the 1½” configuration without ring reflectors, including 3 HEU plates and 1 ⅛” top reflector.

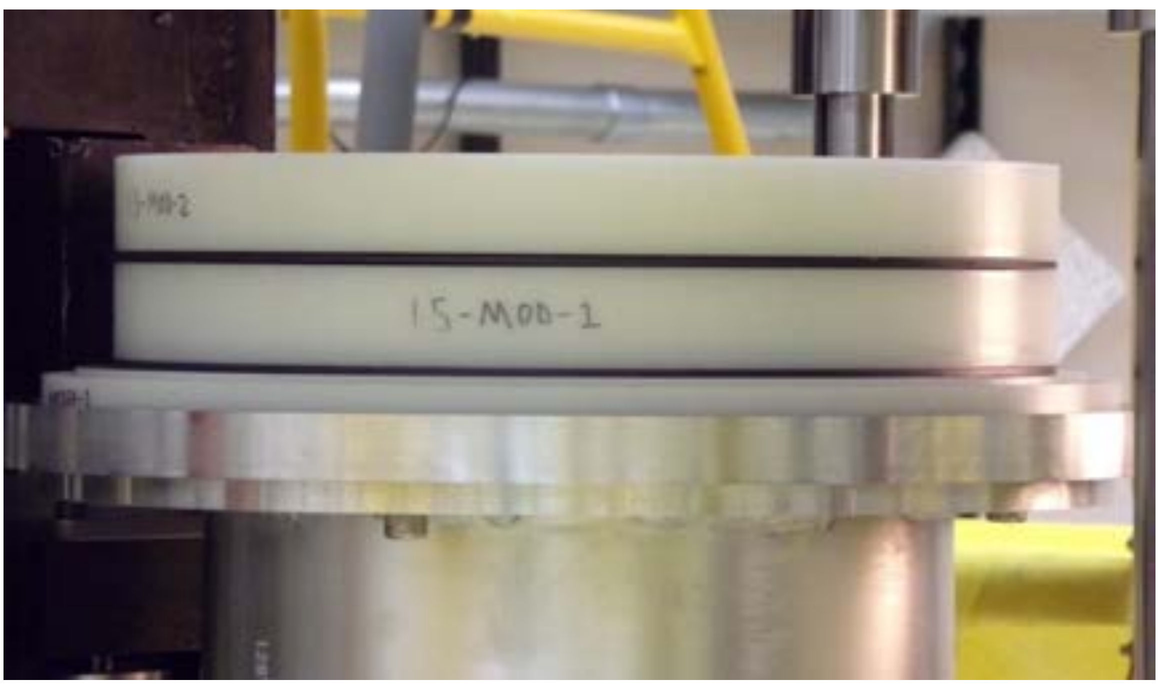

Figure 89: Partially complete lower half of the 1½” configuration without ring reflectors.

Figure 90: Levelness measurement for the upper half of the 1½” configuration.

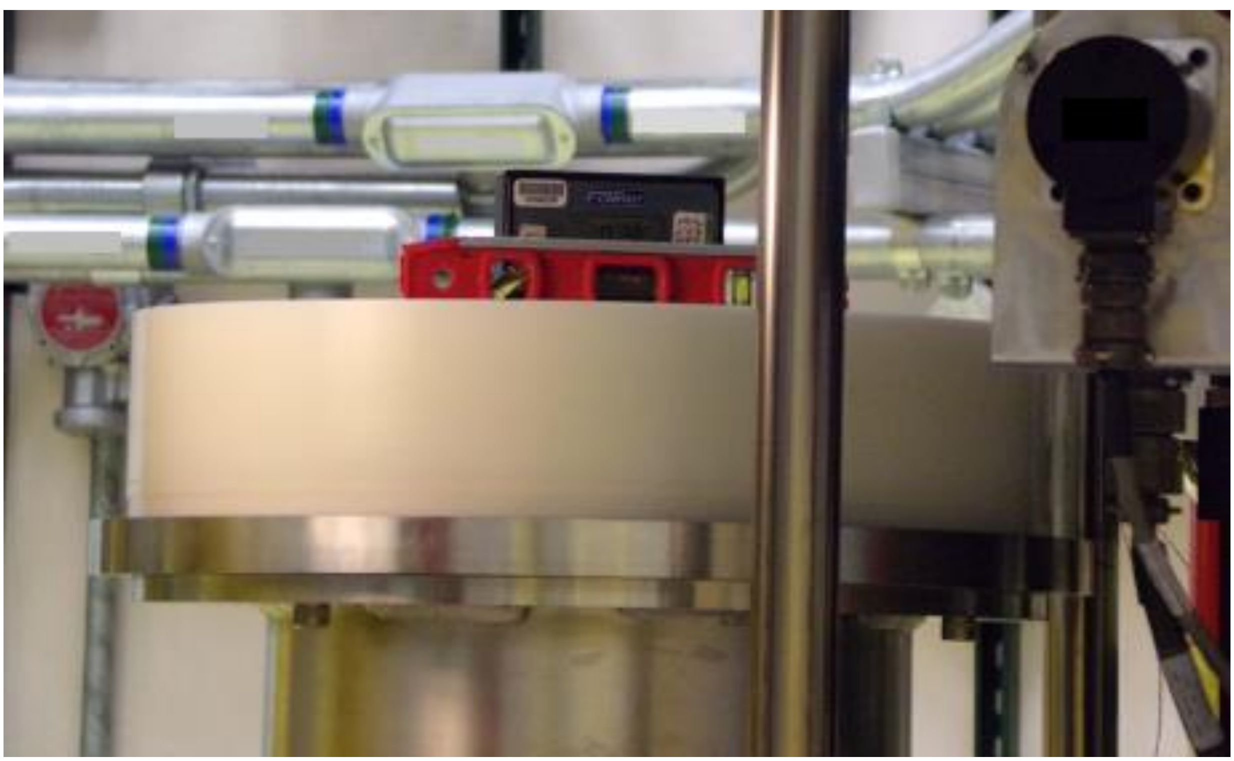

Figure 91: Levelness measurement for the lower half of the 1½” configuration.

3.5.1 1.5-MOD-2 Irregularity

During disassembly of the 1½" experiment the operators noticed the 1.5-MOD-2 moderator plate was not flush with the HEU plate (10493) it was placed on, shown in Figure 92 and Figure 93. This irregularity in 1.5-MOD-2 was not found during part inspection and could not be substituted during the experiment because it was not noticed until after the benchmark experiment configuration was documented and measured.

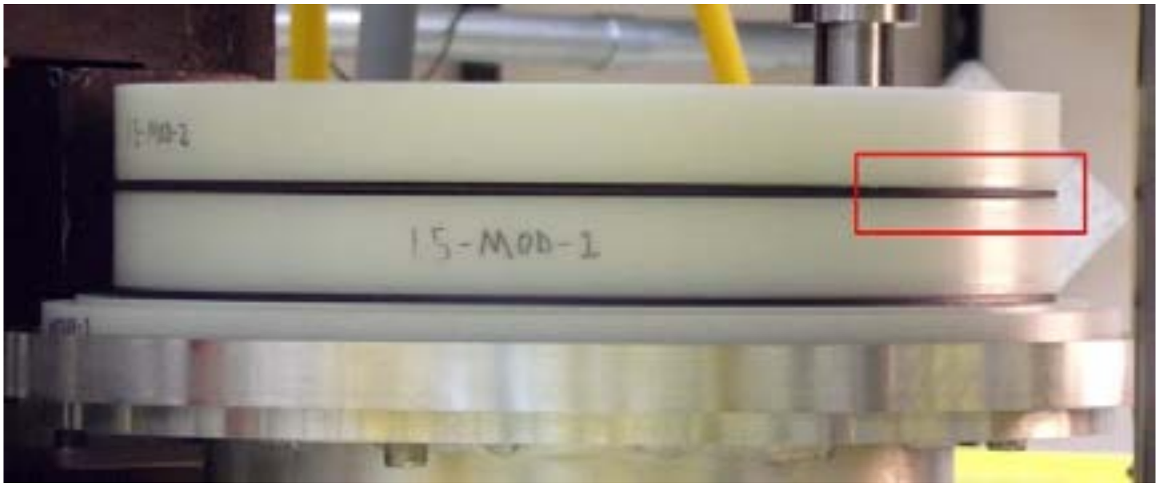

Figure 92: Moderator plate (1.5-MOD-2) not sitting flush with the HEU plate (10493).

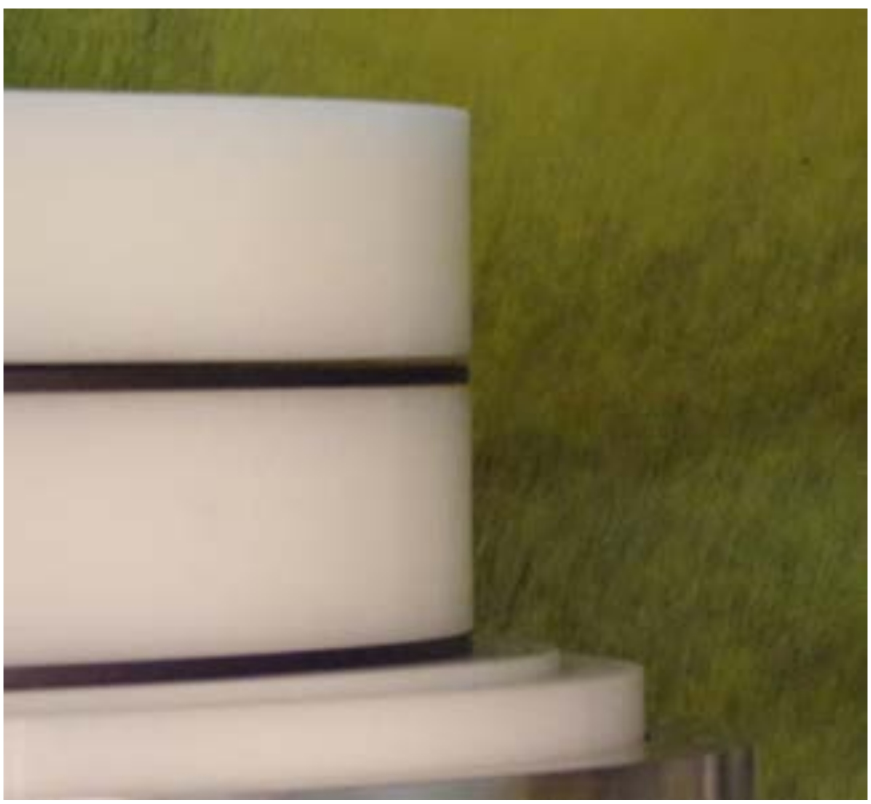

Figure 93: Close-up of the irregularity in 1.5-MOD-2.

Appendix A

Part Measurements

The following sections include the masses and dimensions of all the parts used in the TEX-HEU critical configurations. The sections also include drawings of the parts to fully describe the dimensions.

The HEU plates were weighed and measured following the critical experiments at NCERC. The HDPE and aluminum parts were weighed and measured by Lawrence Livermore National Laboratory's Dimensional Inspection staff prior to shipment to NCERC.

The HEU plates were weighed with a Mettler Toledo MS16001L under the NCERC calibration program (Cal No. 017284). The calibration for this balance was certified on June 19, 2019 and is valid through June 19, 2020. These measurements were taken on June 2, 2020. The manufacturer of the MS16001L reports a maximum capacity of 16,200 grams, precision of 0.1 grams, and linearity of 0.2 grams[22]. The HEU plate thickness was measured with calipers. The thickness was measured at three separate locations for each plate. No instrument was available to measure the outer diameter or the annuli diameter of the plates.

The HDPE and aluminum parts were measured with a coordinate measuring machine (CMM) and calipers. The CMM measured the cord length of the diameter at many different positions, reporting the minimum, maximum, and average diameter (as a least-squares fit of all cord lengths). The CMM has a precision of 0.0001". The calipers were used to measure the thickness of the aluminum parts, which a precision of 0.0005".

[22] Mettler Toledo Precision Balance MS16001L. Retrieved on September 1, 2020, available at https://www.mt.com/gb/en/home/products/Laboratory_Weighing_Solutions/Precision_Balances/Advanced/MS-L-Precision-Balances/MS16001L-01.html. Archived on November 30, 2020, available at https://web.archive.org/web/20201130224941/https://www.mt.com/gb/en/home/products/Laboratory_Weighing_Solutions/Precision_Balances/Advanced/MS-L-Precision-Balances/MS16001L-01.html.

Highly Enriched Uranium Plates

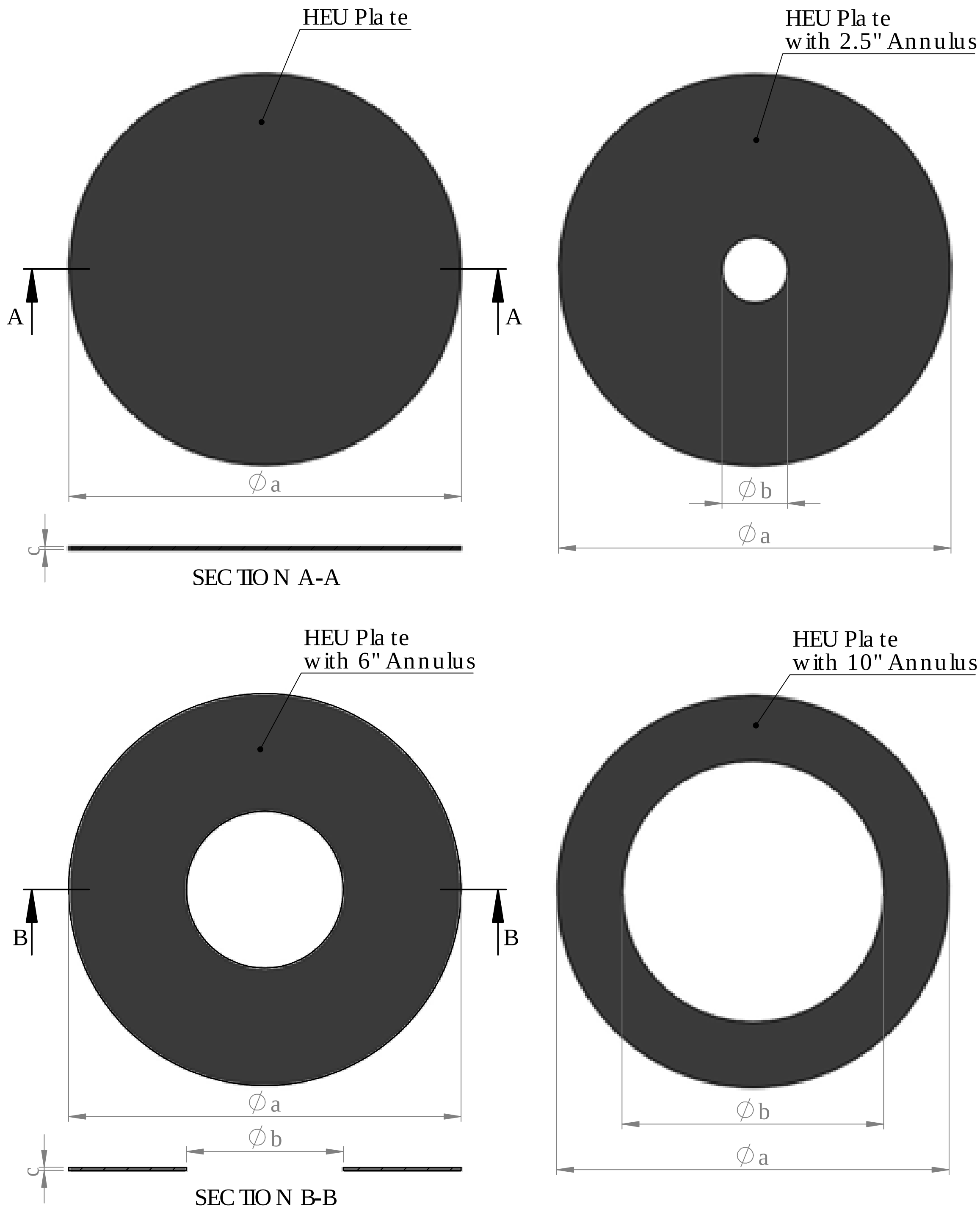

Figure 94: Design drawing of the HEU plates.

Table 35: HEU plates masses and dimensions, variables defined in Figure 94.

ID	Mass (g)	Outer Diameter[23], A (in)	Inner Diameter[23], B (in)	Thickness, C (mm)		
				Min	Max	Average
11017	6501.6	15	-	3.11	3.39	3.29
11019	6470.0	15	-	3.06	3.43	3.21
11147	6517.4	15	-	3.14	3.37	3.28
11149	6383.6	15	-	3.04	3.30	3.16
11150	6410.3	15	-	3.11	3.29	3.21
10464	6258.5	15	2.5	3.14	3.40	3.31
10467	6335.8	15	2.5	3.13	3.36	3.22
10470	6279.0	15	2.5	3.04	3.30	3.18
10475	6230.0	15	2.5	3.04	3.16	3.11
10487	6274.9	15	2.5	3.16	3.41	3.26
10489	6343.8	15	2.5	3.24	3.48	3.35
10491	6392.4	15	2.5	3.14	3.46	3.35
11018	5369.9	15	6	3.03	3.11	3.06
10457	5574.1	15	6	3.20	3.45	3.32
10477	5499.2	15	6	3.12	3.83	3.38
10493	5437.2	15	6	3.17	3.28	3.21
10463	3631.7	15	10	3.18	3.27	3.22
10472	3585.7	15	10	3.04	3.18	3.11
10479	3564.7	15	10	3.09	3.49	3.32

[23] Nominal measurements.

Aluminum Inserts

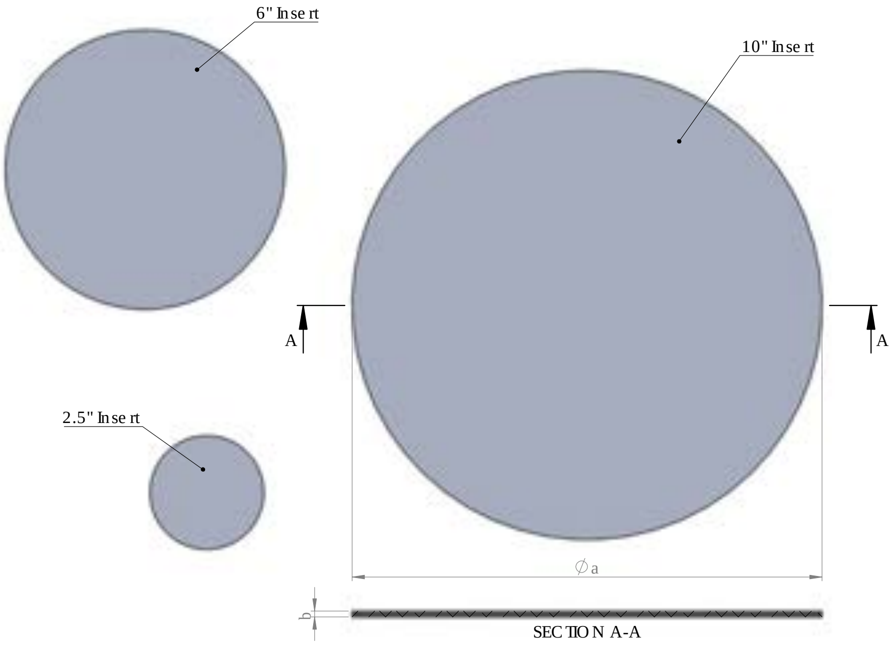

Figure 95: Design drawing of the inserts, showing all three diameters.

Table 36: Aluminum inserts masses and dimensions, variables defined in Figure 95.

ID	Mass (g)	Diameter, a (in)			Thickness, b (in)
		Min	Max	Average	
2.5-DISK-1	24.6	2.3945	2.3945	2.3945	0.1240
2.5-DISK-2	24.8	2.3955	2.3960	2.3958	0.1245
2.5-DISK-3	24.7	2.3960	2.3960	2.3960	0.1245
2.5-DISK-4	24.9	2.3960	2.3960	2.3960	0.1255
2.5-DISK-5	24.9	2.3950	2.3950	2.3950	0.1250
2.5-DISK-6	25.0	2.3940	2.3950	2.3945	0.1255
2.5-DISK-7	24.9	2.3945	2.3950	2.3953	0.1250
2.5-DISK-8	24.8	2.3945	2.3950	2.3948	0.1250
2.5-DISK-9	24.6	2.3945	2.3950	2.3948	0.1240
2.5-DISK-10	24.9	2.3955	2.3955	2.3955	0.1250
6-DISK-1	149.9	5.9835	5.9845	5.8940	0.1240
6-DISK-2	149.7	5.8915	5.8915	5.8915	0.1235
6-DISK-3	151.1	5.8915	5.8915	5.8920	0.1250
6-DISK-4	151.3	5.8930	5.8935	5.8933	0.1250
10-DISK-1	423.9	9.8915	9.8920	9.8918	0.1240
10-DISK-2	424.0	9.8920	9.8935	9.8928	0.1245
10-DISK-3	426.5	9.8925	9.8925	9.8925	0.1250

Moderator and Reflector Plates

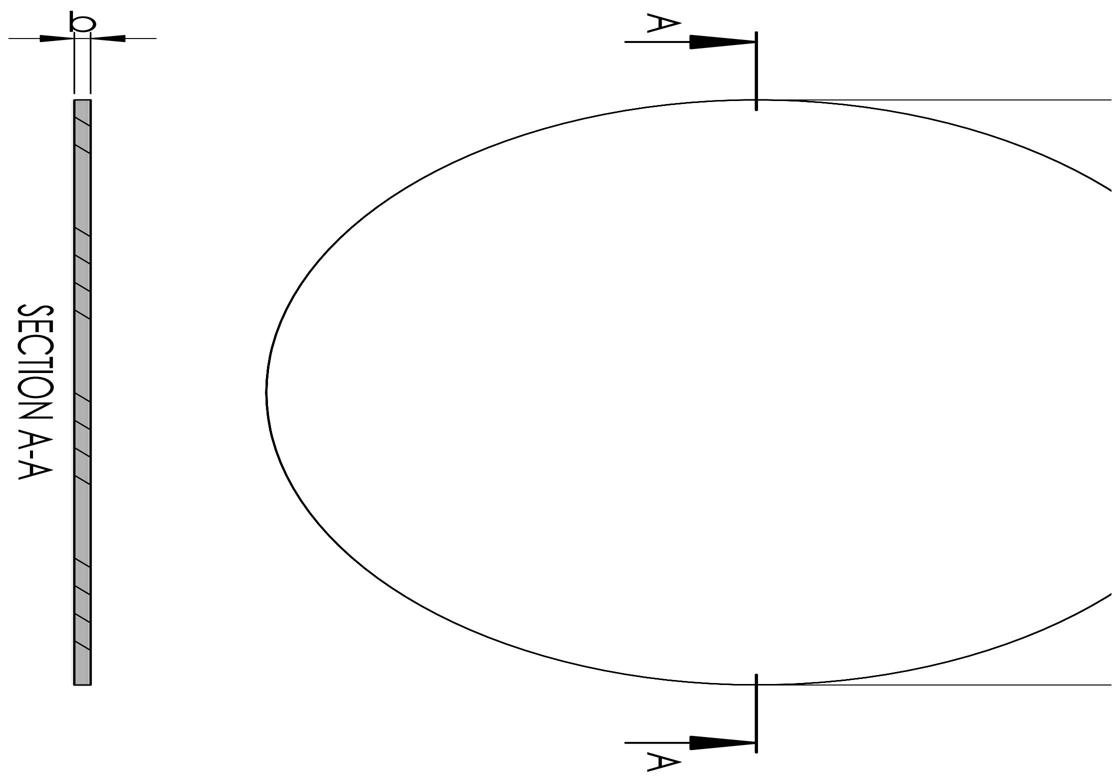

Figure 96: Design drawing of the moderator and reflector plates, showing a nominal ¼” moderator plate.

Table 37: Moderator and reflector plate masses and dimensions, variables defined in Figure 96.

ID	Mass (g)	Diameter, a (in)			Thickness, b (in)
		Min	Max	Average	
1/32-REF-1	85.0	14.9832	14.9996	14.9908	0.0334
1/16-REF-1	182.4	14.9831	14.9858	14.9858	0.0728
1-REF-2	2767.2	14.9844	14.9922	14.9883	1.0015
1/8-MOD-1	343.0	14.9894	14.9979	14.9948	0.1249
1/8-MOD-2	342.1	14.9895	14.9991	14.9947	0.1259
1/8-MOD-3	344.0	14.9894	14.9993	14.9950	0.1253
1/8-MOD-4	344.3	14.9878	14.9999	14.9944	0.1251
1/8-MOD-5	343.0	14.9913	14.9995	14.9955	0.1246
1/8-MOD-6	344.7	14.9934	15.0018	14.9965	0.1255
1/8-MOD-7	345.0	14.9908	15.0017	14.9959	0.1248
1/8-MOD-8	345.2	14.9901	15.0003	14.9956	0.1251
1/8-MOD-9	343.4	14.9885	14.9969	14.9940	0.1248
1/8-MOD-10	343.5	14.9904	15.0004	14.9962	0.1266
1/8-MOD-11	343.2	14.9901	14.9998	14.9954	0.1249
1/8-MOD-12	344.6	14.9876	15.0001	14.9951	0.1264
1/8-MOD-13	343.9	14.9895	15.0002	14.9945	0.1250
1/8-MOD-14	345.4	14.9908	15.0006	14.9964	0.1259
1/8-MOD-15	345.3	14.9924	14.9986	14.9961	0.1256
1/8-MOD-16	343.8	14.9931	15.0005	14.9972	0.1247
1/8-MOD-17	344.0	14.9921	14.9991	14.9957	0.1253
1/8-MOD-18	344.7	14.9917	15.0000	14.9964	0.1255
1/8-MOD-19	350.8	14.9917	15.0013	14.9967	0.1275
1/8-MOD-20	350.2	14.9888	14.9980	14.9943	0.1280
1/8-MOD-21	350.6	14.9893	14.9995	14.9953	0.1285
1/4-MOD-1	690.2	14.9835	14.9910	14.9879	0.2512
1/4-MOD-2	689.1	14.9821	14.9912	14.9866	0.2532
1/4-MOD-3	688.0	14.9804	14.9915	14.9853	0.2497
1/4-MOD-5	689.7	14.9824	14.9903	14.9868	0.2558
1/4-MOD-6	689.2	14.9822	14.9923	14.9869	0.2555
1/4-MOD-7	687.5	14.9806	14.9909	14.9862	0.2539
1/4-MOD-8	688.4	14.9792	14.9872	14.9843	0.2531
1/4-MOD-9	689.2	14.9786	14.9903	14.9855	0.2524
1/2-MOD-1	1377.9	14.9884	14.9953	14.9925	0.5079
1/2-MOD-2	1377.8	14.9866	14.9957	14.9909	0.5047
1/2-MOD-3	1385.0	14.9880	14.9951	14.9914	0.5095
1/2-MOD-4	1378.1	14.9877	14.9974	14.9926	0.5044
1/2-MOD-6	1378.2	14.9870	14.9955	14.9910	0.5003
1/2-MOD-7	1383.7	14.9882	14.9963	14.9917	0.5068
1.5-MOD-1	4150.8	14.9962	15.0107	15.0035	1.4998
1.5-MOD-2	4132.6	14.9968	14.9977	14.9933	1.5100
1.5-MOD-3	4125.6	14.9846	14.9962	14.9988	1.5087
1.5-MOD-4	4136.2	14.9879	15.0005	14.9946	1.5146

Reflector Rings

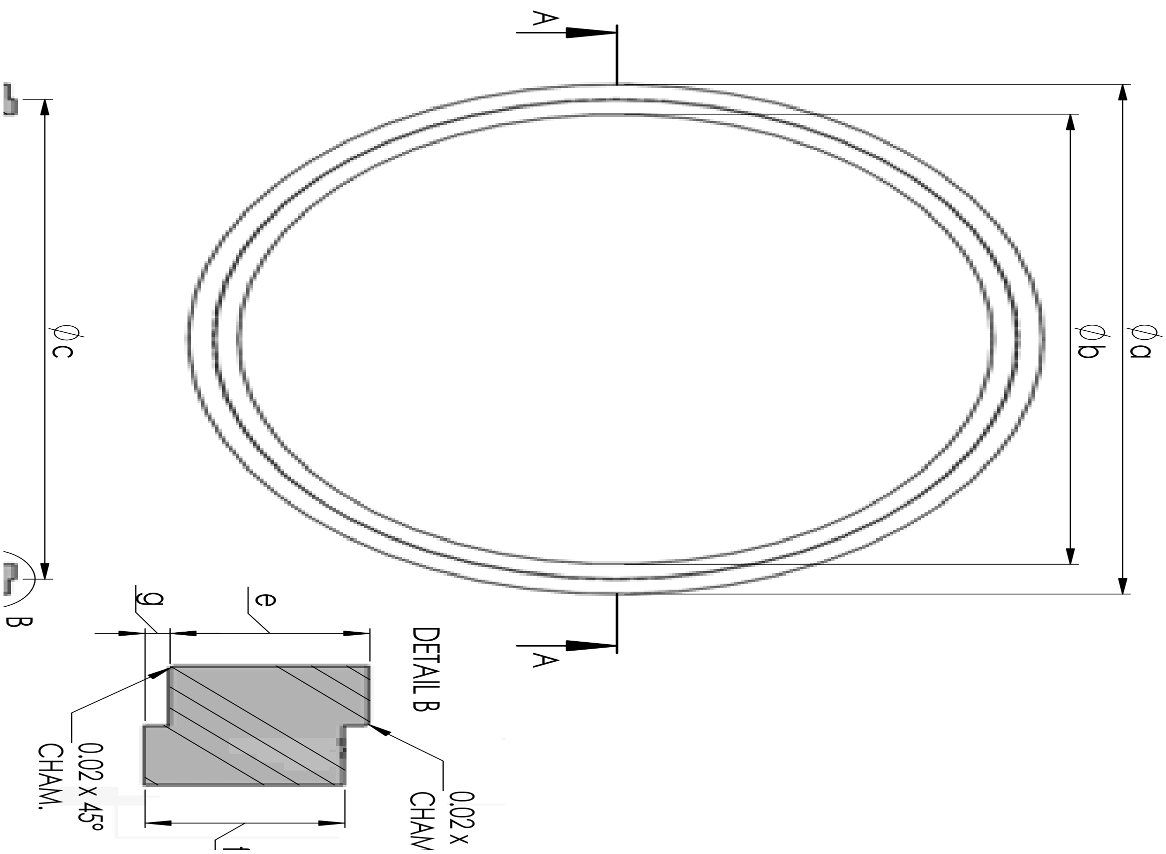

Figure 97: Design drawing of the reflector ring, showing a nominal 1/4" ring (dimensions in inches).

Table 38: Ring reflector masses and dimensions, variables defined in Figure 97.

ID	Mass (g)	Outer Diameter, a (in)			Inner Diameter, b (in)		
		Min	Max	Average	Min	Max	Average
1/4-RING-1	199.1	17.0822	17.1050	17.0933	15.0657	15.0912	15.0789
1/4-RING-2	198.9	17.0821	17.1019	17.0927	15.0690	15.0925	15.0813
1/2-RING-1	394.1	17.0770	17.0870	17.0818	15.0620	15.0728	15.0670
1/2-RING-2	394.4	17.0802	17.0854	17.0830	15.0660	15.0729	15.0682
1/2-RING-3	392.9	17.0806	17.0855	17.0828	15.0652	15.0721	15.0680
1-RING-1	805.8	17.0787	17.0852	17.0824	15.0605	15.0691	15.0660
1-RING-3	805.8	17.0808	17.0888	17.0837	15.0622	15.0700	15.0666
1-RING-4	804.9	17.0696	17.0766	17.0729	15.0509	15.0606	15.0560
1-RING-5	804.8	17.0812	17.0868	17.0839	15.0671	15.0714	15.0691
3-RING-1	2384.7	17.0879	17.0916	17.0898	15.0875	15.0912	15.0896
3-RING-5	2384.2	17.0855	17.0915	17.0888	15.0894	15.0928	15.0913

ID	Top Step Diameter, c (in)			Bottom Step Diameter, d (in)			Outer Edge Height, e (in)	Top Step Height, f (in)	Bottom Step Height, g (in)
	Min	Max	Average	Min	Max	Average			
1/4-RING-1	16.0527	16.0778	16.0654	16.0876	16.1120	16.0990	0.2568	0.3727	0.1205
1/4-RING-2	16.0532	16.0787	16.0654	16.0906	16.1096	16.1003	0.2585	0.3748	0.1209
1/2-RING-1	16.0480	16.0596	16.0537	16.0836	16.0956	16.0895	0.5027	0.6140	0.1198
1/2-RING-2	16.0507	16.0575	16.0533	16.0871	16.0919	16.0894	0.5042	0.6156	0.1205
1/2-RING-3	16.0471	16.0528	16.0496	16.0894	16.0965	16.0922	0.5053	0.6166	0.1179
1-RING-1	16.0564	16.0653	16.0615	16.0800	16.0845	16.0824	1.0016	1.1275	0.1219
1-RING-3	16.0590	16.0661	16.0628	16.0799	16.0862	16.0823	1.0014	1.1268	0.1219
1-RING-4	16.0420	16.0531	16.0485	16.0989	16.1075	16.1037	1.0052	1.1232	0.1161
1-RING-5	16.0624	16.0693	16.0653	16.0850	16.0906	16.0880	0.9991	1.1252	0.1205
3-RING-1	16.0726	16.0780	16.0742	16.0975	16.1006	16.0993	2.9952	3.1229	0.1231
3-RING-5	16.0710	16.0733	16.0720	16.0994	16.1029	16.1014	2.9961	3.1243	0.1231

Reflector Base

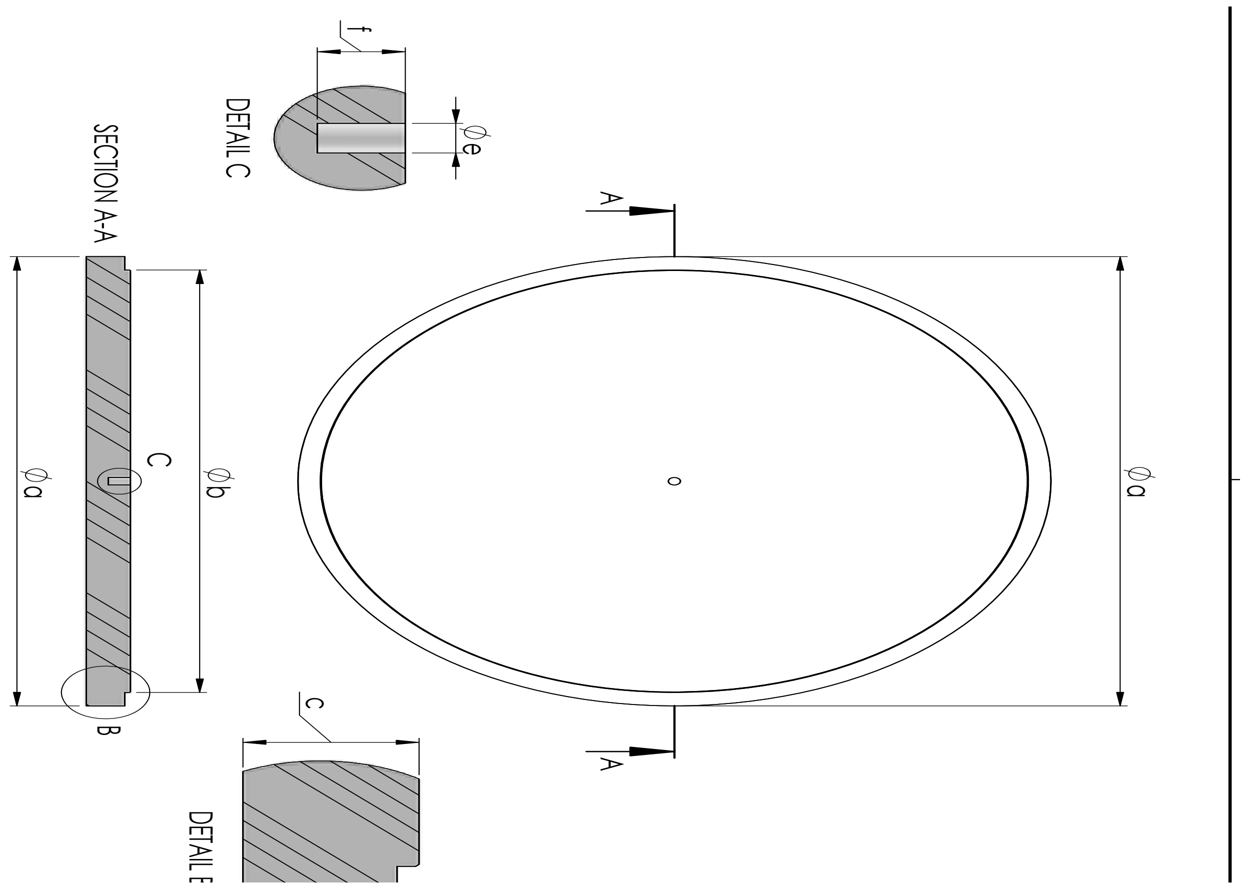

Figure 98: Design drawing of the reflector base (dimensions in inches).

Table 39: Reflector base mass and dimensions, variables defined in Figure 98.

ID	Mass (g)	Outer Diameter, a (in)			Step Diameter, b (in)			Thickness, c (in)	Outer Edge Thickness, d (in)	Source Diameter, e (in)	Source Depth, f (in)
		Min	Max	Average	Min	Max	Average				
BOTREF-1	3543.2	17.0.0715	17.0814	17.0766	16.0468	16.0592	16.0536	1.0225	0.9057	0.2814	0.5043

Reflector Caps

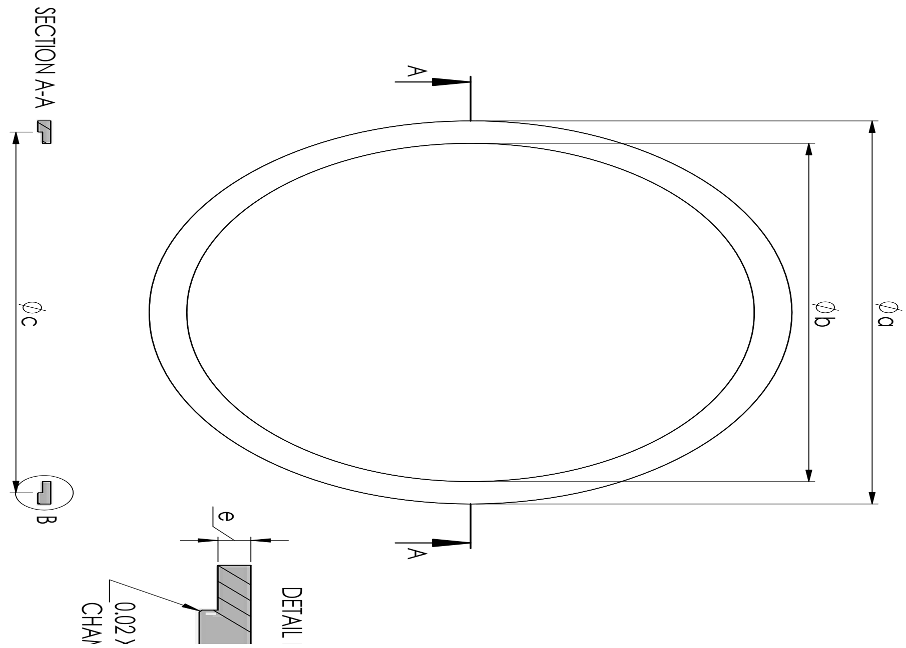

Figure 99: Design drawing of the reflector cap (dimensions in inches).

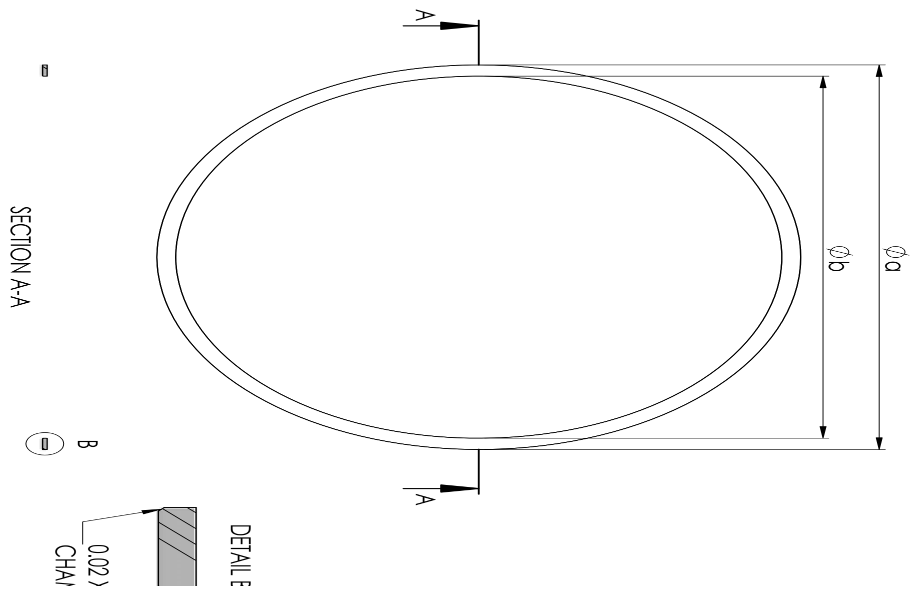

Figure 100: Design drawing of the bottom reflector cap (dimensions in inches).

Table 40: Reflector cap masses and dimensions, variables defined in Figure 100 and Figure 99.

ID	Mass (g)	Outer Diameter, a (in)			Inner Diameter, b (in)			Step Diameter, c (in)			Outer Edge Height, d (in)	Step Height, e (in)
		Min	Max	Average	Min	Max	Average	Min	Max	Average		
0-BOTCAP-1	48.2	-	-	16.053	-	-	15.066	-	-	-	0.131	-
0-CAP-1	50.7	-	-	17.047	-	-	16.079	-	-	-	0.126	-
0-CAP-2	50.8	-	-	17.046	-	-	16.077	-	-	-	0.126	-
1/32-CAP-1	76.8	17.0612	17.0763	17.0689	15.0604	15.0828	15.0738	16.0833	16.1000	16.0930	0.1647	0.0344
1/32-CAP-3	76.9	17.0651	17.0758	17.0710	15.0731	15.0847	15.0773	16.0906	16.0989	16.0943	0.1664	0.0350
1/16-CAP-1	101.5	17.0457	17.1074	17.0794	15.0554	15.1168	15.0842	16.0727	16.1328	16.1012	0.1953	0.0681
3/32-CAP-1	127.9	17.0414	17.1020	17.0725	15.0511	15.1100	15.0807	16.0645	16.1234	16.0946	0.2431	0.1006
1/8-CAP-1	149.0	17.0753	17.0845	17.0788	15.0748	15.0873	15.0824	16.0928	16.1036	16.0993	0.2531	0.1292
1/8-CAP-2	148.9	17.0692	17.0909	17.0791	15.0748	15.0921	15.0817	16.0913	16.1076	16.0981	0.2540	0.1290
1/8-CAP-3	149.0	17.0582	17.0977	17.0781	15.0652	15.1004	15.0815	16.0838	16.1214	16.1011	0.2535	0.1281
7/32-CAP-1	225.4	17.0781	17.0919	17.0860	15.0790	15.0933	15.0861	16.0990	16.1155	16.1073	0.3444	0.2290

Appendix B

Material Composition

The following sections include material compositions for the materials used in TEX-HEU: AL 6061, high density polyethylene, and highly enriched uranium.

Aluminum alloy 6061

AL 6061 was used in the experiment platform, lower adapter, membrane, and the inserts for the HEU plates. Table 40 shows the elemental composition limits for standard AL 6061.

Table 41: Composition limits for aluminum alloy 6061[24].

Component	Wt. %
Al	95.8 – 98.6
Mg	0.8 – 1.2
Si	0.4 – 0.8
Cu	0.15 – 0.4
Cr	0.04 – 0.35
Fe	Max 0.7
Zn	Max 0.25
Mn	Max 0.15
Ti	Max 0.15
Other, each	Max 0.05
Other, total	Max 0.15

A sample of the aluminum from the inserts was analyzed for impurities, which can be found in the following Elemental Analysis Report under "Aluminum". These impurities are specific to the inserts and not the other parts that are made of AL 6061 as they came from separate sources.

Polyethylene

Polyethylene was used in the moderator plates and the reflector rings. An impurity analysis of the polyethylene can be found in the following Elemental Analysis Report under "TEX".

Highly Enriched Uranium

The HEU plates have a long history in experiments, their composition can be found in the reports referenced in Section 2.2.1.

[24] Aluminum alloy 6061 properties, Materials Data Repository, National Institute of Standards and Technology (NIST), U.S. Department of Commerce.

Elemental Analysis By ICP-MS

Agilent 8800 QQQ

Model: G3663A / Serial Number: JP13360210

Project Title:	Elemental Analysis of Polymer and Aluminum Samples	
Date of Analysis:	July 9, 2019	
Analyst/Contact info:	P. Spackman	x2-7716

Sample preparation and instrument method:

Samples received consisted of two mailing envelopes containing shavings of a polymeric substance, white in color and opaque. Accompanying the envelopes was a plastic screw capped vial (~20 ml) containing clippings of aluminum metal. Samples were identified as "PNS" and "TEX" for the poly shavings and "Aluminum" for the metal clippings. The samples were weighed (noted below). The Aluminum sample was leached for 4 hours in 10% HNO3 in order to remove any surface transfer contamination during its subsampling. The Aluminum sample was weighed after leaching and was dried. The PNS and TEX samples were added to a digestion pressure vessel along with 10 mL 6M HNO3 and digested in the MARS6 microwave digester (Model: 910900, S/N: MJ6421) using the CEM "Polyethylene" method. The Aluminum sample was digested in the presence of a 1:1 solution of 6M HNO3 and 6M HCl using the "Aluminum Alloy" method. The digested solutions were decanted into 15 ml conical polypropylene screw capped vials, and were then subsequently diluted 10:1 in 10% HNO3 for PNS and TEX. Aluminum was diluted 10^3:1 in 10% HNO3. All samples were then analyzed by ICP-MS in the semi-quantitative, MS/MS mode.

Semi-Quantitative Analysis

Sample Name		23 Na	24 Mg	27 Al	28 Si	51 V	52 Cr	55 Mn	60 Ni
PNS mass: 257.54 ug	SQ Units				ug/g				
	Average (n=5)	ND	ND	ND	790.43	ND	ND	ND	ND
	STD Dev				53.79				
	%RSD				7%				
TEX mass: 246.97 ug	SQ Units	ug/g		ug/g	mg/g		ng/g		
	Average (n=5)	14.38	ND	23.92	1.17	ND	921.35	ND	ND
	STD Dev	1.82		1.74	0.06		7.08		
	%RSD	13%		7%	5%		1%		
Aluminum mass: 299.52 ug	SQ Units		ug/g		ug/g	ng/g	ng/g	ng/g	ng/g
	Average (n=5)	ND	8.92	ND	58.25	69.35	554.09	904.72	8.56
	STD Dev		0.78		12.43	4.97	109.17	26.29	1.29
	%RSD		9%		21%	7%	20%	3%	15%

Sample Name		63 Cu	66 Zn	69 Ga	90 Zr	95 Mo	118 Sn	139 La	208 Pb
PNS mass: 257.54 ug	SQ Units	ug/g	ug/g		ng/g	ng/g	ug/g		
	Average (n=5)	7.54	43.81	ND	441.71	557.23	4.90	ND	ND
	STD Dev	0.67	1.59		92.65	159.34	0.73		
	%RSD	9%	4%		21%	29%	15%		
TEX mass: 246.97 ug	SQ Units								
	Average (n=5)	ND	ND	ND	ND	ND	ND	ND	ND
	STD Dev								
	%RSD								
Aluminum mass: 299.52 ug	SQ Units	ng/g	ng/g	ng/g				ng/g	ng/g
	Average (n=5)	456.54	84.78	100.49	ND	ND	ND	2.48	36.45
	STD Dev	17.44	3.22	3.48				0.41	0.93
	%RSD	4%	4%	3%				17%	3%

1 of 2

Elemental Analysis By ICP-MS

Agilent 8800 QQQ

Model: G3663A / Serial Number: JP13360210

Comments:
All reported elements met the selection criteria: >Bkg(x3), CPS > 5000 ND = Not Detected (selection criteria not met) Sample volume used = 1.0 ml
Additional measurement parameters:
Elemental analysis was performed using an Agilent Technologies (Santa Clara, CA) 8800 Triple Quadrupolar ICP-MS (ICP-QQQ). A semi-quantitative MS/MS scan was performed with the following parameters: carrier gas (0.65 L/min), nebulizer pump (0.50 rps), spray chamber temperature (15 °C), and dilution gas (0.40 L/min). Argon was used as plasma, carrier, and dilution gas. In the collision cell, a helium flow was used as follows: 0 mL/min in No Gas tuning mode and 4.0 mL/min in He mode. The measurements were performed as three replicates, with 50 sweeps per replicate. Integration time per mass was held at 0.10 sec. The rinse time was set to 30 sec at 0.3 rps of the nebulizer pump, followed by 10 sec at 0.3 rps. Sample introduction was performed using an ASX-500 autosampler (Cetac, Omaha, NE).

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Appendix C

Vertical Lift Machine Part Drawings

The following sections include various as-designed part drawings for the Comet vertical lift machine components. These drawing are NCERC Project Drawing (LA-UR-20-30439) provided by Los Alamos National Laboratory.

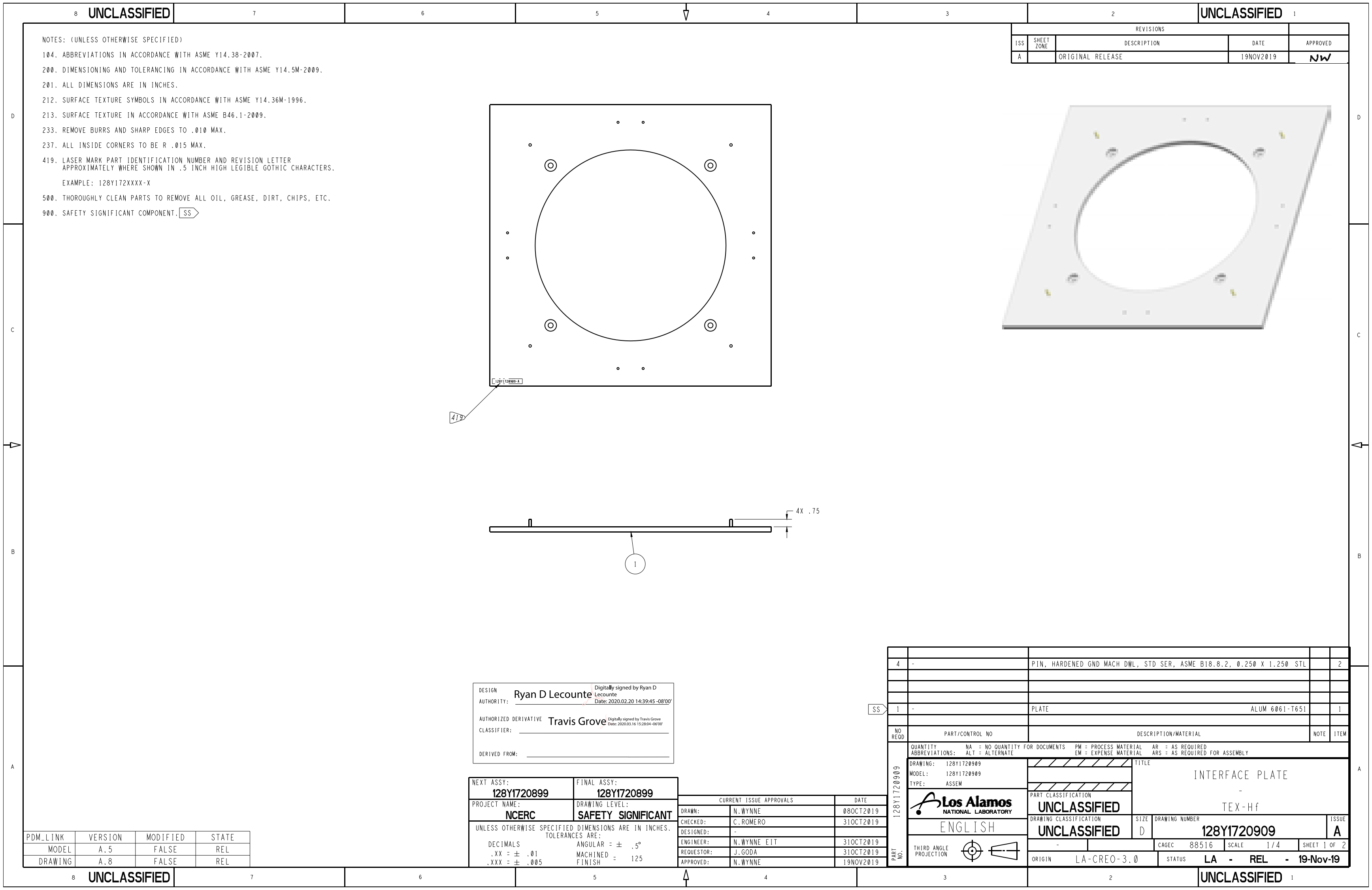
The experiment platform is affixed to the stationary platform of the vertical lift machine. The experiment platform consists of an interface plate (128Y1720909) and four standoffs that hold the platform in place. There are four models of the legs which differ only in their length. These experiments only use the 12” standoffs (128Y1720908-01).

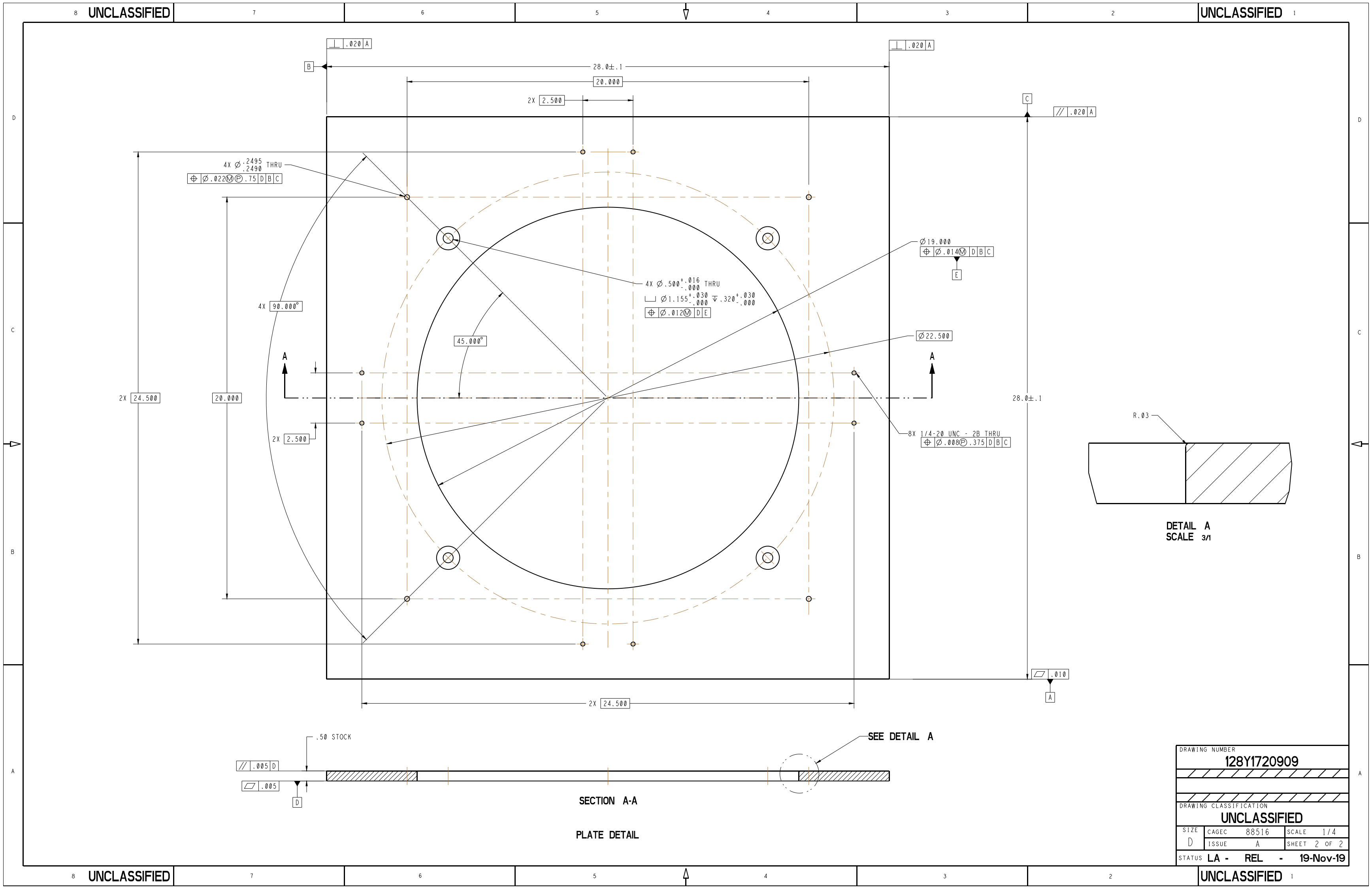
The lower adapter consists of two parts which are fastened to the movable platen. The lower adapter plate (128Y1720900) provides the base which holds the bottom reflector. This plate is affixed to the movable platen with the lower adapter extension (128Y1720916).

The membrane (128Y1720910) and alignment plate (128Y1720901) provide the support and the alignment for the upper half of the experiment. These two plates sit on top of the experiment platform using the four pegs on the interface plate.

The alignment brackets (128Y1720913) are a removable alignment fixture that attaches to the interface plate. The brackets hold and position a T-square to ensure the reflectors used in the experiments are in vertical alignment prior to final measurements. They are removed before experiment execution.

Experiment Platform




UNCLASSIFIED
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Ø19.000
Ø22.500
8X 1/4-20 UNC - 2B THRU
2X 24.500
20.000
2X 2.500
R.03
DETAIL A
SCALE 3/1
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SECTION A-A
PLATE DETAIL
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128Y1720909
DRAWING CLASSIFICATION
UNCLASSIFIED
SIZE D
CAGEC 88516
SCALE 1/4
ISSUE A
SHEET 2 OF 2
STATUS LA - REL - 19-Nov-19

ISS	SHEET ZONE	DESCRIPTION	DATE	APPROVED
A		ORIGINAL ISSUE	19NOV2019	NW
B		FCR-2019-NCERC-005	12FEB2020	NW

REVISIONS

NOTES: (UNLESS OTHERWISE SPECIFIED)

104. ABBREVIATIONS IN ACCORDANCE WITH ASME Y14.38-2007.

200. DIMENSIONING AND TOLERANCING IN ACCORDANCE WITH ASME Y14.5M-2009.

201. ALL DIMENSIONS ARE IN INCHES.

212. SURFACE TEXTURE SYMBOLS IN ACCORDANCE WITH ASME Y14.36M-1996.

213. SURFACE TEXTURE IN ACCORDANCE WITH ASME B46.1-2009.

233. REMOVE BURRS AND SHARP EDGES TO .010 MAX.

237. ALL INSIDE CORNERS TO BE R .015 MAX.

419. LASER MARK PART IDENTIFICATION NUMBER AND REVISION LETTER APPROXIMATELY WHERE SHOWN IN .25 INCH HIGH LEGIBLE GOTHIC CHARACTERS.

EXAMPLE: 128Y172XXXX-XX-X

500. THOROUGHLY CLEAN PARTS TO REMOVE ALL OIL, GREASE, DIRT, CHIPS, ETC.

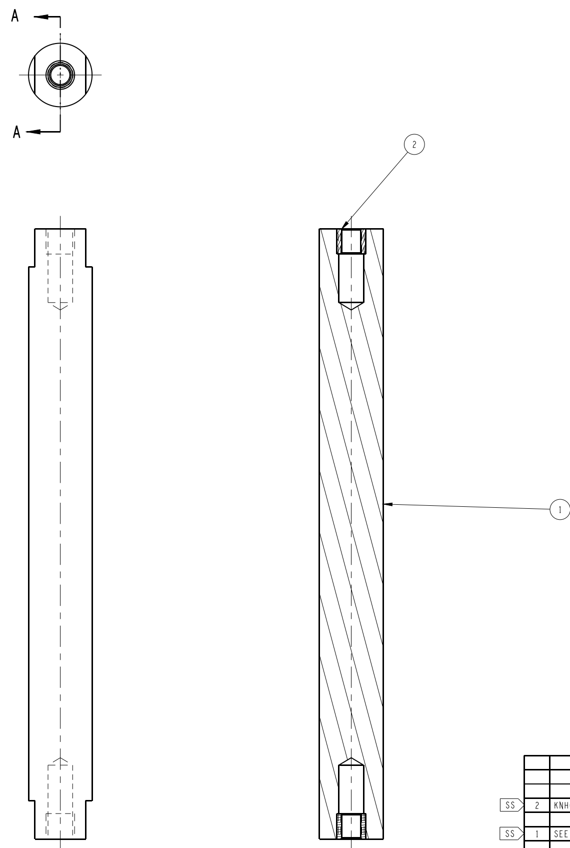
900. MATERIAL PER ASTM B211-12.

901. PART MAY HAVE THRU HOLE.

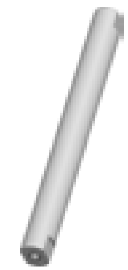
902. LASER MARK NOMINAL DIMENSION "A IN." APPROXIMATELY WHERE SHOWN IN .25 INCH HIGH LEGIBLE GOTHIC CHARACTERS.

EXAMPLE: 12 IN. FOR PART# 128Y1720908-01-A

903. SAFETY SIGNIFICANT COMPONENT. SS



SECTION A-A



SCALE 1/2

DESIGN AUTHORITY: Ryan D Lecounte — Digitally signed by Ryan D Lecounte Date: 2020.02.12 15:29:48 -08'00'

AUTHORIZED DERIVATIVE CLASSIFIER: James M Strelow — Digitally signed by James M Strelow Date: 2020.02.12 15:38:13 -08'00'

DERIVED FROM:

SS	2	KNH616J	THREADED INSERT, 3/8-16 KEENSERT		2
SS	1	SEE TABULATION SH 2	ROD AL 6061-T6	900	1
	NO REQD	PART/CONTROL NO	DESCRIPTION/MATERIAL	NOTE	ITEM

QUANTITY ABBREVIATIONS: NA = NO QUANTITY FOR DOCUMENTS; ALT = ALTERNATE; PM = PROCESS MATERIAL; EM = EXPENSE MATERIAL; AR = AS REQUIRED; ARS = AS REQUIRED FOR ASSEMBLY

PDM_LINK	VERSION	MODIFIED	STATE
MODEL	B.2	FALSE	REL
DRAWING	B.2	FALSE	REL

NEXT ASSY: 128Y1720899

FINAL ASSY: 128Y1720899

PROJECT NAME: NCERC

DRAWING LEVEL: SAFETY SIGNIFICANT

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ARE:

DECIMALS .XX = ± .01 .XXX = ± .005

ANGULAR = ± .5°

MACHINED FINISH = 125

ORIGINAL ISSUE APPROVALS		DATE
DRAWN:	N.WYNNE	14OCT2019
CHECKED:	C.ROMERO	31OCT2019
DESIGNED:	-	
ENGINEER:	N.WYNNE EIT	31OCT2019
REQUESTOR:	J.GODA	31OCT2019
APPROVED:	N.WYNNE	19NOV2019

PART NO. 128Y1720908

DRAWING: 128Y1720908
MODEL: 128Y1720908
TYPE: PART

Los Alamos NATIONAL LABORATORY

ENGLISH

THIRD ANGLE PROJECTION

PART CLASSIFICATION: UNCLASSIFIED

DRAWING CLASSIFICATION: UNCLASSIFIED

TITLE: UPPER PLATE STANDOFF THREADED TEX-Hf

SIZE: D

DRAWING NUMBER: 128Y1720908

ISSUE: B

CAGEC 88516 SCALE 1/1 SHEET 1 OF 2

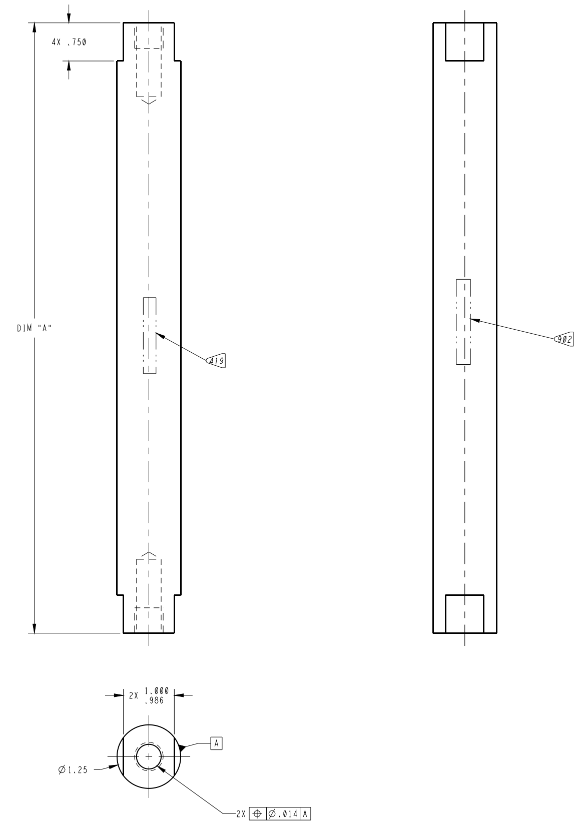
ORIGIN CREO 3.0

STATUS LA - REL - 12-Feb-20

UNCLASSIFIED

TABULATED DIMENSIONS

PART NO.	A
128Y1720908-01	12.000
128Y1720908-03	10.000
128Y1720908-05	8.000
128Y1720908-07	6.000
128Y1720908-09	4.000
901. 128Y1720908-11	2.000



ROD DETAIL

DRAWING NUMBER 128Y1720908

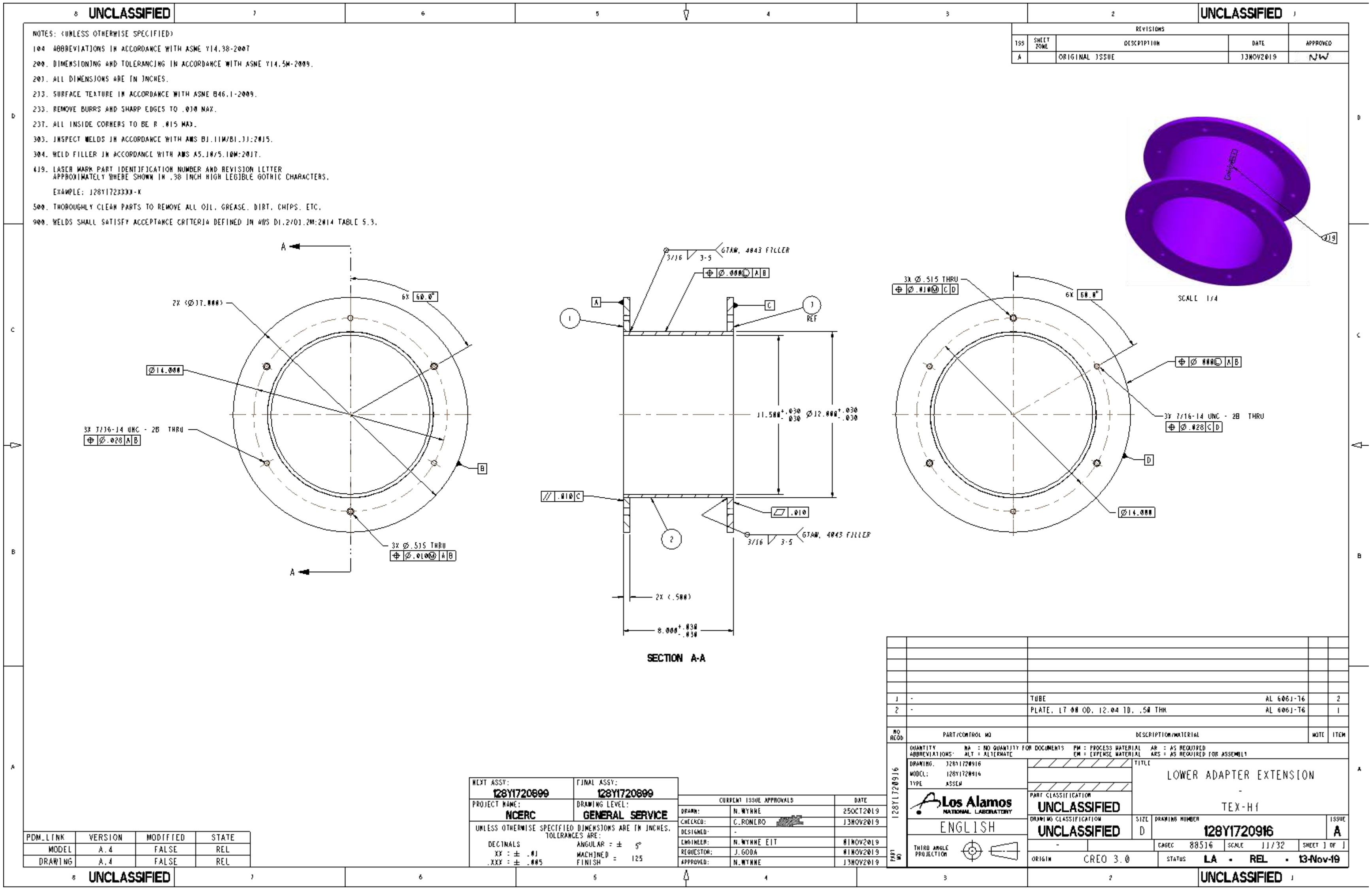
DRAWING CLASSIFICATION UNCLASSIFIED

SIZE	CAGEC	88516	SCALE	1/1
D	ISSUE	B	SHEET	2 OF 2

STATUS LA - REL - 12-Feb-20

UNCLASSIFIED

Lower Adapter



UNCLASSIFIED

REVISIONS				
ISS	SHEET ZONE	DESCRIPTION	DATE	APPROVED
A		ORIGINAL ISSUE	07-15-19	ES
B		ADDED 17.825 BC HOLE PATTERN	31OCT2019	NW

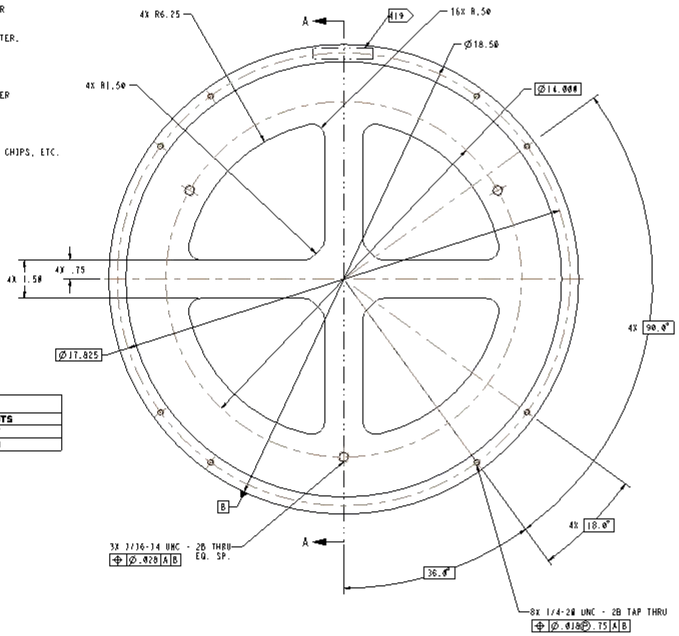
NOTES: (UNLESS OTHERWISE SPECIFIED)

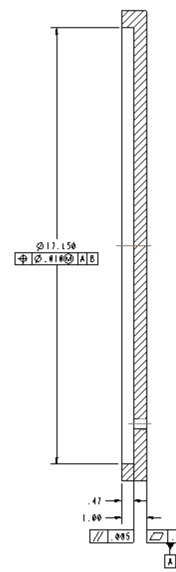
100. ABBREVIATIONS IN ACCORDANCE WITH ASME Y14.38-1999.
200. DIMENSIONING AND TOLERANCING IN ACCORDANCE WITH ASME Y14.5M-1994.
201. ALL DIMENSIONS ARE IN INCHES.
212. SURFACE TEXTURE SYMBOLS IN ACCORDANCE WITH ASME Y14.36M-1996.
213. SURFACE TEXTURE IN ACCORDANCE WITH ASME B46.1-1995.
217. ALL UNIFIED INCH THREAD DIMENSIONS AND TOLERANCES IN ACCORDANCE WITH ANSI B1.1-1989.
224. ALL THREADS TO BE UNIFIED CLASS 2.
225. ALL THREADS SHALL BE FREE FROM BURRS, NICKS AND ROUGH OR CHATTERED SURFACES VISIBLE WITHOUT MAGNIFICATION.
226. COUNTERSINK ALL TAPPED HOLES 100 DEGREES TO MAJOR DIAMETER.
233. REMOVE BURRS AND SHARP EDGES TO .010 MAX.
237. ALL INSIDE CORNERS TO BE R .015 MAX.
419. LASER MARK PART IDENTIFICATION NUMBER AND REVISION LETTER APPROXIMATELY WHERE SHOWN IN .13 INCH HIGH LEGIBLE GOTHIC/LEROY CHARACTERS.

    EXAMPLE: 128Y172XXXX-XX-X

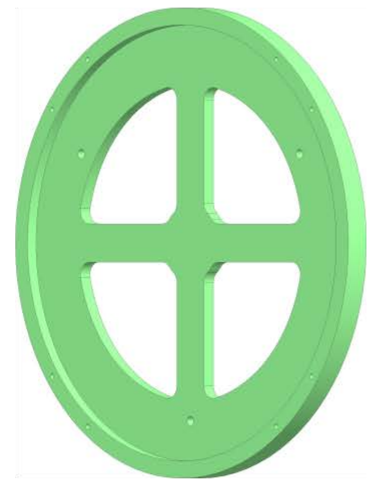
500. THOROUGHLY CLEAN PARTS TO REMOVE ALL OIL, GREASE, DIRT, CHIPS, ETC.

TABULATED DIMENSIONS		
PART NO.	250-20-HOLE-PATTERN	SLOTS
128Y1720900-01	N	Y
128Y1720900-03	Y	N





SECTION A-A



NEXT ASSY:	FINAL ASSY:
128Y1720899	128Y1720899
PROJECT NAME: NCERC	DRAWING LEVEL: GENERAL SERVICE

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ARE:
DECIMALS .XX = ± .01, .XXX = ± .005
ANGULAR = ± 5°
MACHINED FINISH = 125

ORIGINAL ISSUE APPROVALS		DATE
DRAWN:	C. ROMERO	07-08-19
CHECKED:	N. WYNNE	07-15-19
DESIGNED:	J GODA	07-05-19
ENGINEER:	N. WYNNE EIT	07-15-19
REQUESTOR:	J. GODA	07-15-19
APPROVED:	E. SORENSEN	07-15-19

PDM_LINK	VERSION	MODIFIED	STATE
MODEL	B.5	FALSE	REL
DRAWING	B.4	FALSE	REL

NO REQD	PART/CONTROL NO	DESCRIPTION/MATERIAL	NOTE	ITEM
	-	PLATE OR EQUIV ALUM, 6061-T6		

QUANTITY ABBREVIATIONS: NA = NO QUANTITY FOR DOCUMENTS; ALT = ALTERNATE; PM = PROCESS MATERIAL; EM = EXPENSE MATERIAL; AR = AS REQUIRED; ARA = AS REQUIRED FOR ASSEMBLY

SEE TABULATION

DRAWING: 128Y1720900
MODEL: 128Y1720900
TYPE: PART

Los Alamos NATIONAL LABORATORY

ENGLISH

THIRD ANGLE PROJECTION

PART CLASSIFICATION: UNCLASSIFIED

DRAWING CLASSIFICATION: UNCLASSIFIED

TITLE: LOWER ADAPTER PLATE TEX-HI NCERC

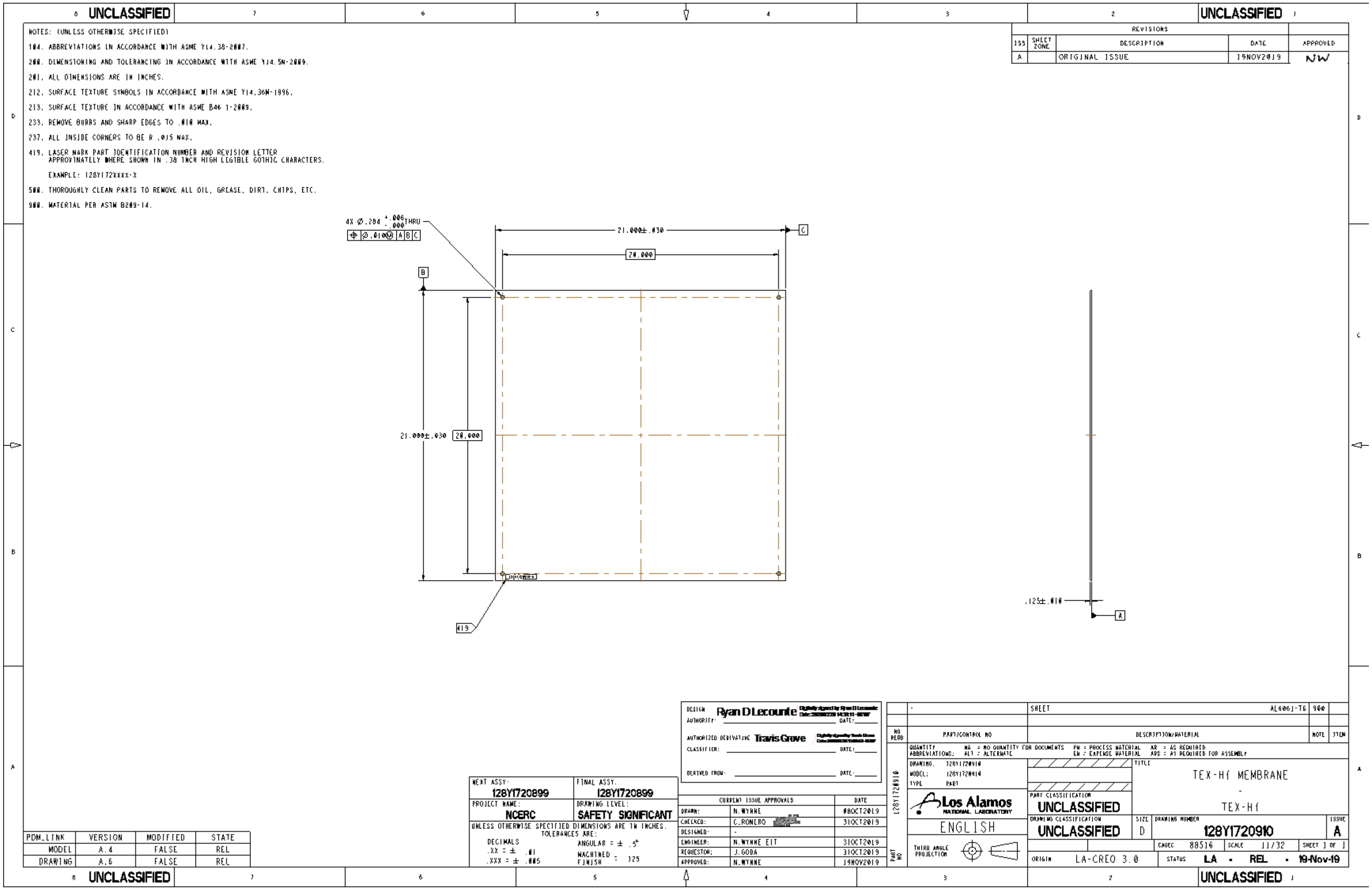
SIZE: D | DRAWING NUMBER: 128Y1720900 | ISSUE: B

CAGEC 88516 | SCALE 1/2 | SHEET 1 OF 1

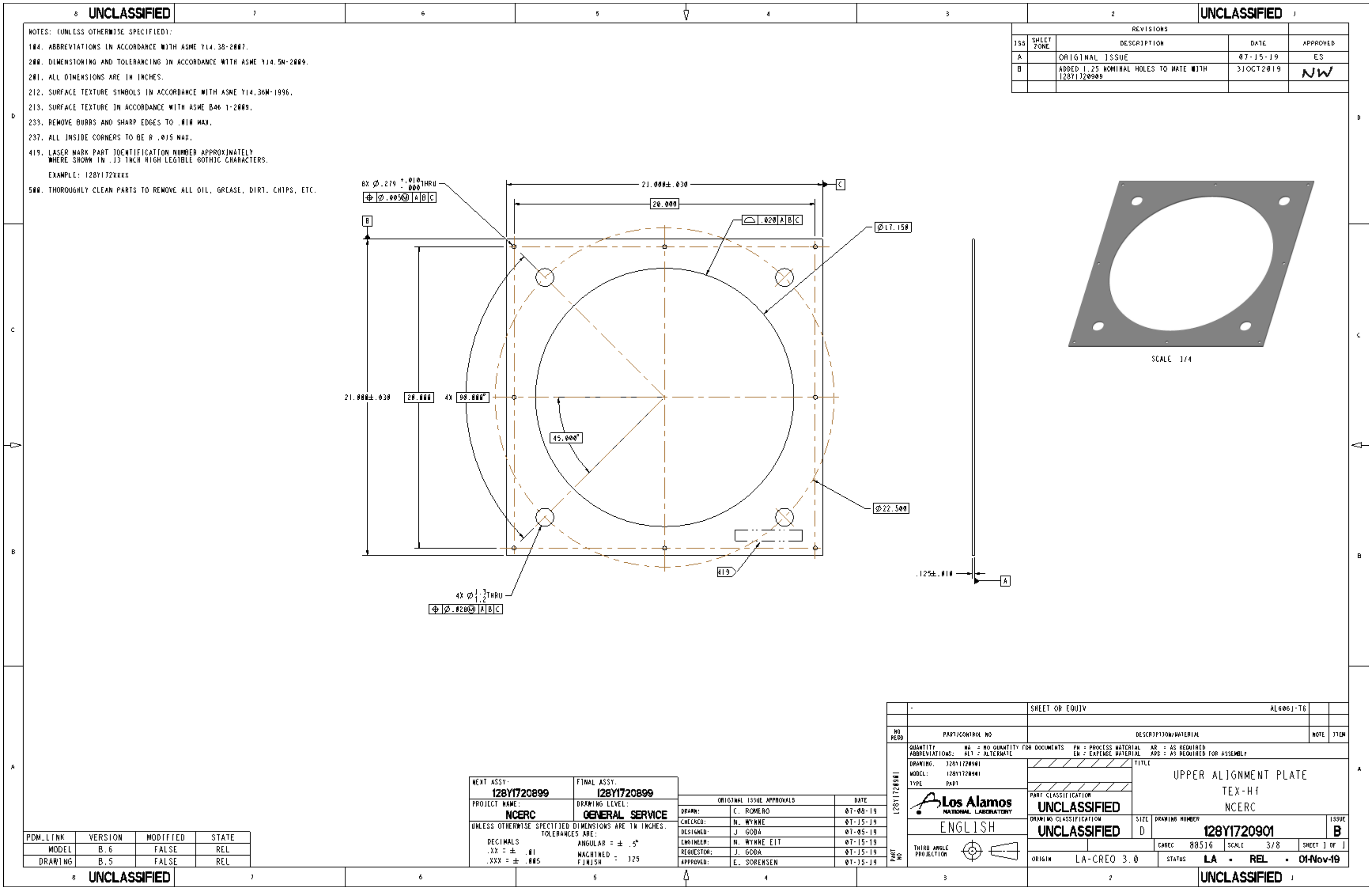
ORIGIN CREO 3.0 | STATUS LA - REL - 01-Nov-19

UNCLASSIFIED

Membrane


UNCLASSIFIED
NOTES: (UNLESS OTHERWISE SPECIFIED)
104. ABBREVIATIONS IN ACCORDANCE WITH ASME Y14.38-2007.
200. DIMENSIONING AND TOLERANCING IN ACCORDANCE WITH ASME Y14.5M-2009.
201. ALL DIMENSIONS ARE IN INCHES.
212. SURFACE TEXTURE SYMBOLS IN ACCORDANCE WITH ASME Y14.36M-1996.
213. SURFACE TEXTURE IN ACCORDANCE WITH ASME B46 1-2009.
233. REMOVE BURRS AND SHARP EDGES TO .010 MAX.
237. ALL INSIDE CORNERS TO BE R .015 MAX.
419. LASER MARK PART IDENTIFICATION NUMBER AND REVISION LETTER APPROXIMATELY WHERE SHOWN IN .38 INCH HIGH LEGIBLE GOTHIC CHARACTERS.
EXAMPLE: 128Y172XXXX-X
500. THOROUGHLY CLEAN PARTS TO REMOVE ALL OIL, GREASE, DIRT, CHIPS, ETC.
900. MATERIAL PER ASTM B209-14.
REVISIONS
A ORIGINAL ISSUE 19NOV2019
21.000±.030
20.000
.125±.010
419
NEXT ASSY: 128Y1720899
FINAL ASSY: 128Y1720899
PROJECT NAME: NCERC
DRAWING LEVEL: SAFETY SIGNIFICANT
DRAWN: N.WYNNE 08OCT2019
CHECKED: C.ROMERO 31OCT2019
ENGINEER: N.WYNNE EIT 31OCT2019
REQUESTOR: J.GODA 31OCT2019
APPROVED: N.WYNNE 19NOV2019
AL6061-T6 900
Los Alamos NATIONAL LABORATORY
ENGLISH
THIRD ANGLE PROJECTION
TITLE TEX-HI MEMBRANE - TEX-HI
DRAWING NUMBER 128Y1720910
ISSUE A
SIZE D
CAGEC 88516
SCALE 11/32
SHEET 1 OF 1
ORIGIN LA-CREO 3.0
STATUS LA - REL - 19-Nov-19

Alignment Plate



Alignment Bracket