LLNL-TR-850980

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

IER-532 CED-3b

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External Audience (Unlimited)

June 30, 2023

Disclaimer

Acknowledgements

This work was funded by the U.S. Department of Energy's Nuclear Criticality Safety Program (NCSP). These experiments were executed at the National Criticality Experiments Research Center (NCERC) under the operation of Los Alamos National Laboratory's Advanced Nuclear Technology Group (NEN-2). The NEN-2 experimenters involved in this campaign include Travis Grove, Theresa Cutler, Rene Sanchez, Kelsey Amundson, Nicholas Thompson, Kenneth Valdez, Justin Martin, Jessie Walker, and Alex McSpaden. Hardware design for this campaign, originally used for TEX-HEU, was performed by Nicholas Wynne, with review by Chris Romero. The experiments were conducted with facility support by NCERC-FO and Mission Support and Test Services (MSTS). The hafnium plates were procured and provided to the NCSP by the Naval Nuclear Laboratory (NNL). All experiment photos are courtesy of NEN-2.

Table of Contents

Section 1. Detailed Description ... 1
1.1 Overview of Experiment ... 1
1.2 Description of Experimental Configuration ... 2
1.2.1 Design of the Critical Assembly ... 2
1.2.2 Comet General Purpose Critical Assembly Machine ... 3
1.2.2.1 Stationary Platform ... 5
1.2.2.2 Movable Platen ... 5
1.2.3 Highly Enriched Uranium Plates ... 6
1.2.4 Hafnium Plates ... 6
1.2.5 Polyethylene Parts ... 12
1.2.5.1 Moderator and Reflector Plates ... 12
1.2.5.2 Reflector Rings ... 17
1.2.5.3 Reflector Caps ... 20
1.2.5.4 Bottom Reflector ... 23
1.2.6 Aluminum Inserts ... 24
1.2.7 Experimental Configurations ... 25
1.3 Description of Material Data ... 25
1.3.1 Comet General Purpose Critical Assembly Machine ... 25
1.3.2 Highly Enriched Uranium ... 25
1.3.2.1 ^{235}U Enrichment ... 25
1.3.2.2 Uranium Impurities ... 27
1.3.3 Hafnium ... 28
1.3.3.1 Hafnium Density Measurements ... 28
1.3.3.2 Hafnium Impurity Analysis ... 29
1.3.4 Polyethylene ... 30
1.3.4.1 Polyethylene Density Measurements ... 30
1.3.4.2 Polyethylene Impurity Analysis ... 30
1.3.5 Aluminum ... 31
1.4 Temperature ... 32
1.5 Supplemental Experimental Measurements ... 33
Section 2. Experimental Measurements and Configurations ... 35
2.1 Experimental Measurements ... 35
2.1.1 Period Measurements ... 35
2.1.2 Temperature Measurements ... 37
2.1.3 Height Measurements ... 38
2.1.4 Levelness ... 40
2.1.5 Additional Measurements ... 41
2.1.5.1 HEU Stacking Density ... 41
2.1.5.2 Membrane Deflection ... 42
2.1.5.3 Feeler Gage Measurements ... 44
2.1.5.4 Room and Comet Measurements ... 44
2.2 Experimental Configurations ... 46
2.2.1 0” Standard Configuration ... 46
2.2.2 1/8” Standard Configuration ... 48
2.2.3 1/4” Standard Configuration ... 50
2.2.4 1/2” Standard Configuration ... 52
2.2.5 1-1/2” Standard Configuration ... 54
2.2.6 1/4” Sandwich Stacking Configuration ... 56
2.2.7 0” Bunched Configuration ... 58

2.3 Supplemental Experimental Measurements 60
2.3.1 Extrapolation to Delayed Critical by Top Reflector Thickness 60
2.3.2 Ring Reflector Gap Reactivity Worth 61
Section 3. Bibliography 63
Appendix A. Engineering Drawings 65

Executive Summary

This report documents the experimental configurations and measurements for IER-532, Thermal/Epithermal eXperiments (TEX) with highly enriched uranium (HEU) fuel and interstitial hafnium (Hf), moderated and reflected by polyethylene. TEX-Hf is a variation of and based on the TEX-HEU (IER-297) design, with the inclusion of hafnium. These configurations provide integral experiments for validation of hafnium in the thermal, intermediate, and fast neutron energy regimes by maximizing the sensitivity in k_{eff} to the hafnium isotope cross sections.

The experiment campaign was completed over seven weeks during the end of FY22 and beginning of FY23 at the National Critical Experiments Research Center at the Nevada National Security Site. The campaign produced seven experimental configurations, four reproducibility measurements, and many additional dimensional measurements that will be of use to the future benchmark evaluation of this experiment and other experiments using the same HEU fuel. Table 1 summarizes the TEX-Hf experimental configurations, including their physical parameters, calculated fission fractions, and estimated excess reactivities.

Table 1. Summary of TEX-Hf experimental configurations.

Configuration	Benchmark Date	HEU Mass (kg)	Hf Mass (kg)	Moderator Thickness (in)	Fission Fractions[1]	Excess Reactivity (¢)
0” Standard	2023-10-13	135.5	38.7	-	7 / 19 / 74	14.1 ± 0.1
1/8” Standard	2023-09-19	99.4	24.2	0.125	9 / 51 / 40	13.2 ± 0.1
1/4” Standard	2023-09-12	82.8	19.4	0.250	16 / 55 / 40	24.2 ± 0.5
1/2” Standard	2023-09-22	63.9	14.5	0.500	32 / 48 / 20	8.1 ± 0.1
1-1/2” Standard	2023-09-28	70.4	16.1	1.500	60 / 28 / 12	10.9 ± 0.0
1/4” Sandwich	2023-10-26	88.4	21.0	0.250	13 / 57 / 30	15.7 ± 0.1
0” Bunched	2023-10-19	124.7	33.9	-	1 / 14 / 85	12.0 ± 0.0

The Comet General Purpose Critical Assembly Machine was used to conduct the TEX-Hf experiments. This experiment used the same hardware and similar measurement procedures as TEX-HEU, which will allow these previous experiments to provide a baseline when evaluating the effects of the hafnium diluent. The experimental configurations documented in Section 2.2 will undergo evaluation as a benchmark in the International Criticality Safety Benchmark Evaluation Project Handbook.

[1] Reported as thermal (<0.625 eV) / intermediate (0.625 eV – 100 keV) / fast (>100 keV).

Section 1

Detailed Description

1.1 Overview of Experiment

This report documents the Thermal Epithermal eXperiments (TEX) experimental configurations with highly enriched uranium (HEU) and hafnium (Hf) as the diluent material, known as TEX-Hf. This experiment is a variation of HEU-MET-MIXED-021 (TEX-HEU Baseline Assemblies) with the inclusion of hafnium. The purpose of the TEX-HEU design is to provide multiple configurations that span the entire neutron energy spectrum. The TEX-Hf configurations furthers this by providing integral experiments for validation of hafnium in the thermal, intermediate, and fast neutron energy regimes by maximizing the sensitivity in k_{eff} to the hafnium isotope cross sections.

The main parameter that is varied between the experimental configurations is the thickness, or presence, of high-density polyethylene (HDPE) plates between the HEU plates. Varying the thickness of these HDPE plates allows the fission fractions to be majority fast (0” Std. and 0” Bunch.), intermediate (1/8”, 1/4”, 1/2” Std. and 1/4” Sand.), and thermal (1-1/2” Std.). Table 2 reports these fission fractions based on calculations performed for the preliminary design[2].

Table 2. Comparison of the HDPE plate thicknesses and resulting fission fractions grouped by neutron energy regime [1].

Configuration	Nominal Moderator Thickness, in (cm)	Calculated Fission Fractions		
		Thermal (<0.625 eV)	Intermediate (0.625 eV – 100 keV)	Fast (>100 keV)
0” Standard	-	7.2	19.0	73.8
1/8” Standard	0.125 (0.3175)	9.3	51.0	39.7
1/4” Standard	0.250 (0.6350)	15.9	54.7	29.4
1/2” Standard	0.500 (1.2700)	31.7	48.0	20.3
1-1/2” Standard	1.500 (3.8100)	59.8	27.7	12.5
1/4” Sandwich	0.250 (0.6350)	13.3	57.2	29.5
0” Bunched	-	1.5	13.6	84.9

[2] The configurations in [1] slightly differ from these experimental configurations.

These experiments were funded by the U.S. Department of Energy's Nuclear Criticality Safety Program and conducted over seven weeks in August, September, and October of 2022 at the National Critical Experiments Research Center (NCERC) at the Nevada National Security Site in the United States of America. They were executed as a collaboration between Lawrence Livermore National Laboratory's Nuclear Criticality Safety Division and Los Alamos National Laboratory's (LANL) Advanced Nuclear Technology Group with the facility support of NCERC-FO and Mission Support and Test Services.

The HEU plates used in this experiment have a long history in many critical experiments executed by LANL. The earliest usage of similar HEU plates is in the "extension of the earlier Jemima experiments" in 1956, which used 3 mm thick U(93.4) plates with a 15" outer diameter (IEU-MET-FAST-002). Since then, these same HEU plates have been used in the Big Ten experiments in the 1970s (IEU-MET-FAST-007), the first three Zeus experiments in 1999-2002 (HEU-MET-INTER-006, HEU-MET-FASTER-073, and HEU-MET-FAST-072), and the Nb-1Zr experiment in 2004 (HEU-MET-FAST-047). More recently, these HEU plates have been in the Curie (HEU-MET-INTER-011), TEX-HEU (HEU-MET-MIXED-021), and Zeus-Pb (HEU-MET-FAST-102) experiments.

1.2 Description of Experimental Configuration

1.2.1 Design of the Critical Assembly

Figure 1 shows a rendering of the TEX-HEU experiment design. The main parameter that is varied between these experiments is the thickness of the polyethylene moderator plates. Varying this thickness allows the neutron spectrum to be varied between majority thermal, intermediate, and fast. The mass of the HEU is then changed by adding or removing plates. Finally, the thickness of the upper reflector is adjusted in increments of 1/32 in (0.079375 cm) to provide fine reactivity adjustments. The polyethylene ring reflector height is adjusted to match the HEU and polyethylene plate stack to the nearest 1/32 in (0.079375 cm). For TEX-Hf, hafnium plates were place as a diluent material within this design.

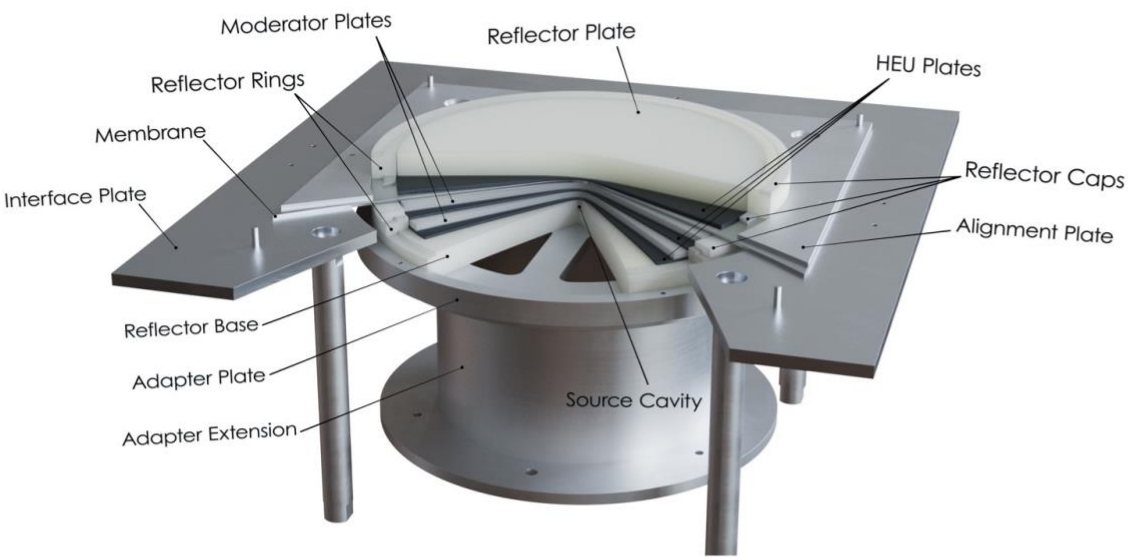

Figure 1. TEX-HEU experiment design and components.

Figure 2 shows the three different methods of placing the Hf plates in the experimental configurations. This figure shows the bottom halves of the TEX-Hf 1/8" Standard, TEX-Hf 1/4" Sandwich, and TEX-Hf 0" Bunched configurations, from left to right. The HEU plates are dark gray, the HDPE moderator plates and reflector are white, and the Hf plates are silver. The Standard and Sandwich photos show the bottom halves of the benchmark experimental configurations with the HDPE side reflector removed. The Bunched photo shows an experimental configuration with the HDPE side reflector removed during its approach to critical, prior to the two halves of the experiment being separate on the upper and lower components of the critical assembly machine.

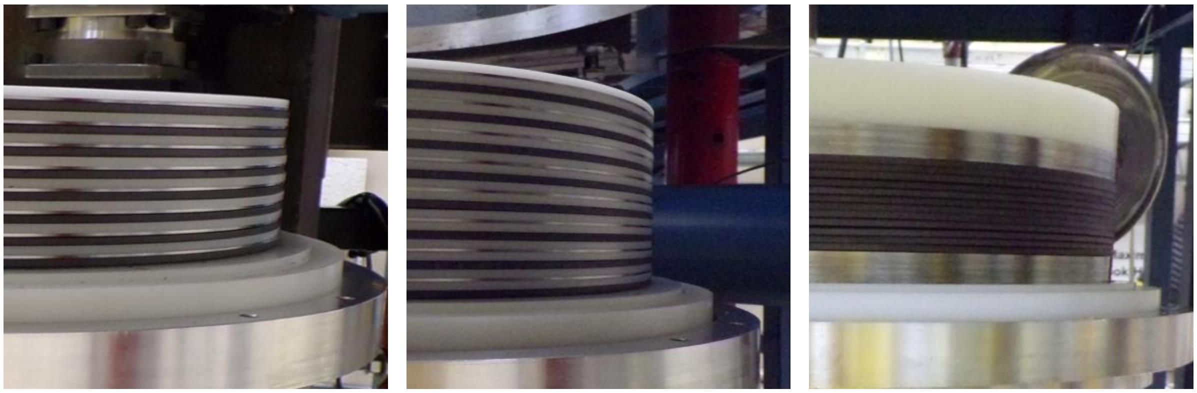

Figure 2.TEX-Hf stacking methods: Standard (left), Sandwich (middle), and Bunched (right).

The first method, referred to as Standard (Std.), placed the Hf plates between the HEU plates and HDPE plates, matching the TEX-HEU design with a diluent between the layers. The second method, referred to as Sandwich (Sand.), placed the Hf plates between two HDPE plates, in a flux-trap design. The third method, referred to as Bunched (Bunch.), placed the Hf plates in two monoliths, consisting of 12 Hf plates each, on the top and bottom of the HEU plate stack between the HDPE reflectors.

1.2.2 Comet General Purpose Critical Assembly Machine

The Comet General Purpose Critical Assembly Machine is a vertical lift machine used to remotely assemble a critical mass. As shown in Figure 3, Comet consists of the surrounding structure, stationary platform, and movable platen. For TEX-HEU and TEX-Hf, additional parts were affixed to Comet: an experiment platform, affixed to the stationary platform, and a lower adapter, extending the movable platen.

During assembly, roughly half of the experiment is built on the upper 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.

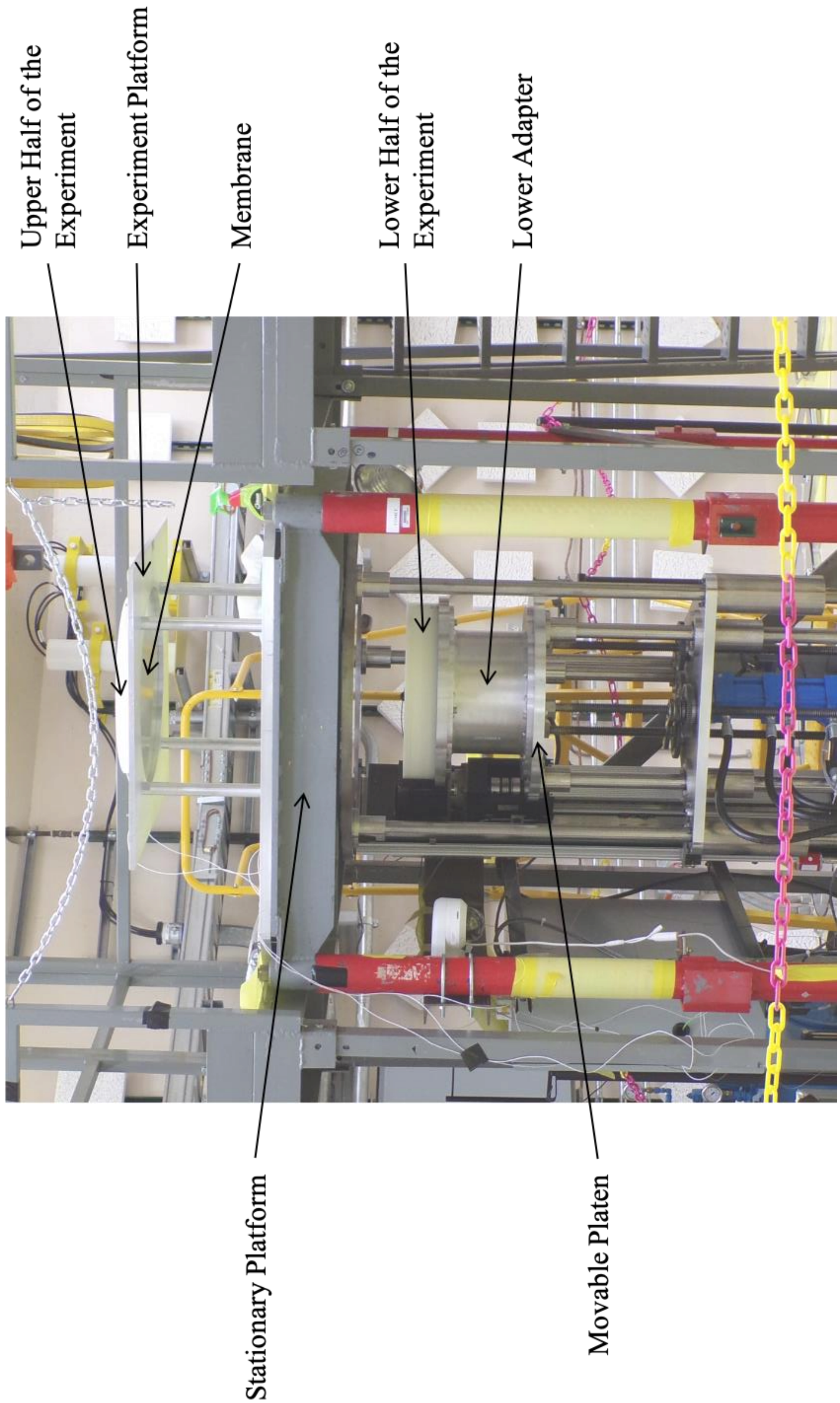

Figure 3. The Comet General Purpose Critical Assembly Machine.

1.2.2.1 Stationary Platform

The experiment platform holds the upper half of the experiment, shown in Figure 4. The platform consists of an interface plate and four standoffs, which connect the interface plate to the stationary platform. 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 meets the upper half of the experiment through the membrane. The interface plate includes four pegs to hold the membrane and alignment plate in place while still allowing vertical movement.

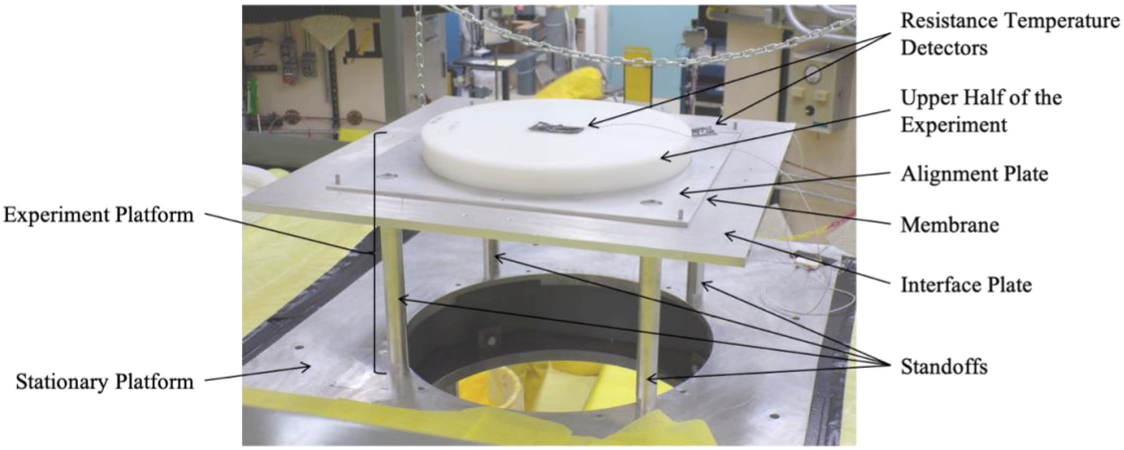

Figure 4. Upper stationary platform of Comet, with the experiment platform.

The interface plate is a 28 in x 28 in x 0.5 in (71.12 cm x 71.12 cm x 1.27 cm) AL 6061-T6 plate with a 19 in (48.26 cm) diameter hole through its center. The standoffs are 12 in (30.48 cm) long AL 6061-T6 cylinders with a 1.25 in (3.175 cm) diameter. The membrane is a 21 in x 21 in (53.34 cm x 53.34 cm) AL 6061-T6 plate with a thickness of 0.125 in (0.3175 cm). The membrane features four holes, one in each corner, ensuring consistent alignment when placed onto the interface plate using the four pegs. The design allows the membrane to be lifted up to 0.75 in (1.905 cm).

1.2.2.2 Movable Platen

The lower adapter holds the lower half of the experiment, shown in Figure 5. This lower adapter consists of an adapter plate and an adapter extension, which affixes the lower adapter to the movable platen.

Figure 5. Lower movable platen of Comet, with the lower adapter.

The adapter plate has a 0.53 in (1.3462 cm) thickness and 18.5 in (46.99 cm) outer diameter. This plate features a 17.15 in (43.561 cm) inner diameter with an additional 0.47 in (1.1938 cm) lip height, to hold the bottom polyethylene reflector plate. The adapter extension is an 8 in (20.32 cm) tall annular cylinder with a wall thickness of 0.25 in (0.635 cm) and a 12 in (30.48 cm) outer diameter. This extension includes a 2.5 in (6.35 cm) wide and 0.5 in (1.27 cm) 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.

1.2.3 Highly Enriched Uranium Plates

The HEU plates are nominal 0.118 in (0.29972 cm) thick, 15 in (38.1 cm) outer diameter U(93+) plates, collectively known as the “Jemima” plates. These plates are either full or annular cylinders with an inner annulus of 2.5 in (6.35 cm), 6 in (15.24 cm), or 10 in (25.4 cm). The annulus removes some of the HEU mass resulting in lower and higher mass plate variants. The plates are identified in this, and previous evaluations, based on their annulus: 15/0-HEU (Full, HEU1), 15/2.5-HEU (2.5”, HEU2, Id. No. 403), 15/6-HEU (6”, HEU4, “Six Inch”, Id. No. 401), and 15/10-HEU (10”, HEU5, “Ten Inch”, Id. No. 402). Each of these four variants are shown in Figure 6.

Table 4 reports the nominal dimensions of the HEU plates and the mass measurement performed during this experiment campaign. During this campaign, the mass measurements were performed using a Mettler Toledo Electronic Scale (Cal No. 012708, valid through May 17, 2023). The manufacturer reports a maximum capacity of 16,200 grams, precision of 0.1 grams, and linearity of 0.2 grams. The measurement procedure involved the HEU plates being weighed in a plastic bag to contain any contamination. Each bag was weighed before placing the HEU plate in the bag. Then the weight of the HEU plate in the bag was measured. After performing this measurement, the balance was checked to ensure the measurement returned to zero with the HEU plate and bag removed. The plate mass is calculated by subtracting the bag mass. Table 4 also includes the mass measurement of the plates involved in the TEX-HEU experiment campaign, refer to [2] for the measurement description and procedure. Table 5 includes the HEU plate thickness measurements that are part of MIX-MET-FAST-016, taken in 2019. These were performed using an IP67 Mitutoyo caliper (CD-24”C) with a resolution of ±0.02 in.

1.2.4 Hafnium Plates

The hafnium (Hf) plates have a nominal 15 in (38.1 cm) diameter and 0.04 in (0.1016 cm) thickness. The dimensions and design tolerances of these plates are reported Table 3.

Table 3: Hafnium plate nominal dimensions and tolerances.

Parameter	Dimension [in (cm)]	Tolerance [in (cm)]
Thickness	0.040 (0.1016)	±0.004 (±0.01016)
Diameter	15.000 (38.1)	+0.000/-0.005 (+0.000/-0.0127)

During the acceptance testing of these plates, the manufacturer was requested to performed additional thickness measurements for each plate, reported in Table 7. These measurements were performed using a 45MG Digital Ultrasonic Thickness Gage (UTG). The measurement procedure involved performing an initial measurement using a caliper to calibrate the UTG to the thickness at that location. Then with the plate flat on a granite table, the UTG was used to measure the thickness at 10 additional locations on each plate. These measurements show that thicknesses of the plates were on slightly larger than the nominal thickness with a smaller tolerance: 0.0419 ± 0.0004 in (0.1064 ± 0.0010 cm).

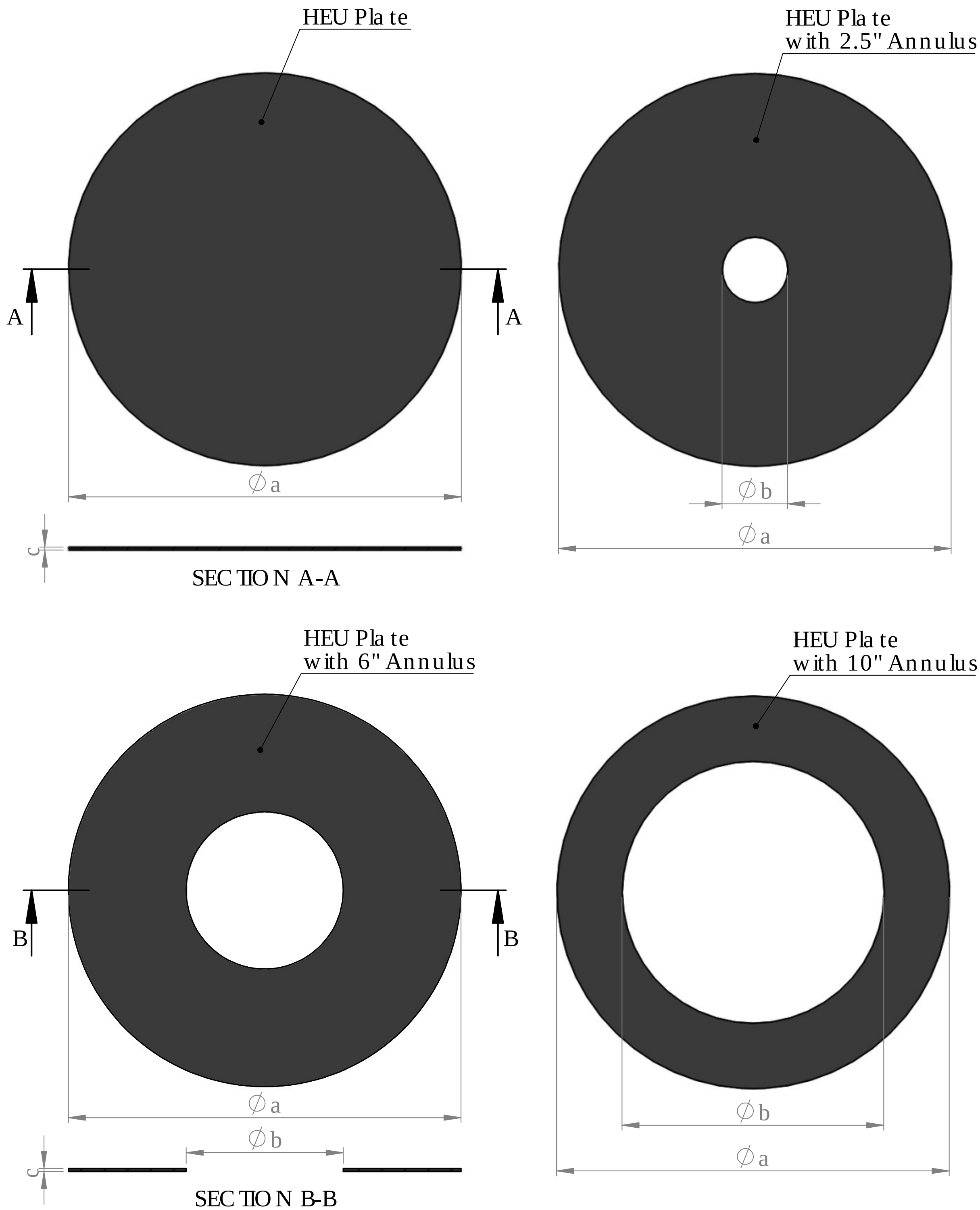

Figure 6. Drawing of the HEU plates, showing the 15/0-HEU (upper left), 15/2.5-HEU (upper right), 15/6-HEU (lower left), and 15/10-HEU (lower right).

Table 4. HEU plate mass and dimension measurements.

Part Type	Part ID	Mass (g)		Inner Diameter [in (cm)]	Outer Diameter [in (cm)]
		TEX-HEU	TEX-Hf		
15/10-HEU	10458	-	3618.3	10.005 +0.005/-0.000 (25.4127 +0.0127/-0.0000)	15 +0.000/-0.005 (38.1 +0.0000/-0.0127)
	10463	3631.7	3632.1		
	10472	3585.7	3586.8		
	10473	-	3607.3		
	10479	3565.0	3565.0		
	10481	-	3594.7		
	10485	-	3604.7		
15/6-HEU	10457	5574.1	5574.5	6.005 +0.005/-0.000 (15.2527 +0.0127/-0.0000)	
	10477	5499.2	5499.5		
	10932	-	5433.5		
	10933	-	5438.0		
	10935	-	5435.5		
	11018	5369.9	5370.2		
15/2.5-HEU	10464	6258.5	6259.1	2.510 +0.005/-0.000 (6.3754 +0.0127/-0.0000)	
	10467	6335.8	6336.3		
	10470	6279.0	6279.3		
	10475	6230.0	6229.2		
	10487	6274.9	6276.1		
	10489	6343.8	6344.4		
	10491	6392.4	6392.3		
15/0-HEU	11017	6501.6	6498.5	-	
	11019	6470.0	6469.9		
	11147	6517.3	6513.1		
	11149	6383.6	6382.9		
	11150	6410.3	6405.4		
6/0-HEU	Q2-16	-	1075.7	-	6 +0.000/-0.005 (15.24 +0.0000/-0.0127)

Table 5. HEU plate thickness measurements from MIX-MET-FAST-016.

Part Type	Part ID	Mass (g)	Thickness [in (cm)]		
			1	2	3
15/10-HEU	10458	-	-	-	-
	10463	-	-	-	-
	10472	3587.0	0.1245 (0.3162)	0.1215 (0.3086)	0.1200 (0.3048)
	10473	-	-	-	-
	10479	-	-	-	-
	10481	-	-	-	-
	10485	-	-	-	-
15/6-HEU	10457	-	-	-	-
	10477	5497.5	0.1265 (0.3213)	0.1205 (0.3061)	0.1235 (0.3137)
	10932	-	-	-	-
	10933	-	0.1115 (0.2832)	0.1095 (0.2781)	0.1110 (0.2819)
	10935	-	-	-	-
	11018	5368.5	0.1190 (0.3023)	0.1190 (0.3023)	0.1195 (0.3035)
15/2.5-HEU	10464	6392.5	0.1175 (0.2985)	0.1220 (0.3099)	0.1190 (0.3023)
	10467	6335.6	0.1275 (0.3239)	0.1225 (0.3112)	0.1235 (0.3137)
	10470	6278.5	0.1250 (0.3175)	0.1190 (0.3023)	0.1240 (0.3150)
	10475	6229.9	0.1285 (0.3264)	0.1275 (0.3239)	0.1295 (0.3289)
	10487	6274.9	0.1210 (0.3073)	0.1215 (0.3086)	0.1185 (0.3010)
	10489	6344.0	0.1245 (0.3162)	0.1220 (0.3099)	0.1230 (0.3124)
	10491	-	-	-	-
15/0-HEU	11017	6505.8	0.1215 (0.3086)	0.1200 (0.3048)	0.1210 (0.3073)
	11019	6473.8	0.1195 (0.3035)	0.1190 (0.3023)	0.1185 (0.3010)
	11147	6519.8	0.1200 (0.3048)	0.1200 (0.3048)	0.1185 (0.3010)
	11149	6385.5	0.1215 (0.3086)	0.1250 (0.3175)	0.1200 (0.3048)
	11150	6419.3	0.1200 (0.3048)	0.1220 (0.3099)	0.1235 (0.3137)
6/0-HEU	Q2-16	-	-	-	-

Table 6: Hafnium plate mass and dimensional measurements.

Part ID	Mass (g)	Thickness (in)	Diameter [in (cm)]
HF-01	1590.0	0.0420 to 0.0430	14.997 (38.092)
HF-02	1593.6	0.0420 to 0.0435	14.997 (38.092)
HF-03	1579.7	0.0410 to 0.0430	14.999 (38.097)
HF-04	1614.0	0.0410 to 0.0450	14.998 (38.095)
HF-05	1559.7	0.0410 to 0.0420	14.996 (38.090)
HF-06	1570.2	0.0415 to 0.0425	14.996 (38.090)
HF-07	1564.2	0.0410 to 0.0420	14.997 (38.092)
HF-08	1578.4	0.0415 to 0.0420	14.997 (38.092)
HF-09	1564.9	0.0410 to 0.0420	14.995 (38.087)
HF-10	1584.8	0.0410 to 0.0430	14.997 (38.092)
HF-11	1573.6	0.0415 to 0.0420	14.997 (38.092)
HF-12	1556.1	0.0410 to 0.0420	14.998 (38.095)
HF-13	1555.0	0.0410 to 0.0420	14.998 (38.095)
HF-14	1555.4	0.0410 to 0.0410	14.998 (38.095)
HF-15	1568.6	0.0410 to 0.0450	14.995 (38.087)
HF-16	1559.2	0.0410 to 0.0430	14.996 (38.090)
HF-17	1560.0	0.0410 to 0.0430	14.998 (38.095)
HF-18	1567.0	0.0410 to 0.0420	14.997 (38.092)
HF-19	1570.4	0.0410 to 0.0420	14.997 (38.092)
HF-20	1566.1	0.0410 to 0.0420	14.997 (38.092)
HF-21[3]	1569.7	0.0410 to 0.0450	14.998 (38.095)
HF-22	1554.7	0.0410 to 0.0430	14.996 (38.090)
HF-23	1559.6	0.0410 to 0.0430	14.999 (38.097)
HF-24	1559.8	0.0410 to 0.0420	14.998 (38.095)
HF-25	1570.9	0.0410 to 0.0420	14.995 (38.087)
HF-26	1573.5	0.0410 to 0.0420	14.998 (38.095)
HF-27	1550.5	0.0400 to 0.0420	14.996 (38.090)

[3] Plate scrapped and not delivered due to not meeting certification requirements.

Table 7: Hafnium plate thickness measurements.

Part ID	Thickness [in (cm)]										
	1	2	3	4	5	6	7	8	9	10	Average
HF-01	0.0430	0.0422	0.0417	0.0424	0.0432	0.0427	0.0421	0.0419	0.0422	0.0428	0.0424 (0.1077)
HF-02	0.0423	0.0423	0.0427	0.0424	0.0421	0.0426	0.0429	0.0423	0.0424	0.0427	0.0425 (0.1079)
HF-03	0.0427	0.0417	0.0422	0.0423	0.0424	0.0419	0.0417	0.0426	0.0418	0.0422	0.0422 (0.1071)
HF-04	0.0428	0.0431	0.0429	0.0428	0.0432	0.0444	0.0430	0.0426	0.0430	0.0432	0.0431 (0.1095)
HF-05	0.0417	0.0416	0.0412	0.0415	0.0431	0.0417	0.0413	0.0418	0.0417	0.0414	0.0417 (0.1059)
HF-06	0.0418	0.0421	0.0428	0.0419	0.0415	0.0417	0.0422	0.0420	0.0419	0.0418	0.0420 (0.1066)
HF-07	0.0416	0.0414	0.0419	0.0417	0.0413	0.0418	0.0427	0.0418	0.0417	0.0417	0.0418 (0.1061)
HF-08	0.0420	0.0422	0.0423	0.0423	0.0422	0.0419	0.0422	0.0417	0.0419	0.0422	0.0421 (0.1069)
HF-09	0.0411	0.0415	0.0422	0.0415	0.0420	0.0422	0.0417	0.0417	0.0414	0.0419	0.0417 (0.1060)
HF-10	0.0421	0.0417	0.0418	0.0421	0.0423	0.0421	0.0429	0.0429	0.0423	0.0422	0.0422 (0.1073)
HF-11	0.0425	0.0429	0.0422	0.0418	0.0420	0.0416	0.0415	0.0416	0.0418	0.0421	0.0420 (0.1067)
HF-12	0.0422	0.0418	0.0413	0.0411	0.0415	0.0417	0.0415	0.0416	0.0416	0.0413	0.0416 (0.1056)
HF-13	0.0420	0.0417	0.0411	0.0416	0.0429	0.0415	0.0410	0.0417	0.0416	0.0413	0.0416 (0.1058)
HF-14	0.0415	0.0419	0.0415	0.0413	0.0413	0.0416	0.0417	0.0413	0.0415	0.0414	0.0415 (0.1054)
HF-15	0.0414	0.0418	0.0436	0.0434	0.0417	0.0415	0.0418	0.0416	0.0415	0.0419	0.0420 (0.1067)
HF-16	0.0412	0.0415	0.0419	0.0416	0.0414	0.0419	0.0425	0.0415	0.0414	0.0415	0.0416 (0.1058)
HF-17	0.0417	0.0411	0.0417	0.0420	0.0415	0.0411	0.0414	0.0430	0.0417	0.0412	0.0416 (0.1058)
HF-18	0.0420	0.0414	0.0415	0.0415	0.0416	0.0417	0.0418	0.0421	0.0416	0.0421	0.0417 (0.1060)
HF-19	0.0419	0.0414	0.0413	0.0420	0.0422	0.0424	0.0418	0.0417	0.0420	0.0419	0.0419 (0.1063)
HF-20	0.0419	0.0417	0.0416	0.0418	0.0422	0.0415	0.0414	0.0416	0.0419	0.0420	0.0418 (0.1061)
HF-22	0.0418	0.0428	0.0414	0.0414	0.0418	0.0415	0.0414	0.0408	0.0410	0.0416	0.0416 (0.1055)
HF-23	0.0417	0.0417	0.0414	0.0413	0.0413	0.0414	0.0411	0.0415	0.0417	0.0415	0.0415 (0.1053)
HF-24	0.0420	0.0415	0.0412	0.0418	0.0421	0.0415	0.0411	0.0424	0.0415	0.0415	0.0417 (0.1058)
HF-25	0.0420	0.0415	0.0417	0.0421	0.0420	0.0419	0.0417	0.0419	0.0418	0.0420	0.0419 (0.1063)
HF-26	0.0418	0.0416	0.0414	0.0418	0.0420	0.0420	0.0419	0.0424	0.0424	0.0421	0.0419 (0.1065)
HF-27	0.0411	0.0412	0.0411	0.0418	0.0422	0.0413	0.0408	0.0409	0.0414	0.0416	0.0413 (0.1050)

1.2.5 Polyethylene Parts

The polyethylene parts are all high-density polyethylene (HDPE). All parts were weighed and measured, using a CMM, by LLNL's Dimensional Inspection Facility as part of the TEX-HEU experiment campaign. These dimensional measurements performed by the CMM report minimum, maximum, and average values for the diameters and a single value for the thicknesses. The diameter measurements are performed by measuring many cord lengths of the diameter. The thickness measurements are performed by creating a best-fit plane to many points measured at the surface. The thickness represents the distance between the base and this best-fit plane and does not provide the same statistics as the diameter measurement.

1.2.5.1 Moderator and Reflector Plates

The moderator and reflector plates are 15 in (38.1 cm) diameter plates with varying thicknesses, shown in Figure 7. The moderator plates are interspersed with the HEU plates and come in four nominal thicknesses: 0.125 in (0.3175 cm), 0.25 in (0.635 cm), 0.5 in (1.27 cm), and 1.5 in (3.81 cm). The reflector plates are used as the top reflector and come in three nominal thicknesses: 0.03125 in (0.079375 cm), 0.0625 in (1.5875 cm), and 1 in (2.54 cm). The moderator plates were also used in the top reflector to aid in the fine reactivity control for Cases 1, 3, and 4. The mass and dimensional measurements are reported in Table 8, Table 9, Table 10, Table 11, and Table 12.

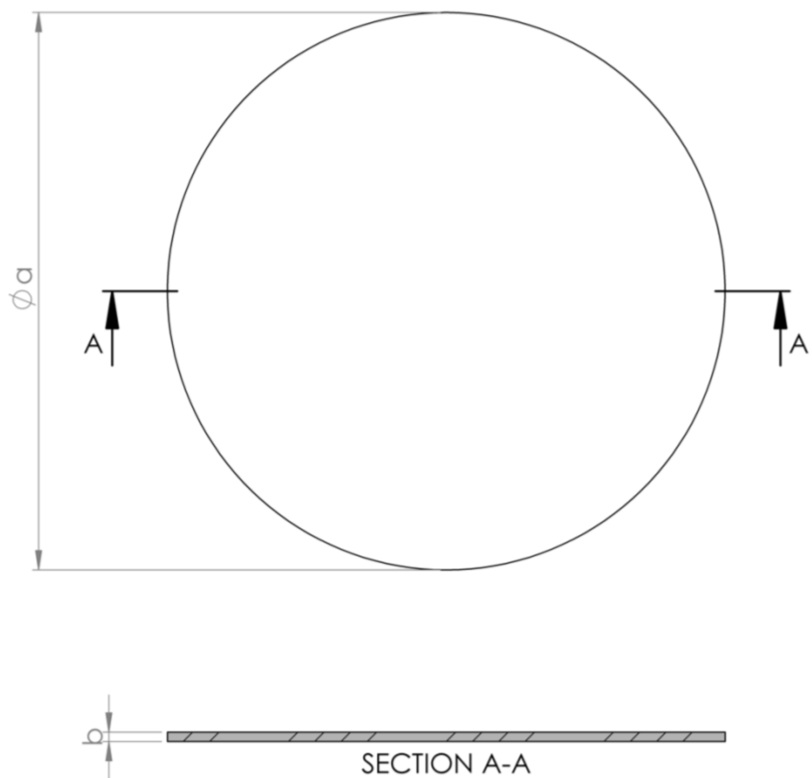

Figure 7. Schematic of the moderator and reflector plate.

Table 8: Mass and dimension measurements of the 1/8-MOD parts.

Part ID	Mass (g)	Thickness, *b* [in (cm)]	Diameter, *a* [in (cm)]		
			Min	Max	Average
1/8-MOD-1	343.0	0.1249 (0.3172)	14.9894	14.9979	14.9948 (38.0947)
1/8-MOD-2	342.1	0.1259 (0.3198)	14.9895	14.9991	14.9947 (38.0977)
1/8-MOD-3	344.0	0.1253 (0.3183)	14.9894	14.9993	14.9950 (38.0982)
1/8-MOD-4	344.3	0.1251 (0.3178)	14.9878	14.9999	14.9944 (38.0997)
1/8-MOD-5	343.0	0.1246 (0.3165)	14.9913	14.9995	14.9955 (38.0987)
1/8-MOD-6	344.7	0.1255 (0.3188)	14.9934	15.0018	14.9965 (38.1046)
1/8-MOD-7	345.0	0.1248 (0.3170)	14.9908	15.0017	14.9959 (38.1043)
1/8-MOD-8	345.2	0.1251 (0.3178)	14.9901	15.0003	14.9956 (38.1008)
1/8-MOD-9	343.4	0.1248 (0.3170)	14.9885	14.9969	14.9940 (38.0921)
1/8-MOD-10	343.5	0.1266 (0.3216)	14.9904	15.0004	14.9962 (38.1010)
1/8-MOD-11	343.2	0.1249 (0.3172)	14.9901	14.9998	14.9954 (38.0995)
1/8-MOD-12	344.6	0.1264 (0.3211)	14.9876	15.0001	14.9951 (38.1003)
1/8-MOD-13	343.9	0.1250 (0.3175)	14.9895	15.0002	14.9945 (38.1005)
1/8-MOD-14	345.4	0.1259 (0.3198)	14.9908	15.0006	14.9964 (38.1015)
1/8-MOD-15	345.3	0.1256 (0.3190)	14.9927	14.9986	14.9961 (38.0964)
1/8-MOD-16	343.8	0.1247 (0.3167)	14.9931	15.0005	14.9972 (38.1013)
1/8-MOD-17	344.0	0.1253 (0.3183)	14.9921	14.9991	14.9957 (38.0977)
1/8-MOD-18	344.7	0.1255 (0.3188)	14.9917	15.0000	14.9964 (38.1000)
1/8-MOD-19	350.8	0.1275 (0.3239)	14.9917	15.0013	14.9967 (38.1033)
1/8-MOD-20	350.2	0.1280 (0.3251)	14.9888	14.9980	14.9943 (38.0949)
1/8-MOD-21	350.6	0.1285 (0.3264)	14.9893	14.9995	14.9953 (38.0987)
1/8-MOD-22	351.0	0.1274 (0.3236)	14.9905	15.0001	14.9961 (38.1003)
1/8-MOD-23	351.4	0.1274 (0.3236)	14.9899	14.9998	14.9955 (38.0995)
1/8-MOD-24	351.4	0.1271 (0.3228)	14.9916	14.9987	14.9958 (38.0967)
1/8-MOD-25	349.4	0.1268 (0.3221)	14.9903	14.9995	14.9951 (38.0987)
1/8-MOD-26	351.9	0.1269 (0.3223)	14.9919	15.0000	14.9957 (38.1000)
1/8-MOD-27	349.3	0.1263 (0.3208)	14.9937	15.0004	14.9965 (38.1010)
1/8-MOD-28	349.3	0.1272 (0.3231)	14.9922	15.0015	14.9974 (38.1038)
1/8-MOD-29	347.9	0.1314 (0.3338)	14.9894	14.9999	14.9957 (38.0997)
1/8-MOD-30	348.3	0.1283 (0.3259)	14.9908	15.0003	14.9950 (38.1008)
1/8-MOD-31	351.1	0.1268 (0.3221)	14.9886	14.9990	14.9953 (38.0975)
1/8-MOD-32	348.8	0.1270 (0.3226)	14.9890	14.9992	14.9952 (38.0980)
1/8-MOD-33	350.0	0.1271 (0.3228)	14.9892	14.9990	14.9948 (38.0975)
1/8-MOD-34	351.3	0.1277 (0.3244)	14.9880	14.9979	14.9942 (38.0947)
1/8-MOD-35	351.2	0.1288 (0.3272)	14.9909	14.9984	14.9957 (38.0959)
1/8-MOD-36	348.3	0.1306 (0.3317)	14.9908	15.0015	14.9965 (38.1038)
1/8-MOD-37	347.3	0.1293 (0.3284)	14.9922	15.0009	14.9963 (38.1023)
1/8-MOD-38	351.1	0.1321 (0.3355)	14.9923	15.0008	14.9973 (38.1020)
1/8-MOD-39	350.5	0.1276 (0.3241)	14.9864	15.0007	14.9946 (38.1018)

Table 9: Mass and dimension measurements of the 1/4-MOD parts.

Part ID	Mass (g)	Thickness, *b* [in (cm)]	Diameter, *a* [in (cm)]		
			Min	Max	Average
1/4-MOD-1	690.2	0.2512 (0.6380)	14.9835	14.9910	14.9879 (38.0771)
1/4-MOD-2	689.1	0.2532 (0.6431)	14.9821	14.9912	14.9866 (38.0776)
1/4-MOD-3	688.0	0.2497 (0.6342)	14.9804	14.9915	14.9853 (38.0784)
1/4-MOD-4	689.7	0.2558 (0.6497)	14.9824	14.9903	14.9868 (38.0754)
1/4-MOD-5	689.2	0.2555 (0.6490)	14.9822	14.9923	14.9869 (38.0804)
1/4-MOD-6	687.5	0.2539 (0.6449)	14.9806	14.9909	14.9862 (38.0769)
1/4-MOD-7	688.4	0.2531 (0.6429)	14.9792	14.9872	14.9843 (38.0675)
1/4-MOD-8	689.2	0.2524 (0.6411)	14.9786	14.9903	14.9855 (38.0754)
1/4-MOD-9	688.8	0.2540 (0.6452)	14.9850	14.9913	14.9883 (38.0779)
1/4-MOD-10	689.5	0.2514 (0.6386)	14.9792	14.9887	14.9844 (38.0713)
1/4-MOD-11	688.1	0.2499 (0.6347)	14.9790	14.9885	14.9849 (38.0708)
1/4-MOD-12	688.5	0.2516 (0.6391)	14.9842	14.9909	14.9872 (38.0769)
1/4-MOD-13	689.4	0.2511 (0.6378)	14.9806	14.9899	14.9864 (38.0743)
1/4-MOD-14	689.5	0.2507 (0.6368)	14.9803	14.9897	14.9858 (38.0738)
1/4-MOD-15	689.1	0.2515 (0.6388)	14.9806	14.9893	14.9858 (38.0728)
1/4-MOD-16	688.2	0.2532 (0.6431)	14.9815	14.9924	14.9872 (38.0807)
1/4-MOD-17	687.6	0.2605 (0.6617)	14.9796	14.9899	14.9851 (38.0743)
1/4-MOD-18	688.9	0.2530 (0.6426)	14.9812	14.9898	14.9859 (38.0741)
1/4-MOD-19	688.2	0.2547 (0.6469)	14.9769	14.9887	14.9838 (38.0713)
1/4-MOD-20	688.7	0.2599 (0.6601)	14.9814	14.9890	14.9860 (38.0721)
1/4-MOD-21	686.9	0.2600 (0.6604)	14.9804	14.9877	14.9840 (38.0688)
1/4-MOD-22	688.2	0.2605 (0.6617)	14.9817	14.9889	14.9851 (38.0718)
1/4-MOD-23	688.0	0.2499 (0.6347)	14.9775	14.9879	14.9841 (38.0693)
1/4-MOD-24	688.3	0.2528 (0.6421)	14.9810	14.9878	14.9854 (38.0690)
1/4-MOD-25	687.6	0.2525 (0.6414)	14.9800	14.9903	14.9849 (38.0754)
1/4-MOD-26	688.4	0.2542 (0.6457)	14.9812	14.9907	14.9860 (38.0764)
1/4-MOD-27	687.9	0.2574 (0.6538)	14.9803	14.9881	14.9849 (38.0698)
1/4-MOD-28	687.9	0.2595 (0.6591)	14.9820	14.9887	14.9857 (38.0713)
1/4-MOD-29	688.0	0.2621 (0.6657)	14.9830	14.9924	14.9864 (38.0807)
1/4-MOD-30	688.3	0.2594 (0.6589)	14.9837	14.9914	14.9870 (38.0782)
1/4-MOD-31	688.2	0.2515 (0.6388)	14.9821	14.9892	14.9861 (38.0726)
1/4-MOD-32	688.2	0.2509 (0.6373)	14.9807	14.9910	14.9859 (38.0771)
1/4-MOD-33	688.3	0.2511 (0.6378)	14.9815	14.9922	14.9871 (38.0802)
1/4-MOD-34	687.7	0.2581 (0.6556)	14.9810	14.9887	14.9849 (38.0713)
1/4-MOD-35	688.2	0.2583 (0.6561)	14.9830	14.9918	14.9879 (38.0792)
1/4-MOD-36	688.1	0.2576 (0.6543)	14.9833	14.9900	14.9875 (38.0746)

Table 10: Mass and dimension measurements of the 1/2-MOD parts.

Part ID	Mass (g)	Thickness, *b* [in (cm)]	Diameter, *a* [in (cm)]		
			Min	Max	Average
1/2-MOD-1	1377.9	0.5079 (1.2901)	14.9884	14.9953	14.9925 (38.0881)
1/2-MOD-2	1377.8	0.5047 (1.2819)	14.9866	14.9957	14.9909 (38.0891)
1/2-MOD-3	1385.0	0.5095 (1.2941)	14.9880	14.9951	14.9914 (38.0876)
1/2-MOD-4	1378.1	0.5044 (1.2812)	14.9877	14.9974	14.9926 (38.0934)
1/2-MOD-5	1380.2	0.5033 (1.2784)	14.9882	14.9950	14.9913 (38.0873)
1/2-MOD-6	1378.2	0.5003 (1.2708)	14.9870	14.9955	14.9910 (38.0886)
1/2-MOD-7	1383.7	0.5068 (1.2873)	14.9882	14.9963	14.9917 (38.0906)
1/2-MOD-8	1386.3	0.5047 (1.2819)	14.9854	14.9925	14.9888 (38.0810)
1/2-MOD-9	1385.4	0.5035 (1.2789)	14.9867	14.9912	14.9888 (38.0776)
1/2-MOD-10	1379.6	0.5045 (1.2814)	14.9861	14.9939	14.9890 (38.0845)
1/2-MOD-11	1384.5	0.5068 (1.2873)	14.9849	14.9937	14.9889 (38.0840)
1/2-MOD-12	1376.8	0.5005 (1.2713)	14.9867	14.9937	14.9901 (38.0840)
1/2-MOD-13	1385.5	0.5061 (1.2855)	14.9900	14.9961	14.9923 (38.0901)
1/2-MOD-14	1378.1	0.5079 (1.2901)	14.9841	14.9947	14.9884 (38.0865)
1/2-MOD-15	1381.5	0.5060 (1.2852)	14.9839	14.9936	14.9896 (38.0837)
1/2-MOD-16	1378.8	0.5063 (1.2860)	14.9848	14.9943	14.9891 (38.0855)
1/2-MOD-17	1378.8	0.5075 (1.2891)	14.9856	14.9942	14.9886 (38.0853)
1/2-MOD-18	1384.9	0.5127 (1.3023)	14.9840	14.9949	14.9892 (38.0870)
1/2-MOD-19	1380.5	0.5105 (1.2967)	14.9825	14.9922	14.9871 (38.0802)
1/2-MOD-20	1378.2	0.5016 (1.2741)	14.9862	14.9924	14.9893 (38.0807)
1/2-MOD-21	1379.3	0.5005 (1.2713)	14.9867	14.9921	14.9896 (38.0799)
1/2-MOD-22	1377.0	0.5030 (1.2776)	14.9858	14.9925	14.9888 (38.0810)
1/2-MOD-23	1385.3	0.5104 (1.2964)	14.9858	14.9934	14.9896 (38.0832)
1/2-MOD-24	1378.2	0.5092 (1.2934)	14.9854	14.9937	14.9887 (38.0840)
1/2-MOD-25	1385.6	0.5109 (1.2977)	14.9842	14.9920	14.9890 (38.0797)
1/2-MOD-26	1377.8	0.5066 (1.2868)	14.9837	14.9928	14.9870 (38.0817)
1/2-MOD-27	1385.1	0.5082 (1.2908)	14.9833	14.9934	14.9886 (38.0832)
1/2-MOD-28	1377.3	0.4996 (1.2690)	14.9855	14.9931	14.9889 (38.0825)
1/2-MOD-29	1376.3	0.5041 (1.2804)	14.9874	14.9942	14.9901 (38.0853)
1/2-MOD-30	1377.5	0.5084 (1.2913)	14.9857	14.9935	14.9900 (38.0835)
1/2-MOD-31	1377.8	0.5051 (1.2830)	14.9878	14.9952	14.9915 (38.0878)
1/2-MOD-32	1381.2	0.5073 (1.2885)	14.9862	14.9937	14.9889 (38.0840)

Table 11: Mass and dimension measurements of the 1.5-MOD parts.

Part ID	Mass (g)	Thickness, *b* [in (cm)]	Diameter, *a* [in (cm)]		
			Min	Max	Average
1.5-MOD-1	4150.8	1.4998 (3.8095)	14.9962	15.0107	15.0035 (38.1272)
1.5-MOD-2	4132.6	1.5100 (3.8354)	14.9968	14.9977	14.9933 (38.0942)
1.5-MOD-3	4125.6	1.5087 (3.8321)	14.9846	14.9962	14.9988 (38.0903)
1.5-MOD-4	4136.2	1.5146 (3.8471)	14.9879	15.0005	14.9946 (38.1013)
1.5-MOD-5	4147.2	1.4945 (3.7960)	14.9967	15.0075	15.0038 (38.1191)
1.5-MOD-6	4173.6	1.5086 (3.8318)	14.9811	14.9896	14.9859 (38.0736)
1.5-MOD-7	4167.4	1.5241 (3.8712)	14.9851	14.9984	14.9913 (38.0959)
1.5-MOD-8	4175.3	1.5105 (3.8367)	14.9803	14.9896	14.9856 (38.0736)
1.5-MOD-9	4135.6	1.5027 (3.8169)	14.9879	14.9949	14.9917 (38.0870)
1.5-MOD-10	4168.4	1.5103 (3.8362)	14.9784	14.9898	14.9841 (38.0741)
1.5-MOD-11	4171.2	1.5263 (3.8768)	14.9827	14.9948	14.9887 (38.0868)
1.5-MOD-12	4146.4	1.5188 (3.8578)	14.9915	15.0022	14.9965 (38.1056)

Table 12: Mass and dimension measurements of the 1-REF, 1/16-REF, and 1/32-REF parts.

Part ID	Mass (g)	Thickness, *b* [in (cm)]	Diameter, *a* [in (cm)]		
			Min	Max	Average
1/32-REF-1	85.0	0.0334 (0.0848)	14.9832	14.9996	14.9908 (38.0990)
1/32-REF-2	85.9	0.0325 (0.0826)	14.9833	14.9983	14.9905 (38.0957)
1/16-REF-1	182.4	0.0728 (0.1849)	14.9831	14.9890	14.9858 (38.0721)
1/16-REF-2	182.9	0.0671 (0.1704)	14.9829	14.9884	14.9856 (38.0705)
1-REF-1	2766.9	0.9995 (2.5387)	14.9860	14.9934	14.9902 (38.0832)
1-REF-2	2767.2	1.0015 (2.5438)	14.9844	14.9922	14.9883 (38.0802)

1.2.5.2 Reflector Rings

The reflector rings are 17.1 in (43.434 cm) outer diameter and 15.1 in (38.354 cm) inner diameter annular cylinders which come in four nominal thicknesses: 0.25 in (0.635 cm), 0.5 in (1.27 cm), 1 in (2.54 cm), and 3 in (7.62 cm). Figure 8 shows a diagram of the reflector ring part. The rings stack around the HEU, moderator, and reflector plates to provide 1 in (2.54 cm) of reflection around the configuration. They are designed to interlock, using step joints, which keep the rings in alignment as they are stacked. 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. The mass and dimensional measurements are reported in Table 13 and Table 14.

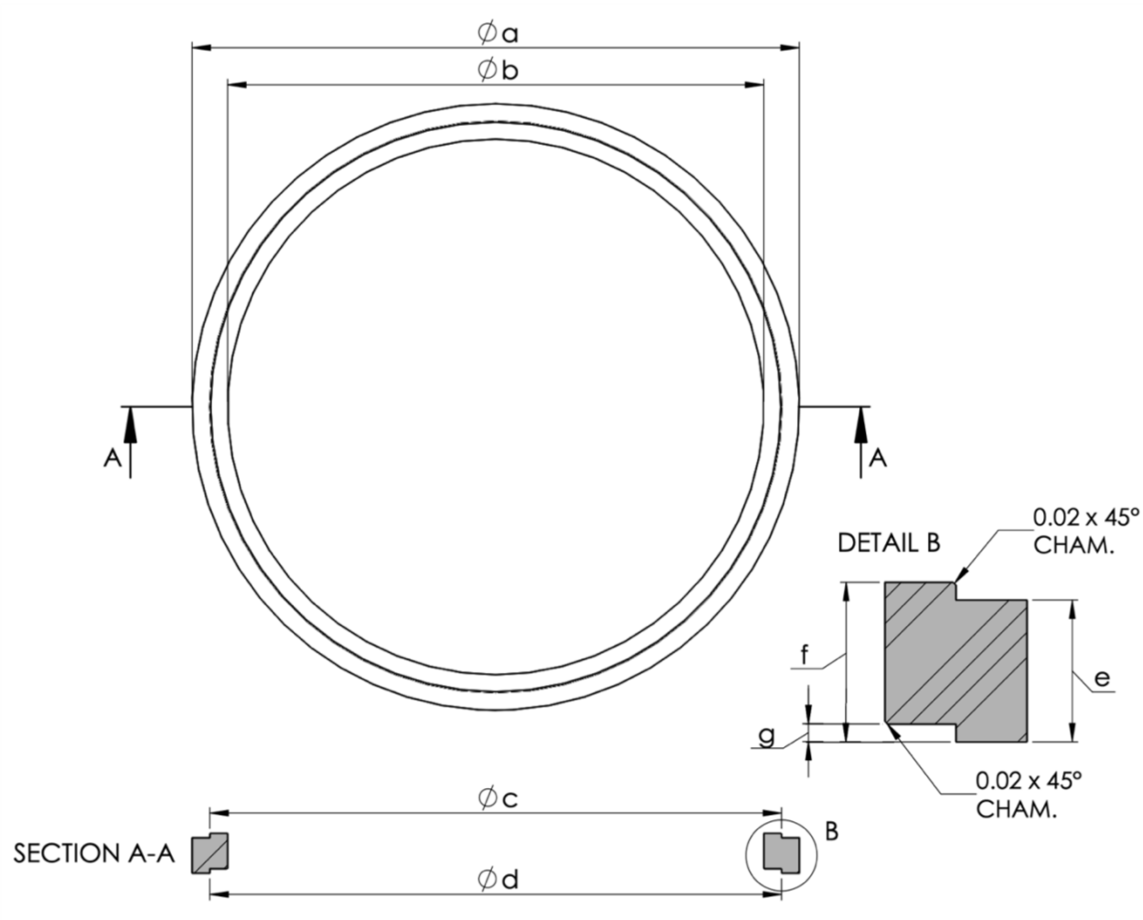

Figure 8. Schematic of the reflector ring (dimensions in inches).

Table 13. Mass and dimension measurements of the 1/4-RING and 1/2-RING parts.

Part ID	Mass (g)	Outer Diameter, *a* [in (cm)]			Inner Diameter, *b* [in (cm)]		
		Min	Max	Average	Min	Max	Average
1/4-RING-1	199.1	17.0822	17.1050	17.0933 (43.4170)	15.0657	15.0912	15.0789 (38.3004)
1/4-RING-2	198.9	17.0821	17.1019	17.0927 (43.4155)	15.0690	15.0925	15.0813 (38.3065)
1/4-RING-3	198.7	17.0816	17.1060	17.0939 (43.4185)	15.0699	15.0912	15.0811 (38.3060)
1/4-RING-4	199.4	17.0838	17.1047	17.0937 (43.4180)	15.0681	15.0897	15.0792 (38.3012)
1/2-RING-1	394.1	17.0770	17.0870	17.0818 (43.3878)	15.0620	15.0728	15.0670 (38.2702)
1/2-RING-2	394.4	17.0802	17.0854	17.0830 (43.3908)	15.0660	15.0729	15.0682 (38.2732)
1/2-RING-3	392.9	17.0806	17.0855	17.0828 (43.3903)	15.0652	15.0721	15.0680 (38.2727)
1/2-RING-4	393.3	17.0793	17.0865	17.0822 (43.3888)	15.0650	15.0703	15.0676 (38.2717)

Part ID	Top Step Diameter, *c* [in (cm)]			Bottom Step Diameter, *d* [in (cm)]		
	Min	Max	Average	Min	Max	Average
1/4-RING-1	16.0527	16.0778	16.0654 (40.8061)	16.0876	16.1120	16.0895 (40.8673)
1/4-RING-2	16.0532	16.0787	16.0654 (40.8061)	16.0906	16.1096	16.1003 (40.8948)
1/4-RING-3	16.0491	16.0743	16.0630 (40.8000)	16.0896	16.1120	16.1010 (40.8965)
1/4-RING-4	16.0509	16.0746	16.0634 (40.8010)	16.0895	16.1082	16.0993 (40.8922)
1/2-RING-1	16.0480	16.0596	16.0537 (40.7764)	16.0836	16.0956	16.0895 (40.8673)
1/2-RING-2	16.0507	16.0575	16.0533 (40.7754)	16.0871	16.0919	16.0894 (40.8671)
1/2-RING-3	16.0471	16.0528	16.0496 (40.7660)	16.0894	16.0965	16.0922 (40.8742)
1/2-RING-4	16.0495	16.0543	16.0515 (40.7708)	16.0880	16.0938	16.0904 (40.8696)

Part ID	Outer Edge Height, *e* [in (cm)]	Top Step Height, *f* [in (cm)]	Bottom Step Height, *g* [in (cm)]
1/4-RING-1	0.2568 (0.6523)	0.3727 (0.9467)	0.1205 (0.3061)
1/4-RING-2	0.2585 (0.6566)	0.3748 (0.9520)	0.1209 (0.3071)
1/4-RING-3	0.2575 (0.6541)	0.3721 (0.9451)	0.1205 (0.3061)
1/4-RING-4	0.2566 (0.6518)	0.3711 (0.9426)	0.1199 (0.3045)
1/2-RING-1	0.5027 (1.2769)	0.6140 (1.5596)	0.1198 (0.3043)
1/2-RING-2	0.5042 (1.2807)	0.6156 (1.5636)	0.1205 (0.3061)
1/2-RING-3	0.5053 (1.2835)	0.6166 (1.5662)	0.1179 (0.2995)
1/2-RING-4	0.5050 (1.2827)	0.6156 (1.5636)	0.1184 (0.3007)

Table 14. Mass and dimension measurements of the 1-RING and 3-RING parts.

Part ID	Mass (g)	Outer Diameter, *a* [in (cm)]			Inner Diameter, *b* [in (cm)]		
		Min	Max	Average	Min	Max	Average
1-RING-1	805.8	17.0787	17.0852	17.0824 (43.3893)	15.0605	15.0691	15.0660 (38.2676)
1-RING-2	805.8	17.0745	17.0781	17.0767 (43.3748)	15.0572	15.0629	15.0609 (38.2547)
1-RING-3	805.8	17.0808	17.0888	17.0837 (43.3926)	15.0622	15.0700	15.0666 (38.2692)
1-RING-4	804.9	17.0696	17.0766	17.0729 (43.3652)	15.0509	15.0606	15.0560 (38.2422)
1-RING-5	804.8	17.0812	17.0868	17.0839 (43.3931)	15.0671	15.0714	15.0691 (38.2755)
1-RING-6	805.8	17.0775	17.0810	17.0788 (43.3802)	15.0595	15.0647	15.0624 (38.2585)
3-RING-1	2384.7	17.0879	17.0916	17.0898 (43.4081)	15.0875	15.0912	15.0896 (38.3276)
3-RING-2	2387.0	17.0877	17.0923	17.0896 (43.4076)	15.0891	15.0932	15.0910 (38.3311)
3-RING-3	2388.8	17.0872	17.0938	17.0915 (43.4124)	15.0880	15.0913	15.0898 (38.3281)
3-RING-4	2388.1	17.0887	17.0928	17.0912 (43.4116)	15.0873	15.0922	15.0905 (38.3299)
3-RING-5	2384.2	17.0855	17.0915	17.0888 (43.4056)	15.0894	15.0928	15.0913 (38.3319)
3-RING-6	2384.7	17.0861	17.0933	17.0892 (43.4066)	15.0877	15.0933	15.0909 (38.3309)

Part ID	Top Step Diameter, *c* [in (cm)]			Bottom Step Diameter, *d* [in (cm)]		
	Min	Max	Average	Min	Max	Average
1-RING-1	16.0564	16.0653	16.0615 (40.7962)	16.0800	16.0845	16.0824 (40.8493)
1-RING-2	16.0517	16.0575	16.0550 (40.7797)	16.0897	16.0939	16.0923 (40.8744)
1-RING-3	16.0590	16.0661	16.0628 (40.7995)	16.0799	16.0862	16.0823 (40.8490)
1-RING-4	16.0420	16.0531	16.0485 (40.7632)	16.0989	16.1075	16.1037 (40.9034)
1-RING-5	16.0624	16.0693	16.0653 (40.8059)	16.0850	16.0906	16.0880 (40.8635)
1-RING-6	16.0554	16.0604	16.0581 (40.7876)	16.0915	16.0967	16.0934 (40.8772)
3-RING-1	16.0726	16.0780	16.0742 (40.8285)	16.0975	16.1006	16.0993 (40.8922)
3-RING-2	16.0713	16.0748	16.0729 (40.8252)	16.0982	16.1025	16.1000 (40.8940)
3-RING-3	16.0685	16.0751	16.0713 (40.8211)	16.0970	16.1014	16.0994 (40.8925)
3-RING-4	16.0714	16.0751	16.0738 (40.8275)	16.0981	16.1035	16.1007 (40.8958)
3-RING-5	16.0710	16.0733	16.0720 (40.8229)	16.0994	16.1029	16.1014 (40.8976)
3-RING-6	16.0710	16.0736	16.0722 (40.8234)	16.1022	16.1048	16.1033 (40.9024)

Part ID	Outer Edge Height, *e* [in (cm)]	Top Step Height, *f* [in (cm)]	Bottom Step Height, *g* [in (cm)]
1-RING-1	1.0016 (2.5441)	1.1275 (2.8639)	0.1219 (0.3096)
1-RING-2	1.0036 (2.5491)	1.1256 (2.8590)	0.1196 (0.3038)
1-RING-3	1.0014 (2.5436)	1.1268 (2.8621)	0.1219 (0.3096)
1-RING-4	1.0052 (2.5532)	1.1232 (2.8529)	0.1161 (0.2949)
1-RING-5	0.9991 (2.5377)	1.1252 (2.8580)	0.1205 (0.3061)
1-RING-6	1.0036 (2.5491)	1.1255 (2.8588)	0.1190 (0.3023)
3-RING-1	2.9952 (7.6078)	3.1229 (7.9322)	0.1231 (0.3127)
3-RING-2	2.9957 (7.6091)	3.1223 (7.9306)	0.1230 (0.3124)
3-RING-3	2.9974 (7.6134)	3.1235 (7.9337)	0.1232 (0.3129)
3-RING-4	2.9953 (7.6081)	3.1223 (7.9306)	0.1225 (0.3112)
3-RING-5	2.9961 (7.6101)	3.1243 (7.9357)	0.1231 (0.3127)
3-RING-6	2.9951 (7.6076)	3.1226 (7.9314)	0.1224 (0.3109)

1.2.5.3 Reflector Caps

There are two different types of reflector caps: one for fine height adjustment on the top of the reflector rings and one to provide a base for the first reflector ring on the upper half of the experiment. Figure 9 and Figure 10 show diagrams of the reflector cap part types. The reflector caps allow the ring reflector to be brought to within 0.03125 in (0.079375 cm) 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 mass and dimensional measurements are reported in Table 15.

The reflector caps are 15.1 in (38.354 cm) inner diameter, 16.1 in (40.894 cm) step diameter, and 17.1 in (43.434 cm) outer diameter rings with a 0.125 in (0.3175 cm) base thickness and additional step thickness. There are eight step thicknesses, in increments of 0.03125 in (0.079375 cm): 0 in, 0.03125 in (0.079375 cm), 0.0625 in (0.15875 cm), 0.09375 in (0.238125 cm), 0.125 in (0.3175 cm), 0.15625 in (0.396875 cm), 0.1875 in (0.47625 cm), and 0.21875 in (0.555625 cm). 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 0.125 in (0.3175 cm) thick ring with a 15.1 in (38.354 cm) inner diameter and 16.1 in (40.894 cm) 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 in step thickness are zero-height caps, meaning they sit within the step joint of the reflector ring without adding additional height.

Table 15. Mass and dimension measurements of the 0-BOTCAP and 0-CAP parts.

Part ID	Mass (g)	Outer Diameter, *a* [in (cm)]	Inner Diameter, *b* [in (cm)]	Outer Edge Height, *d* [in (cm)]
0-BOTCAP-1	48.2	16.0530 (40.7746)	15.0660 (38.2676)	0.1310 (0.3327)
0-BOTCAP-2	48.0	16.0530 (40.7746)	15.0650 (38.2651)	0.1250 (0.3175)
0-CAP-1	50.7	17.0470 (43.2994)	16.0790 (40.8407)	0.1260 (0.3200)
0-CAP-2	50.8	17.0460 (43.2968)	16.0770 (40.8356)	0.1255 (0.3188)
0-CAP-3	50.9	17.0470 (43.2994)	16.0710 (40.8203)	0.1250 (0.3175)

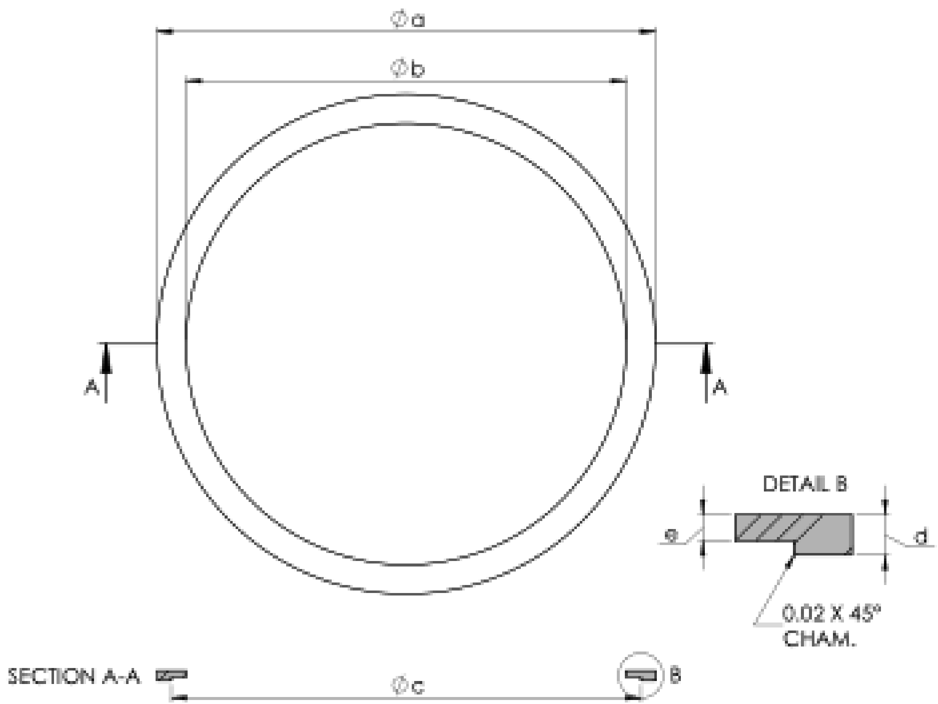

Figure 9. Schematic of the reflector cap (dimensions in inches).

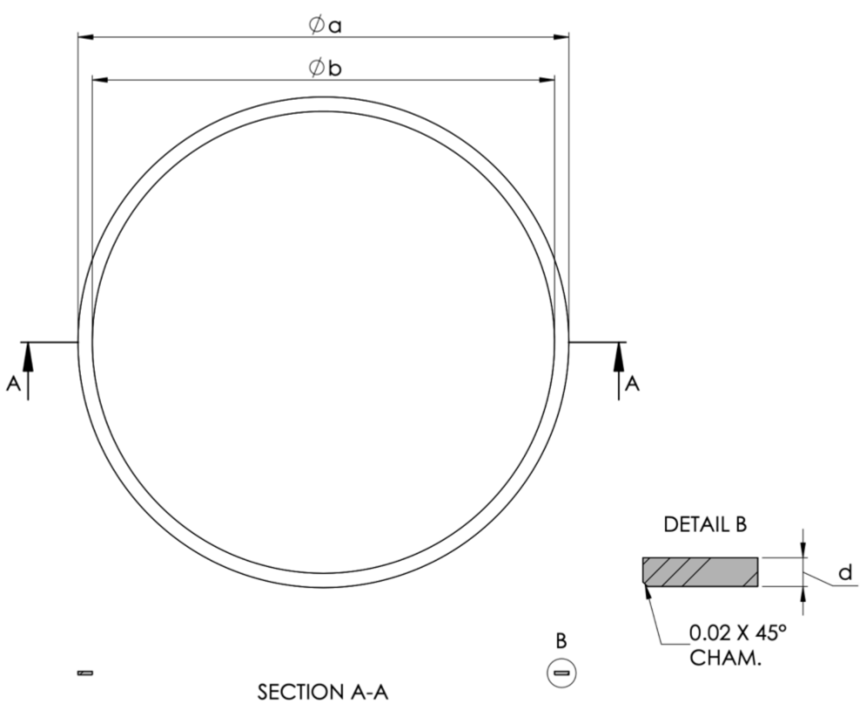

Figure 10. Schematic of the bottom reflector cap (dimensions in inches).

Table 16. Mass and dimension measurements of the 1/32-CAP, 1/16-CAP, 3/32-CAP, 1/8-CAP, and 7/32-CAP parts.

Part ID	Mass (g)	Outer Diameter, *a* [in (cm)]			Inner Diameter, *b* [in (cm)]		
		Min	Max	Average	Min	Max	Average
1/32-CAP-1	76.8	17.0612	17.0763	17.0689 (43.3550)	15.0604	15.0828	15.0738 (38.2875)
1/32-CAP-2	76.8	17.0620	17.0804	17.0711 (43.3606)	15.0645	15.0875	15.0769 (38.2953)
1/32-CAP-3	76.9	17.0651	17.0758	17.0710 (43.3603)	15.0731	15.0847	15.0773 (38.2963)
1/16-CAP-1	101.5	17.0457	17.1074	17.0794 (43.3817)	15.0554	15.1168	15.0842 (38.3139)
1/16-CAP-2	101.2	17.0690	17.0906	17.0803 (43.3840)	15.0741	15.0933	15.0850 (38.3159)
1/16-CAP-3	101.0	17.0496	17.1070	17.0765 (43.3743)	15.0456	15.1037	15.0773 (38.2963)
3/32-CAP-1	127.9	17.0414	17.1020	17.0725 (43.3642)	15.0511	15.1100	15.0807 (38.3050)
3/32-CAP-2	126.7	17.0687	17.0734	17.0713 (43.3611)	15.0821	15.0893	15.0850 (38.3159)
3/32-CAP-3	127.5	17.0620	17.0836	17.0728 (43.3649)	15.0676	15.0920	15.0796 (38.3022)
1/8-CAP-1	149.0	17.0753	17.0845	17.0788 (43.3802)	15.0748	15.0873	15.0824 (38.3093)
1/8-CAP-2	148.9	17.0692	17.0909	17.0791 (43.3809)	15.0748	15.0921	15.0817 (38.3075)
1/8-CAP-3	149.0	17.0582	17.0977	17.0781 (43.3784)	15.0652	15.1004	15.0815 (38.3070)
5/32-CAP-1	173.7	17.0691	17.0927	17.0788 (43.3802)	15.0714	15.0913	15.0836 (38.3123)
5/32-CAP-2	173.7	17.0668	17.0892	17.0775 (43.3769)	15.0752	15.0944	15.0847 (38.3151)
5/32-CAP-3	172.9	17.0664	17.0908	17.0787 (43.3799)	15.0733	15.0934	15.0848 (38.3154)
3/16-CAP-1	198.2	17.0697	17.0946	17.0797 (43.3824)	15.0708	15.0966	15.0851 (38.3162)
3/16-CAP-2	194.1	17.0714	17.0906	17.0806 (43.3847)	15.0781	15.0972	15.0867 (38.3202)
3/16-CAP-3	193.9	17.0754	17.0867	17.0808 (43.3852)	15.0828	15.0950	15.0876 (38.3225)
7/32-CAP-1	225.4	17.0781	17.0919	17.0860 (43.3984)	15.0790	15.0933	15.0861 (38.3187)
7/32-CAP-2	225.2	17.0662	17.0774	17.0706 (43.3593)	15.0692	15.0857	15.0780 (38.2981)
7/32-CAP-3	225.6	17.0548	17.0841	17.0686 (43.3542)	15.0602	15.0909	15.0774 (38.2966)

Part ID	Step Diameter, *c* [in (cm)]			Outer Edge Height, *d* [in (cm)]	Step Height, *e* [in (cm)]
	Min	Max	Average		
1/32-CAP-1	16.0833	16.1000	16.0930 (40.8762)	0.1647 (0.4183)	0.0344 (0.0874)
1/32-CAP-2	16.0874	16.1030	16.0950 (40.8813)	0.1649 (0.4188)	0.0351 (0.0892)
1/32-CAP-3	16.0906	16.0989	16.0943 (40.8795)	0.1664 (0.4227)	0.0350 (0.0889)
1/16-CAP-1	16.0727	16.1328	16.1012 (40.8970)	0.1953 (0.4961)	0.0681 (0.1730)
1/16-CAP-2	16.0898	16.1123	16.1025 (40.9004)	0.1912 (0.4856)	0.0673 (0.1709)
1/16-CAP-3	16.0673	16.1258	16.0999 (40.8937)	0.1904 (0.4836)	0.0729 (0.1852)
3/32-CAP-1	16.0645	16.1234	16.0946 (40.8803)	0.2431 (0.6175)	0.1006 (0.2555)
3/32-CAP-2	16.0948	16.1025	16.0978 (40.8884)	0.2443 (0.6205)	0.1000 (0.2540)
3/32-CAP-3	16.0813	16.1057	16.0930 (40.8762)	0.2451 (0.6226)	0.1005 (0.2553)
1/8-CAP-1	16.0928	16.1036	16.0993 (40.8922)	0.2531 (0.6429)	0.1292 (0.3282)
1/8-CAP-2	16.0913	16.1076	16.0981 (40.8892)	0.2540 (0.6452)	0.1290 (0.3277)
1/8-CAP-3	16.0838	16.1214	16.1011 (40.8968)	0.2535 (0.6439)	0.1281 (0.3254)
5/32-CAP-1	16.0874	16.1091	16.0999 (40.8937)	0.2832 (0.7193)	0.1618 (0.4110)
5/32-CAP-2	16.0905	16.1128	16.1009 (40.8963)	0.2836 (0.7203)	0.1620 (0.4115)
5/32-CAP-3	16.0889	16.1098	16.1009 (40.8963)	0.2824 (0.7173)	0.1606 (0.4079)
3/16-CAP-1	16.0891	16.1102	16.1020 (40.8991)	0.3147 (0.7993)	0.1935 (0.4915)
3/16-CAP-2	16.0982	16.1164	16.1070 (40.9118)	0.3116 (0.7915)	0.1866 (0.4740)
3/16-CAP-3	16.1019	16.1163	16.1086 (40.9158)	0.3116 (0.7915)	0.1856 (0.4714)
7/32-CAP-1	16.0990	16.1155	16.1073 (40.9125)	0.3444 (0.8748)	0.2290 (0.5817)
7/32-CAP-2	16.0823	16.0973	16.0904 (40.8696)	0.3517 (0.8933)	0.2242 (0.5695)
7/32-CAP-3	16.0723	16.1012	16.0887 (40.8653)	0.3531 (0.8969)	0.2251 (0.5718)

1.2.5.4 Bottom Reflector

The bottom reflector is a 1 in (2.54 cm) thick plate with a 17.1 in (43.434 cm) diameter and outer step joint, shown in Figure 11. 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 lower adapter plate on the Comet movable platen, held in place by the lip of the plate. The center of the base has a small hole to hold the neutron source during the approach to critical. The mass and dimensional measurements are reported in Table 17.

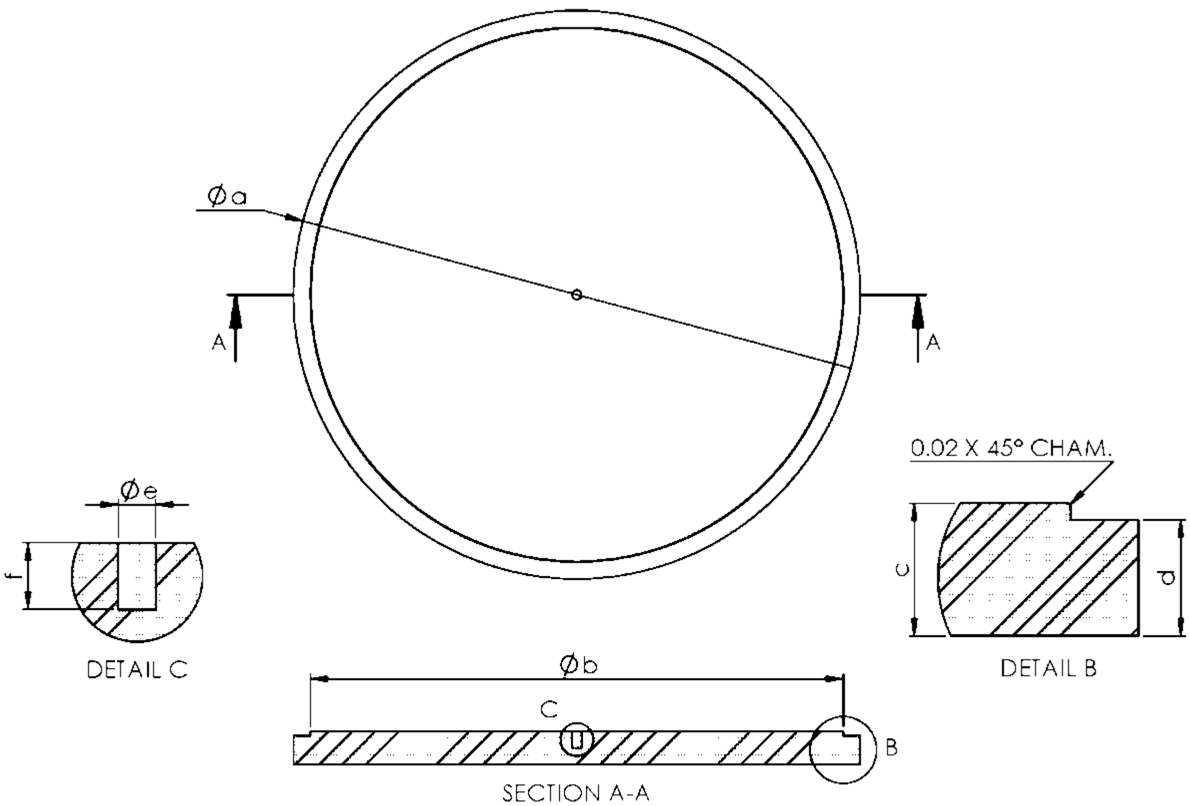

Figure 11. Schematic of the bottom reflector (dimensions in inches).

Table 17. Mass and dimension measurements of the BOTREF parts.

Part ID	Mass (g)	Outer Diameter, *a* [in (cm)]			Step Diameter, *b* [in (cm)]		
		Min	Max	Average	Min	Max	Average
BOTREF-1	3543.2	17.0711	17.0820	17.0761 (43.3733)	16.0507	16.0634	16.0572 (40.7853)
BOTREF-2	3544.9	17.0715	17.0814	17.0766 (43.3746)	16.0468	16.0592	16.0536 (40.7761)

Part ID	Thickness, *c* [in (cm)]	Outer Edge Height, *d* [in (cm)]	Source Diameter, *e* [in (cm)]	Source Depth, *f* [in (cm)]
BOTREF-1	1.0110 (2.5679)	0.8909 (2.2629)	0.2810 (0.7137)	0.4959 (1.2596)
BOTREF-2	1.0225 (2.5972)	0.9057 (2.3005)	0.2814 (0.7148)	0.5043 (1.2809)

1.2.6 Aluminum Inserts

The aluminum inserts are 0.125 in (0.3175 cm) thick AL 6061 disks which come in three diameters: 2.4 in (6.096 cm), 5.9 in (14.986 cm), and 9.9 in (25.146 cm). 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 in (0.254 cm) smaller in diameter than the corresponding HEU plate annuli.

These inserts were weighed and measured, using a CMM by LLNL's Dimensional Inspection Laboratory prior to the experiment campaign. These measurements are reported in Table 18. A description of the CMM measurements is provide in Section 1.2.5.

Table 18: Mass and dimensions of the 2.5-DISK, 6-DISK, and 10-DISK inserts.

Part ID	Mass (g)	Thickness [in (cm)]	Diameter [in (cm)]		
			Min	Max	Average
2.5-DISK-1	24.6	0.1240 (0.3150)	2.3945	2.3945	2.3945 (6.0820)
2.5-DISK-2	24.8	0.1245 (0.3162)	2.3955	2.3960	2.3958 (6.0858)
2.5-DISK-3	24.7	0.1245 (0.3162)	2.3960	2.3960	2.3960 (6.0858)
2.5-DISK-4	24.9	0.1255 (0.3188)	2.3960	2.3960	2.3960 (6.0858)
2.5-DISK-5	24.9	0.1250 (0.3175)	2.3950	2.3950	2.3950 (6.0833)
2.5-DISK-6	25.0	0.1255 (0.3188)	2.3940	2.3950	2.3945 (6.0833)
2.5-DISK-7	24.9	0.1250 (0.3175)	2.3950	2.3955	2.3953 (6.0846)
2.5-DISK-8	24.8	0.1250 (0.3175)	2.3945	2.3950	2.3948 (6.0833)
2.5-DISK-9	24.6	0.1240 (0.3150)	2.3945	2.3950	2.3948 (6.0833)
2.5-DISK-10	24.9	0.1250 (0.3175)	2.3955	2.3955	2.3955 (6.0846)
6-DISK-1	149.9	0.1240 (0.3150)	5.9835	5.9845	5.8940 (15.2006)
6-DISK-2	149.7	0.1235 (0.3137)	5.8915	5.8915	5.8915 (14.9644)
6-DISK-3	151.1	0.1250 (0.3175)	5.8915	5.8915	5.8920 (14.9644)
6-DISK-4	151.3	0.1250 (0.3175)	5.8930	5.8935	5.8933 (14.9695)
6-DISK-5	150.1	0.1240 (0.3150)	5.8905	5.8915	5.8910 (14.9644)
6-DISK-6	150.4	0.1245 (0.3162)	5.8920	5.8925	5.8923 (14.9670)
10-DISK-1	423.9	0.1240 (0.3150)	9.8915	9.8920	9.8918 (25.1257)
10-DISK-2	424.0	0.1245 (0.3162)	9.8920	9.8935	9.8928 (25.1295)
10-DISK-3	426.5	0.1250 (0.3175)	9.8925	9.8925	9.8925 (25.1270)
10-DISK-4	426.3	0.1250 (0.3175)	9.8925	9.8930	9.8928 (25.1282)
10-DISK-5	426.9	0.1255 (0.3188)	9.8880	9.8900	9.8890 (25.1206)
10-DISK-6	427.1	0.1250 (0.3175)	9.8935	9.8940	9.8938 (25.1308)
10-DISK-7	426.5	0.1250 (0.3175)	9.8910	9.8920	9.8915 (25.1257)
10-DISK-8	426.2	0.1250 (0.3175)	9.8915	9.8920	9.8918 (25.1257)
10-DISK-9	425.3	0.1245 (0.3162)	9.8915	9.8925	9.8920 (25.1270)
10-DISK-10	423.1	0.1245 (0.3162)	9.8900	9.8925	9.8913 (25.1270)

1.2.7 Experimental Configurations

As part of the benchmark evaluation, the experimental configurations documented in Section 2.2 will be analyzed and judged as to their acceptability as benchmark experimental configurations.

1.3 Description of Material Data

The following material descriptions originate from the TEX-HEU experiment description and benchmark evaluation, documented in [2] and [3]. The relevant descriptions from those documents are reproduced in the following sections.

1.3.1 Comet General Purpose Critical Assembly Machine

The additional parts for TEX-HEU affixed to Comet were weighed prior to installation on Comet. The weights are reported in Table 19 and were measured during the TEX-HEU experiment campaign 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 was 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.

Table 19. Additional TEX-HEU parts used on Comet.

Part ID		Mass (g)
Membrane		2396.1
Experiment Platform	Interface Plate	11242.5
	Standoffs	633.8 634.4 634.0 635.0
Lower Adapter	Adapter Plate	5014.7
	Adapter Extension	8365.3

1.3.2 Highly Enriched Uranium

The following sections summarize and reproduce relevant material information from previous ICSBEP benchmark evaluations that use the same HEU plates. These benchmark evaluations include IEU-MET-FAST-007 and HEU-MET-FAST-072. The IEU-MET-FAST-007 experiments and benchmark evaluation use the 15/2.5-HEU, 15/6-HEU, and 15/10-HEU plate types, identified as Id No. 403, 401, and 402, respectively. The HEU-MET-FAST-072 experiments and benchmark evaluation use the 15/0-HEU and 15/2.5-HEU plates.

1.3.2.1 ^{235}U Enrichment

Table 20 reproduces the relevant HEU plate enrichments from IEU-MET-FAST-007 and HEU-MET-FAST-072. As noted in those benchmark evaluations, the enrichment values were obtained from the LANL MASS systems for the plates used in the Big Ten assembly and a letter from Dixon Callihan (ORNL) to Hugh Paxton (LANL) dated May 20, 1960.

The IEU-MET-FAST-007 benchmark evaluation, using the HEU4 and HEU5 plates, does not report the individual plate ^{235}U enrichments, instead it lists individual enrichment values grouped by part type.

Therefore, the ^{235}U enrichments for these HEU plate types are represent as an average and standard deviation of the values from the corresponding plate type in IEU-MET-FAST-007. The HEU-MET-FAST-072 benchmark evaluation reports ^{235}U enrichment values for each individual plate. Some of the HEU plate Part IDs in HEU-MET-FAST-072 are prefaced with "B10" which has been removed in favor of the ending 5-digit identifier.

Table 20. HEU plate ^{235}U enrichment.

Part Type	Part ID	Enrichment
15/10-HEU[4]	10463	93.34 ± 0.10[(a)]
	10472	
	10479	
15/6-HEU[5]	10457	93.24 ± 0.12[(a)]
	10477	
	10493	
	11018	
15/2.5-HEU[6]	10464	93.38[(b)]
	10467	93.41[(b)]
	10470	93.41[(b)]
	10475	93.40[(b)]
	10487	93.26[(b)]
	10489	93.39[(b)]
	10491	93.37[(b)]
15/0-HEU[7]	11017	93.31[(b)]
	11019	93.18[(b)]
	11147	93.17[(b)]
	11149	93.24[(b)]
	11150	93.17[(b)]

(a) IEU-MET-FAST-007
(b) HEU-MET-FAST-072

[4] Referred to in previous evaluations as 10" or HEU5.

[5] Referred to in previous evaluations as 6" or HEU4.

[6] Referred to in previous evaluations as 2.5" or HEU2.

[7] Referred to in previous evaluations as Full or HEU1.

In addition to the ^{235}U enrichment values reported in IEU-MET-FAST-007 and HEU-MET-FAST-072, the benchmark evaluations present mass spectrometry measurements performed at LANL for HEU isotopic content of the plate, reproduced in Table 21. The measurements are reported as atomic ratios relative to ^{235}U and the uncertainties are at the 95% confidence level (2σ).

Table 21. HEU plate uranium isotopic content measurements.

Part Type	Part ID	Uranium Isotope (Atom Ratio Relative to ^{235}U)			
		^{234}U	^{235}U	^{236}U	^{238}U
15/10-HEU[4]	10458	0.0111 ± 0.0002	1.00	<2E-5	0.0577 ± 0.0012
15/6-HEU[5]	10493	0.0115 ± 0.0001	1.00	(8.40 ± 0.42)E-4	0.0592 ± 0.0002
	10932	0.0108 ± 0.0001	1.00	(3.50 ± 0.04)E-3	0.0586 ± 0.0002
	11018	0.0110 ± 0.0001	1.00	(5.56 ± 0.06)E-3	0.0555 ± 0.0002

1.3.2.2 Uranium Impurities

Table 22 reproduces the HEU plate impurity measurements from IEU-MET-FAST-007 and HEU-MET-FAST-072. The reported impurities are assumed to be by weight.

Table 22: Measured HEU plate impurities.

Impurity (ppm U)	15/0-HEU[7]			15/6-HEU[5]	
	11147	11149	11150	10932	10933
Li	<0.1	<0.1	<0.1	<0.1	<0.1
Be	<0.1	<0.1	<0.1	<0.1	<0.1
B	0.6	0.6	0.3	0.2	<0.1
C	1100	270	320	170	170
Na	<1	<1	<1	<1	<1
Mg	<1	<1	<1	<1	1
Al	50	40	20	150	100
Si	300	400	210	80	130
Ca	<2	<2	<2	<2	<2
V	<20	<20	<20	<20	<20
Cr	5	15	5	2	3
Mn	4	7	6	7	6
Fe	100	190	90	70	30
Co	<5	<5	<5	<5	<5
Ni	20	30	20	15	15
Cu	6	5	4	4	3
Mo	50	<25	<25	-	-
Sn	<1	<1	<1	-	-
Pb	5	<1	<1	-	-

1.3.3 Hafnium

The following sections report density measurement and impurity analysis of the hafnium plates. These measurements were performed and certified by ATI Specialty Alloys & Components Millersburg Operations on March 28, 2022 (Purchase Order No: 142122 Amend No 1). Additional measurements have been performed by NNL which will be included as part of a separate report.

1.3.3.1 Hafnium Density Measurements

Table 23 reports the measured densities of the hafnium plates.

Table 23: Hafnium plate density measurements.

Part ID	Density (g/cm^3)
HF-01	12.9
HF-02	13.0
HF-03	13.0
HF-04	13.0
HF-05	13.0
HF-06	13.1
HF-07	13.0
HF-08	13.1
HF-09	13.0
HF-10	13.0
HF-11	13.1
HF-12	13.0
HF-13	12.9
HF-14	13.1
HF-15	12.6
HF-16	12.8
HF-17	12.8
HF-18	13.0
HF-19	13.1
HF-20	13.0
HF-22	12.8
HF-23	12.8
HF-24	13.0
HF-25	13.1
HF-26	13.1
HF-27	13.1

1.3.3.2 Hafnium Impurity Analysis

Table 60 reports the measured elemental impurity content of the hafnium material used to produce the hafnium plates, including the maximum specification. Measurements were performed with three samples of the ingot and one sample from the product.

Table 24. Hafnium impurity analysis results from samples of the ingot and product.

Element	Elemental Composition (%)				
	Spec. Max.	Ingot			Product
		1	2	3	
Hf	Balance	-	-	-	-
Zr	4.5	2.6	2.7	2.7	2.7
Al	0.010	<0.0025	<0.0025	<0.0025	<0.0025
C	0.015	0.003	0.003	0.003	0.004
Cr	0.010	<0.003	-	<0.003	<0.003
Cu	0.010	<0.002	<0.002	<0.002	<0.002
H	0.0025	<0.0003	-	<0.0003	<0.0003
Fe	0.050	0.014	0.015	0.016	0.016
Mo	0.0020	<0.0010	<0.0010	<0.0010	<0.0010
Ni	0.0050	<0.0025	-	<0.0025	<0.0025
Nb	0.010	<0.005	<0.005	<0.005	<0.005
N	0.010	0.005	-	0.005	0.004
O	0.040	0.021	-	0.021	0.017
Si	0.010	<0.0025	-	<0.0025	<0.0025
Ta	0.020	<0.001	<0.001	<0.001	<0.001
Sn	0.0050	<0.0010	-	<0.0010	<0.0010
Ti	0.010	<0.002	<0.002	<0.002	<0.002
W[8]	0.0150	<0.002	<0.002	<0.002	<0.0020
U	0.0010	<0.0002	-	<0.0002	<0.0002
V	0.0050	<0.0010	-	<0.0010	<0.0010

[8] The reported precision for the ingot and product in the original report do not match but have the same value of <0.002.

1.3.4 Polyethylene

1.3.4.1 Polyethylene Density Measurements

The density of the polyethylene was analyzed at LLNL by performing high-precision volume and mass measurements of small samples taken from seven different polyethylene parts. The volume measurements were performed using a Micromeritics AccuPyc II gas displacement pycnometry system. The system used a 100 cm^3 sample chamber and was calibrated using a 51.08755 cm^3 calibration ball prior to each series of sample measurements. Each volume measurement was performed 10 times per sample. The mass measurements were performed on a balance with a precision of 10 µg. Each sample was weighed three times.

Table 25 reports the results of density measurements performed on the seven polyethylene samples. The uncertainty in the mas and volume measurements is presented as the standard deviation of the three mass measurements and 10 volume measurements. These uncertainties are then propagated in quadrature to determine the standard deviation of the calculated density.

Table 25. Polyethylene part density measurements.

Part ID	Mass (g)	Volume (cm^3)	Density (g/cm^3)[9]
0-CAP-3	39.92816 ± 0.00003	41.1483 ± 0.0047	0.9703 ± 0.0001
3/32-CAP-3	48.90154 ± 0.00004	50.4268 ± 0.0033	0.9698 ± 0.0001
1-RING-6	44.30622 ± 0.00001	45.6667 ± 0.0063	0.9702 ± 0.0001
1/8-MOD-38	46.37212 ± 0.00007	48.1521 ± 0.0047	0.9630 ± 0.0001
1/4-MOD-36	58.59803 ± 0.00001	61.2725 ± 0.0043	0.9564 ± 0.0001
1/2-MOD-32	57.58423 ± 0.00007	60.1526 ± 0.0022	0.9573 ± 0.0000
1.5-MOD-12	42.35975 ± 0.00002	44.2152 ± 0.0059	0.9580 ± 0.0001

1.3.4.2 Polyethylene Impurity Analysis

Elemental analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was performed on a sample of the polyethylene. This process involved adding the sample to a digestion pressure vessel with 10 mL of 6M nitric acid (HNO_3) and then digesting it in a MARS6 Microwave Digestion System (Model 910900) following the CEM "Polyethylene" procedure in the semi-quantitative, MS/MS mode.

The measured elemental impurities are reported in Table 26. The samples used for this measurement were small shavings taken from the polyethylene parts. The samples were weighed prior to digestion having a total mass of 246.97 µg. The selection criteria required >5000 counts per second, elements included in the analysis were as follows: Mg, V, Mn, Ni, Cu, Zn, Ga, Zr, Mo, Sn, La, and Pb.

[9] Derived quantity based on mass and volume measurements.

Table 26. Polyethylene impurity analysis results (elements not meeting the selection criteria have a hyphen).

Elemental Impurity	Unit	Average	Standard Deviation
Na	µg/g	14.38	1.82
Al	µg/g	23.92	1.74
Si	mg/g	1.17	0.06
Cr	ng/g	921.35	7.08

1.3.5 Aluminum

The aluminum inserts are Aluminum Alloy 6061 (AL 6061) and all other aluminum parts, including the membrane, interface plate and standoffs, adapter plate and extension, and Comet stationary platform and movable platen are AL 6061-T6. The elemental composition of AL 6061 and AL 6061-T6 is equivalent as they are the same alloy. Therefore, all aluminum in these experiments is AL 6061. Table 27 presents handbook data for standard AL 6061.

Table 27. Elemental composition limits for standard Aluminum Alloy 6061[10].

Element	Wt. %
Al[11]	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

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

[11] Aluminum content reported is calculated as the remainder.

1.4 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 4. The RTDs were placed on top of the polyethylene reflector (RTD #1) and the aluminum membrane (RTD #2), which was in direct contact with an HEU plate[12]. 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 RTDs place on the Comet support structure (RTD #3) and measuring the ambient air temperature (RTD #5). Finally, during the measurements of the 1/4" Sand. configuration, a Fluke 971 Temperature Humidity Meter was placed in the hallway just outside the experiment room. The temperature measurements performed with the Fluke are further discussed in Section 2.1.2.

Table 28 reports the temperature measurements taken during the benchmark period measurements, including the Comet structure (RTD #3) and ambient air (RTD #5). Table 29 reports the temperature measurements taken prior to removing RTDs #1 and #2 to perform the benchmark measurements, which was sometimes many days before the period measurement.

Table 28: Experimental configuration temperature measurements during benchmark period measurements.

Configuration	Date/Time	Temperature (°C)		
		Comet	Ambient	Fluke
0" Standard	2023-10-13 09:00	16.0	13.3	-
1/8" Standard	2023-09-19 09:00	16.6	14.2	-
1/4" Standard	2023-09-12 10:20	18.3	16.8	-
1/2" Standard	2023-09-22 10:45	16.4	14.1	-
1-1/2" Standard	2023-09-28 11:40	16.7	14.0	-
1/4" Sandwich	2023-10-26 09:15	15.5	13.4	15.5
0" Bunched	2023-10-19 15:15	16.0	13.6	-

Table 29. Experimental configuration temperature measurements prior to removing RTDs #1 and #2.

Configuration	Date/Time	Temperature (°C)				
		RTD #1	RTD #2	RTD #3	RTD #5	Fluke
0" Standard[12]	2023-10-12 13:50	14.0	17.7	16.3	13.9	-
1/8" Standard	2023-09-14 09:43	16.6	19.2	17.9	15.0	-
1/4" Standard	2023-09-01 10:03	16.4	17.9	18.1	16.4	-
1/2" Standard	2023-09-22 08:59	14.7	16.9	16.2	13.8	-
1-1/2" Standard	2023-09-28 08:43	14.5	17.8	16.3	13.7	-
1/4" Sandwich	2023-10-25 10:54	13.7	16.8	15.7	13.3	15.4
0" Bunched	2023-10-19 13:05	13.9	17.3	15.9	13.5	-

[12] The RTDs for the 0" Std. configuration were swapped compared to the other configurations: RTD #1 placed on the membrane and RTD #2 place on the top reflector.

1.5 Supplemental Experimental Measurements

As part of the benchmark evaluation, the supplemental experiments documented in Section 2.3 will be analyzed and judged as to their acceptability and applicability to the benchmark experimental configurations.

Section 2

Experimental Measurements and Configurations

2.1 Experimental Measurements

2.1.1 Period Measurements

Period measurements were performed using three compensated ion chambers[13], referred to as linear channels (LC), and four ^{3}He proportional counters[14], referred to as start-up (SU) detectors, for all experimental configurations. Time series data, reporting count rates for the SUs and amps for the LCs, from these detectors spanning the entire experiment campaign was provided by Los Alamos National Laboratory. An example of this data for the 1/4” Std. benchmark period measurement from the SU detectors is shown in Figure 12. The period measurement data for TEX-Hf is stored in the LLNL Nuclear Criticality Safety Division file server accessible through LLNL at:

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smb://the-lab.llnl.gov/cfs1/fs1/NucOps/NCSD/NCSP/IER/IER-532/Data/Period/
```

A total of 35 period measurements were performed during this experiment campaign, summarized in Table 30. Of these 35 period measurements, seven were of the benchmark experimental configurations, four were of reproducibility measurements for the experimental configurations, 19 were of intermediate configurations while approaching the benchmark experimental configurations, and four were of reactivity worth measurements for the benchmark experimental configurations.

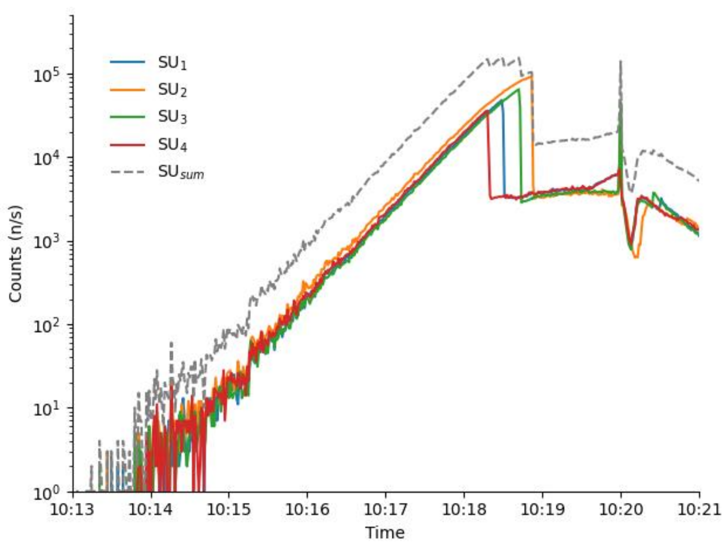


Figure 12. Example period measurement from the SU detectors during the 1/4” Std. benchmark measurement.

[13] A fourth compensated ion chamber is present, but not recorded due to its use as a safety system.

[14] The period measurement for the SU is typically fit as a sum of the four detectors for improved statistics.

Table 30. Period measurements performed during TEX-Hf experiment campaign (benchmark – yellow, reproducibility – green).

Configuration	Measurement Date/Time	^{3}He Proportional Counters (SU)		Compensated Ion Chambers (LC)		Notes
		Period (s)	Excess (¢)	Period (s)	Excess (¢)	
0" Std.	10-12 12:35	-	-	109.7 ± 0.6	8.9 ± 0.0	Approach to critical
	10-12 13:50	-	-	28.7 ± 0.1	22.5 ± 0.0	
	10-12 15:45	64.6	13.2	63.0 ± 0.6	13.5 ± 0.1	
	10-13 09:00	61.4	13.7	59.2 ± 0.6	14.1 ± 0.1	Benchmark
	10-13 15:00	73.4	12.1	71.9 ± 0.2	12.2 ± 0.0	Reproducibility
1/8" Std.	09-15 14:20	47.1	16.5	48.3 ± 0.4	16.2 ± 0.1	Approach to critical
	09-15 15:10	38.9	18.7	42.0 ± 0.4	17.8 ± 0.1	
	09-15 15:45	70.5	12.4	67.9 ± 0.2	12.6 ± 0.2	
	09-19 09:00	65.7	13.1	64.8 ± 0.4	13.2 ± 0.1	Benchmark
1/4" Std.	09-01 10:30	-	-	6.0 ± 0.1	47.8 ± 0.4	Approach to critical
	09-01 12:05	-	-	19.3 ± 0.1	28.1 ± 0.1	
	09-01 15:20	27.6	23.0	25.7 ± 0.1	24.0 ± 0.5	
	09-12 10:20	26.8	23.2	25.4 ± 0.1	24.2 ± 0.5	Benchmark
	09-13 09:20	26.4	23.6	25.2 ± 0.1	24.3 ± 0.3	Reproducibility
1/2" Std.	09-21 15:45	68.3	12.7	73.8 ± 0.3	12.0 ± 0.3	Approach to critical
	09-22 09:10	63.6	13.4	70.2 ± 0.5	12.5 ± 0.5	
	09-22 10:45	127.9	7.8	122.9 ± 0.5	8.1 ± 0.1	Benchmark
1-1/2" Std.	09-27 15:40	-	-	154.7 ± 0.9	6.7 ± 0.0	Approach to critical
	09-28 08:50	-	-	128.5 ± 3.0	7.8 ± 0.1	
	09-28 10:10	-	-	66.9 ± 0.6	12.9 ± 0.1	
	09-28 11:40	92.2	10.2	84.5 ± 0.5	10.9 ± 0.0	Benchmark
	09-28 15:20	77.3	11.6	74.9 ± 0.4	11.8 ± 0.2	Reproducibility
	10-10 09:30	120.4	8.2	111.2 ± 0.7	8.8 ± 0.0	Machine setup
1/4" Sand.	10-25 10:50	-	-	10.6 ± 0.1	37.9 ± 0.1	Approach to critical
	10-25 13:00	-	-	36.0 ± 0.1	19.6 ± 0.0	
	10-25 14:35	-	-	52.7 ± 0.2	15.3 ± 0.0	
	10-26 09:15	53.6	15.1	50.7 ± 0.2	15.7 ± 0.0	Benchmark
	10-26 11:40	39.9	18.4	37.9 ± 0.1	19.0 ± 0.0	Reflector ring gap reactivity worth configurations (2.3.2)
	10-26 13:25	38.7	18.7	37.4 ± 0.2	19.1 ± 0.1	
	10-26 15:15	53.5	15.1	50.7 ± 0.2	15.7 ± 0.0	Reproducibility
0" Bunch	10-19 13:05	21.9	26.3	22.6 ± 0.2	25.8 ± 0.1	Approach to critical
	10-19 14:00	38.5	18.8	36.5 ± 0.2	19.4 ± 0.1	Extrapolation to delayed critical configurations (2.3.1)
	10-19 14:35	77.6	11.6	72.5 ± 0.3	12.2 ± 0.0	
	10-19 15:50	78.1	11.5	73.8 ± 0.0	12.0 ± 0.0	Benchmark

2.1.2 Temperature Measurements

In addition to the RTD temperature measurements reported in Section 1.4, measurements were performed using a Fluke 971 Temperature Humidity Meter during the 1/4" Sand. experimental configuration. The Fluke was place on top of the load sensor in the hallway just outside the experiment room. The experiment room has negative pressure compared to the hallway. The Fluke measures temperature using a negative temperature coefficient thermistor and relative humidity (RH) using an electronic capacitance polymer film sensor. The temperature measurement has a reported accuracy of ±0.5°C between 0°C and 45°C with a resolution of 0.1°C. The relative humidity measurement has a manufacturer accuracy of ±2.5% RH at 23°C between 10% and 90% RH (±5.0% RH otherwise). The Fluke came with a calibration certificate through the manufacturer dated August 16, 2022.

Table 31 reports the temperatures measured during the 1/4" Sand. experimental configuration. Based on these results, the RTD located on the Comet structure (RTD #3) agrees with the Fluke while the RTD measuring the ambient temperature (RTD #5) is consistently 2.0-2.5°C lower.

Table 31. Fluke and RTD temperature measurements during 1/4" Sand (*indicates RTD not in place).

Date	Time	RTD (°C)				Fluke (°C/%)	
		#1	#2	#3	#5	Temp.	Humid.
2023-10-25	08:20	13.5*	16.8*	15.5	13.3	-	-
	10:30	13.7	16.8	15.6	13.2	15.6	19.5
	10:45	13.7	16.8	15.5	13.2	15.5	19.6
	11:00	13.7	16.8	15.7	13.3	15.5	19.6
	11:15	13.7	16.8	15.7	13.3	15.5	19.5
	12:00	13.7	16.8	15.7	13.3	15.4	19.5
	12:30	13.6	16.8	15.7	13.3	15.7	20.4
	13:00	13.7	16.8	15.6	13.2	15.5	19.6
	14:08	13.9*	17.1*	15.9	13.4	15.6	19.5
	14:30	13.6*	17.0*	15.8	13.4	15.6	20.2
	15:00	13.6*	16.9*	15.8	13.4	15.6	19.6
	15:15	13.6*	17.0*	15.7	13.4	15.5	19.6
2023-10-26	08:25	13.4*	16.6*	15.5	13.2	15.5	22.1
	09:00	13.4*	16.7*	15.5	13.2	15.5	23.2
	10:10	13.7*	17.0*	15.6	13.5	15.8	24.0
	10:25	13.5*	16.9*	15.7	13.5	15.7	24.4
	11:01	13.7*	17.0*	15.8	13.5	15.8	25.3
	11:30	13.5*	16.8*	15.7	13.5	15.6	25.3
	12:35	13.4*	16.7*	15.7	13.5	15.5	24.7
	13:00	13.7*	17.0*	15.7	13.5	15.7	24.5
	14:15	13.8*	17.0*	15.7	13.6	15.7	23.6
	15:10	13.5*	16.8*	15.8	13.6	15.8	24.2
	15:30	13.5*	16.8*	15.7	13.6	15.6	23.2

2.1.3 Height Measurements

The need for highly accurate height measurements was determined during the design phase of this experiment in [1] and found to be the primary source of experimental uncertainty for the benchmark evaluation in [2]. To perform such measurements a Westward Electronic Height Gauge (Model No. 2YND5) was procured. The manufacturer of the gauge reports an indication accuracy of ±0.04 mm and resolution of 0.01 mm. These height measurements were performed by the LANL experimenters during the execution of the experiment campaign. Measurements were taken of both the core stack and reflector ring of the upper and lower halves of each experimental configuration.

For the upper stack, the height gauge was placed on the membrane. To perform the measurement, the height gauge was electronically zeroed next to the reflector ring, on the membrane. For the lower stack, the height gauge was either held in place or clamped to the movable platen. To perform the measurement, the height gauge was electronically zeroed next to the reflector ring, on the lip of the adapter plate. Figure 13 shows a picture of this procedure on the lower stack. The lip of the adapter plate in nominally 0.47 in (1.1938 cm), with measurements reported in [2]. This means all the lower stack heights need to account for this lip height to determine the total stack height.

Once the height gauge was zeroed, the scribe was raised, and the height gauge was rotated over the desired location of the measurement. Once in position the scribe was lowered to measure either the core stack or the reflector ring. After the measurement was taken, the height gauge was again rotated to the location where it was initially zeroed, and a measurement of that position was performed again. This re-measurement of the zero location serves to characterize the drift of the height gauge as the scribe is raised and lowered and the height gauge itself is rotated.

A total of five positions were measured for the upper and lower core stack heights, shown in Figure 14. A single height measurement was performed for the upper and lower reflector rings. On the lower reflector ring, this measurement was done to ensure that the reflector ring was at the same height or slightly lower than the core stack. The requirement was not necessary for the upper reflector ring.

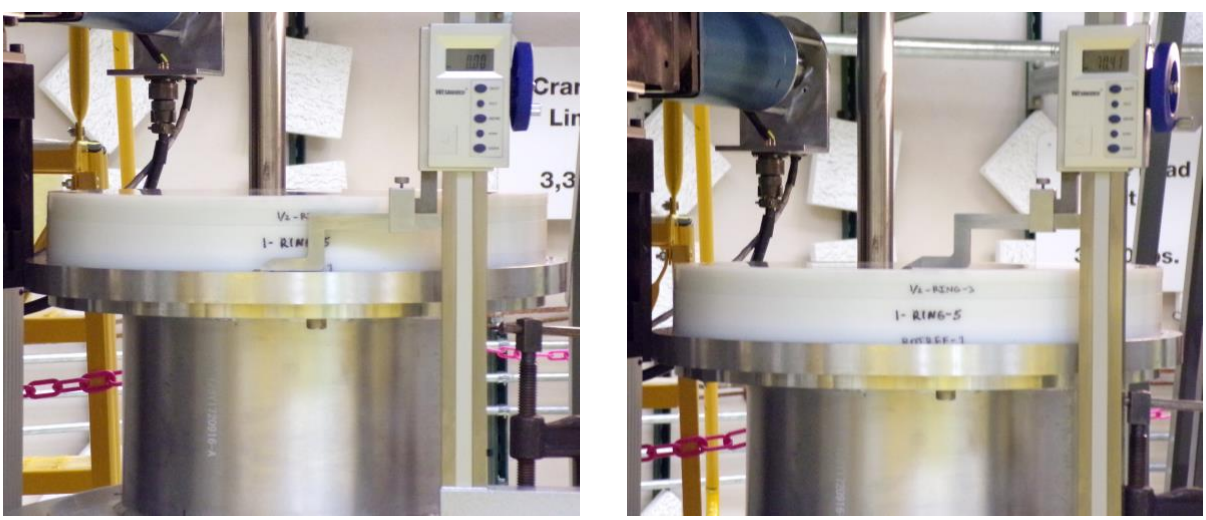


Figure 13. Height gauge measuring the overall stack height of the lower half of the experiment where it must be zeroed on the lip of the lower adapter plate.

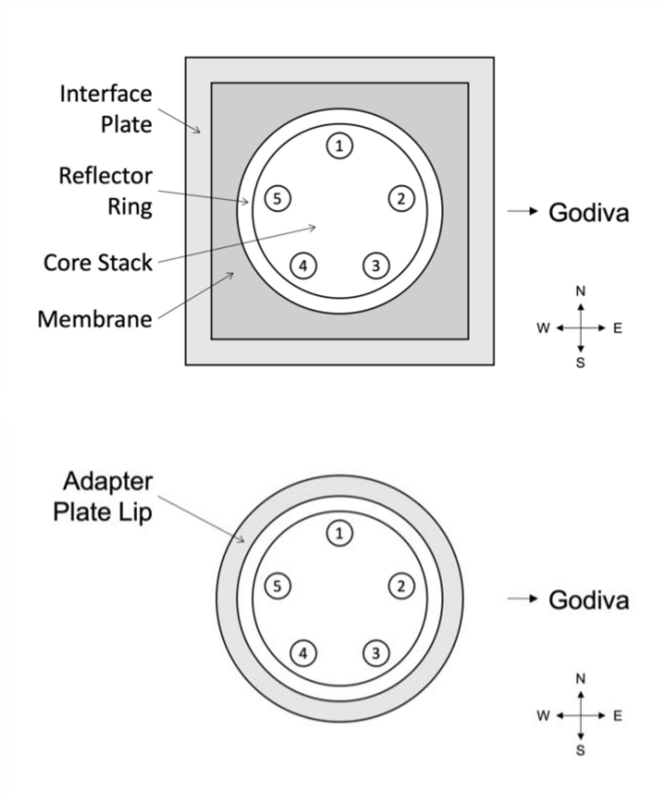


Figure 14. Upper (top) and lower (bottom) stack height measurement locations.

Table 33 reports a summary of the measured upper and lower core stack and reflector ring heights. The core stack height measurements represent the average and standard deviation of the five measurements, which are reported for each experimental configuration in the following sections. The lower height measurements do not account for the height of the adapter plate lip.

Table 32. Summary of upper and lower core stack and reflector ring height measurements for TEX-Hf.

Configuration	Upper (cm)		Lower (cm)[15]	
	Core Stack	Reflector Ring	Core Stack	Reflector Ring
0” Standard	8.307 ± 0.016	8.484	6.519 ± 0.018	6.467
1/8” Standard	7.675 ± 0.026	7.913	7.376 ± 0.038	7.272
1/4” Standard	9.201 ± 0.021	9.122	7.688 ± 0.014	7.649
1/2” Standard	9.673 ± 0.014	9.752	9.819 ± 0.018	9.791
1-1/2” Standard	25.533 ± 0.034	25.548	22.580 ± 0.029	22.408
1/4” Sandwich	8.001 ± 0.029	8.030	9.866 ± 0.056	9.774
0” Bunched	7.417 ± 0.011	7.483	6.508 ± 0.031	6.421

[15] The lower height measurements do not account of the nominal 0.47 in adapter plate lip where the height gauge was zeroed (as shown in Figure 13).

2.1.4 Levelness

A check of the core stack levelness was performed for the upper and lower core stack of the experimental configurations. This measurement was performed using both a bubble level and digital level. The bubble level was used to verify the core stack was slightly taller than the ring reflector, as shown in Figure 15. The digital level was used to record the levelness of the core stacks. The levelness measurements for the experimental configurations are reported in Table 33.

Table 33. Levelness measurements of the upper and lower core stacks of the experimental configurations.

Configuration	Upper Core Stack		Lower Core Stack	
	N/S (°)	E/W (°)	N/S (°)	E/W (°)
0” Standard	0.30	0.20	0.10	0.15
1/8” Standard	0.30	0.10	0.00	0.25
1/4” Standard	0.20	0.15	0.05	0.20
1/2” Standard	0.25	0.05	0.00	0.20
1-1/2” Standard	0.30	0.00	0.05	0.15
1/4” Sandwich	0.30	0.15	0.05	0.20
0” Bunched	0.30	0.15	0.00	0.15

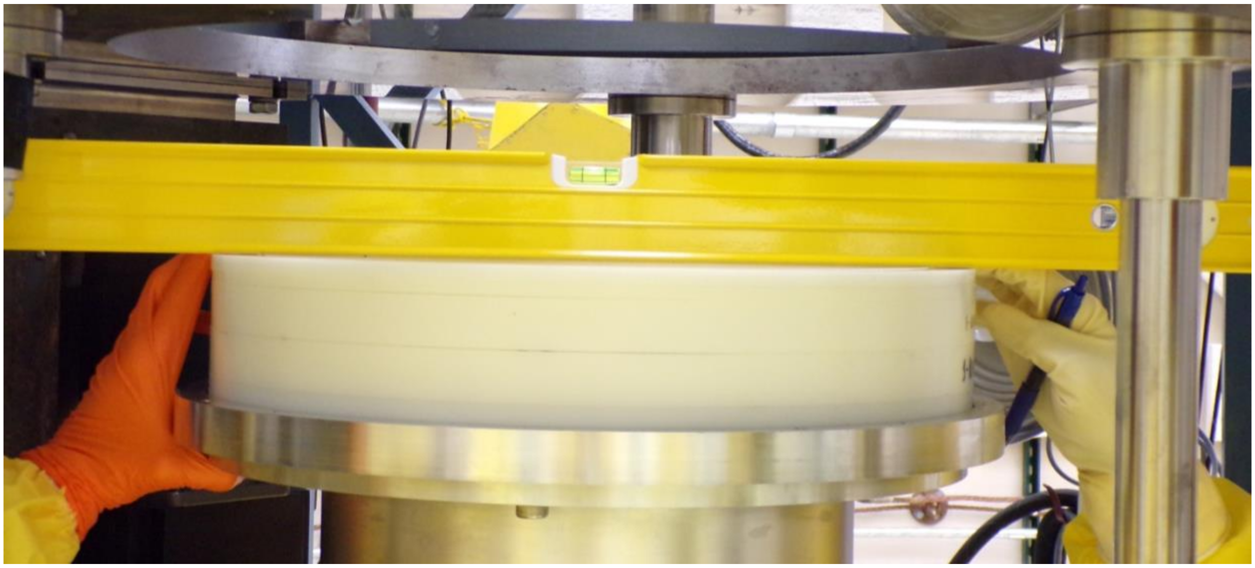


Figure 15. Levelness measurement for the lower core stack of 1/4" Std. using the bubble level.

2.1.5 Additional Measurements

The following sections document additional dimensional measurements performed during the TEX-Hf experiment campaign. All these measurements may also be relevant to the analysis of TEX-HEU [3].

2.1.5.1 HEU Stacking Density

During the benchmark dimensional measurements and disassembly of the 0” Bunch. configuration, a stacking density measurement of the HEU plates were performed. This measurement was performed on the upper core stack after the top polyethylene reflector, hafnium plates, and polyethylene reflector rings were removed. This left only the HEU plates and aluminum inserts. Due to the stacking order of the HEU plates in this configuration, having the higher mass plates on bottom, the HEU plates were in direct contact throughout the whole stack. Therefore, performing height measurements of this stack can be used to calculate the stacking density of the HEU plates.

Figure 16 shows a diagram of the upper core stack of the 0” Bunch. configuration while this measurement was performed. Table 34 reports the height measurements of this upper core stack for the HEU stacking density measurement. The positions are the same as the height measurements reported in Section 2.1.3.

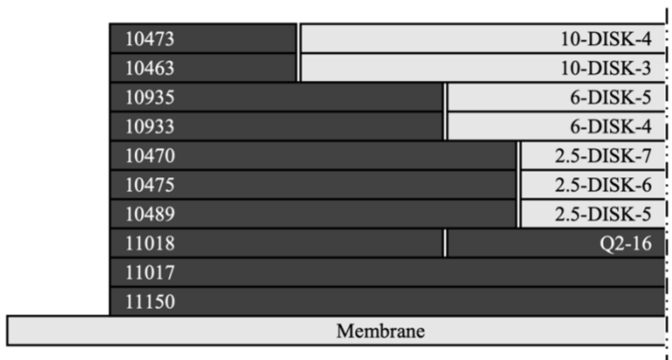


Figure 16. Diagram of the 0” Bunch. upper core stack during the HEU stacking density measurement, with the polyethylene reflector, hafnium plates, and polyethylene reflector rings removed.

Table 34. HEU stacking density height measurement performed on the configuration in Figure 16.

Position	Stack Height (mm)	
	Height	Drift
1	31.44	0.07
2[16]	31.09	0.06
3	31.60	-0.03
4	31.70	0.12
5	31.56	0.00

[16] The height measurement at this position was less than 2σ of the height measurements at the other positions. Therefore, this measurement was performed two additional times to ensure consistency of the measured value. These additional measurements produced 31.04 mm and 31.11 mm confirming the initial measurement.

2.1.5.2 Membrane Deflection

The membrane was observed to deflect while loaded with the higher mass upper stacks. This deflection is shown in Figure 18 and Figure 19 for the 0” Std. and 1-1/2” Std. experimental configurations, respectively. This deflection is not present in the benchmark configuration given that the lower stack is fully lifting the upper stack. However, this deflection is present while the two halves are separated, which is the case when performing the stack height measurements. While the effect of this membrane deflection is mitigated by zeroing the height gauge close to the measurement position for the stack height measurements, it may still introduce a bias in the measurement. Therefore, height measurements were performed to characterize this membrane deflection while performing the stack height measurements for the 0” Std. experimental configuration.

Figure 17 shows the four positions where the membrane deflection measurements were performed. These four positions correspond to the four posts on the interface plate used to align the membrane. These measurements were performed using a similar procedure to the stack height measurements described in Section 2.1.3. First, the height gauge was zeroed on the interface plate close to the position being measured. Then the height gauge was moved over the position being measured and cranked down into contact with the top surface of the membrane. Once the measurement was recorded, the height gauge was returned to the position where it was zeroed to re-zero and record any drift. Table 35 reports the membrane deflection measurements performed while the 0” Std. upper stack was in place on the membrane.

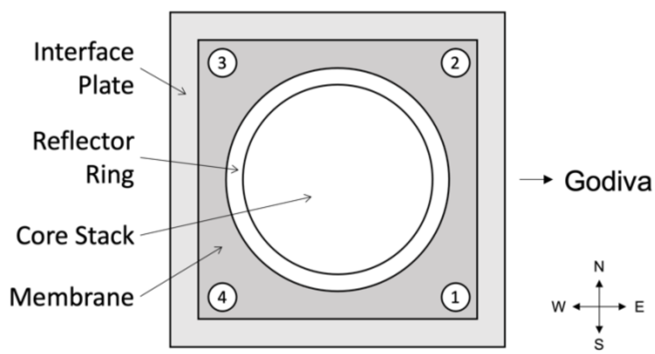


Figure 17. Membrane deflection measurement positions.

Table 35. Membrane deflection height measurements performed with the 0” Std. upper stack in place.

Position	0” Std.		0” Bunch.[17]	
	Height (mm)	Drift (mm)	Height (mm)	Drift (mm)
1	5.01	0.00	4.30	-0.03
2	5.05	0.02	4.32	0.00
3	4.87	0.00	4.26	0.02
4	5.68	0.00	5.01	0.03

[17] Performed on the upper core stack of the 0” Bunch. configuration during the HEU stacking density measurement (Figure 16).

Figure 18. Membrane deflection under the weight of the 0" Std. upper stack.

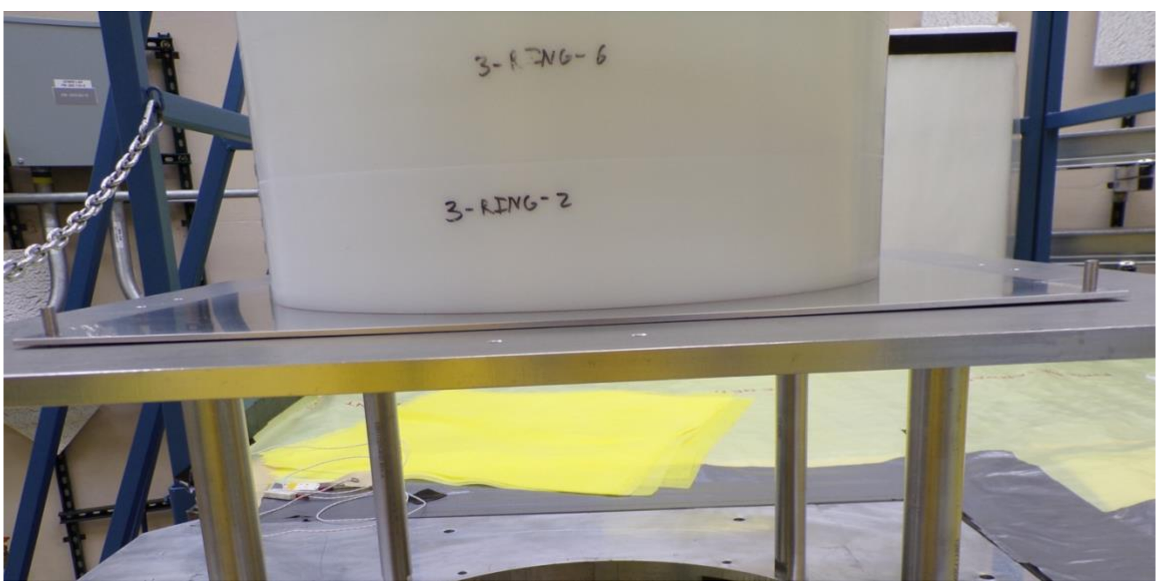


Figure 19. Membrane deflection under the weight of the 1-1/2" Std. upper stack.

2.1.5.3 Feeler Gage Measurements

A feeler gage was used to measure gaps between various parts in the experimental configurations. These gaps include between the alignment plate the lower ring reflector, between bottom reflector cap and an HEU plate, and between the adapter plate and the bottom reflector plate. The gap between the alignment plate and lower ring reflector determines the possible offset between the alignment of the upper and lower core stacks which are separated by the membrane. This gap was measured by bring up the lower reflector ring (1/16-CAP-1 and 1/4-RING-1) up without the membrane in place. The gap between the adapter plate and the bottom reflector (BOTREF-1) also influences this possible offset. The gap between the bottom reflector cap (0-BOTCAP-1) and the HEU plate (15/0-HEU-11147) determines the position of the upper core stack within the upper reflector ring. Table 36 reports these feeler gage measurements and Figure 20, Figure 21, and Figure 22 show the measurement locations for each of these gaps.

Table 36. Feeler gage measurements

Position	Gap Distance (mils)		
	Alignment Plate & Ring Reflector[18] (Figure 20)	0-BOTCAP-1 & 15/0-HEU-11147 (Figure 21)	Adapter Plate & BOTREF-1 (Figure 22)
1	38.5	25.0	59.5
2	7.0	47.5	20.0
3	24.0	59.5	9.0
4	44.5	43.0	36.0

2.1.5.4 Room and Comet Measurements

Table 28 reports additional measurements performed to characterize the location of the experimental configurations within the experiment room and on Comet. The measurements between the interface plate and the ceiling or wall were performed using a laser distance sensor. The other measurements were performed by hand using a tape measure.

Table 37. Additional measurements of the experiment room and Comet.

Location	Measurement
Top of Interface Plate to the Ceiling	2.329 m
West Side of Interface Plate to the Wall	3.128 m
North Side of Interface Plate to Start-Up Counters	1.125 m
Top of Comet Stationary Platform to the Floor	207 cm
Top of Interface Plate to Top of Comet Stationary Platform	31.8 cm

[18] The gap measurement between the alignment plate and ring reflector was performed while aligning the lower stack of the 1/4" Sand. experimental configuration. At that time, the ring reflector consisted of the 1/16-CAP-1 and 1/4-RING-1 parts.

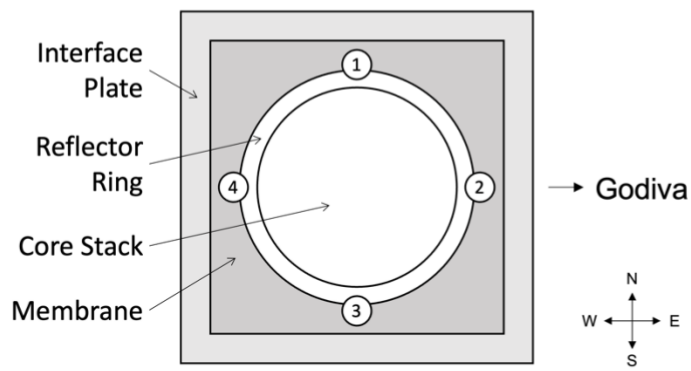


Figure 20. Feeler gage measurements positions of the gap between the alignment plate and ring reflector.

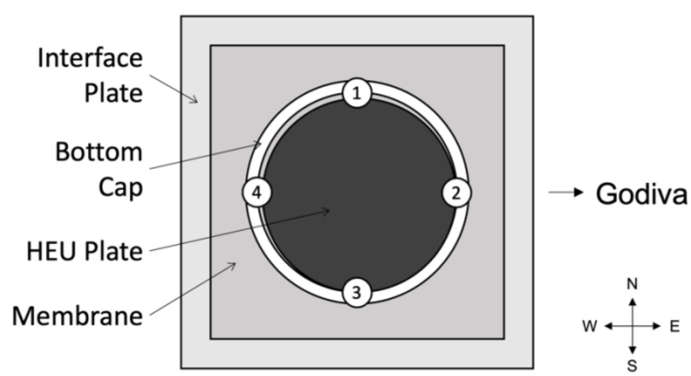


Figure 21. Feeler gage measurement positions of the gap between the 0-BOTCAP-1 and 15/0-HEU-11147 parts.

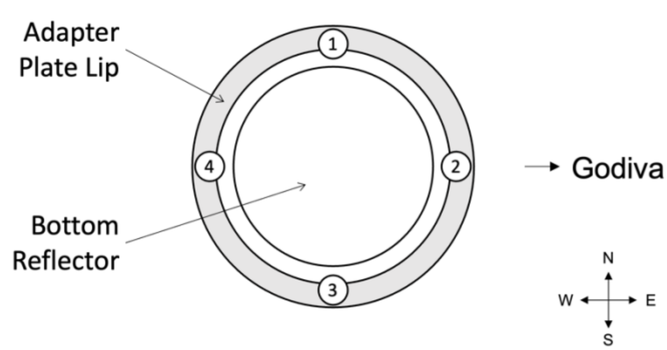


Figure 22. Feeler gage measurement positions of the gap between the adapter plate and BOTREF-1 part.

2.2 Experimental Configurations

2.2.1 0” Standard Configuration

The 0” Standard (0” Std.) experimental configuration includes 25 HEU plates, 24 Hf plates, no HDPE moderator plates, and a nominal 1.15625” (2.93688 cm) top HDPE reflector. These 25 HEU plates consisted of six 15/0-HEU[19], seven 15/2.5-HEU, five 15/6-HEU, and seven 15/10-HEU plates, for a total HEU mass of 135.5 kg.

Figure 23 shows a diagram of the 0” Std. experimental configuration. Table 38 and Table 39 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 39 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 38. Upper and lower core stack height measurements for 0” Std.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	83.01	0.00	65.31	0.01
2	82.84	-0.04	65.25	-0.02
3	83.12	0.05	65.25	-0.12
4	83.28	-0.03	65.27	0.06
5	83.12	0.00	64.87	-0.04

Table 39. Upper and lower ring reflector height measurements for 0” Std.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	84.84	0.03	64.67	0.02

Table 40. Benchmark period and reproducibility measurement for 0” Std.

Detector	Benchmark Measurement			Reproducibility Measurement		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	61.41	13.71	10,000	73.44	12.05	10,000
LC_1	59.08	14.09	10^{-9}	72.04	12.22	10^{-9}
LC_2	59.71	13.99	10^{-9}	71.68	12.27	10^{-9}
LC_3	58.80	13.71	10^{-9}	71.92	12.24	10^{-9}

[19] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

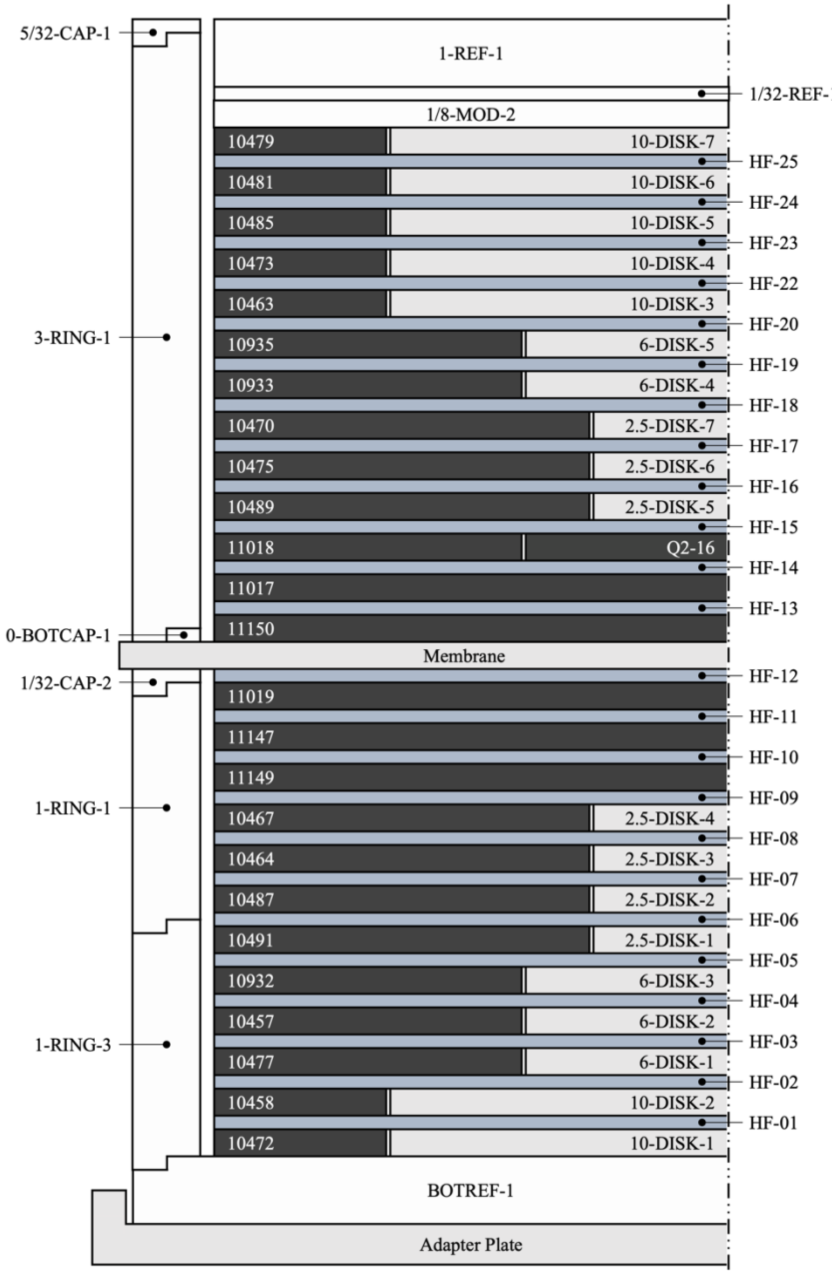


Figure 23. Diagram of the 0" Std. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.2 1/8” Standard Configuration

The 1/8” Standard (1/8” Std.) experimental configuration includes 16 HEU plates, 15 Hf and 1/8” (0.3175 cm) HDPE moderator plates, and a nominal 0.875” (2.2225 cm) top HDPE reflector. These 16 HEU plates consisted of six 15/0-HEU[20], seven 15/2.5-HEU, and 3 15/6-HEU plates, for a total HEU mass of 99.4 kg.

Figure 24 shows a diagram of the 1/8” Std. experimental configuration. Table 41 and Table 42 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 43 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 41. Upper and lower core stack height measurements for 1/8” Std.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	77.01	0.00	73.40	0.00
2	76.46	0.07	73.48	0.06
3	76.79	0.02	73.63	0.02
4	76.49	-0.01	74.03	0.16
5	76.99	0.08	74.28	-0.01

Table 42. Upper and lower ring reflector height measurements for 1/8” Std.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	79.13	-0.01	72.72	-0.01

Table 43. Benchmark period measurement for 1/8” Std.

Detector	Benchmark Measurement		
	Period (s)	Excess (¢)	Scale
SU	65.66	13.07	10,000
LC_1	64.97	13.17	10^{-9}
LC_2	65.15	13.15	10^{-9}
LC_3	64.40	13.26	10^{-9}

[20] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

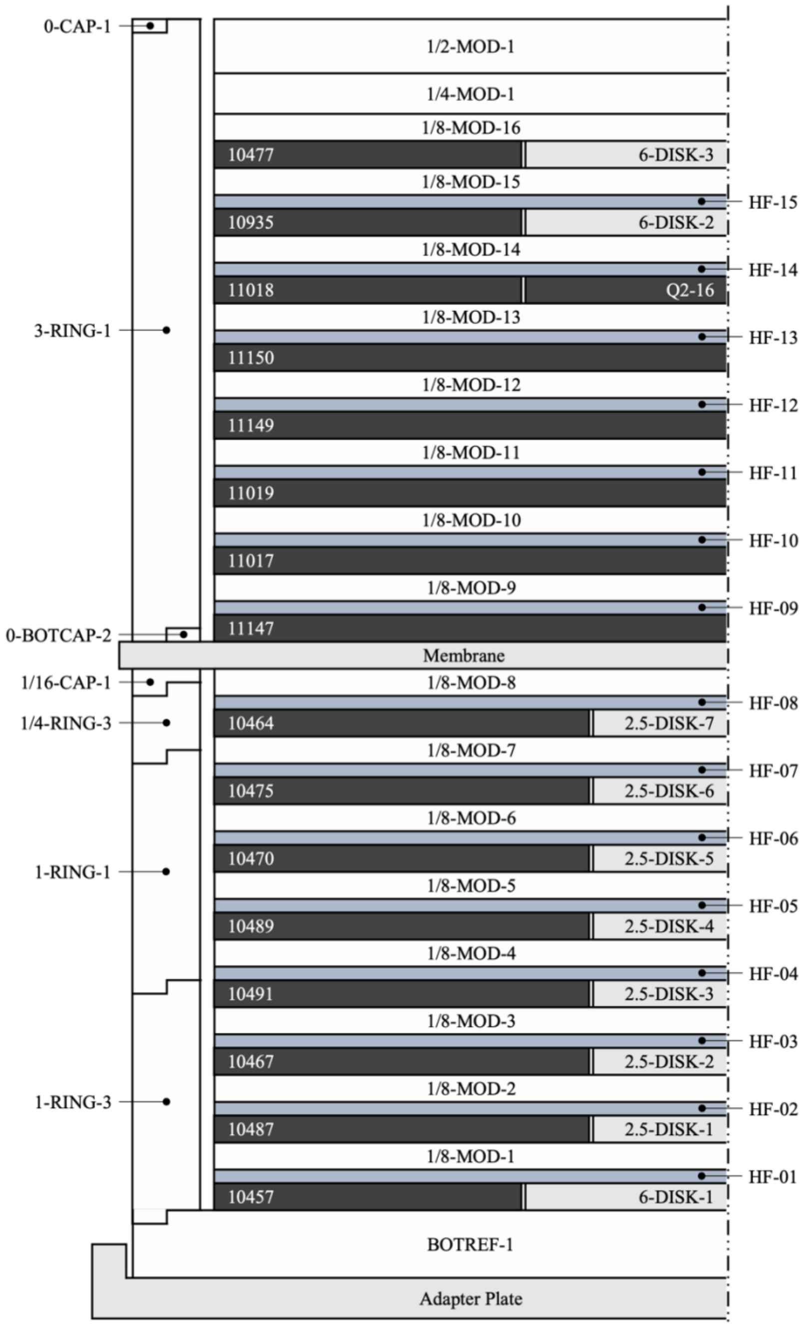


Figure 24. Diagram of the 1/8" Std. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.3 1/4" Standard Configuration

The 1/4" Standard (1/4" Std.) experimental configuration includes 13 HEU plates, 12 Hf and 1/4" (0.635 cm) HDPE moderator plates, and a nominal 0.96875" (2.46063 cm) top HDPE reflector. These 13 HEU plates consisted of six 15/0-HEU[21] and seven 15/2.5-HEU plates, for a total HEU mass of 82.8 kg.

Figure 25 shows a diagram of the 1/4" Std. experimental configuration. Table 44 and Table 45 report the upper and lower core stack and ring reflector height measurements for the 0" Std. experimental configuration, as described in Section 2.1.3. Table 46 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 44. Upper and lower core stack height measurements for 1/4" Std.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	91.83	0.11	76.77	0.06
2	92.11	0.06	77.08	0.08
3	92.32	-0.07	76.92	0.02
4	91.82	0.06	76.90	0.01
5	91.96	-0.03	76.71	-0.11

Table 45. Upper and lower ring reflector height measurements for 1/4" Std.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	91.22	0.00	76.49	0.01

Table 46. Benchmark period and reproducibility measurement for 1/4" Std.

Detector	Benchmark Measurement			Reproducibility Measurement		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	26.76	23.15	10,000	26.42	23.62	10,000
LC_1	25.43	24.15	10^{-8}	25.18	24.28	10^{-9}
LC_2	25.52	24.10	10^{-8}	25.24	24.25	10^{-9}
LC_3	25.32	24.21	10^{-8}	25.06	24.35	10^{-9}

[21] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

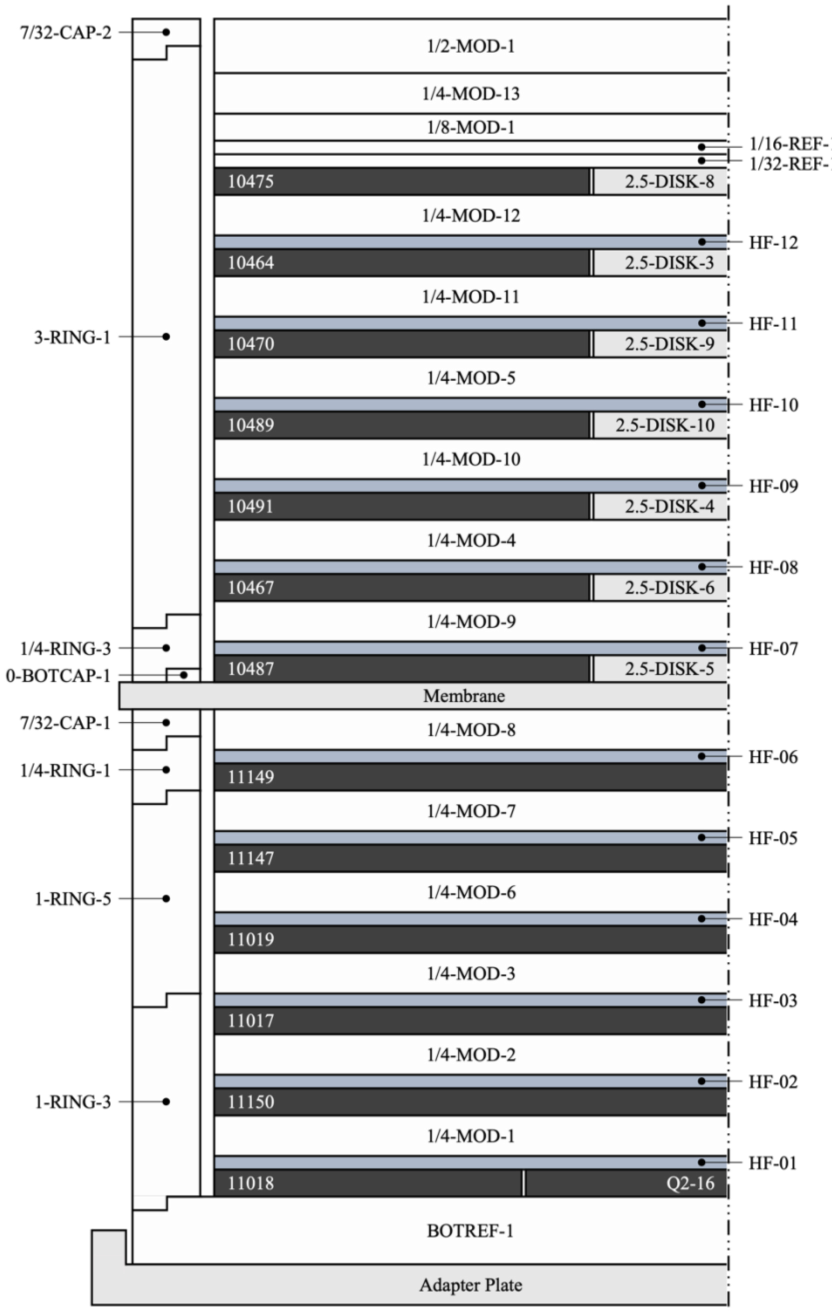


Figure 25. Diagram of the 1/4" Std. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.4 1/2” Standard Configuration

The 1/2” Standard (1/2” Std.) experimental configuration includes 10 HEU plates, nine Hf and 1/2” (1.27 cm) HDPE moderator plates, and a nominal 1” (2.54 cm) top HDPE reflector. These 10 HEU plates consisted of five 15/0-HEU and five 15/2.5-HEU plates, for a total HEU mass of 63.9 kg.

Figure 26 shows a diagram of the 1/2” Std. experimental configuration. Table 47 and Table 48 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 49 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 47. Upper and lower core stack height measurements for 1/2” Std.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	96.71	0.03	98.39	-0.04
2	96.57	0.00	98.29	0.02
3	96.65	0.00	97.90	-0.04
4	96.80	-0.01	98.19	0.00
5	96.94	0.04	98.18	0.07

Table 48. Upper and lower ring reflector height measurements for 1/2” Std.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	97.52	0.02	97.91	0.05

Table 49. Benchmark period measurement for 1/2” Std.

Detector	Benchmark Measurement		
	Period (s)	Excess (¢)	Scale
SU	127.86	7.83	10,000
LC_1	122.75	8.10	10^{-9}
LC_2	123.50	8.06	10^{-9}
LC_3	122.51	8.11	10^{-9}

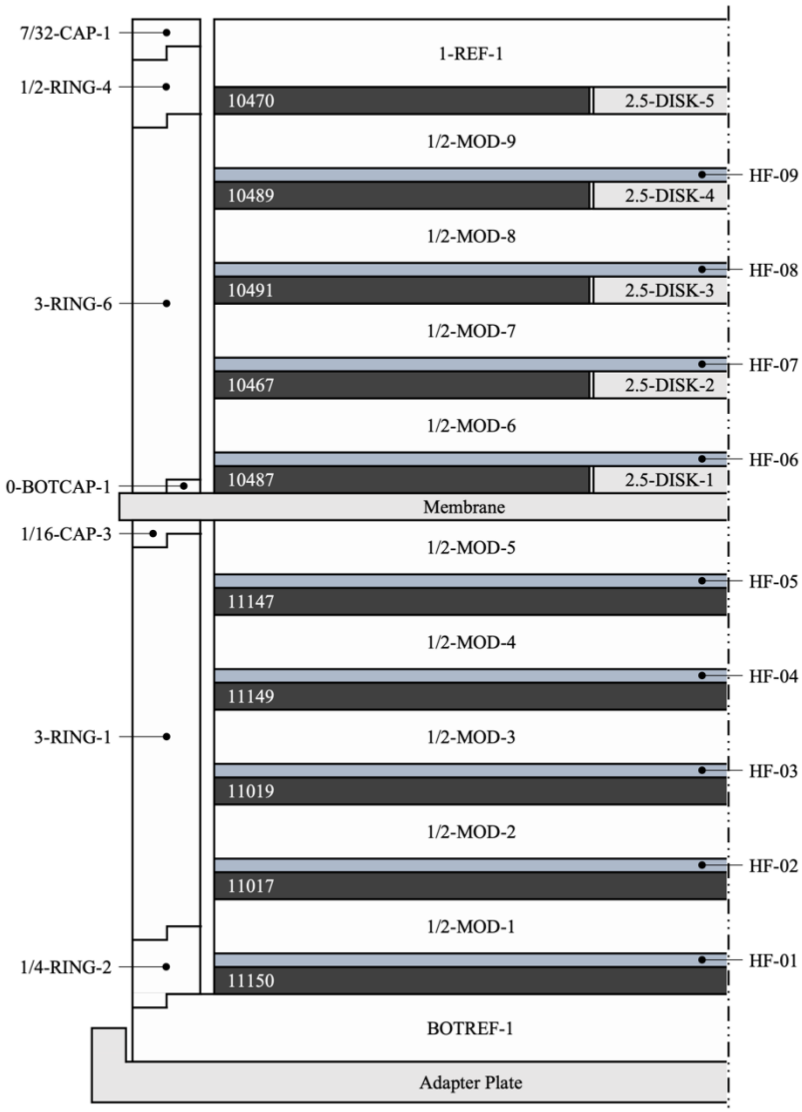


Figure 26. Diagram of the 1/2" Std. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.5 1-1/2” Standard Configuration

The 1-1/2” Standard (1-1/2” Std.) experimental configuration includes 11 HEU plates, 10 Hf and 1.5” (3.81 cm) HDPE moderator plates, and a nominal 1.5” (3.81 cm) top HDPE reflector. These 11 HEU plates consisted of six 15/0-HEU[22] and five 15/6-HEU plates, for a total HEU mass of 70.4 kg.

Figure 27 shows a diagram of the 1-1/2” Std. experimental configuration. Table 50 and Table 51 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 52 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 50. Upper and lower core stack height measurements for 1-1/2” Std.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	254.95	-0.01	226.01	0.08
2	255.22	0.10	226.16	-0.15
3	255.12	0.07	225.62	-0.11
4	255.70	0.06	225.78	0.03
5	255.68	0.08	225.44	-0.05

Table 51. Upper and lower ring reflector height measurements for 1-1/2” Std.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	255.48	0.19	224.08	0.03

Table 52. Benchmark period and reproducibility measurement for 1-1/2” Std.

Detector	Benchmark Measurement			Reproducibility Measurement		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	92.16	10.15	10,000	77.31	11.60	10,000
LC_1	84.30	10.87	10^{-9}	74.70	11.90	10^{-9}
LC_2	85.04	10.80	10^{-9}	75.30	11.83	10^{-9}
LC_3	84.06	10.89	10^{-9}	74.64	11.60	10^{-9}

[22] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

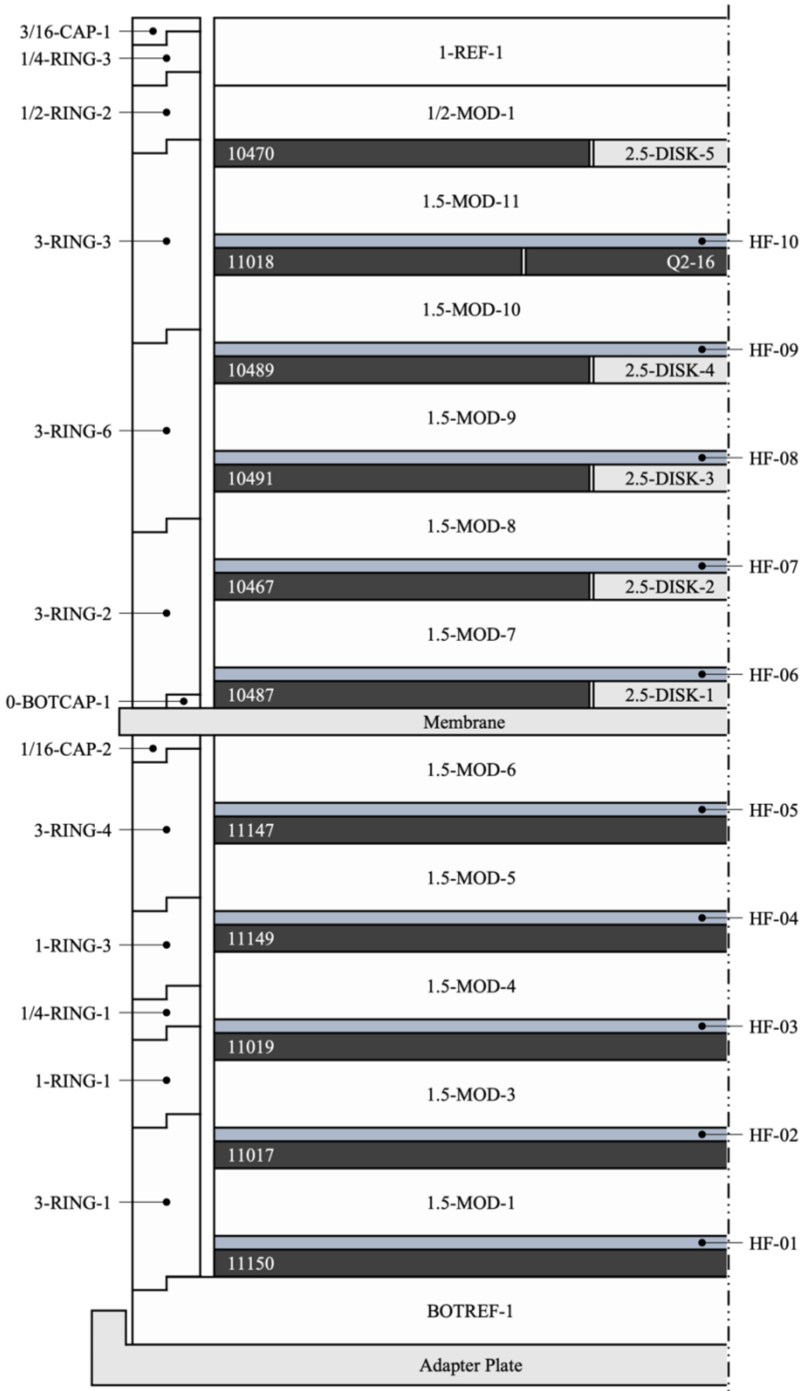


Figure 27. Diagram of the 1-1/2" Std. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.6 1/4” Sandwich Stacking Configuration

The 1/4” Sandwich Stacking (1/4” Sand.) experimental configuration includes 14 HEU plates, 13 Hf plates, 23 1/4” (0.635 cm) HDPE moderator plates, and a nominal 0.96875” (2.46063 cm) top HDPE reflector. These 14 HEU plates consisted of six 15/0-HEU[23], seven 15/2.5-HEU, and one 15/6-HEU plate, for a total HEU mass of 88.4 kg.

Figure 28 shows a diagram of the 1/4” Sand. experimental configuration. Table 53 and Table 54 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 55 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 53. Upper and lower core stack height measurements for 1/4” Sand.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	79.99	-0.10	98.91	0.07
2	79.69	-0.02	98.52	0.07
3	79.80	-0.11	99.12	-0.08
4	80.19	0.12	99.02	0.15
5	80.40	-0.02	97.74	0.02

Table 54. Upper and lower ring reflector height measurements for 1/4” Sand.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	80.30	0.03	97.74	0.00

Table 55. Benchmark period and reproducibility measurement for 1/4” Sand.

Detector	Benchmark Measurement			Reproducibility Measurement		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	53.59	15.09	10,000	53.47	15.11	10,000
LC_1	50.57	15.70	10^{-9}	50.64	15.68	10^{-9}
LC_2	50.96	15.70	10^{-9}	50.91	15.63	10^{-9}
LC_3	50.53	15.70	10^{-9}	50.56	15.70	10^{-9}

[23] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

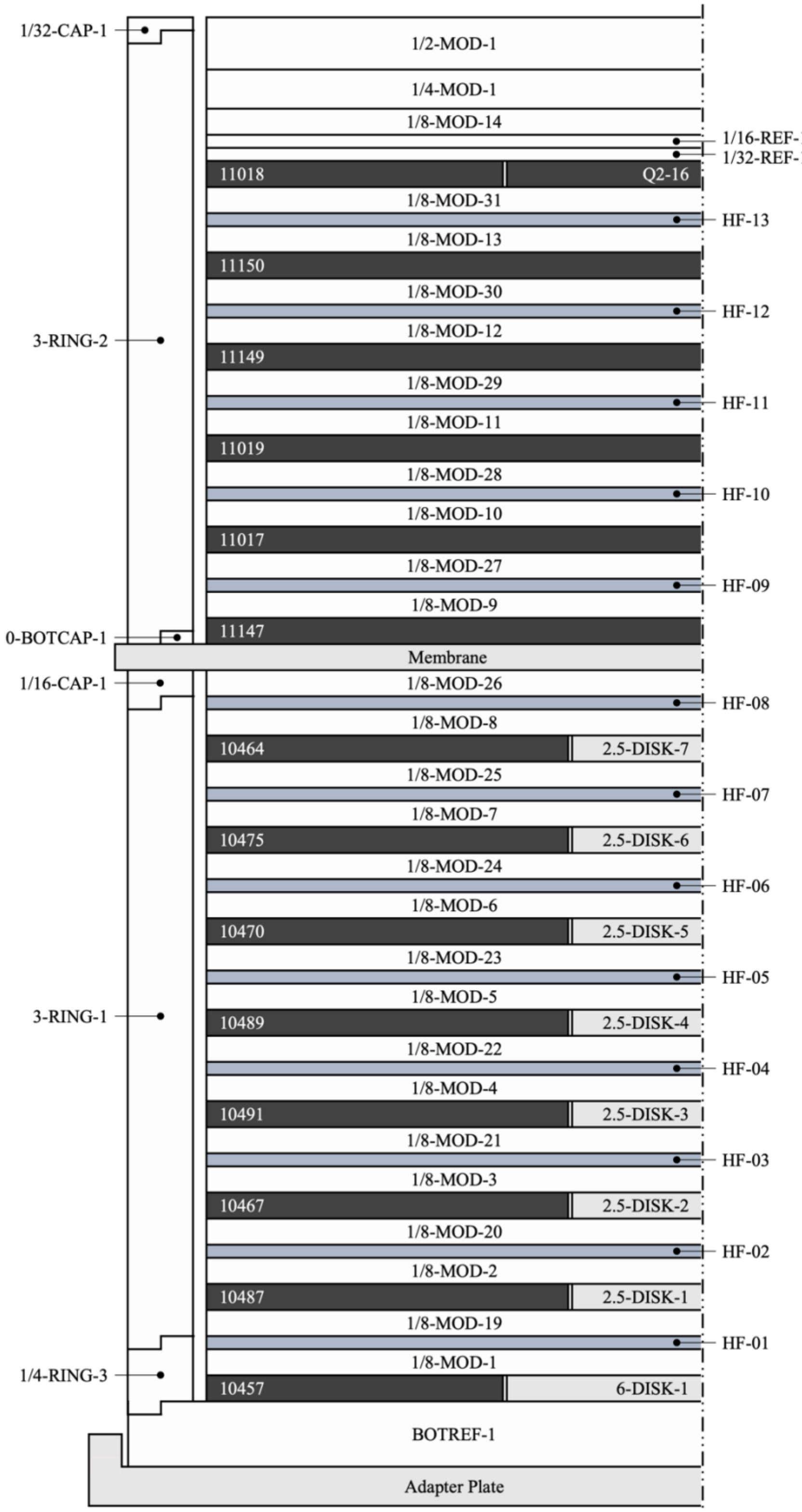


Figure 28. Diagram of the 1/4" Sand. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.2.7 0” Bunched Configuration

The 0” Bunched (0” Bunch.) experimental configuration includes 22 HEU plates, 24 Hf plates, no HDPE moderator plates, and a nominal 1.1875” (3.01625 cm) top HDPE reflector. These 22 HEU plates consisted of six 15/0-HEU[24], seven 15/2.5-HEU, five 15/6-HEU, and four 15/10-HEU plates, for a total HEU mass of 124.7 kg.

Figure 29 shows a diagram of the 0” Bunch. experimental configuration. Table 56 and Table 57 report the upper and lower core stack and ring reflector height measurements for the 0” Std. experimental configuration, as described in Section 2.1.3. Table 58 reports an initial fit of the benchmark and reproducibility period measurements, based on the data described in Section 2.1.1.

Table 56. Upper and lower core stack height measurements for 0” Bunch.

Position	Upper Core Stack (mm)		Lower Core Stack (mm)	
	Height	Drift	Height	Drift
1	74.04	0.05	65.40	0.05
2	74.08	-0.08	64.79	0.01
3	74.23	0.09	65.29	0.08
4	74.32	0.00	64.71	-0.03
5	74.18	0.07	65.19	0.00

Table 57. Upper and lower ring reflector height measurements for 0” Bunch.

Position	Upper Ring Reflector (mm)		Lower Ring Reflector (mm)	
	Height	Drift	Height	Drift
~4	74.83	0.03	64.21	-0.04

Table 58. Benchmark period and reproducibility measurement for 0” Bunch.

Detector	Benchmark Measurement		
	Period (s)	Excess (¢)	Scale
SU	78.10	11.51	10,000
LC_1	73.63	12.03	10^{-9}
LC_2	74.15	11.96	10^{-9}
LC_3	73.62	12.03	10^{-9}

[24] One of the 15/0-HEU plates represents the 15/6-HEU-11018 plate with the Q2-16 piece to form the full plate.

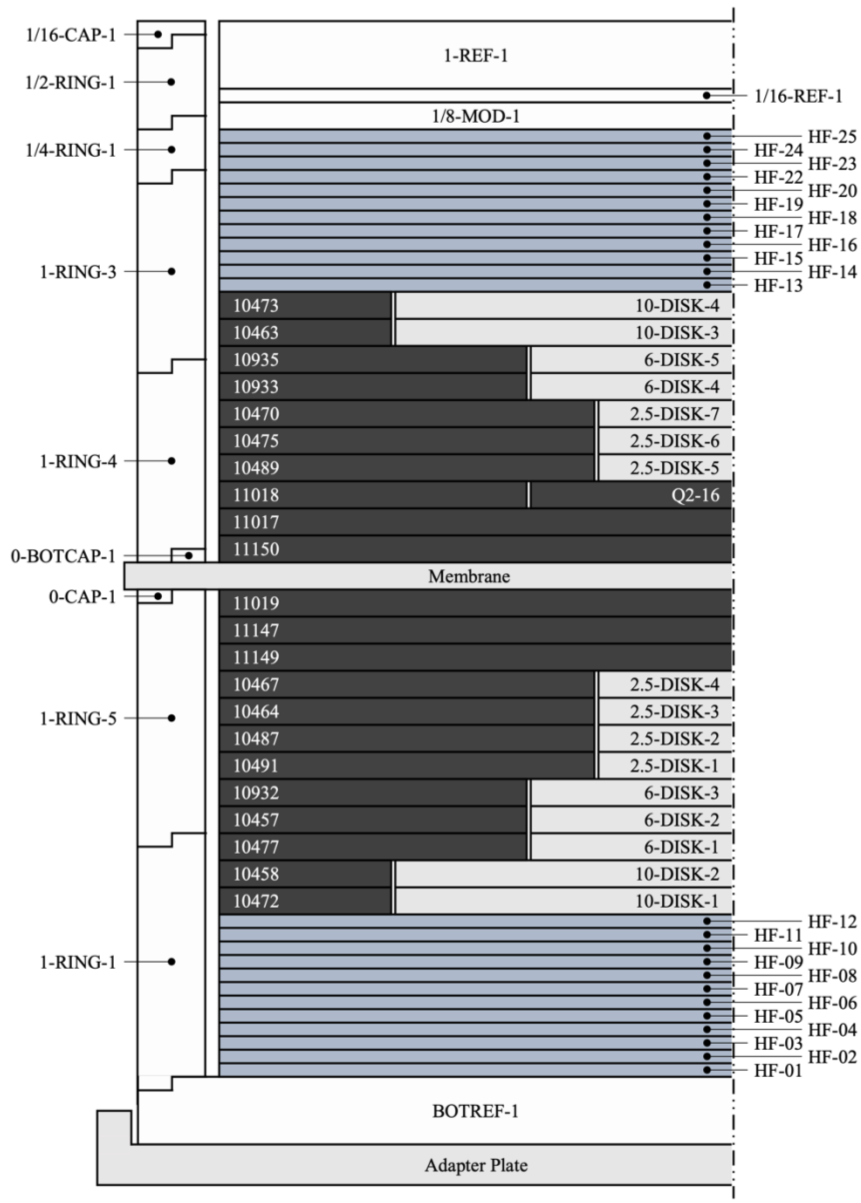


Figure 29. Diagram of the 0" Bunch. benchmark configuration (not to scale, gaps shown are not necessarily present).

2.3 Supplemental Experimental Measurements

This section describes two supplemental measurements performed during the TEX-Hf experiment campaign. The first of these measurements forms the basis for an extrapolation to delayed critical by top reflector thickness for the 0” Bunch. experimental configuration. The second of these measurements characterizes the reactivity worth of gaps in the ring reflector for the 1/4” Sand. experimental configuration.

2.3.1 Extrapolation to Delayed Critical by Top Reflector Thickness

In addition to the benchmark experimental configuration for 0” Bunch. described in Section 2.2.7, two additional experimental configurations were measured to provide the basis for an extrapolation to delayed critical by top reflector thickness. These measurements were performed by adding an additional 1/16” (0.15875 cm) top reflector to the 0” Bunch. experimental configuration. To accommodate this thicker top reflector, the ring reflector cap was also increased from a 1/16-CAP part to 1/8-CAP part.

Figure 30 shows these two additional configurations. This figure shows the changes to the benchmark configuration (Figure 29) in red. Table 59 reports the period measurements of these additional experimental configurations.

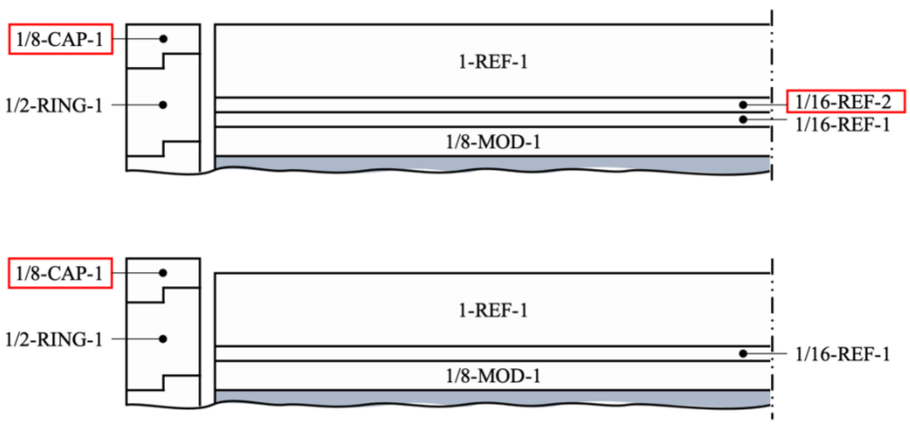


Figure 30. Diagram of the 0” Bunch. delayed critical extrapolation configurations (not to scale). The red boxes show the parts that differ from the benchmark configuration in Figure 29.

Table 59. Period measurements for the additional 0” Bunch. experimental configurations.

Detector	0” Bunch. with 1/8-CAP & 1/16-REF			0” Bunch. with 1/8-CAP		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	38.51	18.78	10,000	77.57	11.57	10,000
LC_1	36.47	19.44	10^{-9}	72.42	12.17	10^{-9}
LC_2	36.68	19.37	10^{-9}	72.81	12.13	10^{-9}
LC_3	36.37	19.47	10^{-9}	72.33	12.18	10^{-9}

2.3.2 Ring Reflector Gap Reactivity Worth

In addition to the benchmark experimental configuration for 1/4” Sand. described in Section 2.2.6, two additional experimental configurations were measured to characterize the reactivity worth of gaps in the ring reflector. These measurements were performed by first swapping the reflector parts used in the lower ring reflector, then swapping the reflector parts used in both the lower and upper ring reflectors.

Figure 31 shows these two additional configurations. This figure shows the changes to the benchmark configuration (Figure 28) in red. Table 60 reports the period measurements of these additional experimental configurations.

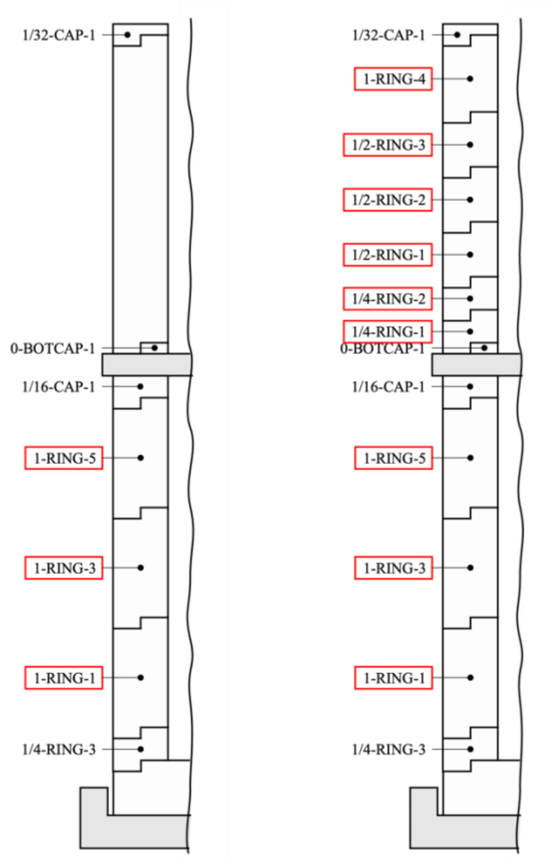


Figure 31. Diagram of the 1/4” Sand. ring reflector reactivity worth configurations (not to scale). The red boxes show the parts that differ from the benchmark configuration in Figure 28.

Table 60. Period measurements for the additional 1/4” Sand. experimental configurations.

Detector	1/4” Sand. with lower swap			1/4” Sand. with lower and upper swap		
	Period (s)	Excess (¢)	Scale	Period (s)	Excess (¢)	Scale
SU	39.87	18.37	10,000	38.65	18.74	10,000
LC_1	37.88	18.98	10^{-9}	37.31	19.16	10^{-9}
LC_2	38.03	18.93	10^{-9}	37.56	19.08	10^{-9}
LC_3	37.82	19.00	10^{-9}	37.25	19.18	10^{-9}

Bibliography

[1] A. Nelson, C. Percher, W. Zywiec and H. David, "IER-297 CED-2: Final Design of the Thermal/Epithermal eXperiments with Jemima Plates with Polyethylene and Hafnium," Lawrence Livermore National Laboratory, 2017.

[2] J. Norris, C. Percher, A. Nelson, W. Wyziec and D. Heinrichs, "TEX-HEU: Integral Experiment Execution of Thermal/Epithermal eXperiments using Highly Enriched Uranium with Polyethylene (IER-297 CED-3b Report)," Lawrence Livermore National Laboratory, 2020.

[3] J. Norris, R. Araj, D. Heinrichs and C. Percher, "TEX-HEU Baseline Assemblies: Highly Enriched Uranium Plates with Polyethylene Moderator and Polyethylene Reflector (IER-297 CED-4b Report)," Lawrence Livermore National Laboratory, 2023.

Appendix A

Engineering Drawings

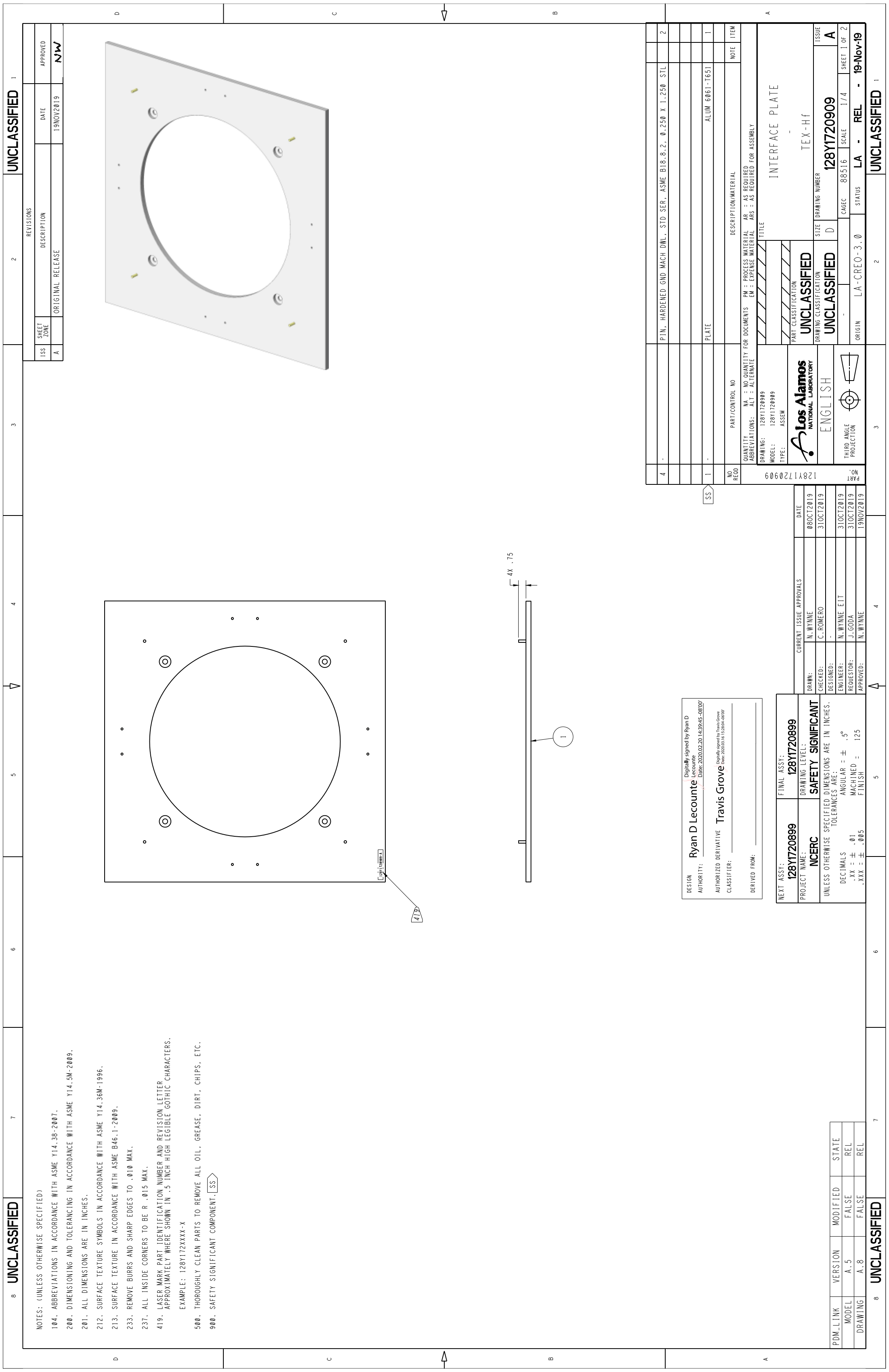
The following sections include various as-designed part drawings for select components of TEX-Hf. Most of these drawings are part of NCERC Project Drawing (LA-UR-20-30439) provided by Los Alamos National Laboratory. The hafnium plate drawing was provided by the Naval Nuclear Laboratory.

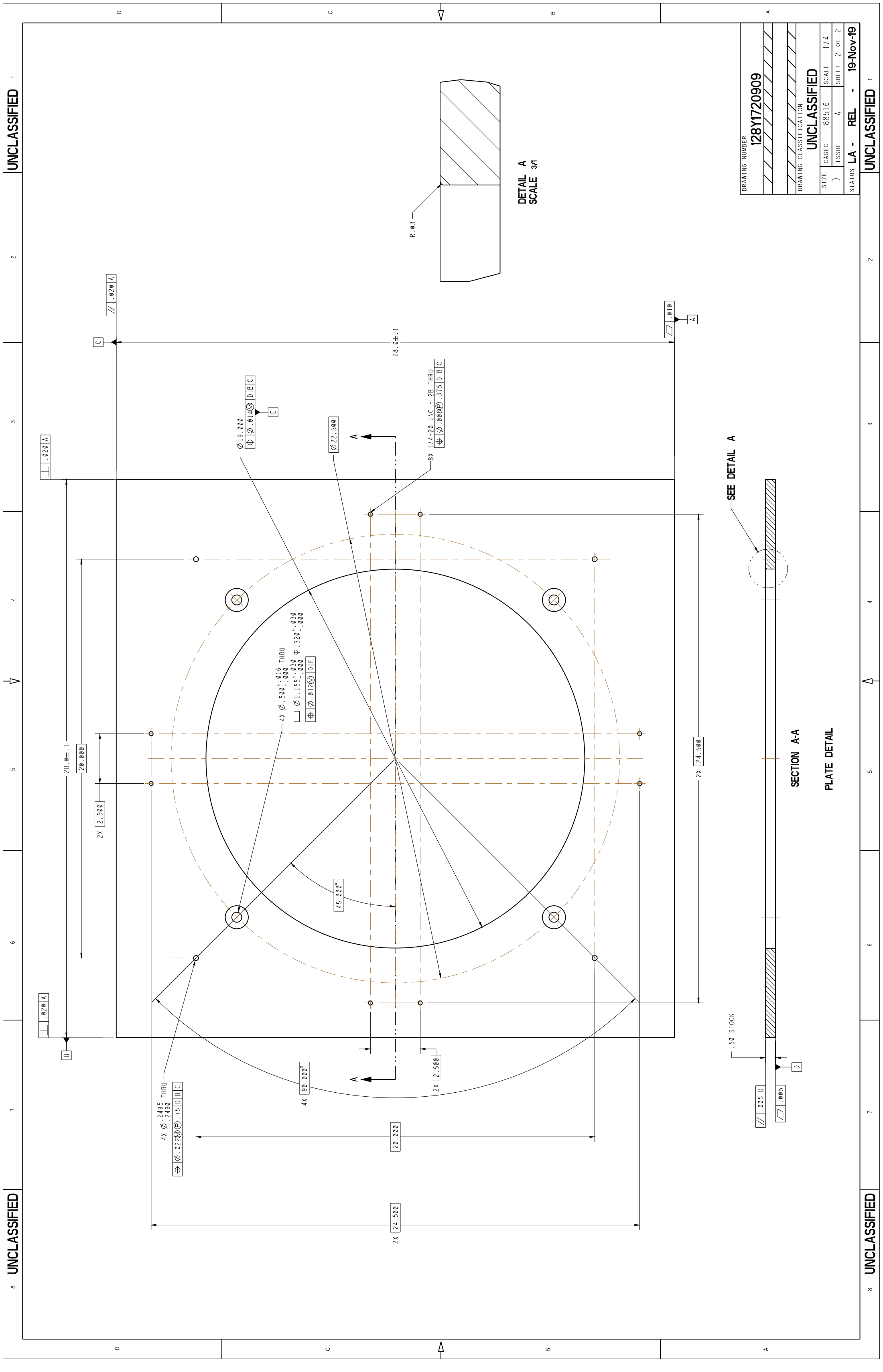
The interface plate (128Y1720909) is affixed to the Comet stationary platform using the 12 in standoffs (128Y1720908-01). The lower adapter consists of two parts which are fastened to the Comet movable platen. The adapter plate (128Y1720900) provides the base which holds the bottom reflector. This plate 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 interface plate using the four pegs.

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 the experiment measurements.

Interface Plate

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DRAWING NUMBER
128Y1720909
DRAWING CLASSIFICATION
UNCLASSIFIED
SIZE D
CAGEC 88516
SCALE 1/4
ISSUE A
SHEET 2 OF 2
STATUS LA - REL - 19-Nov-19
DETAIL A
SCALE 3/1
SEE DETAIL A
SECTION A-A
PLATE DETAIL
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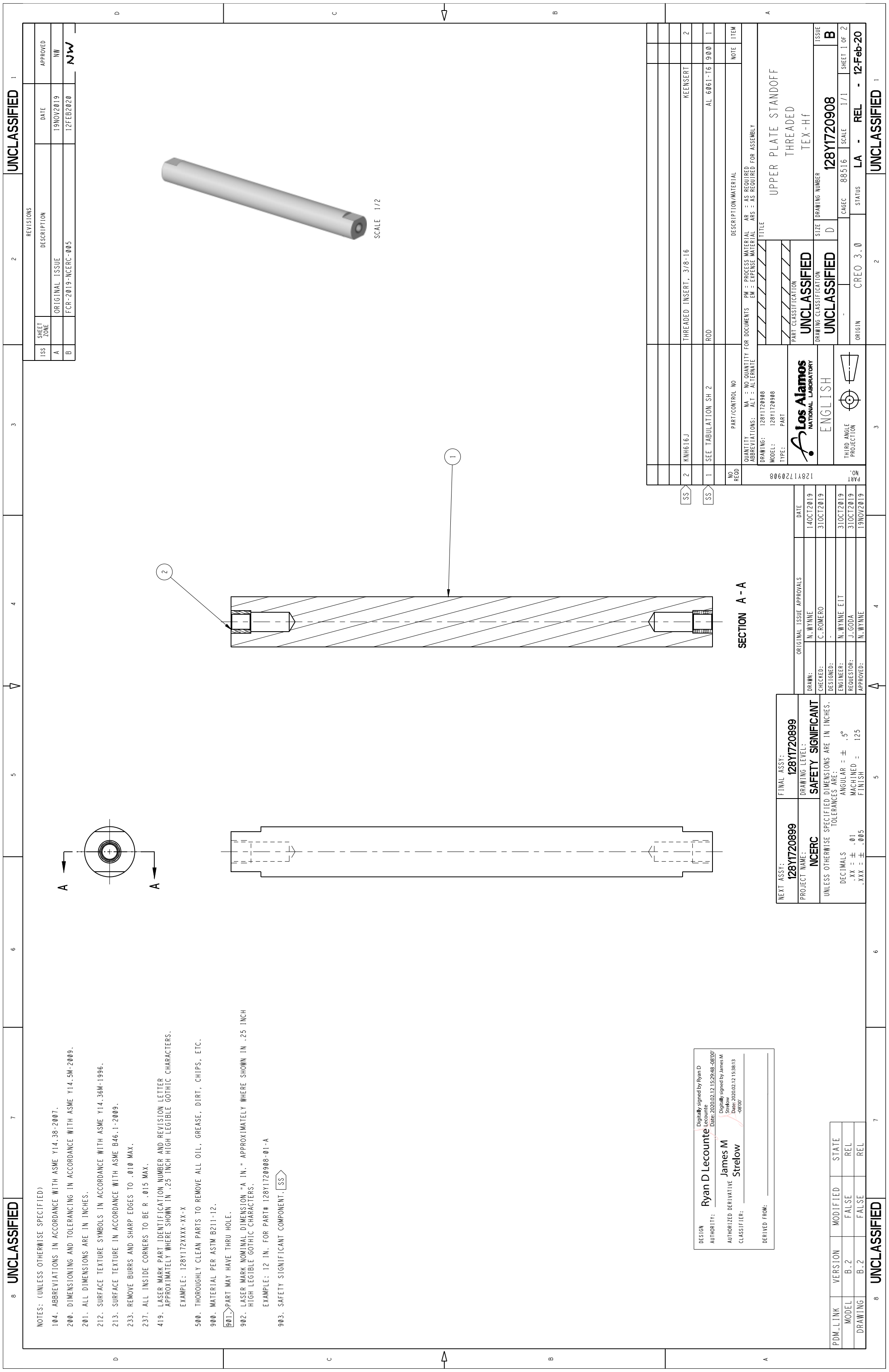
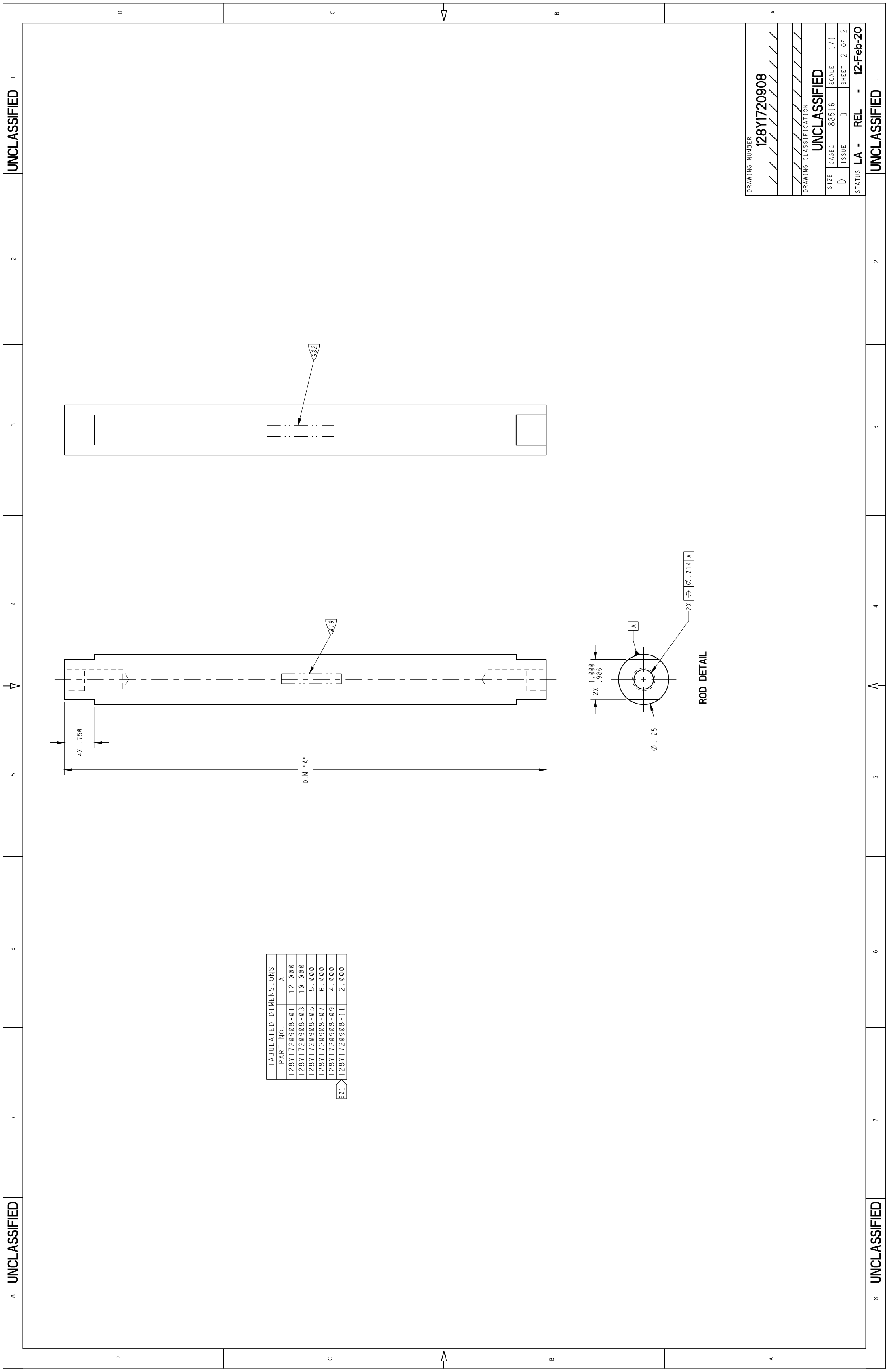
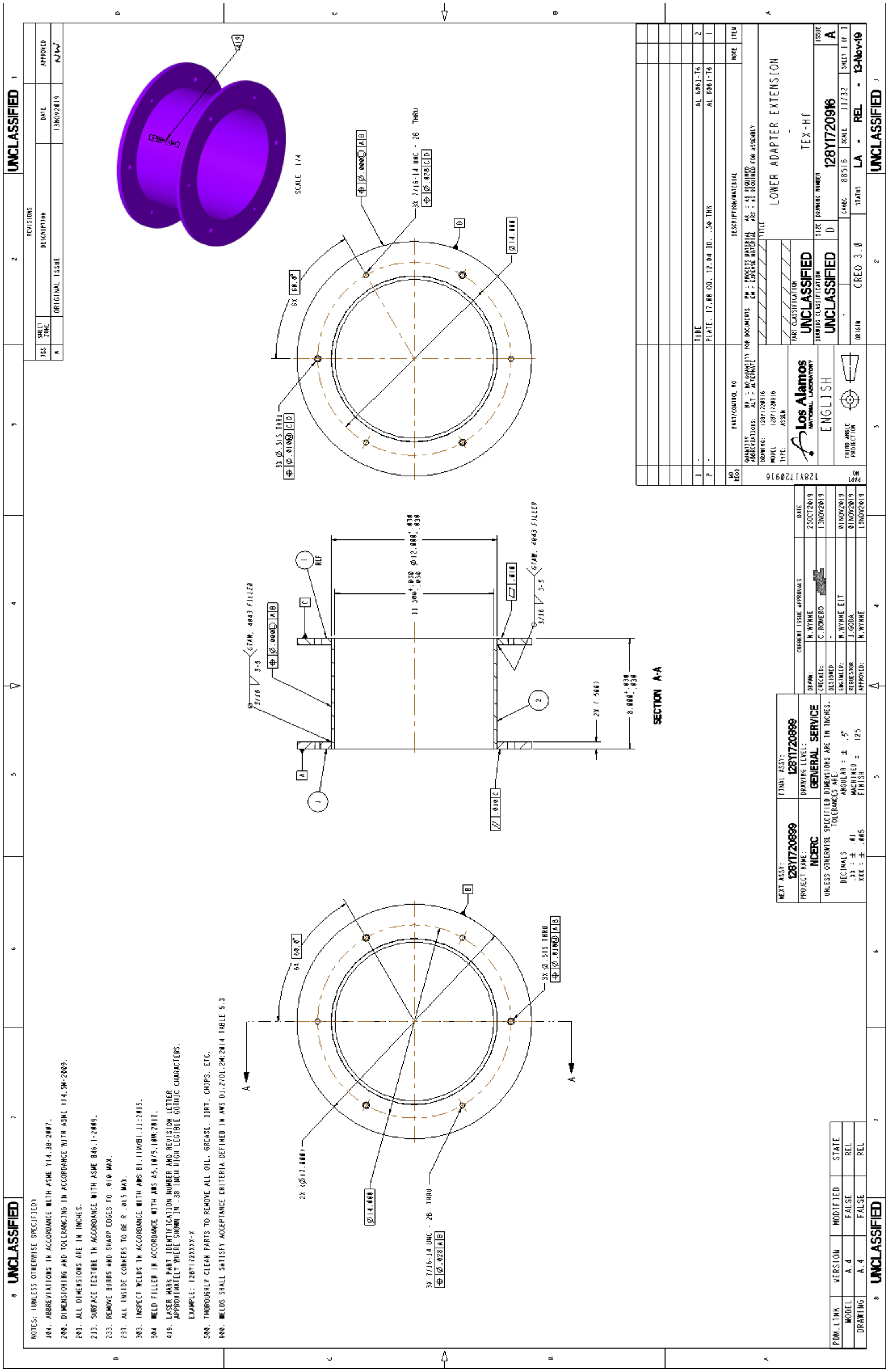
2X 2.500
45.000°
4X 90.000°
.50 STOCK

Standoffs

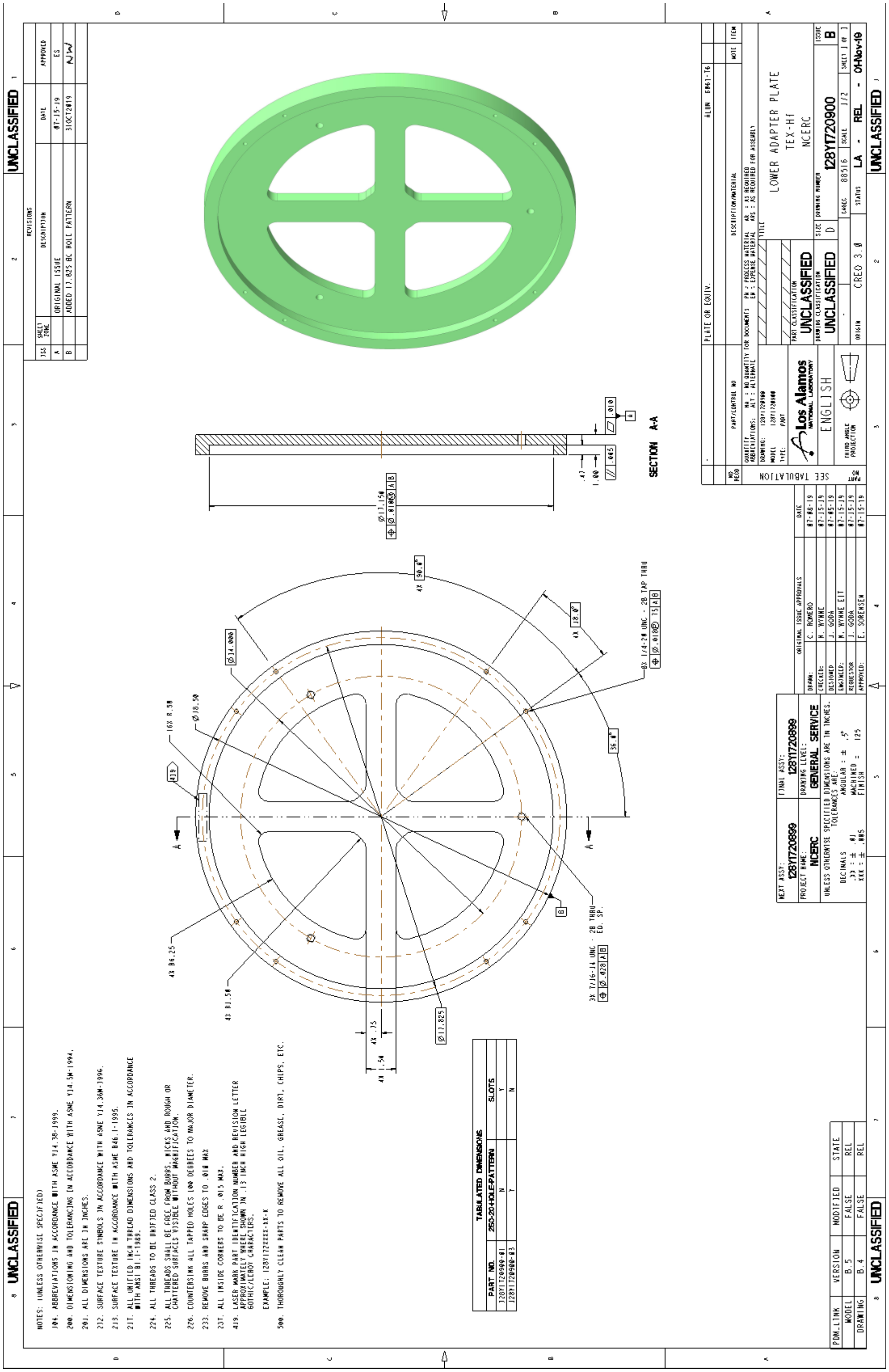

UNCLASSIFIED
UPPER PLATE STANDOFF
THREADED
TEX-Hf
128Y1720908
SECTION A-A
SCALE 1/2
Los Alamos NATIONAL LABORATORY
SAFETY SIGNIFICANT
12-Feb-20


UNCLASSIFIED
DRAWING NUMBER
128Y1720908
DRAWING CLASSIFICATION
UNCLASSIFIED
SIZE D
CAGEC 88516
SCALE 1/1
ISSUE B
SHEET 2 OF 2
STATUS LA - REL - 12-Feb-20
ROD DETAIL
4X .750
DIM "A"
2X 1.000 .986
Ø1.25
2X Ø.014 A
A
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
128Y1720908-11 2.000
901.

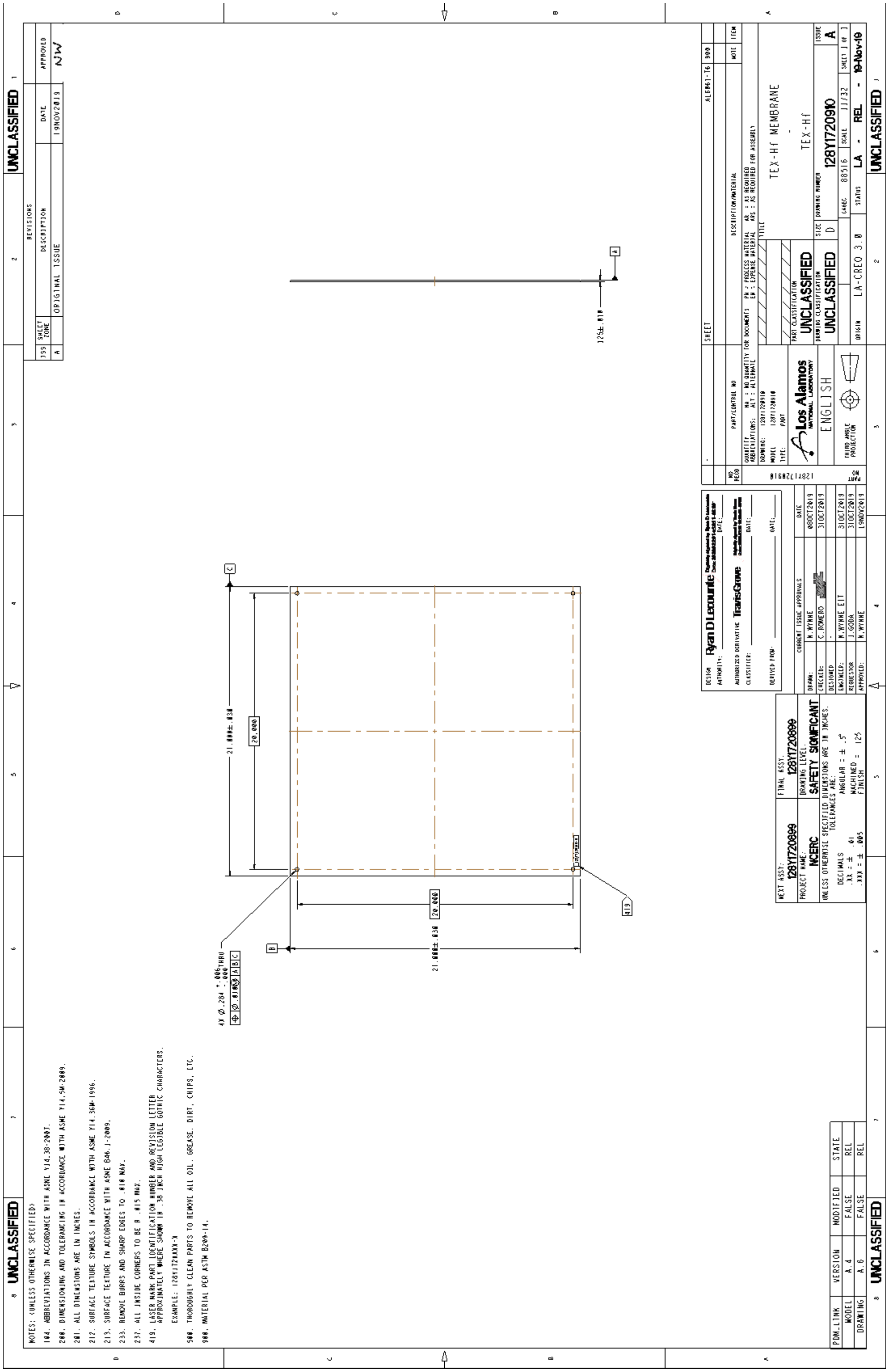
Adapter Extension



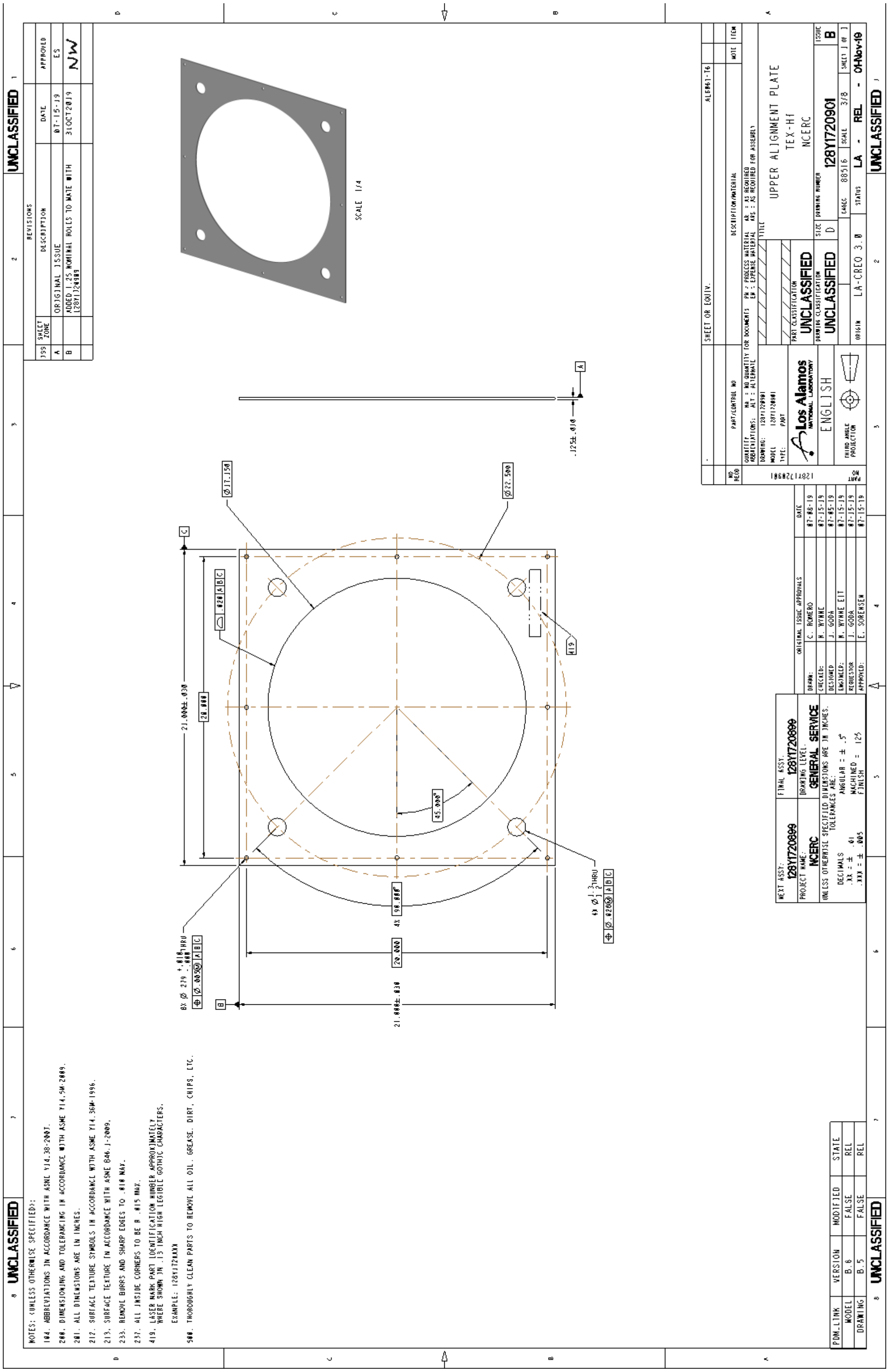
Adapter Plate



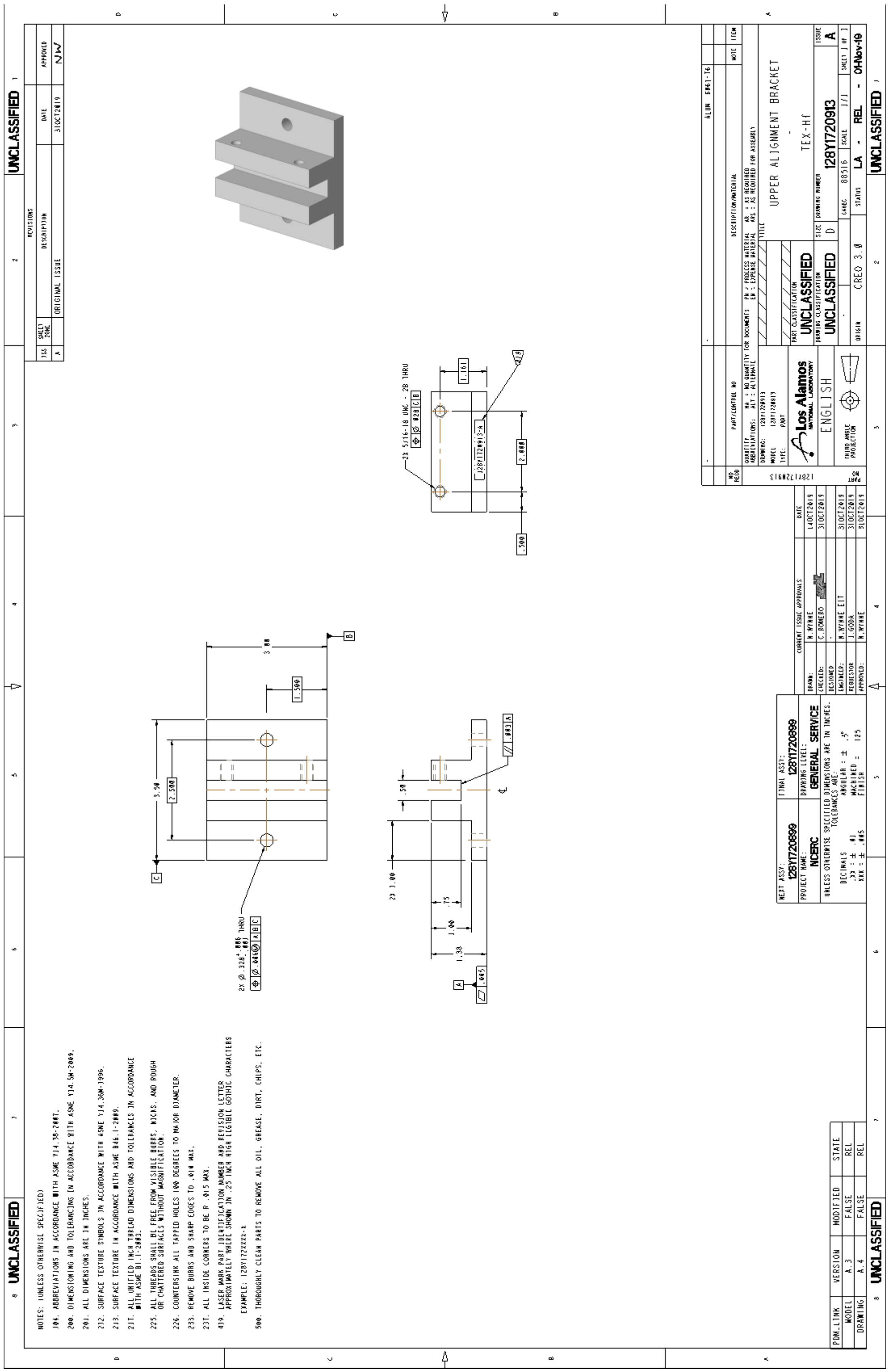
Membrane


UNCLASSIFIED
ORIGINAL ISSUE
19NOV2019
21.000±.030
20.000
TEX-Hf MEMBRANE
TEX-Hf
128Y1720910
Los Alamos NATIONAL LABORATORY
ENGLISH
128Y1720899
NCERC
SAFETY SIGNIFICANT
LA-CREO 3.0

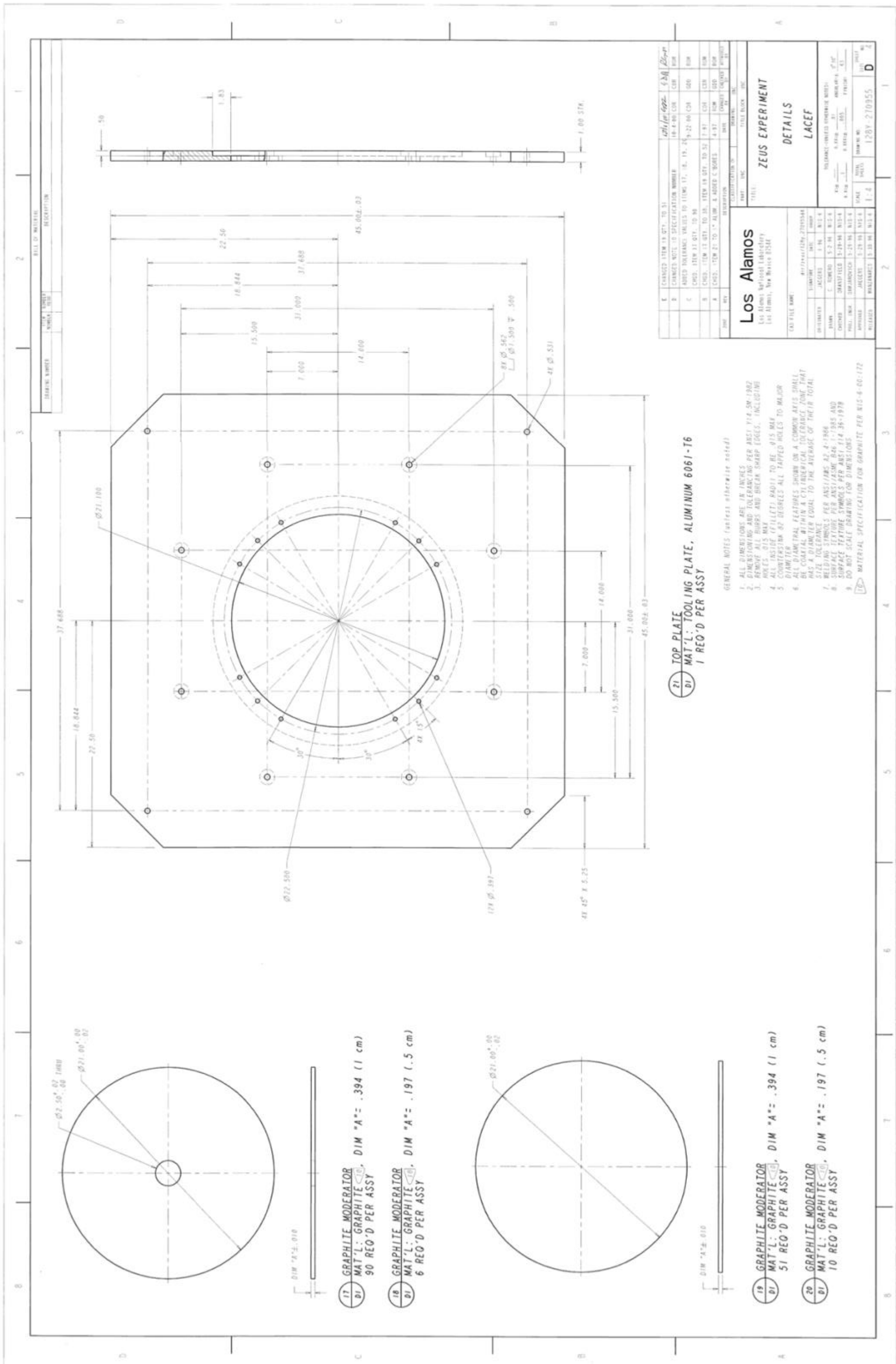
Alignment Plate



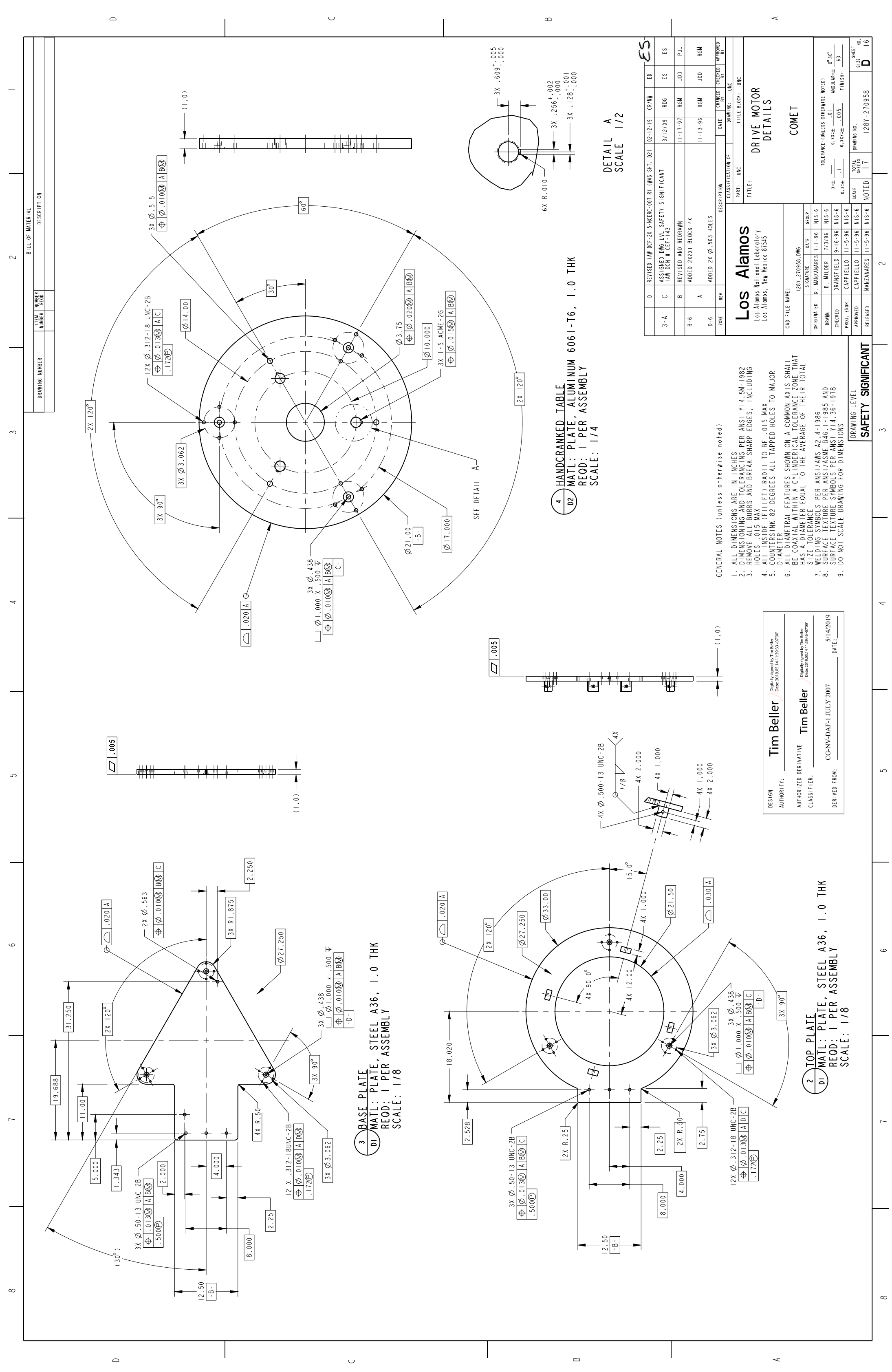
Alignment Bracket



Comet Stationary Platform



Comet Movable Platen



Hafnium Plate