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HEU Pancake (Jemima) Plate Preliminary Characterization Report

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Los Alamos NATIONAL LABORATORY

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The measurements outlined in this report required multiple people to assist with material handling, recording results, performing the measurements, etc. The people who assisted with these measurements include K. Amundson, T. Cutler, S. Garger, A. Harper, C. Kiehne, Z. Lemke, E. Quarshie, N. Rench, R. Sanchez, K. Stolte, N. Whitman, K. Valdez, as well as multiple people from MSTS who support NCERC.

CONTENTS

ACRONYMS AND ABBREVIATIONS

Acronym	Definition
CERBERUS	Critical Experiment Reflected By copper to bEtteR Understand Scattering
CMM	Coordinate Measuring Machine
HEU	Highly Enriched Uranium
ICSBEP	International Criticality Safety Benchmark Evaluation Project
LANL	Los Alamos National Laboratory
NCERC	National Criticality Experiments Research Center
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site

1 Purpose of Characterization

The HEU pancake (Jemima) plates have been used in multiple International Criticality Safety Benchmark Evaluation Project (ICSBEP) evaluations, including: HEU-MET-FAST-072, HEU-MET-FAST-073, HEU-MET-FAST-102, HEU-MET-INTER-006, HEU-MET-INTER-011, HEU-MET-MIXED-021, and IEU-MET-FAST-025. This report only focuses on the physical dimension characterization, since concerns have been identified about reliable diameter and height measurements. Historically, height measurements with calipers and mass measurements have been performed for every plate. However, the combination of previous measurements (mass and caliper height measurements) with the drawing dimensions for the diameters led to unrealistic densities (>19 g/cm^3) or large ranges of densities for parts that were manufactured at the same time (17 g/cm^3 to >19 g/cm^3). Due to the oxidation of the plates, questions about the flatness of each plate and what gaps are introduced into the system have been discussed, since gaps tend to be one of the largest sources of uncertainty in stacked benchmark experiments.[1]

The purpose of this report is to characterize a subset of this commonly used fuel. A uniform method for how to define the HEU pancake plates for ICSBEP evaluations will also be proposed with a discussion on what measurements should be performed on the remaining HEU pancake plates in the NCERC inventory.

2 Description of HEU Pancake (Jemima) Plates

The HEU pancake plates include solid disks (HEU 15/0 and HEU 6/0), disks with alignment holes (HEU 15/2.5), rings (HEU 21/15, HEU 15/6, and HEU 15/10), and wedges. The naming convention for the plates includes the material (HEU) with the outer diameter / inner diameter (both dimensions in inches). The HEU pancake plates were procured at two different times. The first set, which includes the HEU 15/0, 6/0, 15/2.5, and the wedges, were manufactured by Los Alamos Scientific Laboratory (now LANL) in the mid-1950's.[2] The second set, which includes the HEU 21/15, 15/6, and 15/10, were manufactured by Oak Ridge at a later date. The HEU pancake plates were manufactured such that a disk inside an annular ring would fit tightly together (see Figure 1). Each of the HEU wedges has a central angle of 60°. There are no engineering drawings for the HEU wedges, but it is known that they were made from an existing HEU 15/0 plate. Figure 2 through Figure 4 show the engineering drawings for the HEU pancake plates that are available in the NCERC inventory. Oralloy and OY (Oak Ridge Alloy) mentioned in the engineering drawings refer to HEU. A list of all the HEU pancake plates in the NCERC inventory is given in Table 1.

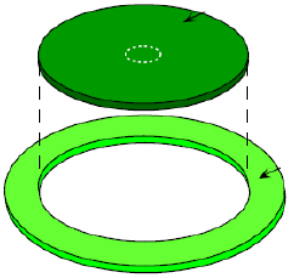

Figure 1: HEU Disks Are Nested Tightly Within HEU Rings.

[1] T. Cutler, K. Amundson, et al., "Analysis of Major Benchmark Uncertainties for Fast Metal Assemblies in the ICSBEP Handbook", *Nuclear Science and Engineering*, vol. 197, issue 7, p. 1331-1355 (July 2023).
[2] J.C. Hoogterp, "Request for Oy (93%)", memo: N-2-871 (May 21, 1958).

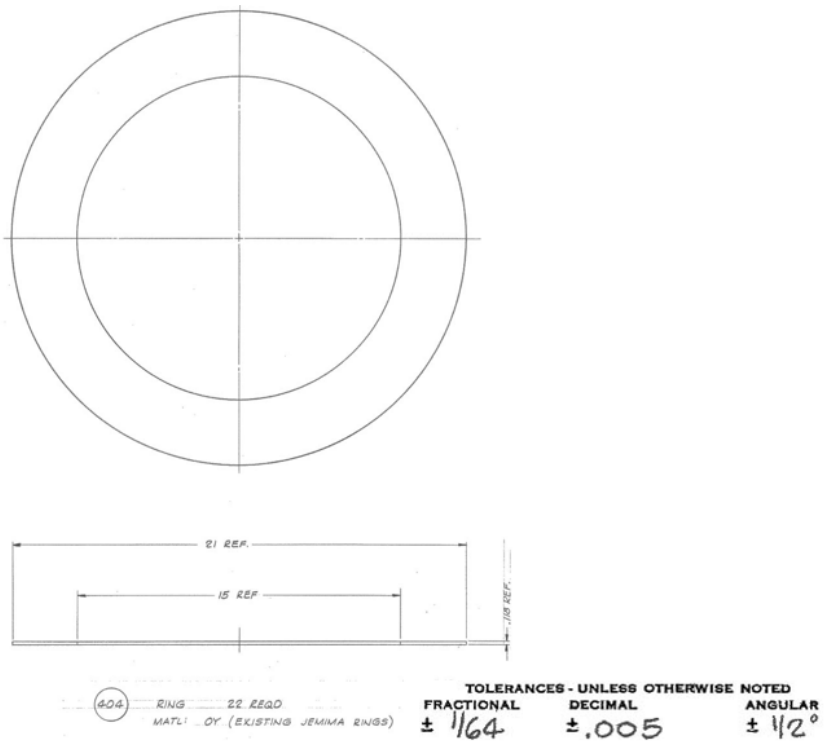

Figure 2: Engineering Drawing (19Y-29621-30A) of the HEU Outer Ring: HEU 21/15 (Dimensions in Inches).

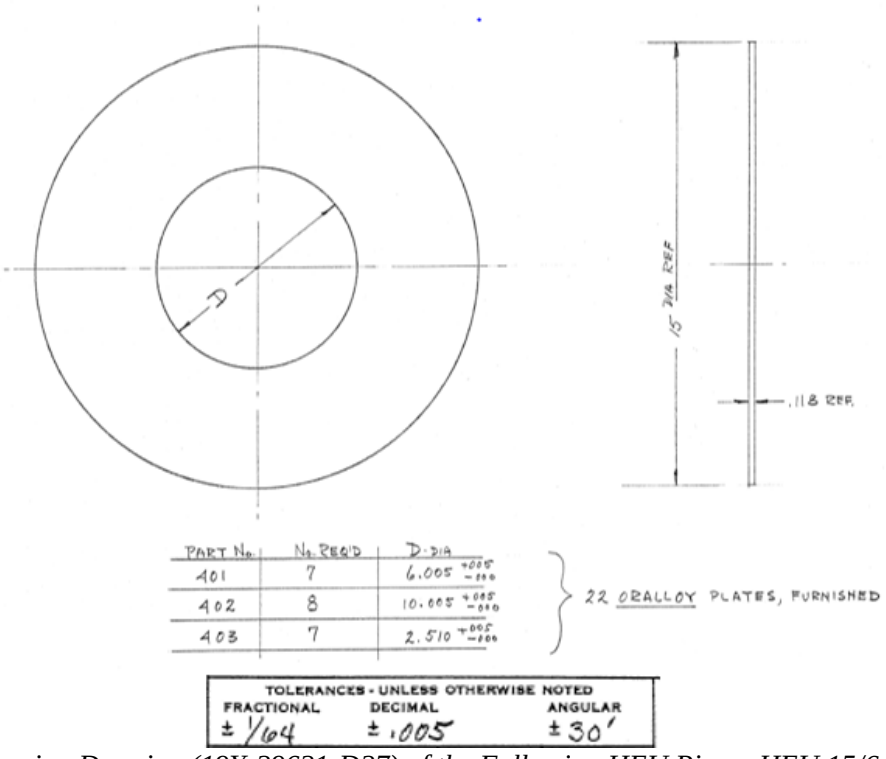

Figure 3: Engineering Drawing (19Y-29621-D27) of the Following HEU Rings: HEU 15/6, 15/10, and 15/2.5 (Dimensions in Inches).

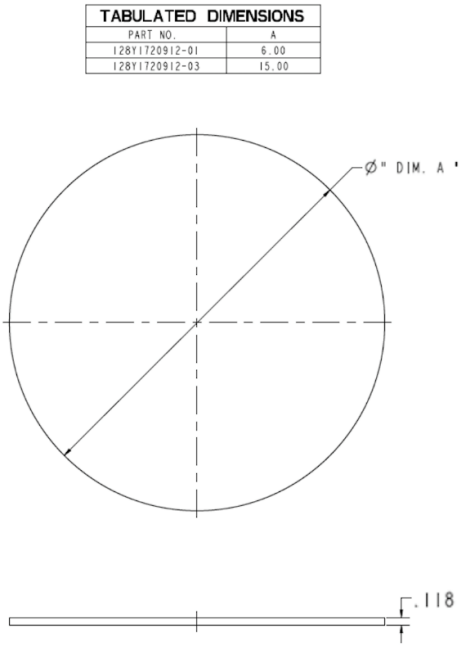

Figure 4: Engineering Drawing (128Y-1720912) of the Following HEU Plates: HEU 15/0 and 6/0 (Dimensions in Inches). (Not an original drawing.)

Table 1: HEU Pancake (Jemima) Plate Inventory at NCERC. Engineering Drawings of the HEU are in Figure 2 through Figure 4.

Plate Type	Outer Diameter [in.]	Inner Diameter [in.]	Height [in.]	Quantity
HEU 15/0	15 ± unspecified	---	0.118 ± unspecified	5
HEU 6/0	6 ± unspecified	---	0.118 ± unspecified	1
HEU 15/2.5	15 ± 0.005	2.510 + 0.005 / - 0.000	0.118 ± 0.005	7
HEU 15/6	15 ± 0.005	6.005 + 0.005 / - 0.000	0.118 ± 0.005	7
HEU 15/10	15 ± 0.005	10.005 + 0.005 / - 0.000	0.118 ± 0.005	8
HEU 21/15	21 ± 0.005	15 ± 0.005	0.118 ± 0.005	31
HEU Wedges	15 ± unspecified	---	0.118 ± unspecified	6

3 Measurements of the HEU Pancake Plates

The three measurements that are evaluated in this report are mass, diameter (outer and inner, if applicable), and height. The most recent set of HEU pancake plate measurements were performed in August 2023 for the Critical Experiment Reflected By copper to bEtteR Understand Scattering (CERBERUS) experiment, which includes both the traditional measurement methods (mass and caliper) and measurements using a coordinate measuring machine (CMM). The measurement results from August 2023 are compared to measurements performed in April 2019. Components measured in 2019 but not in 2023 will be excluded from this report. All measurements were performed using calibrated equipment.

3.1 2019 Measurements

Mass and height measurements of the HEU components were performed in April 2019, to determine if the HEU mass had changed slightly over time due to oxidation. Table 2 lists the dimensions and masses for the HEU pancake plates. The mass measurements were taken using a 16-kg Mettler Toledo scale (MS16001L), which has an accuracy of ±0.2 g on the direct readout and a repeatability of ±0.1 g. Mass measurements of the HEU components were performed with the HEU inside a plastic bag; therefore, measurements of the bag were performed prior to the measurement of the bag and HEU component. The mass reported in Table 2 is the $Mass_{(Bag+HEU)} - Mass_{Bag}$. The 2019 height measurements were performed at three arbitrary points that were roughly 120° apart using a Mitutoyo CD-24 caliper that has an accuracy of ±0.002 in. The caliper has a reading of four digits after the decimal, but the last digit is either a 0 or 5.

Table 2. 2019 Mass and Caliper Measurements of HEU Pancake Plates.

Part Type	ID	2019 Measurements			
		Height [in.]	Avg. [in.]	Standard Deviation [in.]	Mass [g]
HEU 21/15	B-2444-01	0.1190, 0.1190, 0.1190	0.11900	0.00000	6119.7
	B-2444-02	0.1190, 0.1190, 0.1205	0.11950	0.00087	6127.0
	B-2444-03	0.1225, 0.1205, 0.1200	0.12100	0.00132	6105.3
	B-2444-10	0.1195, 0.1190, 0.1175	0.11867	0.00104	6134.5
	B-2444-13	0.1195, 0.1195, 0.1190	0.11933	0.00029	6026.5
	B-2444-19	0.1180, 0.1195, 0.1185	0.11867	0.00076	6125.5
	B-2444-20	0.1180, 0.1185, 0.1185	0.11833	0.00029	6152.2
	B-2444-22	0.1170, 0.1160, 0.1185	0.11717	0.00126	6025.0
	B-2444-24	0.1230, 0.1240, 0.1190	0.12200	0.00265	6089.1
	B-2444-25	0.1185, 0.1180, 0.1175	0.11800	0.00050	6097.8
	B-2444-27	0.1180, 0.1185, 0.1210	0.11917	0.00161	6068.4
	B-2444-29	0.1185, 0.1190, 0.1195	0.11900	0.00050	6130.2
	B-2444-31	0.1225, 0.1190, 0.1210	0.12083	0.00176	6174.8
	B-2444-33	0.1190, 0.1195, 0.1185	0.11900	0.00050	6156.5
	B-2444-36	0.1185, 0.1180, 0.1180	0.11817	0.00029	6124.4
	B-2444-37	0.1190, 0.1185, 0.1185	0.11867	0.00029	6121.4
HEU 15/10	10463	0.1245, 0.1235, 0.1220	0.12333	0.00126	3631.7
	10472	0.1245, 0.1215, 0.1200	0.12200	0.00229	3587.0
HEU 15/2.5	10464	0.1175, 0.1220, 0.1190	0.11950	0.00229	6258.6
	10467	0.1275, 0.1225, 0.1235	0.12450	0.00265	6335.6
	10470	0.1250, 0.1190, 0.1240	0.12267	0.00321	6278.5
	10475	0.1285, 0.1275, 0.1295	0.12850	0.00100	6229.9
	10487	0.1210, 0.1215, 0.1185	0.12033	0.00161	6274.9
	10489	0.1245, 0.1220, 0.1230	0.12317	0.00126	6344.0
	10491	0.1205, 0.1245, 0.1265	0.12383	0.00306	6392.5
HEU 15/0	11017	0.1215, 0.1200, 0.1210	0.12083	0.00076	6505.8
	11019	0.1195, 0.1190, 0.1185	0.11900	0.00050	6473.8
	11147	0.1200, 0.1200, 0.1185	0.11950	0.00087	6519.8
	11149	0.1215, 0.1250, 0.1200	0.12217	0.00257	6385.5
	11150	0.1200, 0.1220, 0.1235	0.12183	0.00176	6419.3
HEU 15/6	11018	0.1190, 0.1190, 0.1195	0.11917	0.00029	5368.5
HEU 6/0	Q2-16	0.1250, 0.1250, 0.1255	0.12517	0.00029	1077.3

3.2 2023 Measurements

Mass, diameter, and height measurements of the HEU components used in the CERBERUS experiment were performed as part of the experiment campaign. Table 3 lists the height and masses for the different HEU components in the assembly. These height measurements were performed at three arbitrary points that were roughly 120° apart using a Brown & Sharpe IP67 caliper that has an accuracy of ±0.001 in. (±0.0254 mm); but the measurements were performed in mm. For plates with an inner diameter, height measurements were performed along the inner diameter as well as the outer diameter.

Mass measurements were taken using a 16-kg Mettler Toledo scale (MS16001L), which has an accuracy of ±0.2 g on the direct readout and a repeatability of ±0.1 g. Mass measurements of the HEU components were performed with the HEU inside a plastic bag; therefore, measurements of the bag were performed prior to the measurement of the bag and HEU component. The mass reported in Table 3 is the $Mass_{(Bag+HEU)} - Mass_{Bag}$. While a single number is reported in Table 3, three mass measurements were performed for each plate and the average is the value reported along with the uncertainty: $\sqrt{\left(\sigma_{bag}/\sqrt{3}\right)^2 + \left(\sigma_{HEU+bag}/\sqrt{3}\right)^2}$.

Table 3. 2023 Mass and Caliper Measurements of the HEU Pancake Plates.

Part Type	ID	2023 Measurements			
		Height [mm]	Avg. [mm]	Standard Deviation [mm]	Avg. Mass [g]
HEU 21/15	B-2444-01	3.00, 3.04, 3.03, 3.04, 3.03, 3.00	3.023	0.017	6110.70 ± 0.061
	B-2444-02	2.97, 2.98, 2.95, 3.04, 3.04, 3.04	3.003	0.038	6109.03 ± 0.054
	B-2444-04	2.97, 3.00, 2.98, 2.99, 2.97, 2.99	2.983	0.011	6105.13 ± 0.119
	B-2444-07	3.04, 3.04, 3.05, 3.01, 3.02, 3.02	3.030	0.014	6107.30 ± 0.082
	B-2444-10	3.03, 3.06, 3.06, 3.04, 3.06, 3.04	3.048	0.012	6129.00 ± 0.077
	B-2444-11	3.03, 3.04, 3.04, 3.05, 3.03, 3.02	3.035	0.010	6120.40 ± 0.061
	B-2444-13	3.05, 3.06, 3.07, 3.03, 3.06, 3.07	3.057	0.014	6021.57 ± 0.027
	B-2444-19	2.99, 2.99, 3.01, 3.00, 2.99, 3.02	3.000	0.012	6121.13 ± 0.027
	B-2444-20	3.02, 3.03, 3.04, 3.02, 3.02, 3.00	3.022	0.012	6152.70 ± 0.038
	B-2444-22	2.95, 2.95, 2.94, 2.85, 2.86, 2.93	2.913	0.042	6023.63 ± 0.152
	B-2444-24	3.02, 3.03, 3.04, 3.00, 3.00, 3.00	3.015	0.016	6089.07 ± 0.027
	B-2444-25	2.99, 3.01, 2.98, 2.98, 2.99, 3.00	2.992	0.011	6095.43 ± 0.178
	B-2444-27	2.99, 2.97, 2.98, 2.98, 2.98, 2.99	2.982	0.007	6065.43 ± 0.166
	B-2444-29	3.05, 3.04, 3.05, 3.05, 3.05, 3.05	3.048	0.004	6126.90 ± 0.000

Part Type	ID	2023 Measurements			
		Height [mm]	Avg. [mm]	Standard Deviation [mm]	Avg. Mass [g]
	B-2444-31	3.04, 3.04, 3.05, 3.04, 3.03, 3.04	3.040	0.006	6165.13 ± 0.038
	B-2444-33	3.01, 3.03, 3.03, 3.01, 3.01, 3.03	3.020	0.010	6155.63 ± 0.061
	B-2444-36	3.03, 3.03, 3.02, 3.03, 3.01, 3.02	3.023	0.007	6124.57 ± 0.077
	B-2444-37	3.01, 3.01, 3.03, 3.00, 3.01, 2.99	3.008	0.012	6122.07 ± 0.038
HEU 15/10	10463	3.10, 3.11, 3.08, 3.11, 3.04, 3.11	3.092	0.025	3632.43 ± 0.128
	10472	3.07, 3.03, 3.04, 3.05, 3.06, 3.03	3.047	0.015	3586.10 ± 0.000
	10479	3.02, 3.01, 3.06, 3.00, 3.03, 3.04	3.027	0.020	3564.27 ± 0.027
HEU 15/2.5	10464	3.07, 3.04, 3.06, 3.05, 3.04, 3.02	3.047	0.016	6258.27 ± 0.038
	10467	3.07, 3.07, 3.08, 3.04, 3.08, 3.08	3.070	0.014	6335.80 ± 0.000
	10470	3.06, 3.06, 3.08, 3.04, 3.00, 3.00	3.040	0.031	6278.33 ±0.072
	10475	3.04, 3.03, 3.03, 2.99, 3.00, 3.02	3.018	0.018	6228.03 ± 0.038
	10487	3.05, 3.06, 3.06, 3.01, 3.03, 3.01	3.037	0.021	6274.83 ± 0.054
	10489	3.10, 3.09, 3.05, 3.04, 3.04, 3.06	3.063	0.024	6343.50 ± 0.038
	10491	3.14, 3.13, 3.14, 3.06, 3.15, 3.15	3.128	0.031	6391.67 ± 0.027
HEU 15/0	11017	3.02, 3.03, 3.02	3.023	0.005	6497.00 ± 0.038
	11019	3.01, 3.01, 3.00	3.007	0.005	6468.60 ± 0.038
	11147	3.07, 3.09, 3.09	3.083	0.009	6511.90 ± 0.000
	11149	3.00, 3.02, 3.02	3.013	0.009	6382.43 ± 0.077
	11150	3.00, 2.99, 3.01	3.000	0.008	6404.37 ± 0.038
HEU 15/6	11018	3.06, 3.06, 3.06, 3.00, 2.99, 2.97	3.023	0.038	5369.00 ± 0.054
	10457	3.14, 3.18, 3.11, 3.12, 3.16, 3.10	3.135	0.028	5574.07 ± 0.072
	10477	3.12, 3.09, 3.11, 3.12, 3.07, 3.03	3.090	0.032	5498.53 ± 0.054
	10493	3.07, 3.05, 3.05, 3.08, 3.03, 3.04	3.053	0.017	5434.47 ± 0.038
HEU 6/0	Q2-16	3.27, 3.22, 3.24	3.243	0.021	1074.87 ± 0.038

Diameter and height measurements were also performed using a Hexagon Absolute Arm V2P, 8525, 7-Axis CMM, which has an accuracy of ±0.001 in. (±0.00254 cm) over the length of the arm. All measurements were performed directly on a granite surfance plate and with the HEU pancake plate laying flat, as it would in recent critical experiments. Diameters were calculated by taking multiple point

measurements moving the ruby tip of the CMM probe along the interface between the granite surface and the surface of the HEU pancake plate. An example of an outer diameter measurmenet being performed is shown in Figure 5. The point measurements were used to calculate the diameter of a best fit cylinder using Hexagon's Inspire software.[3] Along with reporting the diameter of the best fit cylinder, a value is reported to identify how far some points differ from the best fit value. This value, denoted by ± in Table 4, describes the range of calculated diameters using the measured points. The results of the CMM diameter measurements are reported in Table 4.

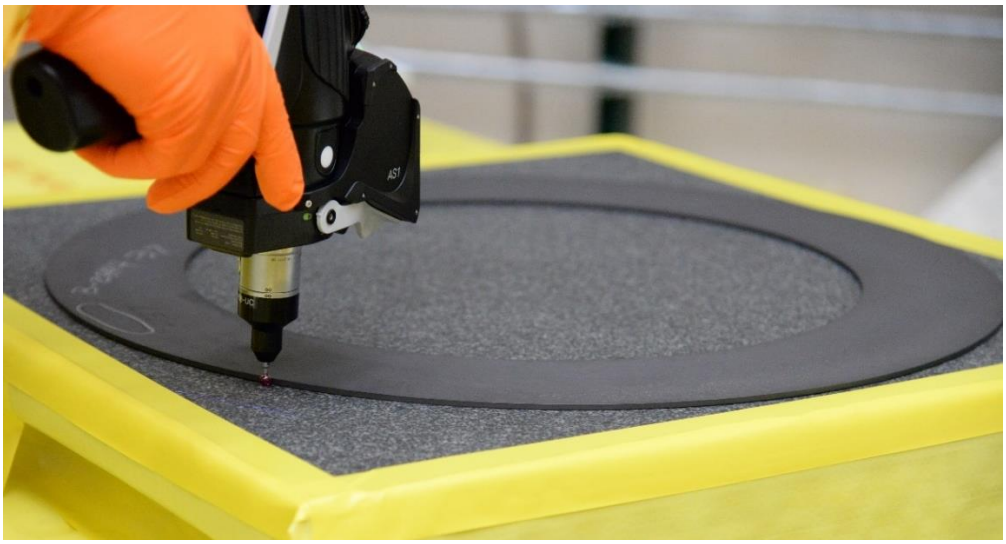

Figure 5. Data Point for Outer Diameter Measurement Using the CMM.

Table 4. Diameter Measurements Using the CMM.

Part Type	ID	Outer Diameter		Inner Diameter	
		[cm]	± [cm]	[cm]	± [cm]
HEU 21/15	B-2444-01	53.356	0.005	38.136	0.003
	B-2444-02	53.354	0.004	38.135	0.002
	B-2444-04	53.353	0.003	38.138	0.005
	B-2444-07	53.365	0.001	38.132	0.002
	B-2444-10	53.359	0.002	38.142	0.002
	B-2444-11	53.350	0.001	38.128	0.003
	B-2444-13	53.354	0.001	38.135	0.003
	B-2444-19	53.355	0.005	38.140	0.004
	B-2444-20	53.361	0.000	38.150	0.001
	B-2444-22	53.374	0.001	38.130	0.002
	B-2444-24	53.290	0.004	38.127	0.011
	B-2444-25	53.349	0.003	38.121	0.001
	B-2444-27	53.359	0.004	38.130	0.006
	B-2444-29	53.354	0.003	38.123	0.001
	B-2444-31	53.353	0.003	38.117	0.004
	B-2444-33	53.357	0.005	38.123	0.005
	B-2444-36	53.359	0.012	38.124	0.002
	B-2444-37	53.350	0.001	38.126	0.005

[3] *Inspire.* [software program]. Hexagon. https://hexagon.com/products/inspire

Part Type	ID	Outer Diameter		Inner Diameter	
		[cm]	± [cm]	[cm]	± [cm]
HEU 15/10	10463	38.086	0.001	25.398	0.001
	10472	38.087	0.001	25.397	0.001
	10479	38.083	0.001	25.398	0.001
HEU 15/2.5	10464	38.088	0.002	6.378	0.001
	10467	38.085	0.001	6.381	0.001
	10470	38.093	0.001	6.338	0.008
	10475	38.085	0.001	6.370	0.001
	10487	38.088	0.001	6.380	0.000
	10489	38.091	0.001	6.379	0.000
	10491	38.084	0.002	6.372	0.001
HEU 15/0	11017	38.096	0.001	Not Applicable	
	11019	38.097	0.001		
	11147	38.101	0.001		
	11149	38.092	0.001		
	11150	38.088	0.007		
HEU 15/6	11018	38.096	0.003	15.258	0.001
	10457	38.091	0.001	15.256	0.001
	10477	38.086	0.001	15.262	0.001
	10493	38.084	0.001	15.255	0.001
HEU 6/0	Q2-16	15.214	0.001	Not Applicable	

Height measurements with the CMM were performed using multiple point measurements to create a plane that represents the top of the HEU pancake plate and another for the granite surface plate. These planes can then be subtracted to calculate the height. Four different planes on top of the HEU pancake plates were used to “measure” the height of each plate. The first plane took ~12 random point measurements over the entire top surface of the HEU (Height 100%). The other three measurements took ~6 random point measurements over ~1/3 of the top surface of the HEU (Height 1/3), which in combination covered the entire top surface of the HEU (see Figure 6). An example of a height measurement being performed is shown in Figure 7. The results of height measurements with the CMM are shown in Table 5. The average and standard deviation are reported using the three Height 1/3 values, which can be compared to the Height 100% value.

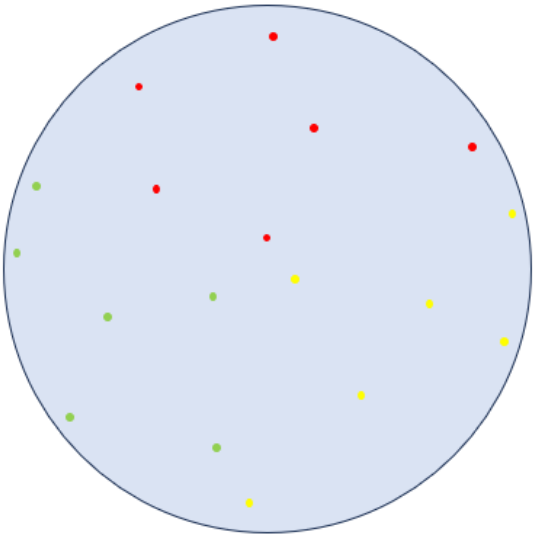

Figure 6. Example data points for the Height 1/3 measurements, where the green, red, and yellow dots represent one of the three measurements Height 1/3 measurements that cover an entire plate.

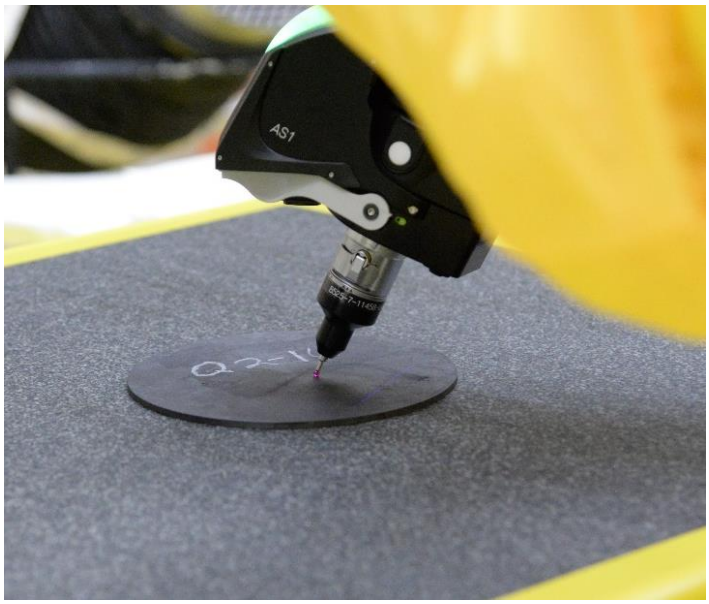

Figure 7. Data Point for Height Measurement Using the CMM.

Table 5. Height Measurements Using the CMM.

Part Type	ID	Height 100% [cm]	Height 1/3 [cm]				
			1	2	3	Average [cm]	Standard Deviation [cm]
HEU 21/15	B-2444-01	0.336	0.338	0.334	0.338	0.3365	0.0019
	B-2444-02	0.322	0.330	0.311	0.325	0.3220	0.0080
	B-2444-04	0.467	0.340	0.658	0.588	0.5287	0.1364
	B-2444-07	0.310	0.312	0.308	0.314	0.3110	0.0025
	B-2444-10	0.345	0.351	0.347	0.334	0.3440	0.0073
	B-2444-11	0.312	0.325	0.310	0.311	0.3145	0.0068

Part Type	ID	Height 100% [cm]	Height 1/3 [cm]				
			1	2	3	Average [cm]	Standard Deviation [cm]
	B-2444-13	0.389	0.401	0.387	0.416	0.3983	0.0118
	B-2444-19	0.329	0.319	0.316	0.338	0.3255	0.0097
	B-2444-20	0.328	0.319	0.309	0.369	0.3313	0.0262
	B-2444-22	0.329	0.329	0.335	0.331	0.3317	0.0025
	B-2444-24	0.322	0.314	0.321	0.320	0.3193	0.0031
	B-2444-25	0.337	0.308	0.345	0.379	0.3440	0.0290
	B-2444-27	0.342	0.344	0.356	0.374	0.3580	0.0123
	B-2444-29	0.339	0.322	0.355	0.323	0.3348	0.0153
	B-2444-31	0.364	0.350	0.373	0.352	0.3583	0.0104
	B-2444-33	0.335	0.328	0.321	0.343	0.3318	0.0092
	B-2444-36	0.341	0.316	0.313	0.360	0.3297	0.0215
	B-2444-37	0.327	0.330	0.336	0.323	0.3297	0.0053
HEU 15/10	10463	0.324	0.326	0.326	0.324	0.3253	0.0009
	10472	0.356	0.353	0.367	0.356	0.3587	0.0060
	10479	0.313	0.317	0.318	0.310	0.3145	0.0036
HEU 15/2.5	10464	0.356	0.371	0.349	0.349	0.3563	0.0104
	10467	0.322	0.324	0.325	0.319	0.3225	0.0026
	10470	0.321	0.328	0.322	0.320	0.3228	0.0034
	10475	0.321	0.328	0.322	0.312	0.3208	0.0066
	10487	0.327	0.327	0.325	0.335	0.3290	0.0043
	10489	0.322	0.318	0.323	0.325	0.3220	0.0029
	10491	0.348	0.345	0.347	0.351	0.3477	0.0025
HEU 15/0	11017	0.323	0.322	0.314	0.330	0.3223	0.0065
	11019	0.319	0.328	0.311	0.329	0.3218	0.0083
	11147	0.348	0.346	0.356	0.348	0.3500	0.0043
	11149	0.325	0.340	0.329	0.321	0.3288	0.0078
	11150	0.342	0.342	0.351	0.338	0.3437	0.0054
HEU 15/6	11018	0.313	0.311	0.308	0.317	0.3120	0.0037
	10457	0.338	0.335	0.343	0.341	0.3393	0.0034
	10477	0.324	0.333	0.331	0.320	0.3280	0.0057
	10493	0.327	0.334	0.321	0.323	0.3260	0.0057
HEU 6/0	Q2-16	0.324	0.324	0.325	0.327	0.3253	0.0012

4 Analysis

The primary motive for performing additional measurements on the HEU pancake plates was to attempt to resolve calculated densities (using measured masses, heights, and nominal diameters) that are unrealistic for HEU (>19 g/cm^3).

4.1 Comparison of Using Different Measurements for Density Calculations

There are multiple combinations of measurements that can be used to calculate the density for each individual HEU pancake plate. Density calculations using the nominal drawing dimensions, caliper height measurements, CMM height measurements, and mass measurements were performed. However, the

density is expected to be similar across the entire inventory because they were manufactured using the same method and have similar compositions.

Figure 8 summarizes the distribution of height measurements that could be used for the density calculations: 2023 caliper measurements, 2023 CMM measurements, or 2019 caliper measurements. The caliper measurements are the most consistent across all the HEU pancake plates, with the 2023 caliper measurements being slightly smaller than the 2019 measurement for the same plate.

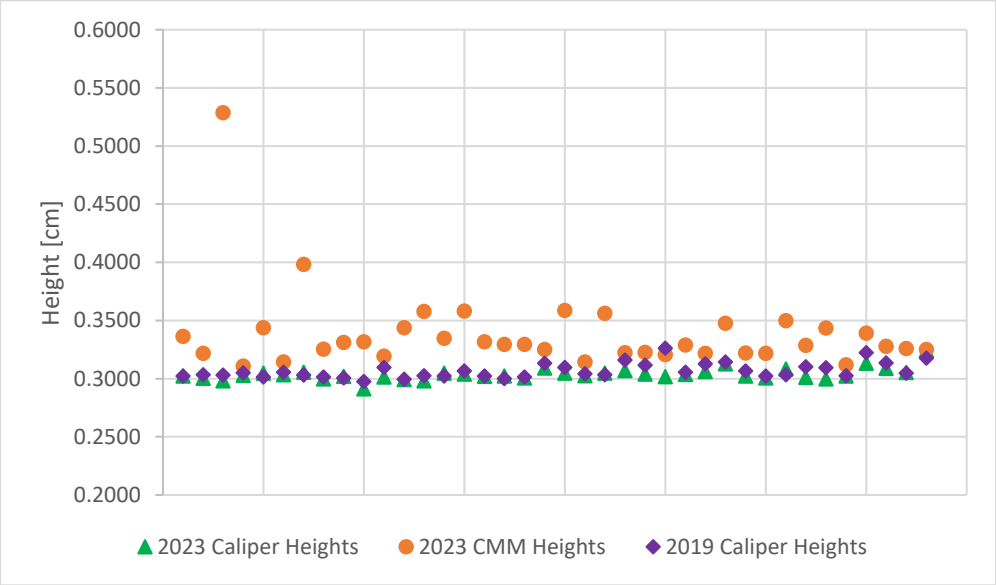

Figure 8. Distribution of Height Measurements.

4.1.1 *Density Calculations Using 2023 Mass Measurements*

In previous ICSBEP evaluations, nominal diameters with caliper height measurements were used to determine the density of the HEU pancake plates. However, this method led to unrealistic density measurements as well as a large distribution of density values. Different combinations of available measurements will be investigated in this report: using only nominal dimensions (Table 6), using nominal diameters and caliper heights (Table 7), using only CMM measurements (Table 8), and using CMM measurements for the diameters and calipers for the heights (Table 9). All density calculations reported in Table 6 through Table 9 use the 2023 mass measurements (see Table 3).

Table 6. Density Calculations of the HEU Pancake Plates Using Nominal Dimensions and 2023 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.34	38.10	0.29972	18.6279
	B-2444-02				18.6228
	B-2444-04				18.6109
	B-2444-07				18.6175
	B-2444-10				18.6837
	B-2444-11				18.6575
	B-2444-13				18.3562
	B-2444-19				18.6597
	B-2444-20				18.7559
	B-2444-22				18.3625
	B-2444-24				18.5620
	B-2444-25				18.5814
	B-2444-27				18.4899
	B-2444-29				18.6773
	B-2444-31				18.7938
	B-2444-33				18.7649
	B-2444-36				18.6702
	B-2444-37				18.6626
HEU 15/10	10463	38.10	12.70635		19.1497
	10472				18.9054
	10479				18.7903
HEU 15/2.5	10464	38.10	3.1877		18.8422
	10467				19.0757
	10470				18.9027
	10475				18.7512
	10487				18.8921
	10489				19.0989
	10491				19.2439
HEU 15/0	11017	38.10	Not Applicable		19.0133
	11019				18.9302
	11147				19.0569
	11149				18.6780
	11150				18.7422
HEU 15/6	11018	38.10	7.62635		18.7110
	10457				19.4256
	10477				19.1624
	10493				18.9391
HEU 6/0	Q2-16	7.62	Not Applicable		19.6598

Table 7. Density Calculations of the HEU Pancake Plates Using Nominal Diameters, Caliper Heights, and 2023 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.34	38.10	0.3023	18.4669
	B-2444-02			0.3003	18.5848
	B-2444-04			0.2983	18.6974
	B-2444-07			0.3030	18.4160
	B-2444-10			0.3048	18.3703
	B-2444-11			0.3035	18.4251
	B-2444-13			0.3057	17.9991
	B-2444-19			0.3000	18.6423
	B-2444-20			0.3022	18.6041
	B-2444-22			0.2913	18.8911
	B-2444-24			0.3015	18.4524
	B-2444-25			0.2992	18.6157
	B-2444-27			0.2982	18.5862
	B-2444-29			0.3048	18.3640
	B-2444-31			0.3040	18.5292
	B-2444-33			0.3020	18.6232
	B-2444-36			0.3023	18.5088
	B-2444-37			0.3008	18.5935
HEU 15/10	10463	38.10	12.70635	0.3092	18.5646
	10472			0.3047	18.5985
	10479			0.3027	18.6074
HEU 15/2.5	10464	38.10	3.1877	0.3047	18.5363
	10467			0.3070	18.6233
	10470			0.3040	18.6365
	10475			0.3018	18.6199
	10487			0.3037	18.6466
	10489			0.3063	18.6865
	10491			0.3128	18.4372
HEU 15/0	11017	38.10	Not Applicable	0.3023	18.8489
	11019			0.3007	18.8706
	11147			0.3083	18.5245
	11149			0.3013	18.5780
	11150			0.3000	18.7247
HEU 15/6	11018	38.10	7.62635	0.3023	18.5492
	10457			0.3135	18.5718
	10477			0.3090	18.5869
	10493			0.3053	18.5909
HEU 6/0	Q2-16	7.62	Not Applicable	0.3243	18.1678

Table 8. Density Calculations for the HEU Pancake Plates Using CMM Measurements and 2023 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.356	38.136	0.3367	16.5960
	B-2444-02	53.354	38.135	0.3220	17.3489
	B-2444-04[4]	53.353	38.138	0.5287	10.5609
	B-2444-07	53.365	38.132	0.3113	17.9201
	B-2444-10	53.359	38.142	0.3440	16.2925
	B-2444-11	53.350	38.128	0.3153	17.7473
	B-2444-13	53.354	38.135	0.4013	13.7202
	B-2444-19	53.355	38.140	0.3243	17.2616
	B-2444-20	53.361	38.150	0.3323	16.9344
	B-2444-22	53.374	38.130	0.3317	16.5778
	B-2444-24	53.290	38.127	0.3183	17.5698
	B-2444-25	53.349	38.121	0.3440	16.1970
	B-2444-27	53.359	38.130	0.3580	15.4828
	B-2444-29	53.354	38.123	0.3333	16.7970
	B-2444-31	53.353	38.117	0.3583	15.7187
	B-2444-33	53.357	38.123	0.3307	17.0080
	B-2444-36	53.359	38.124	0.3297	16.9718
	B-2444-37	53.350	38.126	0.3297	16.9784
HEU 15/10	10463	38.086	25.398	0.3253	17.6491
	10472	38.087	25.397	0.3587	15.8021
	10479	38.083	25.398	0.3150	17.8910
HEU 15/2.5	10464	38.088	6.378	0.3563	15.8593
	10467	38.085	6.381	0.3227	17.7344
	10470	38.093	6.338	0.3233	17.5229
	10475	38.085	6.370	0.3207	17.5397
	10487	38.088	6.380	0.3290	17.2226
	10489	38.091	6.379	0.3220	17.7866
	10491	38.084	6.372	0.3477	16.6038
HEU 15/0	11017	38.096	Not Applicable	0.3220	17.7014
	11019	38.097		0.3227	17.5867
	11147	38.101		0.3500	16.3184
	11149	38.092		0.3300	16.9713
	11150	38.088		0.3437	16.3558
HEU 15/6	11018	38.096	15.258	0.3120	17.9814
	10457	38.091	15.256	0.3397	17.1521
	10477	38.086	15.262	0.3280	17.5296
	10493	38.084	15.255	0.3260	17.4308
HEU 6/0	Q2-16	15.214	Not Applicable	0.3253	18.1739

[4] There is a large distribution of measured values height values for B-2444-04 due to some elastic deformation that creates gaps between the HEU and the granite surface plate. Therefore, this plate is not used in recent critical experiments.

Table 9. Density Calculations for the HEU Pancake Plates Using CMM Measured Diameters, Caliper Measured Heights, and 2023 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.356	38.136	0.3023	18.4807
	B-2444-02	53.354	38.135	0.3003	18.6005
	B-2444-04	53.353	38.138	0.2983	18.7147
	B-2444-07	53.365	38.132	0.3030	18.4130
	B-2444-10	53.359	38.142	0.3048	18.3858
	B-2444-11	53.350	38.128	0.3035	18.4392
	B-2444-13	53.354	38.135	0.3057	18.0143
	B-2444-19	53.355	38.140	0.3000	18.6617
	B-2444-20	53.361	38.150	0.3022	18.6251
	B-2444-22	53.374	38.130	0.2913	18.8729
	B-2444-24	53.290	38.127	0.3015	18.5507
	B-2444-25	53.349	38.121	0.2992	18.6243
	B-2444-27	53.359	38.130	0.2982	18.5897
	B-2444-29	53.354	38.123	0.3048	18.3674
	B-2444-31	53.353	38.117	0.3040	18.5280
	B-2444-33	53.357	38.123	0.3020	18.6224
	B-2444-36	53.359	38.124	0.3023	18.5062
	B-2444-37	53.350	38.126	0.3008	18.6057
HEU 15/10	10463	38.086	25.398	0.3092	18.5720
	10472	38.087	25.397	0.3047	18.6029
	10479	38.083	25.398	0.3027	18.6201
HEU 15/2.5	10464	38.088	6.378	0.3047	18.5488
	10467	38.085	6.381	0.3070	18.6394
	10470	38.093	6.338	0.3040	18.6373
	10475	38.085	6.370	0.3018	18.6341
	10487	38.088	6.380	0.3037	18.6594
	10489	38.091	6.379	0.3063	18.6962
	10491	38.084	6.372	0.3128	18.4526
HEU 15/0	11017	38.096	Not Applicable	0.3023	18.8529
	11019	38.097		0.3007	18.8735
	11147	38.101		0.3083	18.5236
	11149	38.092		0.3013	18.5858
	11150	38.088		0.3000	18.7365
HEU 15/6	11018	38.096	15.258	0.3023	18.5563
	10457	38.091	15.256	0.3135	18.5838
	10477	38.086	15.262	0.3090	18.6075
	10493	38.084	15.255	0.3053	18.6106
HEU 6/0	Q2-16	15.214	Not Applicable	0.3243	18.2300

All four methods to calculate density were investigated and compared by looking at the minimum density, maximum density, range in densities, the average, standard deviation, and variance for all measured plates. A summary of the results is reported in Table 10.

Table 10. Statistical Summary of Density Calculation Methods Using 2023 Mass Measurements.

Parameter	Nominal Dimensions	Nominal Diameters & Caliper Heights	CMM Dimensions[5]	CMM Diameters & Caliper Heights
Minimum Density [g/cm^3]	18.3562	17.9991	13.7202	18.0143
Maximum Density [g/cm^3]	19.6598	18.8911	18.1739	18.8735
Range [g/cm^3]	1.3036	0.8920	4.4537	0.8592
Average [g/cm^3]	18.8191	18.5616	16.9712	18.5744
Standard Deviation	0.2699	0.1638	0.8784	0.1579
Variance	0.0728	0.0268	0.7717	0.0249

4.1.2 *Density Calculations Using 2019 Mass Measurements*

The same density calculations were performed with the 2019 mass and caliper measurements (see Table 2) to be compared to the results using the 2023 measurements. The following density calculations were performed: using only nominal dimensions (Table 11), using nominal diameters and caliper heights (Table 12), using only CMM measurements (Table 13), and using CMM measurements for the diameters and calipers for the heights (Table 14).

[5] These values exclude the B-2444-04 since it is a clear outlier and is not used in recent critical experiments.

Table 11. Density Calculations of the HEU Pancake Plates Using Nominal Dimensions and 2019 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.34	38.10	0.29972	18.6553
	B-2444-02				18.6776
	B-2444-04				18.6307
	B-2444-07				18.6438
	B-2444-10				18.7005
	B-2444-11				18.6739
	B-2444-13				18.3712
	B-2444-19				18.6730
	B-2444-20				18.7544
	B-2444-22				18.3667
	B-2444-24				18.5621
	B-2444-25				18.5886
	B-2444-27				18.4990
	B-2444-29				18.6874
	B-2444-31				18.8233
	B-2444-33				18.7675
	B-2444-36				18.6697
	B-2444-37				18.6605
HEU 15/10	10463	38.10	12.70635		19.1458
	10472				18.9102
	10479				18.7563
HEU 15/2.5	10464	38.10	3.1877		18.8432
	10467				19.0751
	10470				18.9032
	10475				18.7568
	10487				18.8923
	10489				19.1004
	10491				19.2464
HEU 15/0	11017	38.10	Not Applicable		19.0390
	11019				18.9454
	11147				19.0800
	11149				18.6870
	11150				18.7859
HEU 15/6	11018	38.10	7.62635		18.7092
	10457				19.4149
	10477				19.1588
	10493				18.9427
HEU 6/0	Q2-16	7.62	Not Applicable		19.7043

Table 12. Density Calculations of the HEU Pancake Plates Using Nominal Diameters, Caliper Heights, and 2019 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.34	38.10	0.3023	18.4986
	B-2444-02			0.3035	18.4432
	B-2444-04			0.3031	18.4225
	B-2444-07			0.3052	18.3076
	B-2444-10			0.3014	18.5954
	B-2444-11			0.3056	18.3118
	B-2444-13			0.3031	18.1660
	B-2444-19			0.3014	18.5681
	B-2444-20			0.3006	18.7016
	B-2444-22			0.2976	18.4973
	B-2444-24			0.3099	17.9535
	B-2444-25			0.2997	18.5886
	B-2444-27			0.3027	18.3179
	B-2444-29			0.3023	18.5303
	B-2444-31			0.3069	18.3819
	B-2444-33			0.3023	18.6098
	B-2444-36			0.3001	18.6433
	B-2444-37			0.3014	18.5557
HEU 15/10	10463	38.10	12.70635	0.3133	18.3179
	10472			0.3099	18.2902
	10479			0.3044	18.4693
HEU 15/2.5	10464	38.10	3.1877	0.3035	18.6067
	10467			0.3162	18.0792
	10470			0.3116	18.1840
	10475			0.3264	17.2242
	10487			0.3056	18.5260
	10489			0.3128	18.2991
	10491			0.3145	18.3398
HEU 15/0	11017	38.10	Not Applicable	0.3069	18.5926
	11019			0.3023	18.7862
	11147			0.3035	18.8405
	11149			0.3103	18.0496
	11150			0.3095	18.1948
HEU 15/6	11018	38.10	7.62635	0.3027	18.5261
	10457			0.32258	18.2547
	10477			0.31369	18.3056
	10493			0.3048	18.1974
HEU 6/0	Q2-16	7.62	Not Applicable	0.3179	18.5761

Table 13. Density Calculations for the HEU Pancake Plates Using CMM Measurements and 2019 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.356	38.136	0.3367	16.6204
	B-2444-02	53.354	38.135	0.3220	17.3999
	B-2444-04	53.353	38.138	0.5287	10.5721
	B-2444-07	53.365	38.132	0.3113	17.9454
	B-2444-10	53.359	38.142	0.3440	16.3071
	B-2444-11	53.350	38.128	0.3153	17.7629
	B-2444-13	53.354	38.135	0.4013	13.7314
	B-2444-19	53.355	38.140	0.3243	17.2739
	B-2444-20	53.361	38.150	0.3323	16.9331
	B-2444-22	53.374	38.130	0.3317	16.5816
	B-2444-24	53.290	38.127	0.3183	17.5699
	B-2444-25	53.349	38.121	0.3440	16.2033
	B-2444-27	53.359	38.130	0.3580	15.4903
	B-2444-29	53.354	38.123	0.3333	16.8061
	B-2444-31	53.353	38.117	0.3583	15.7433
	B-2444-33	53.357	38.123	0.3307	17.0104
	B-2444-36	53.359	38.124	0.3297	16.9713
	B-2444-37	53.350	38.126	0.3297	16.9766
HEU 15/10	10463	38.086	25.398	0.3253	17.6455
	10472	38.087	25.397	0.3587	15.8061
	10479	38.083	25.398	0.3150	17.8586
HEU 15/2.5	10464	38.088	6.378	0.3563	15.8601
	10467	38.085	6.381	0.3227	17.7338
	10470	38.093	6.338	0.3233	17.5234
	10475	38.085	6.370	0.3207	17.5449
	10487	38.088	6.380	0.3290	17.2228
	10489	38.091	6.379	0.3220	17.7880
	10491	38.084	6.372	0.3477	16.6060
HEU 15/0	11017	38.096	Not Applicable	0.3220	17.7254
	11019	38.097		0.3227	17.6009
	11147	38.101		0.3500	16.3382
	11149	38.092		0.3300	16.9794
	11150	38.088		0.3437	16.3940
HEU 15/6	11018	38.096	15.258	0.3120	17.9797
	10457	38.091	15.256	0.3397	17.1427
	10477	38.086	15.262	0.3280	17.5264
	10493	38.084	15.255	0.3260	17.4341
HEU 6/0	Q2-16	15.214	Not Applicable	0.3253	18.2151

Table 14. Density Calculations for the HEU Pancake Plates Using CMM Measured Diameters, Caliper Measured Heights, and 2019 Mass Measurements.

Part Type	ID	Diameter		Height [cm]	Density [g/cm^3]
		Outer [cm]	Inner [cm]		
HEU 21/15	B-2444-01	53.356	38.136	0.3023	18.5124
	B-2444-02	53.354	38.135	0.3035	18.4587
	B-2444-04	53.353	38.138	0.3031	18.4394
	B-2444-07	53.365	38.132	0.3052	18.3046
	B-2444-10	53.359	38.142	0.3014	18.6111
	B-2444-11	53.350	38.128	0.3056	18.3259
	B-2444-13	53.354	38.135	0.3031	18.1813
	B-2444-19	53.355	38.140	0.3014	18.5875
	B-2444-20	53.361	38.150	0.3006	18.7227
	B-2444-22	53.374	38.130	0.2976	18.4795
	B-2444-24	53.290	38.127	0.3099	18.0492
	B-2444-25	53.349	38.121	0.2997	18.5971
	B-2444-27	53.359	38.130	0.3027	18.3213
	B-2444-29	53.354	38.123	0.3023	18.5338
	B-2444-31	53.353	38.117	0.3069	18.3807
	B-2444-33	53.357	38.123	0.3023	18.6090
	B-2444-36	53.359	38.124	0.3001	18.6407
	B-2444-37	53.350	38.126	0.3014	18.5679
HEU 15/10	10463	38.086	25.398	0.3133	18.3252
	10472	38.087	25.397	0.3099	18.2946
	10479	38.083	25.398	0.3044	18.4819
HEU 15/2.5	10464	38.088	6.378	0.3035	18.6192
	10467	38.085	6.381	0.3162	18.0948
	10470	38.093	6.338	0.3116	18.1848
	10475	38.085	6.370	0.3264	17.2373
	10487	38.088	6.380	0.3056	18.5388
	10489	38.091	6.379	0.3128	18.3086
	10491	38.084	6.372	0.3145	18.3550
HEU 15/0	11017	38.096	Not Applicable	0.3069	18.5965
	11019	38.097		0.3023	18.7892
	11147	38.101		0.3035	18.8395
	11149	38.092		0.3103	18.0572
	11150	38.088		0.3095	18.2063
HEU 15/6	11018	38.096	15.258	0.3027	18.5332
	10457	38.091	15.256	0.32258	18.2665
	10477	38.086	15.262	0.31369	18.3259
	10493	38.084	15.255	0.3048	18.2166
HEU 6/0	Q2-16	15.214	Not Applicable	0.3179	18.6396

All four methods to calculate density were investigated and compared to each other by looking at the minimum density, maximum density, range in densities, the average, standard deviation, and variance for all measured plates. A summary of the results is reported in Table 15.

Table 15. Statistical Summary of Density Calculation Methods Using 2019 Mass Measurements.

Parameter	Nominal Dimensions	Nominal Diameters & Caliper Heights	CMM Dimensions[6]	CMM Diameters & Caliper Heights
Minimum Density [g/cm^3]	18.3667	17.2242	13.7314	17.2373
Maximum Density [g/cm^3]	19.7043	18.8405	18.2151	18.8395
Range [g/cm^3]	1.3376	1.6163	4.4837	1.6022
Average [g/cm^3]	18.8290	18.3882	16.9798	18.4009
Standard Deviation	0.2695	0.2773	0.8772	0.2738
Variance	0.0726	0.0769	0.7694	0.0740

4.2 Impact of Oxidation

Since mass measurements for many plates were performed both in 2019 and 2023, the difference in mass between those dates can be calculated. It is expected that there is a change in mass due to oxidation of the uranium in HEU, which is removed from the HEU pancake plates during handling. Table 16 summarizes the mass lost between 2019 and 2023. Only components that have measurements in 2019 and 2023 are reported in Table 16. There is a difference in the number of significant figures between 2019 and 2023 since multiple measurements (three per plate) were taken in 2023, so an average value can be calculated as opposed to a single measurement. Note, when the difference in mass reported in Table 16 is negative that means mass was lost between 2019 and 2023, which is expected.

There are a few cases where the difference is positive, one value is within the uncertainty of the measurement using the uncertainty associated with the scale[7]: $u_T = \sqrt{2}\sqrt{Nu_r^2 + N^2u_s^2 + \frac{Nr_r^2}{12}}$. For the 2023 mass measurements, $N = 1$, $u_r = 0$, $u_s = 0.2/\sqrt{3}$, and $r_r = 0.1$; which corresponds to a $u_T = 0.17$. However, the remaining measurements that show a positive change in mass between 2019 and 2023 that are outside the uncertainty associated with the scale and the propagated uncertainty for the 2023 mass measurements (shown in Table 3). A contributing factor to this observation could be the plates absorb oxygen but remain part of the plate during handling. Only one value was reported for the 2019 mass measurements; therefore, the standard deviation of those measurements is unknown and the difference in mass could be within the propagated uncertainty for those measurements since the values are small (<1 g).

[6] These values exclude the B-2444-04 since it is a clear outlier and is not used in recent critical experiments.
[7] Derivation provided by J. A. Favorite, Los Alamos National Laboratory, in December 2021. Original equation from the mass uncertainty calculations in the ICSBEP uncertainty guide.

Table 16. Difference in Mass Between 2019 and 2023.

Plate Type	ID	2019 Mass Measurement [g]	2023 Mass Measurement [g]	Mass Difference [g] ($M_{2023} - M_{2019}$)
HEU 15/0	11017	6505.8	6497.00	-8.80
	11019	6473.8	6468.60	-5.20
	11147	6519.8	6511.90	-7.90
	11149	6385.5	6382.43	-3.07
	11150	6419.3	6404.37	-14.93
HEU 6/0	Q2-16	1077.3	1074.87	-2.43
HEU 15/2.5	10464	6258.6	6258.27	-0.33
	10467	6335.6	6335.80	0.20
	10470	6278.5	6278.33	-0.17
	10475	6229.9	6228.03	-1.87
	10487	6274.9	6274.83	-0.07
	10489	6344.0	6343.50	-0.50
	10491	6392.5	6391.67	-0.83
HEU 15/6	11018	5368.5	5369.00	0.50
HEU 15/10	10463	3631.7	3632.43	0.73
	10472	3587.0	3586.10	-0.90
HEU 21/15	B-2444-01	6119.7	6110.70	-9.00
	B-2444-02	6127.0	6109.03	-17.97
	B-2444-10	6134.5	6129.00	-5.50
	B-2444-13	6026.5	6021.57	-4.93
	B-2444-19	6125.5	6121.13	-4.37
	B-2444-20	6152.2	6152.70	0.50
	B-2444-22	6025.0	6023.63	-1.37
	B-2444-24	6089.1	6089.07	-0.03
	B-2444-25	6097.8	6095.43	-2.37
	B-2444-27	6068.4	6065.43	-2.97
	B-2444-29	6130.2	6126.90	-3.30
	B-2444-31	6174.8	6165.13	-9.67
	B-2444-33	6156.5	6155.63	-0.87
	B-2444-36	6124.4	6124.57	0.17
	B-2444-37	6121.4	6122.07	0.67

Some of the more recent ICSBEP evaluations (HEU-MET-FAST-102 and HEU-MET-INTER-011) that use these plates have increased the uncertainty evaluated due to concerns associated with oxidation. These newer evaluations used a $u_T = \sim 2.9$ rather than a $u_T = 0.17$. Using the larger u_T value corresponds to an uncertainty in k_{eff} of ~10 pcm, which is small compared to other uncertainties present in the experiment (e.g., gaps within the core). The larger u_T value bounds most of the mass differences listed in Table 16; however, there are still plates that have a change in mass greater than 2.9 g.

5 Proposed Method for Characterizing the HEU Pancake Plates

All the HEU pancake plates in the NCERC inventory should have approximately the same density, since the composition is similar and they were manufactured using the same method. Therefore, the measurements selected to calculate the density would have the smallest range, standard deviation, and variance in density for all measured plates. Based on the results in **Error! Reference source not found.**, *using the CMM diameter measurements and the caliper height measurements best meet the criteria*. The range in calculated density is <0.86 g/cm^3 and a standard deviation <0.16 g/cm^3, which is slightly better than historical methods of nominal diameters and caliper height measurements (range <0.90 g/cm^3 and standard deviation <0.17 g/cm^3). However, the improvement is not necessarily worth the time it takes to perform CMM measurements. The CMM measurements took slightly over a week of operational time to measure 38 plates, which corresponds to a cost of approximately $120k. In comparison, mass and caliper measurements can be performed in less than half the time.

The results reported in Table 15 (2019 caliper and mass measurements) show a slightly different conclusion than the results reported in Table 10 (2023 caliper and mass measurements). In this case, using nominal dimensions has the smallest range, standard deviation, and variance. However, the density calculations using nominal diameters with caliper heights or CMM diameters with caliper heights are similar to those using nominal dimensions.

Given how thin the HEU pancake plates are in addition to having large diameters, it is expected that there is some elastic deformation. This can lead to complications when performing CMM measurements on the height because the top of the HEU plate may not be parallel with the granite surface plate. The Inspire program uses the difference between the two planes (granite surface plate and top of the HEU plate) to calculate a height. Therefore, when one surface is not parallel to the other surface, gaps between the HEU and surface plate are included in the height measurement. Including a potential gap increases the height and therefore reduces the density, which is why there is a large range of densities when only using the CMM measurements. However, the gap between the HEU and granite surface plate is removed/reduced during an actual experiment due to the additional weight above the plate (e.g., other plates being stacked on top). For example, the standard deviation for stack height measurements in CERBERUS were all comparable to each other, unlike some of the values reported in Table 5.[8]

Using the CMM measurements does not provide a significant improvement in terms of the density calculation compared to historical methods (nominal diameters and caliper heights). When the statistical results for density calculations using nominal dimensions is compared between the 2019 and 2023 mass measurements, the answers are similar. However, results that used caliper measurements had a greater difference in the statistical results between the 2019 and 2023 mass measurements.

Anytime mass measurements are performed, it is recommended to have at least three measurements per plate so an outlier measurement (e.g., plate being placed on the scale off-center or an operator bumping the scale) can be detected and an uncertainty can be calculated. For most of the plates measured, the mass loss between 2019 and 2023 is within 3 g, which has a minimal impact on the total uncertainty of k_{eff}. However, there are plates that show >10 g of mass lost between 2019 and 2023, which would have a larger impact on the total uncertainty.

Based off the results in this report, it is recommended that the density of the HEU pancake plates use the nominal diameters (unless CMM diameters are available) and caliper measurements for the height. The

[8] K. Amundson, et. al., *CERBERUS: A Zeus Configuration with HEU and Copper Reflected by Copper*. IER 537 CED-3B Report, LA-UR-23-33447, December 2023.

mass of the remaining HEU pancake plates in the NCERC inventory should continue to be measured to track material loss due to oxidation. In addition, alternative storage methods should be tested to try to reduce the amount of oxidation that occurs between experiments.