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Two Delayed Critical 7-inch Diameter Interacting Enriched (93.15) Uranium Metal Cylinders without Moderator and Reflector

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December 2019

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Isotope and Fuel Cycle Technology Division

TWO DELAYED CRITICAL 7 INCH DIAMETER INTERACTING ENRICHED (93.15) URANIUM METAL CYLINDERS WITHOUT MODERATOR AND REFLECTOR

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ABSTRACT

This report precisely and accurately documents the configuration and the materials for experiments with two unmoderated, unreflected, interacting, coaxial, highly enriched, 7 in. diameter uranium metal cylinders performed at the Oak Ridge Critical Experiments Facility (ORCEF) in April 1963. These experiments are described in logbook E-19, which is associated with work performed in the east cell of ORCEF. The information is sufficiently accurate that it can be used as the basis for preparation of benchmarks for International Criticality Safety Benchmark Program (ICSBEP) at Idaho National laboratory. The thickness of the cylinders was varied and the spacing between them was adjusted to achieve a delayed critical configuration. The average enrichment of the uranium metal was 94.15 wt.% ^{235}U. The heights of the 7 in. diameter, equal-height cylinders varied from 2 5/8 to 3 1/4 in. All interacting cylinders were assembled coaxially with their flat faces parallel and their combined masses varied between 62 and 76 kg of HEU metal. Once the uncertainty analysis is completed, the data from these six experiments will be acceptable for use as criticality safety benchmark experiments for ICSBEP and EURATOM's Nuclear Energy Agency nuclear criticality safety benchmark program. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainties in k_{eff} are expected to be as low as ±0.0002.

1. DETAILED DESCRIPTION

1.1 OVERVIEW OF EXPERIMENT

A variety of critical experiments were constructed with unreflected and unmoderated highly enriched uranium during the 1960s–1970s at the Oak Ridge Critical Experiments Facility (ORCEF) in support of criticality safety of the Y-12 Plant [1–7]. Of these hundreds of delayed critical assemblies, 6 assemblies of two 7 in. diameter interacting coaxial uranium metal cylinders were assembled to delayed criticality without a moderator or reflector. The heights of the 7 in. diameter equal height cylinders heights varied from 2 5/8 to 3 1/4 in. All interacting cylinders were assembled coaxially with their flat faces parallel, and their combined masses varied between 62 and 76 kg of highly enriched uranium (HEU) metal. The spacing between cylinders was the variable that was adjusted to achieve delayed criticality. The experiments were performed in April 1963 and are recorded in logbook E-19 associated with the east cell of the ORCEF. Interaction experiments with 11 in. diameter HEU metal cylinders have been reported and analyzed in HEU-MET-FAST-051.

The data from these six experiments described are acceptable for use as criticality safety benchmark experiments in the ICSBEP when the uncertainty analysis is performed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, it is expected that the uncertainties in k_{eff} could be as low as ±0.0002.

1.2 DESCRIPTION OF EXPERIMENTAL CONFIGURATION

A wide variety of critical experiments with highly enriched uranium (HEU) metal were constructed during the 1960s and 1970s at the ORCEF. These experiments were performed in the 35 × 35 × 30 ft high east cell of ORCEF. The assemblies of uranium metal were located approximately 11.7 ft from the 5 ft thick concrete west wall, 12.7 ft from the 2 ft thick concrete north wall, and 9.2 ft above the concrete floor. The purpose of these experiments included the evaluation of storage and handling limits for the Y-12 Plant and providing data for verification of calculation methods and cross sections for nuclear criticality safety applications. These included single cylinders of various diameters, two interacting cylinders of various diameters, three interacting cylinders, and complex geometry assemblies. All interacting cylinders were assembled coaxially with their flat faces parallel and the combined masses of the interacting cylinders masses varied between 62 and 325 kg of HEU metal. The experiments described here are two interacting cylinders with nominal diameters of 7 in. with the nominal height of upper and lower sections varied from 2.625 to 3.25 in., with various separation distance between them, unmoderated and unreflected. Note, all dimensions were measured and recorded in inches. When dimensions are rounded to the nearest 1 in. or 1/8 in., they are nominal dimensions, otherwise they are measured. The six experiments are summarized in Table 1. For all configurations, the experimental k_{eff} was 1.0000. These configurations have the lowest uncertainties and include all the support structure and air in, walls of, and floor of the experimental cell and would be best for checking the accuracy of the ability of calculational methods to predict experimental results. This is because corrections for these effects have uncertainties.

Table 1. Summary of masses, measured separation, and experimental k_{eff} for delayed critical experiments with two interacting cylinders of 7 in. diameter.

Experiment	Nominal cylinder thickness (in.), logbook number, and page[(a)]	Mass of [(b)] upper section (g)	Mass of [(b)] lower section (g)	Mass of [(b)] assembly (g)	Measured separation (in.)	Measured k_{eff}
1	2.625, Logbook E-19, page 170	31,051	31,064	62,115	0.1357	1.0000
2	2.750, Logbook E-19, page 177	32,511	32,499	65,010	0.5994	1.0000
3	2.875, Logbook E-19, page 181	33,991	34,023	68,014	0.8763	1.0000
4	3.000, Logbook E-19, page 186	35,472	35,518	70,990	1.1684	1.0000
5	3.125, Logbook E-19, page 193	36,946	36,909	73,855	1.5367	1.0000
6	3.250, Logbook E-19, page 198	38,427	38,435	76,862	1.9228	1.0000

(a) ORCEF logbook number and page number for the initial page of the entry for each experiment.
(b) Masses of each part known to ±0.5 g.

1.3 EXPERIMENT METHODOLOGY

The cylinders comprised layers of discs whose dimensions were machined to precise tolerances. The experiments were performed in a deliberate and step-by-step manner, with observed data recorded.

1.3.1 General Assembly Procedure

The assemblies were constructed on a vertical assembly machine [8], which primarily consisted of a hydraulic lift (22 in. vertical motion see Figure 1 which is a photograph of the assembly machine) to support the lower section and a stationary upper half consisting of four vertical posts that held a low-mass support consisting of a 30 in. ID clamping ring supported off vertical poles by aluminum tubing (see Figure 2 which is a photograph from HEU-MET-FAST-051 for interacting 11 in. diameter cylinders). The aluminum clamping ring held a 0.010 in. thick stainless-steel (304L) diaphragm on which the uranium metal of the upper section was supported. The clamping ring was supported by a lightweight aluminum structure mounted on the four vertical poles of the assembly machine, spaced 4 ft apart (see Figure 2). The clamping ring contained thirty-four 3/8 in. diameter, 1.5 in. long stainless-steel bolts. The lower section was supported on a low-mass aluminum support tower mounted on the vertical lift, also shown in Figure 2. The lower support stand supported the uranium metal with 0.125 in. thick aluminum edges, oriented vertically and 120° apart. Lateral motion on the lower section was restrained by small aluminum pieces bolted to the 120° vertical members. These are also visible in Figure 2. The low-mass support stand was bolted to the vertical lift as shown in Figure 2. The arrangement of Figure 2 was used for these two interacting cylinders, and the only difference was the distance between the upper and lower sections.

These low-mass support structures were used to minimize the reactivity effects of the support structure. The support structures are described in Appendix A.

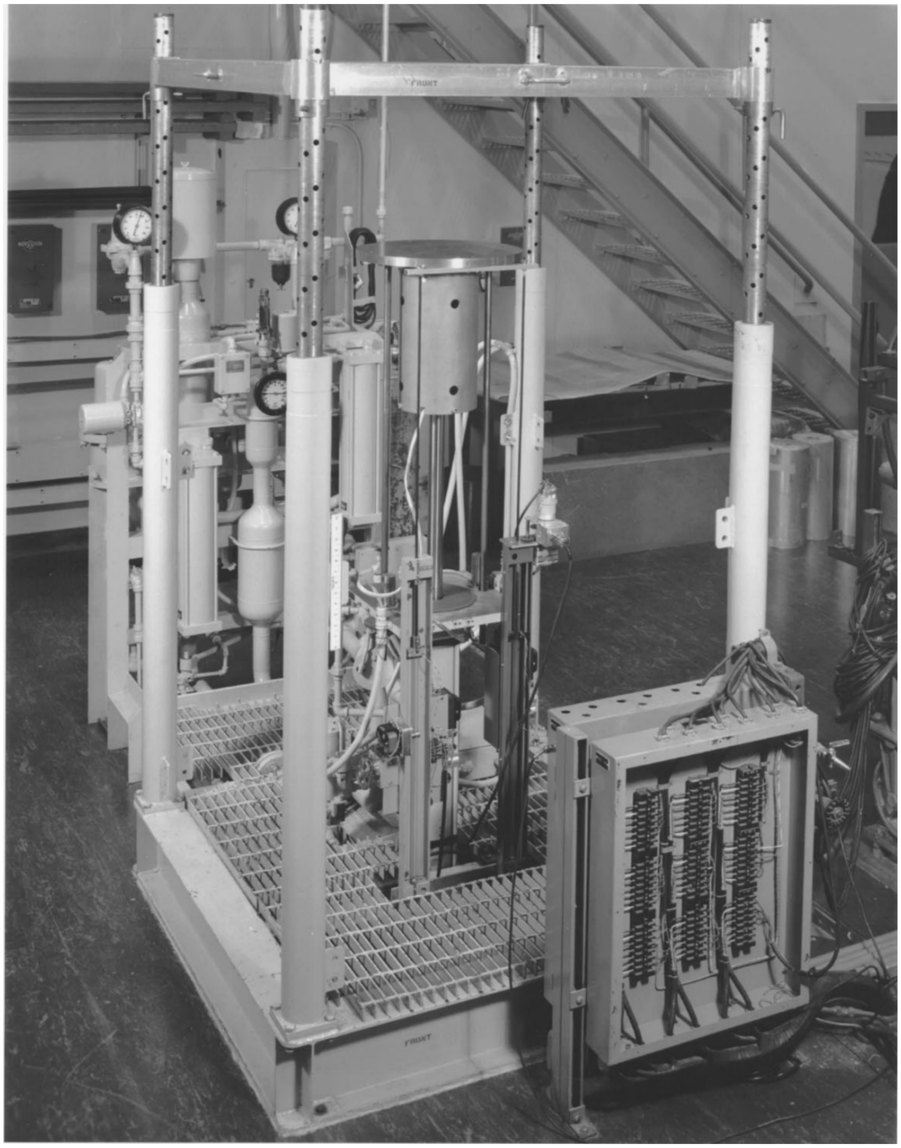

Figure 1. Photograph of the vertical assembly machine with the movable table up. (The upper support structure on the four vertical poles was not used in these measurements. The lower support structures are not shown in this photograph.)[1]

[1] *Safety Review of the Oak Ridge Critical Experiments Facility*, Union Carbide Nuclear Corporation, Oak Ridge National Laboratory (1962).

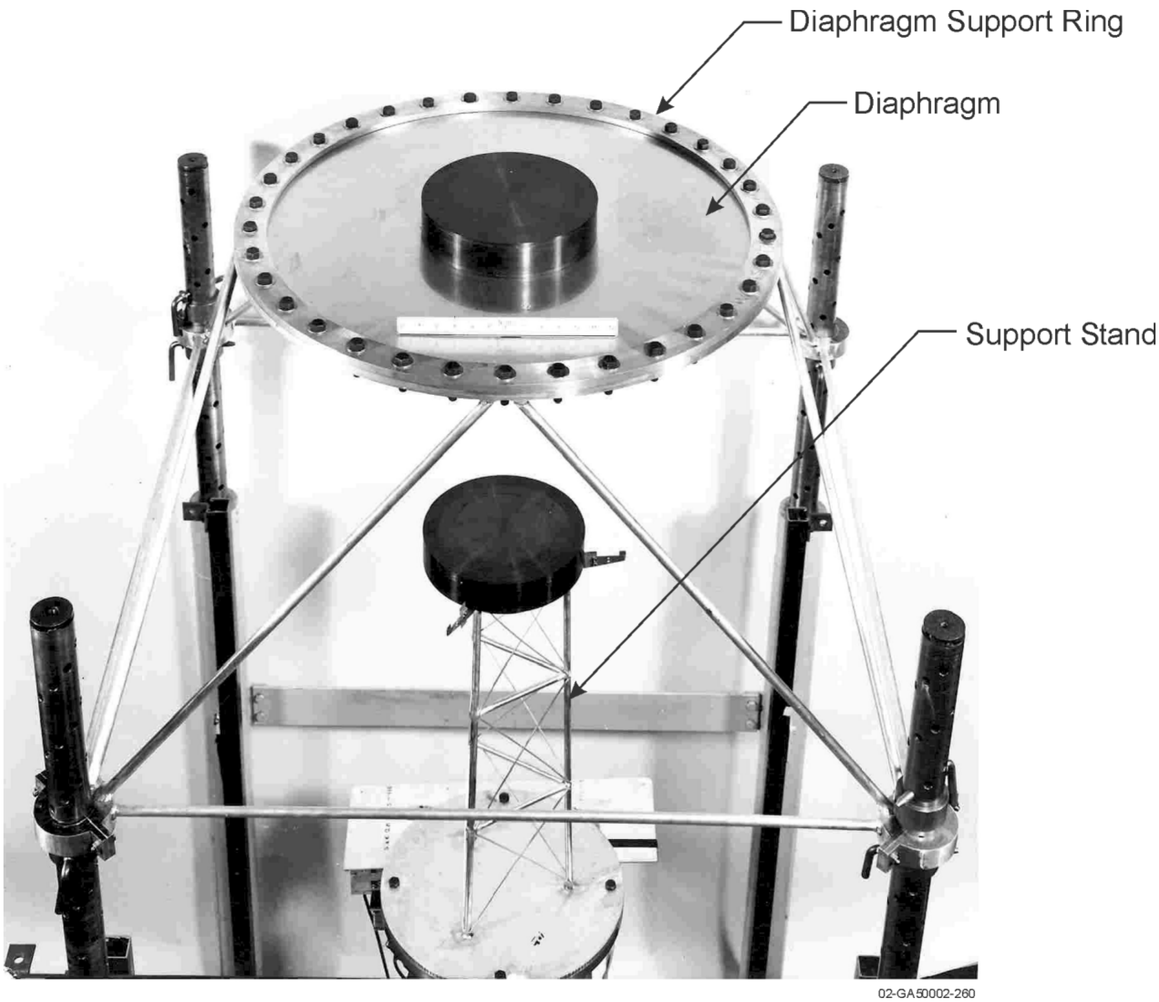

Figure 2. A typical uranium metal assembly for two interacting 11 in. diameter uranium (93.15 wt.% ^{235}U) metal cylinders in the unassembled condition with the lower support tower down. Two interacting 7 in. diameter uranium metal cylinders were assembled in the same manner on this exact same apparatus with the same support structure.

For these interacting-cylinder experiments, the lower section was raised beyond delayed criticality to increase the fission rate to a measurable level. Then the spacing was adjusted until near exactly delayed criticality was achieved (reactor period >5,000 s). Separation of the upper and lower assemblies was monitored remotely by selsyn readout, which was available in the control room. The selsyn readouts were accurate to ±0.0005 in. The separation of the two halves of the assemblies was measured as follows. At several points of the compass (N, NE, E, SE, S, SW, W, NW), the distance between the top (outer diameter) of the lower uranium cylinder and the bottom of the upper diaphragm at the radial location of the outer diameter of the upper cylinder was measured with a micrometer accurate to 0.001 in. The motion of the table was followed with a selsyn motor that indicated the height of the lower support table above the down position to 0.001 in. with one rotation corresponding to ±0.001 in. This selsyn readout was verified against physical measurements of the height of the lower support table above the down position. There were two selsyn readouts 180° apart, which were both used to obtain the separation. The difference between the selsyn readout with the lower support table at the critical position and the selsyn readout with the table down was equal to the distance the vertical support table was raised. The separation between the top of the lower uranium with the vertical table down and the bottom of the stainless-steel diaphragm supporting the upper section was measured. The total separation minus the amount the table was raised is the separation of the two cylinders minus the stainless-steel diaphragm supporting the upper section. The upper diaphragm thickness (0.010 in. thick) was added to this difference to obtain the total vertical distance between the upper and lower uranium metal cylinders. The separation of the two cylinders was measured near the outer diameter.

The assembly heights of the discs were measured to ±0.0005 in. as follows. Hand stacking of each cylinder was used to measure the height of each cylinder. The height of the 7 in. diameter discs for the lower cylinder were measured as assembled on the lower support stand after the measurements. The height of the upper cylinders was measured after the measurements as follows. With the lower cylinder removed from the support stand, the upper cylinders were stacked on the lower support stand for the thickness measurements because this allowed easy access for a micrometer to determine the thickness. Since the individual cylinders were sufficiently subcritical, there were no criticality safety concerns for these height measurements. When the parts in the assemblies were stacked, the azimuthal orientation of the parts was such that the location of the part numbers on the upper surface was always oriented toward the north wall of the experimental cell as they were in the critical configurations. This assured reproducibility when restacking assemblies or parts of assemblies for height measurements. The parts were always positioned with the surface with the scribed part number facing up. Thus, for the height measurements, the orientation of the 7 in. diameter cylinders was as in the assembly. The height of the upper and lower sections of the 7 in. diameter cylinders was normally measured at azimuth locations N, E, S, W, and in some cases SW, and NE. The values were averaged. To obtain the average void in a stack of parts, the sum of the actual measured heights of all the parts was subtracted from the measured stack height. This process was separately performed for the lower section and the upper section. This procedure allowed the safe measurements of the stacked height of each cylinder. The measured heights for the cylinder sets and the average for each assembly are given in the description of each experiment in subsequent sections of this report. From these measurements, the difference between the measured heights, the actual height from the inspection reports, and the number of discs in each half can be used to determine the average gap between the 7 in. diameter discs in each half of the critical assembly. These gaps should be incorporated in exact calculational models of the measurements. In most cases, for the 7 in. diameter discs the sum of the measured parts (known to 0.00005 in.) was larger than the measured cylinder heights (measured to 0.001 in.), and the gap between pieces was assumed to be 0.0 thousandths of an inch. This is a result of the extreme accuracy of the fabrication of the parts and the uncertainty in the measured heights, which were larger than the uncertainty of the individual parts from the inspection reports.

1.3.2 Assembly Alignment

1.3.2.1 Upper Section

For assembly of the upper section, uranium metal was added to the top diaphragm. Using a ruler, the uranium was placed the appropriate distance from the inside of the aluminum ring that holds the stainless diaphragm. The rest of the material was then added to the top cylinder. The location of the material was continuously adjusted with a precise high-quality level with the level in one direction and then rotated 90° on the parts. If the assembly was not exactly centered in the diaphragm, it would not be precisely level because of the sag in the diaphragm as it was loaded. The locations of various layers of material were adjusted so that the outside radii were the same. Two precisely machined steel blocks (± 0.0001 in.) were used to squeeze the material at the outer radial surface until it was aligned radially. An edge of the machined block was held at one outside radial location, and material was adjusted until no light was visible between the machined block and the uranium metal. This process was repeated 90° from the position of the original adjustment, rechecked again at the original position, and small adjustments were made if necessary. This process continued until the outside radii of the parts were precisely aligned and the upper section assembly was complete. The alignment of outer radii of the upper or lower section was less than ± 0.001 in. Of course, if two positions 90° apart were adjusted, the positions at 180° and 270° can be off only by the difference in the diameters of the outside parts.

1.3.2.2 Lower Section

For the lower section, the same procedure was used except the parts were leveled by shimming with aluminum foil. Various thicknesses of aluminum foil were available. The foil was placed between the three 120° upper edges of the support stand and the lowest disc.

In summary, the uncertainty in the radial alignment of parts on each half is ± 0.002 in.

1.3.3 Lateral Alignment of the Upper Section with the Lower Section for Two Interacting Cylinders

Two identical fixtures (see Figure 3) were used for lateral alignment of the upper section and the lower section. The fixtures were U-shaped and machined from 0.375 in. thick aluminum. The end pieces were carefully machined at the Y-12 shops to be perpendicular to the long direction of the fixture and coplanar with each other. When leveled properly, the front face of the 4 × 4 × 1/2 in. end pieces were vertical and in the same plane to within ±0.001 in. To avoid damage, this fixture was carefully machined and handled delicately when not in use. In use, the lower side of the upper leg rested on the top surface of the clamping ring for the diaphragm. The fixture was perpendicular to the outer radial surface of the cylinder. The fixture was moved inward until it touched the uranium of the top section. The leveling screws were adjusted until the fixture was level.

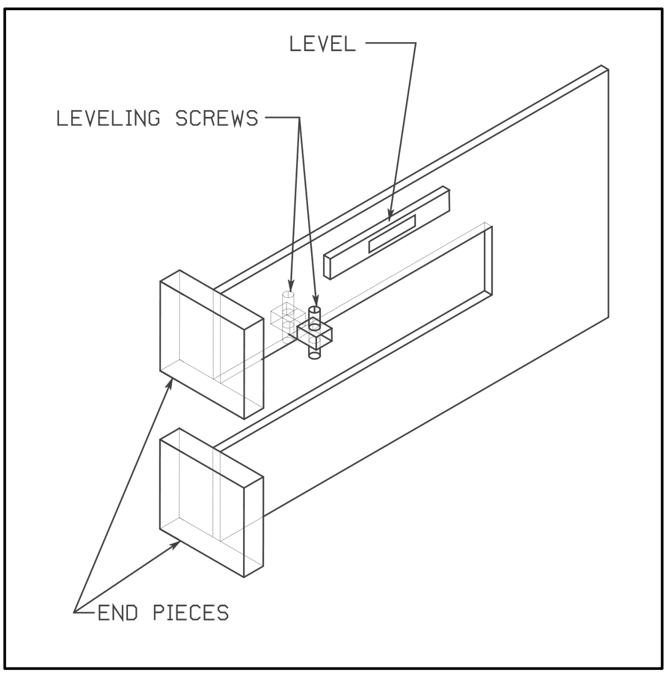

Figure. 3. Sketch of the fixture for lateral alignment of uranium metal cylinders.

The second fixture was placed 90° apart from the first in a similar manner. Both fixtures were moved back slightly, and the lower section was raised until part of the lower cylinder was as high as the lower end piece of the fixture. Then both fixtures were nearly adjusted properly. Removal or additions of material from the top section sometimes required small leveling adjustments. The fixtures were moved in until they touched uranium (either on the top or the lower section). When lack of contact was observed at either of the front faces of the fixture, the lower section was lowered to the full-out position, and the position of the uranium on the lower support stand was adjusted. The lower lift table was raised, and the alignment was checked.

The process was repeated several times as necessary. The final 0.005 in. adjustments were usually made by moving the top section. This was a long and tedious procedure, which took 1–2 hours or more as needed; however, it was always performed. This resulted in the top and bottom sections being aligned within ±0.005 in. For close spacing between cylinders, alignment was done with partial loading with these fixtures. For larger separations, the fixture was used with partial loading and closer spacing than that for delayed criticality.

For assemblies configured as shown in Figure 2, the lateral alignment uncertainty for two interacting cylinders is ± 0.005 in.

1.3.4 Upward Motion Limitation

To prevent the vertical table supporting the lower uranium cylinder from getting too close to the upper cylinder, there were two adjustable flanges on 1 in. diameter threaded rods attached to the bottom of the 1 in. thick plate of the vertical table. These threaded steel rods were 180° apart and penetrated through the thick plate that the movable table rested on when down. As the vertical table moved upward, its motion was limited when the flanges came in contact with the bottom of the fixed steel plate. The location of the flanges with respect to the bottom of the fixed table was measured by vertical distance transmitters that measured the last 0.050 in. to 0.001 in. These were used to measure small displacements of the lower uranium cylinder from the upper. These had to be adjusted in steps appropriately to achieve the position of the lower movable table for criticality. Once adjusted they were used to measure small displacements of the lower table from the critical position. In some experiments they were not adjusted properly and did not provide changes in vertical position for the last 0.05 in.

1.3.5 Position Measurement

The upward location of the vertical table was measured by two mechanical selsyns that read out to 0.001 in. When the vertical table was in the down position, they were adjusted to read 00.000. In many cases, in down position they read slightly different from zero. In these cases, the difference had to be added or subtracted from the distance from the upper surface of the lower uranium to the under surface of the diaphragm supporting the upper uranium cylinder, which was measured at several locations to 0.001 in. with an inside micrometer. These measurements were performed at many angular locations corresponding to the outer lower surface of the uranium cylinders where the uranium was in close contact with the diaphragm. The thickness of the diaphragm was added to the micrometer reading to get the total distance between the uranium cylinders with the vertical table in the down position. This distance with the distance the table was moved upward was used to get the separation of the upper and lower uranium cylinders.

1.3.6 Reactivity Effects of the Support Structure

The support structure reactivity worth consisted primarily of the reactivity effects of the diaphragm(s), the diaphragm support ring(s), and the support stand for the lower section. The removal of the support structure resulted in experimental k_{eff} values lower than unity. The diaphragm support ring and support stand for the lower section were reflectors instead of separators. The combined reactivity effect of all other supports, like the four vertical poles and tubing for the diaphragm support ring, was less than 1 cent and was not evaluated. The reactivity of the support structure was evaluated by assembling the system to delayed critical or a known measured reactivity, adding additional support structure, and obtaining the reactivity of the support structure from the difference in measured reactor period from the assembly without the additional support structure. To evaluate this effect, an inverted support stand like the one used for the lower section was added to the top of the uranium of the upper section. It was suspended in such a way as to not press down on the upper cylinder. The thickness of the diaphragm and clamping ring were doubled. These effects were measured for each assembly. In addition to determining the reactivity of the support structure, the separation of the cylinders was adjusted to delayed criticality. By doing this, the change in the separation associated with the support structure was determined.

The reactivity measurements are listed in Tables 2 and 3. Various multiple detection systems for reactor period measurements were used in each reactivity measurement listed in these tables, so several values are available for each reactivity measurement. The support structure reactivities are summed and are listed in Table 4. The combined reactivity in Table 4 includes an assumed correction for room return of ~3 cents, based on Godiva I indoor–outdoor measurements [8]. This correction should be better estimated by Monte Carlo calculational methods and used instead of the 3 cents.

Table 2. Support-stand reactivity for two interacting 7 in. diameter uranium (93.15 wt.% ^{235}U) metal cylinders without moderation or reflection.

Experiment	Reactivity [(a)] (cents)						
	1	2	3	4		Average	Standard deviation
						12.7[(c)]	
1	12.2	11.7	10.9	—		11.6(4.15)	0.65
2	10.61	9.14	10.6	—		10.12(3.85)	0.85
3	11.3	11.1	11.0	—		11.13(6.5)	0.15
4	10.35	10.25	9.0	9.92		10.12(6.9)	0.77
5	8.59	8.92	—	—		8.76	0.23
6	8.80	9.21	8.62	—		8.77	0.61

(a) Increase in system reactivity because of the presence of the support stand. Consequently, removing this structure reduced the neutron multiplication factor.
(b) As the assemblies got taller, the fraction of neutrons leaking from the bottom decreased, and the reactivity of the support stand was reduced.
(c) This value for the solid 7 in. diameter is included for comparison

Table 3. Reactivity of stainless-steel diaphragm and aluminum clamping ring for two interacting 7 in. diameter uranium cylinders.

Experiment	Reactivity [(a)] (cents)						
	1	2	3	4	5	Average	Standard deviation
(b)	21.75	16.13	18.24	18.70	—	18.70	2.32
1	25.1	26.6		25.8	—	17.79(25.8)[c]	3.47
2	17.02	14.72	18.90	16.88		16.88	1.71
3	17.5	13.7	20.3	17.17		17.17	2.70
4	16.2	14.64	20.2	17.01	—	17.01	2.34
5	16.79	17.36	18.57	17.08		17.08	0.78
6	15.6	16.1	15.4	15.7		15.7	0.31

(a) Increase in system reactivity as a result of the presence of the diaphragm support ring and diaphragm. Consequently, removing these structures reduced the neutron multiplication factor.
(b) The first line includes the values for the solid cylinder with no gap from HEU-MET-FAST-051.
(c) The measured value in parentheses looks wrong, but this value was interpolated between the solid cylinder on line one and experiment 2.

Table 4. Combined support structure reactivity for two interacting 7 in. diameter uranium (93.15 wt.% ^{235}U) metal cylinders without moderation or reflection.

Experiment	Combined [(a)] reactivity (cents)	Combined [(b)] standard deviation (± cents)	Combined [(a)] reactivity (Δk_{eff})	Combined [(b)] standard deviation (Δk_{eff})
1	29.4	3.68	1.94 E-3	2.43 E-4
2	30.0	1.79	1.98 E-3	1.18 E-4
3	31.3	2.73	2.06 E-3	1.80 E-4
4	30.13	2.19	1.98 E-3	1.44 E-4
5	28.84	0.44	1.90 E-3	2.90 E-5
6	27.47	0.46	1.81 E-3	3.04 E-4

(a) The reduction in reactivity resulting from the removal of support structures. The combined reactivity includes a 3 cent reactivity adjustment for room return, based on Godiva I indoor–outdoor reactivity measurements [8]. β_{eff} = 0.0066 to convert reactivity to k_{eff}.
(b) Combined standard deviation based on measurement data and calculated as the square root of the sum of the individual standard deviations squared.

1.3.7 Details of Experiments

The six experiments are summarized in Table 1. The descriptions of the assemblies are extracted from the referenced logbook pages indicated in Table 1.

1.3.7.1 Experiment 1

On April 5, 1963, a symmetric assembly of two 7 in. diameter, interacting, coaxial cylinders with nominal heights of 2.625 in. was measured at delayed criticality (k_{eff} = 1.00000) with a separation of 0.1357 in. The makeup of the assembly is depicted in Figure 4. This is the assembled configuration with the support structure. This configuration would be the best for comparing calculated k_{eff} with measurements because there are no corrections to the system with their associated uncertainties. This comparison calculation should include the support structure; the air in the room; and the walls, floor, and ceiling of the experimental cell. The lower section of the assembly consisted of three 7 in. diameter cylinders. The lower section of the assembly had a mass of 31,064 g. The upper section of the assembly consisted of three cylinders. The upper section of the assembly had a mass of 31,051 g. The total mass of the uranium assembly was 62,115 g. The presence of the support structure consisting of the diaphragm, diaphragm support rings and the lower support stand was evaluated. Without these supports, the separation of the cylinders would have been 0.0078 in. closer (i.e., 0.1279 in.). The reactivity change associated with a change in separation of the upper and lower cylinder was measured to be 3.75 cents per thousandths of an inch (cents/mil). Without the air in the cell and the cell structure, the separation would have been even lower. The measured height of the various sections of the upper and lower cylinder and the sum of the measured heights of the individual parts along with the difference from which the average air gap between parts are given in Table 5. The footnote to the table will not be repeated in subsequent tables for experiments 2–6. These gaps should be included in the detailed model when comparing calculations with measurements.

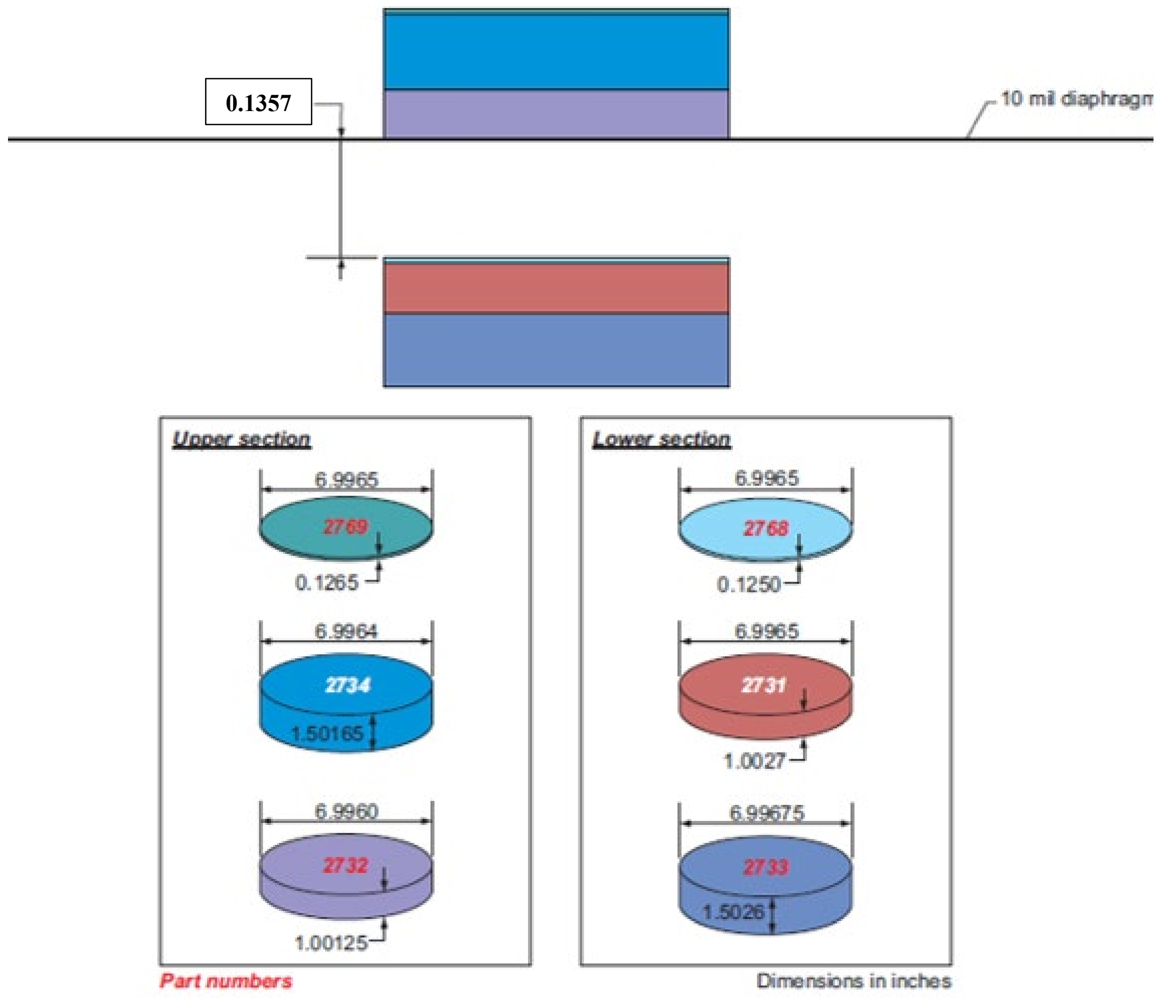

Figure 4. Experiment 1—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 2.625 in., spaced 0.1357 in. apart.

Table 5. Measured thickness, sum of part thicknesses and average gap between parts for two 7 in. diameter cylinders of 2.625 in. thickness.

Section	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	2.628, 2.628, 2.629, 2.629, 2.628, 2.625, 2.627, 2.629
	Average thickness	2.6279 ± 0.0014
	Sum of part thicknesses	2.6294
	Number of gaps	2
	Average gap thickness	0.0
Lower	Measured thicknesses	2.632, 2.629, 2.6305, 2.6295,2.630
	Average thickness	2.6310 ± 0.0012
	Sum of part thicknesses	2.6303
	Number of gaps	2
	Average gap thickness	0.00035

[a] Measured height is an average of several measurements with 0.001 in. accuracy. Part thickness from the inspection reports (with accuracy on 0.0001 in.) were summed. The average gap thickness between 7-in.-diameter discs was the difference between the measured height and the sum of the part thicknesses divide by the number of gaps. This of course assumed the gaps between all parts in a section are the same. If the sum of the part heights was larger than the measured height, it was assumed that the gap thickness between parts was 0.0 thousandths.

1.3.7.2 Experiment 2

On April 8, 1963, a symmetric assembly of two 7 in. diameter, interacting cylinders with nominal heights of 2.750 in. was measured at delayed criticality with a separation of 0.5994 in. The makeup of the assembly s depicted in Figure 5. This assembly is a slight modification of the previous assembly. The upper section of the assembly had a mass of 32,511 g, and the lower section had a mass of 32,499 g. The total mass of the uranium assembly was 65,010 g. The experimental k_{eff} of the configuration as assembled was 1.00000. The presence of the support structure consisting of the diaphragm, diaphragm support rings, and the lower support stand was evaluated. Without these supports, the separation of the cylinders would have been 0.0112 in. closer (i.e., 0.5882 in.). Without the air in the cell and the cell structure, the separation would have been even lower. The reactivity change associated with a change in separation of the upper and lower cylinder is 2.68 cents/mil. Table 6 includes the measured height of the upper and lower cylinder, the sum of the measured heights of the individual parts, and the difference from which the average air gap between parts is obtained.

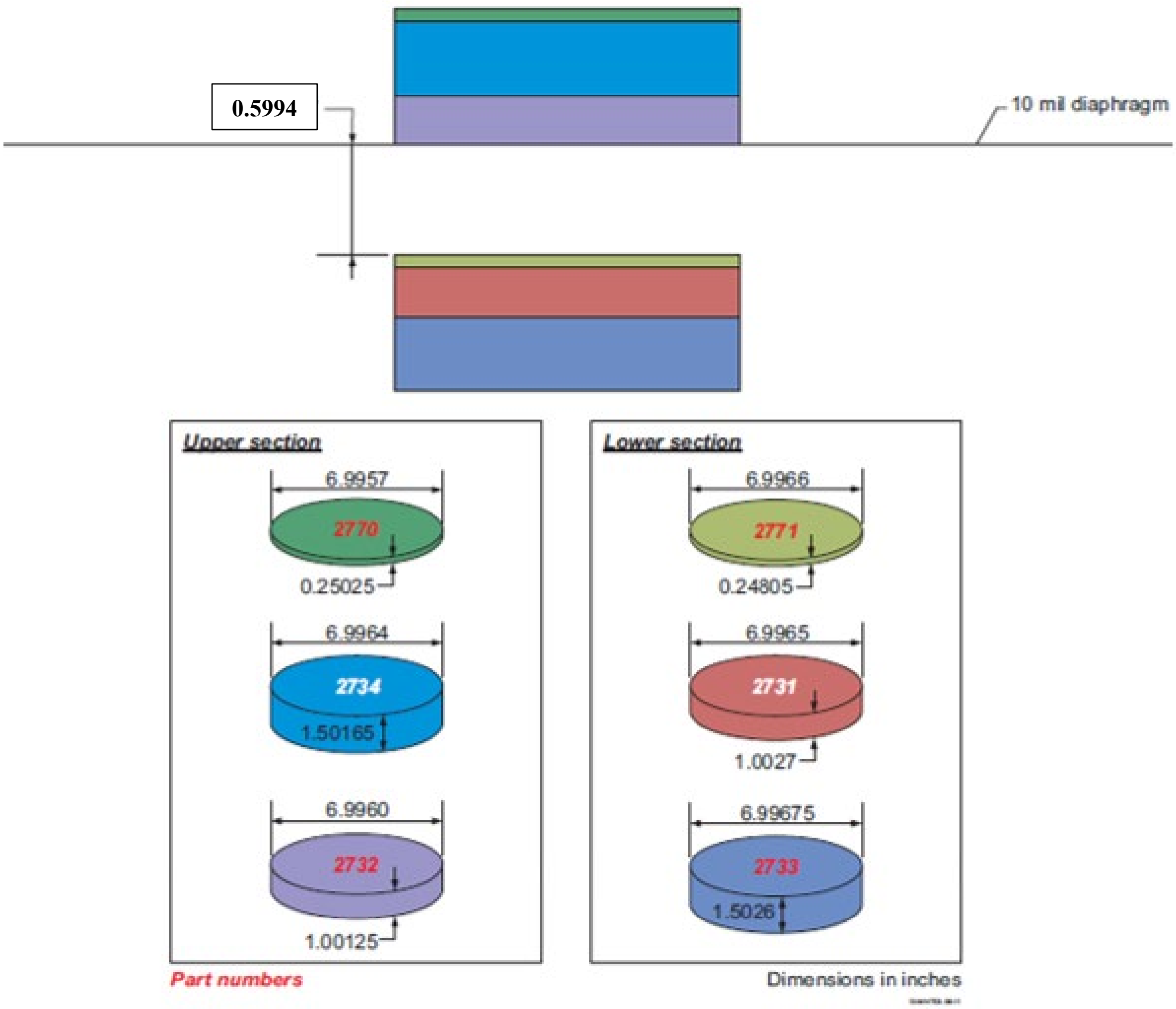

Figure 5. Experiment 2—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 2.75 in., spaced 0.5994 in. apart.

Table 6. Measured thickness, sum of part thicknesses, and average gap between parts for two 7 in. diameter cylinders of 2.75 in. thickness.

Section	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	2.752, 2.752, 2.753, 2.753, 2.752, 2.751, 2.750, 2.752
	Average thickness	2.7519 ± 0.0001
	Sum of part thicknesses	2.75315
	Number of gaps	2
	Average gap thickness	0.0
Lower	Measured thicknesses	2.750, 2.751, 2.750, 2.750
	Average thickness	2.7503 ± 0.0005
	Sum of part thicknesses	2.75335
	Number of gaps	2
	Average gap thickness	0.0

1.3.7.3 Experiment 3

On April 9, 1963, a symmetric assembly of two 7 in. diameter interacting cylinders with nominal heights of 2 7/8 in. was measured at delayed criticality with a separation of 0.8763 in. The makeup of the assembly is depicted in Figure 6. The upper and lower cylinders of the assembly had a mass of 33,991 g and 34,023 g, respectively, and resulted in a total assembly mass of 68,014 g. The experimental k_{eff} of the configuration as assembled was 1.00000. The presence of the support structure consisting of the diaphragm, diaphragm support rings and the lower support stand was evaluated. Without these supports, the separation of the cylinders would have been 0.0147 in. closer (i.e., 0.8616 in.). Without the air in the cell and the cell structure, the separation would have been even lower. The reactivity change associated with a change in separation of the upper and lower cylinder is 2.12 cents/mil. Table 7 includes the measured height of the upper and lower cylinder, the sum of the measured heights of the individual parts, and the difference from which the average air gap between parts is obtained.

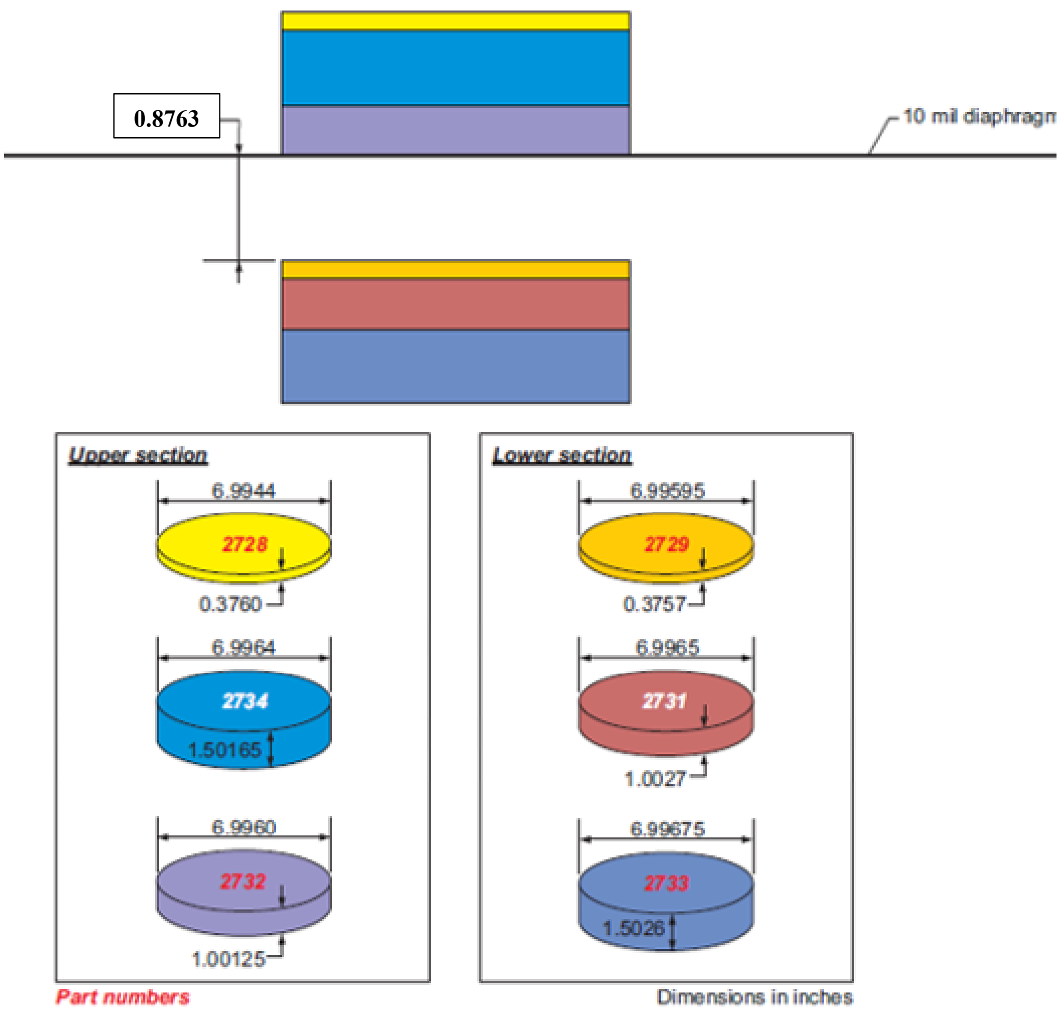

Figure 6. Experiment 3—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 2.875 in., spaced 0.8763 in. apart.

Table 7. Measured thickness, sum of part thicknesses, and average gap between parts for two 7 in. diameter cylinders of 2.875 in. thickness.

Section	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	2.878, 2.878, 2.879, 2.879, 2.875, 2.878, 2.877, 2.877
	Average thickness	2.8776 ± 0.0013
	Sum of part thicknesses	2.8789
	Number of gaps	2
	Average gap thickness	0.00
Lower	Measured thicknesses	2.880, 2.880, 2.880, 2.879
	Average thickness	2.8797 ± 0.0005
	Sum of part thicknesses	2.881
	Number of gaps	2
	Average gap thickness	0.0

1.3.7.4 Experiment 4

On April 10, 1963, a symmetric assembly of two 7 in. diameter, interacting cylinders with nominal heights of 3.0 in. was measured at delayed criticality with a separation of 1.1684 in. The makeup of the assembly is depicted in Figure 7. The upper and lower cylinders of the assembly had a mass of 35,472 g and 35,518 g, respectively, and resulted in a total assembly mass of 70,990 g. The experimental k_{eff} of the configuration as assembled was 1.00000. The presence of the support structure consisting of the diaphragm, diaphragm support rings, and the lower support stand was evaluated. Without these supports, the separation of the cylinders would have been 0.0160 in. closer (i.e., 1.1524 in.). Without the air in the cell and the cell structure, the separation would have been even lower. The reactivity change associated with a change in separation of the upper and lower cylinder is 1.88 cents/mil. Table 8 includes the measured height of the various section of the upper and lower cylinder, the sum of the measured heights of the individual parts, and the difference from which the average air gap between parts is obtained.

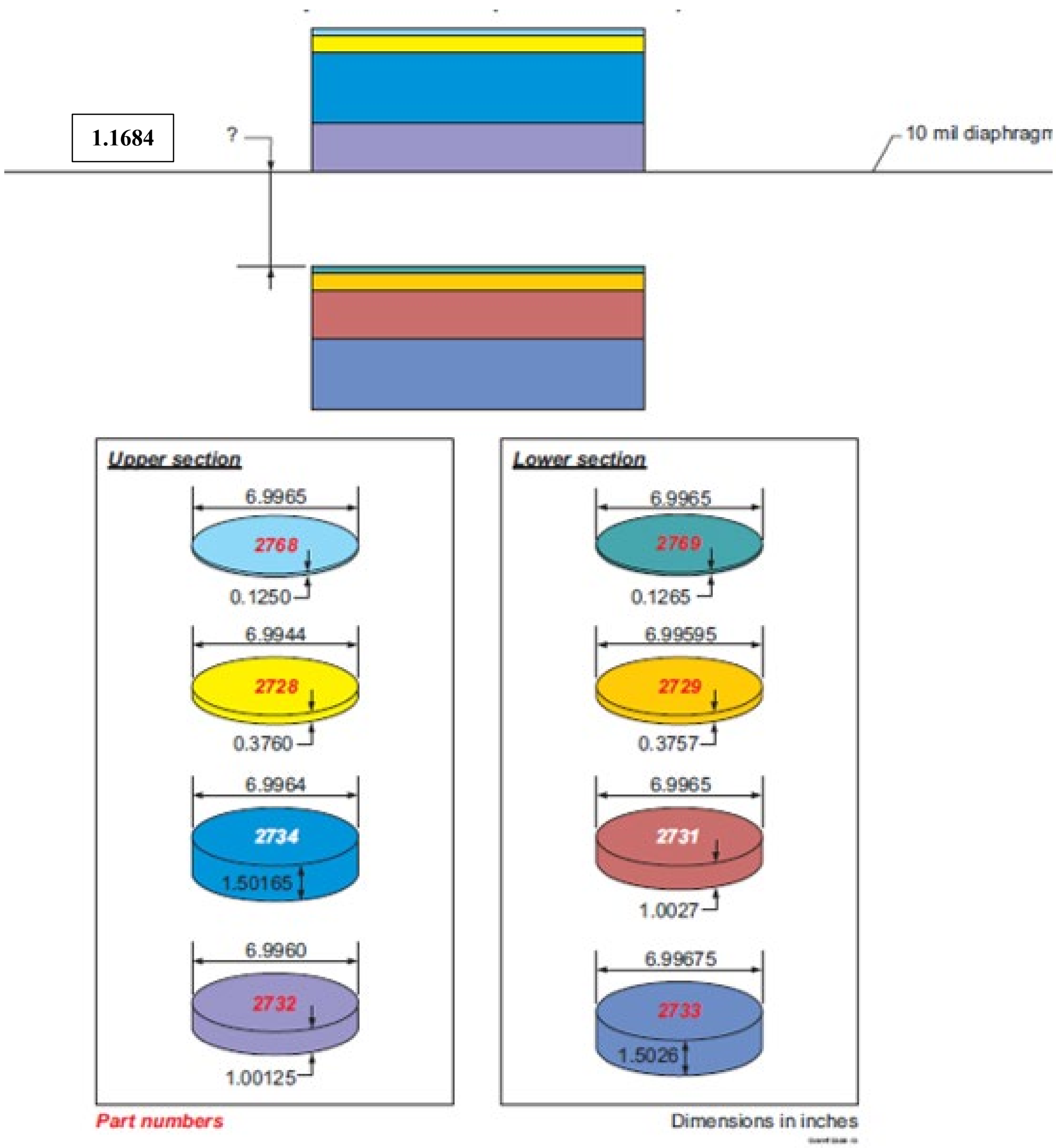

Figure 7. Experiment 4—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 3.0 in., spaced 1.1684 in. apart.

Table 8. Measured thickness, sum of part thicknesses, and average gap between parts for two 7 in. diameter cylinders of 3.00 in. thickness.

Section	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	3.005, 3.004, 3.004, 3.005, 3.003, 3.002, 3.003, 3.004
	Average thickness	3.0038 ± 0.0010
	Sum of part thicknesses	3.0039
	Number of gaps	3
	Average gap thickness	0.00
Lower	Measured thicknesses	3.007, 3.006, 3.007, 3.008, 3.006
	Average thickness	3.0068 ± 0.0008
	Sum of part thicknesses	3.0075
	Number of gaps	3
	Average gap thickness	0.00

1.3.7.5 Experiment 5

On April 14, 1963, a symmetric assembly of two 7-in.-diameter, interacting cylinders with nominal heights of 3.125 in. was measured at delayed criticality with a separation of 1.5367 in. The makeup of the assembly is depicted in Figure 8. The upper and lower cylinders of the assembly had a mass of 36,946 and 36,909 g, respectively, and resulted in a total assembly mass of 73,855 g. The experimental k_{eff} of the configuration as assembled was 1.00000. The presence of the support structure consisting of the diaphragm, diaphragm support rings and the lower support stand was evaluated. Without these supports, the separation of the cylinders would have been 0.0175 in. closer (i.e., 1.5192 in.). Without the air in the cell and the cell structure, the separation would have been even lower. The reactivity change associated with a change in separation of the upper and lower cylinder is 1.65 cents/mil. Table 9 includes the measured height of the various sections of the upper and lower cylinder, the sum of the measured heights of the individual parts, and the difference from which the average air gap between parts is obtained.

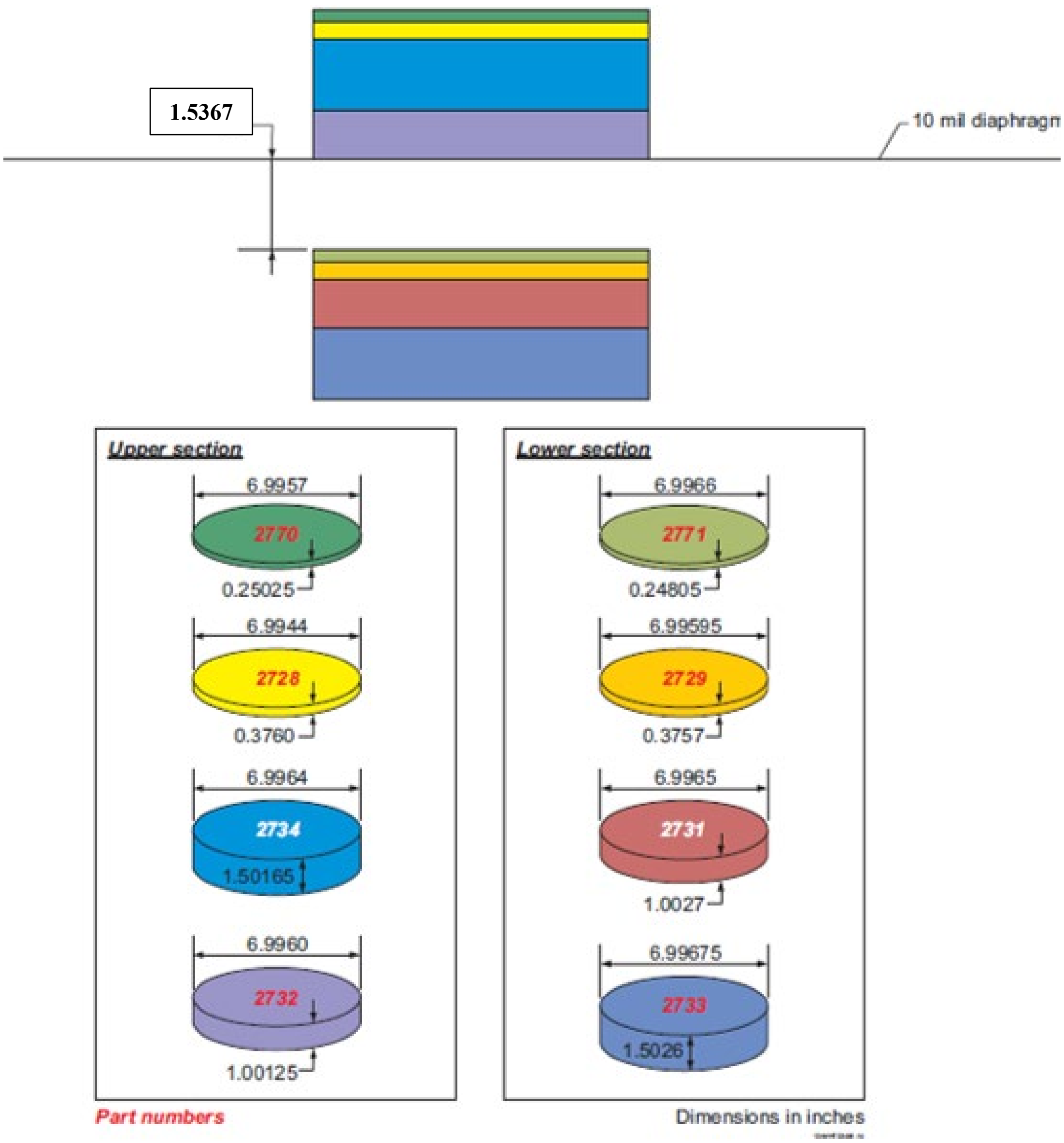

Figure 8. Experiment 5—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 3.125 in., spaced 1.5367 in. apart.

Table 9. Measured thickness, sum of part thicknesses, and average gap between parts for two 7 in. diameter cylinders of 3.125 in. thickness.

Section	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	3.126, 3.127, 3.128, 3.127, 3.127, 3.123, 3.125, 3.125
	Average thickness	3.1263 ± 0.0016
	Sum of part thicknesses	3.12915
	Number of gaps	3
	Average gap thickness	0.0
Lower	Measured thicknesses	3.128, 3.125, 3.125, 3.125
	Average thickness	3.1258 ± 0.0015
	Sum of part thicknesses	3.12905
	Number of gaps	3
	Average gap thickness	0.0

1.3.7.6 Experiment 6

On April 15, 1963, a symmetric assembly of two 7-in.-diameter, interacting cylinders with nominal heights of 3.25 in. was measured at delayed criticality with a separation of 1.9228 in. The makeup of the assembly is depicted in Figure 9. The upper and lower cylinders of the assembly had a mass of 38,427 g and 38,435 g, respectively, and resulted in a total assembly mass of 76,862 g. The experimental k_{eff} of the configuration as assembled was 1.00000. The presence of the support structure consisting of the diaphragm, diaphragm support rings and the lower support stand was evaluated. Without these supports, the separation of the cylinder would have been 0.0200 in. closer (i.e., 1.9028 in.). Without the air in the cell and the cell structure, the separation would have been even lower. The reactivity change associated with a change in separation of the upper and lower cylinder is 1.37 cents/mil. Table 10 includes the measured height of the various sections of the upper and lower cylinder, the sum of the measured heights of the individual parts, and the difference from which the average air gap between parts is obtained.

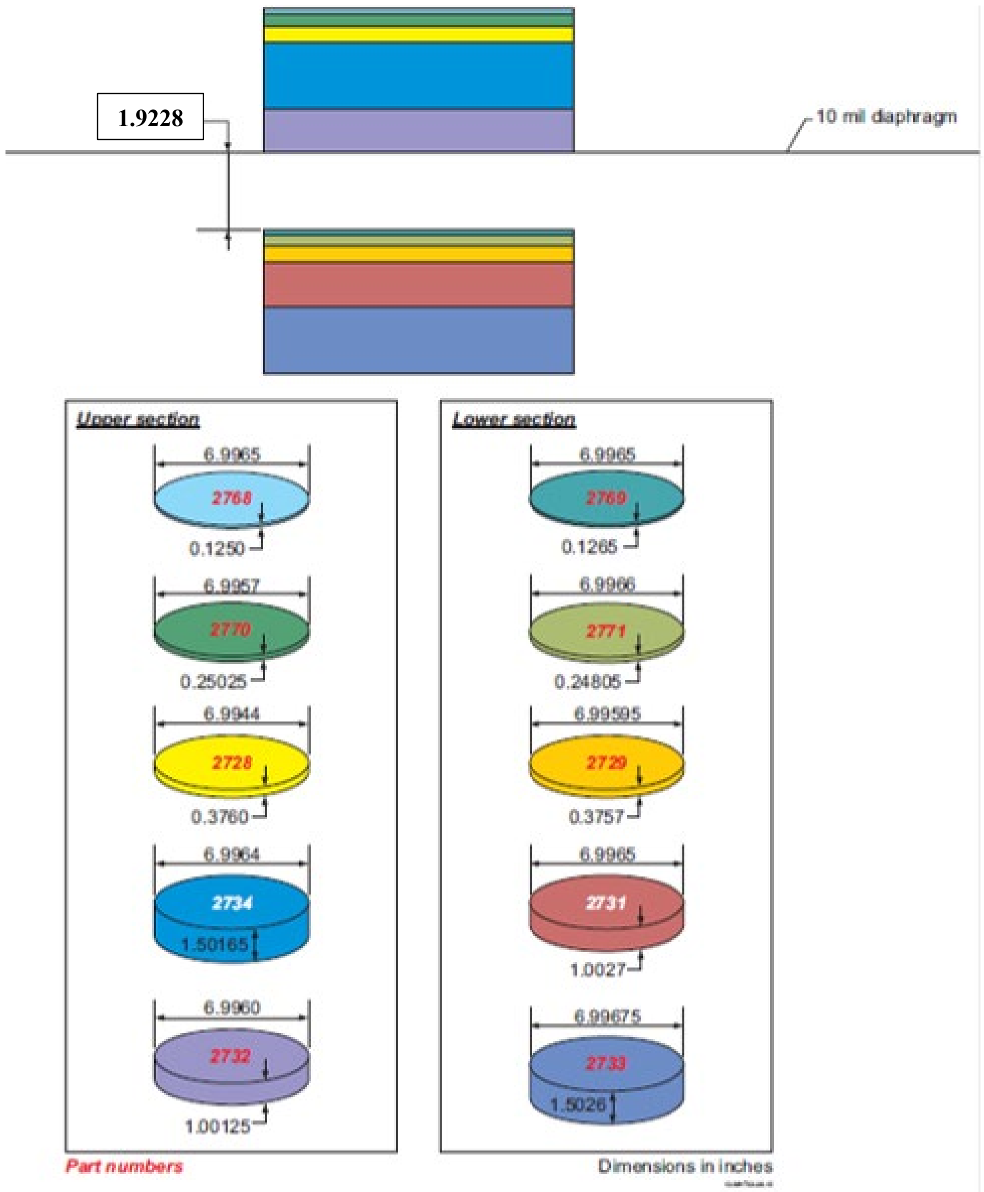

Figure 9. Experiment 4—Configuration of delayed critical unreflected, unmoderated uranium (93.15 wt.% ^{235}U) metal 7 in. diameter interacting cylinders with nominal height of 3.25 in., spaced 1.9228 in. apart.

Table 10. Measured thickness, sum of part thicknesses, and average gap between parts for two 7 in. diameter cylinders of 3.25 in. thickness.

Disc	Thicknesses (in.)	Average gaps (mils)
Upper	Measured thicknesses	3.252, 3.254, 3.254, 3.253, 3.250, 3.251, 3.351, 3.254
	Average thickness	3.2524 ± 0.0016
	Sum of part thicknesses	3.25415
	Number of gaps	4
	Average gap thickness	0.0
Lower	Measured thicknesses	3.252, 3.252, 3.250, 3.251, 3.251
	Average thickness	3.2512 ± 0.0008
	Sum of part thicknesses	3.2555
	Number of gaps	4
	Average gap thickness	0.0

1.4 DESCRIPTION OF MATERIAL DATA

The set of cylinders and annuli were machined from highly enriched uranium metal with a nominal density of 18.75 g/cm^3 and impurity content of 489 ppm. The solid cylinders had a nominal diameter of 7 in. and were fabricated with varying heights up to 1.5 in. The masses were measured at the Y-12 Plant to within 1 g with an uncertainty of ±0.5 g. The dimensions were measured to tenths of thousandths of inches with an uncertainty of ±0.00005 in. The uranium isotopics were measured by spectrographic analysis, and the uncertainty on the ^{234}U, ^{235}U, and ^{236}U isotopic content was ±0.005 wt.%. The ^{238}U content was obtained by the difference from unity [9].

The average isotopic content of the parts from mass spectrographic analysis are 93.151 wt.% ^{235}U, 0.964 wt.% ^{234}U, and 0.245 wt.% ^{236}U. The impurity content was measured by spectrographic analysis with an average impurity content of 489 ppm wt.%. This value is very close to the quoted typical value for cast uranium metal (93.20 wt.% ^{235}U enriched) at the Oak Ridge Y-12 Plant: 99.95 g of U per 100 g of material and average impurity content of 500 ppm wt.% [8].

The masses, dimensions, impurity content, and isotopic content are given in Tables 11, 12, and 13. The average density in parenthesis from Table 11 weighted by the mass of each part is 18.747 g/cm^3. The isotopic analysis of one 7 in. diameter disc was not available. Each uranium metal part has a part number scribed on one flat surface of the part for identification and was also used for orientation of parts in an assembly. The surface of the part with the scribed number was the upper surface for all parts in all assemblies. The numbers given in the tables, and in the figures in the previous section for the part numbers are the last four digits of the part numbers. The first six digits were the same for all part numbers and were used to identify uranium metal parts for ORCEF.

The data in Table 13 is the measured impurity content for the uranium metal used in the all experiments with uranium metal discs and annuli at ORCEF. Eleven randomly sampled cylinder/annuli parts were analyzed. Only average and range information exists [4]. The value assumed at this time for oxygen and nitrogen were 20 ppm for both, but it was assumed that these were the values for the 7 in. diameter discs. The values for carbon at this time (early 1960s) were much lower than present day values, which have added carbon from many recastings of the material.

Table 11. Mass and dimensions of uranium (93.15 wt.% ^{235}U) metal cylinders for delayed critical experiments with two 7 in. diameter interacting cylinders.

Part number	Measured mass (g)	Measured height (in.)	Measured outer diameter (in.)
2728	4435	0.3760	6.9944(18.733)[a]
2729	4440	0.3757	6.99595(18.761)
2730	6646	0.5620	6.9960(18.773)
2731	11841	1.0027	6.9965(18.744)
2732	11814	1.00125	6.9960(18.731)
2733	17742	1.5026	6.99675(18.740)
2734	17742	1.50165	6.9964(18.754)
2768	1481	0.1250	6.9965(18.806)
2769	1495	0.1255	6.9965(18.908)
2770	2955	0.25025	6.9957(18.746)
2771	2916	0.24805	6.9966(18.659)

[a]Values in parentheses are calculated densities in g/cm^3.

Table 12. Summary of uranium isotopics of metal cylinders for delayed critical experiments with two 7 in. diameter interacting cylinders.[(a)]

Part number	Measured ^{235}U (wt.%)	Measured ^{234}U (wt.%)	Measured ^{236}U (wt.%)	^{238}U [(b)] (wt.%)
2728	93.17	0.97	0.24	5.62
2729	93.15	0.99	0.26	5.60
2730	93.14	0.97	0.25	5.64
2731	93.13	0.97	0.22	5.68
2732	93.17	0.95	0.21	5.67
2733	93.15	0.96	0.26	5.63
2734	93.18	0.95	0.24	5.63
2768	93.14	0.92	0.26	5.68
2769	93.15	0.97	0.25	5.63
2770	93.13	0.99	0.26	5.62
2771	Not available	Not available	Not available	Not available
Average	93.151	0.964	0.245	5.640
Deviation	0.017	0.021	0.018	0.028

[(a)] Mass spectrographic analysis.
[(b)] By difference from 100%.

Table 13. Measured average impurity content of uranium metal cylinders for delayed critical experiments with two 7-in.-diameter interacting cylinders.[a]

Element	Parts per million by weight (ppm)	Range (ppm)
Ag	8	3–25
Bi	164	81–311
C	5	0–9
Co	5	2–15
Cr	7	4–12
Cu	25	10–40
Mg	3	2–3
Mn	56	25–89
N	30	—
Na	27	15–50
Ni	100	—
O	20	—
Sb	38	10–80
Ti	1	—

[a] Mass spectrographic analysis, except nitrogen and oxygen which were assumed to be 20 ppm for both.

Some recently discovered data from Y-12 Plant inspection reports for 37 HEU metal parts showed that the mass for each part was measured three times; the dimensions were measured at three different locations for each part; the uranium isotopics were measured usually by dividing a metal chip from the machining process into thirds and performing isotopic analysis on each third. These data are not available for all parts. The masses measured were rounded to grams, and in no case for these 37 parts did the three mass measurements differ by more than 1 g. The heights given in the table were all measured to one-tenth of a thousandth. The height measured at three different locations on the parts to ±0.0001 in. was the same at all locations for 98 % of the parts. Thus, the heights are known to half of a ten thousandth of an inch. The outside diameters for the three measurements for each individual part were identical for over 80% of the parts, where they differed by 0.00005 in.

The isotopic enrichments are measured to 0.01 wt.% and thus are known to ±0.005 wt.%. The weight percent ^{235}U for the three measurements for each individual part was identical for over 95 % of the parts, where it differed by 0.02 wt.%. The weight percent ^{234}U for the three measurements for each individual part was identical for all 37 parts measured. The weight percent ^{234}U for the three measurements for each individual part was identical except for three of the 37 parts, where it differed by 0.02 wt.% for two parts and 0.05 wt.% for the other. Although these data are not available for the parts used in these measurements the accuracies are expected to be similar.

1.5 SUPPLEMENTAL EXPERIMENTAL MEASUREMENTS

Supplemental experimental Rossi-alpha measurements were performed and are not reported here. These data can be acquired from Laboratory Records at ORNL or John Bess at Idaho National Laboratory.

2. CONCLUSIONS

These accurate descriptions of the configuration and materials allow these experiments to be incorporated into to the ICSBEP. Uncertainty analysis needs to be performed to determine the accuracy of the neutron multiplication factors, k_{eff}. This analysis should mimic that performed for other ICSBEP nuclear criticality safety benchmarks already documented with these materials in the ICSBEP and Nuclear Energy Agency programs such as HEU-MET-FAST-051 and others. Because of the accurate descriptions of the configuration and material the uncertainties in the k_{eff} values should be as low as ±0.0002.

REFERENCES

1. J. T. Mihalczo, "Brief Summary of Unreflected and Unmoderated Cylindrical Critical Experiments with Oralloy at Oak Ridge," ORNL/TM-1999/302, Oak Ridge National Laboratory, Oak Ridge, TN (Nov. 1999).
2. J. T. Mihalczo, "Prompt-Neutron Decay in a Two-Component Enriched Uranium Metal Critical Assembly," *Trans. Am. Nucl. Soc.* **6**, 60 (1963).
3. J. T. Mihalczo, "Prompt Neutron Decay in a Two-Component Enriched Uranium Metal Critical Assembly," ORNL/TM-470, Union Carbide Nuclear Corporation, Oak Ridge National Laboratory, Oak Ridge, TN (1963).
4. J. T. Mihalczo, "Graphite and Polyethylene Reflected Uranium-Metal Cylinders and Annuli," Y-DR-81, Oak Ridge Y-12 Plant, Oak Ridge, TN 72).
5. J. T. Mihalczo, "Prompt Neutron Lifetime in Critical Enriched-Uranium Metal Cylinders and Annuli," *Nucl. Sci. Eng*. **20**, 60–65 (1964).
6. J. T. Mihalczo, "Monte Carlo Calculations of Two Core Delayed Critical Assemblies," *Trans. Am. Nucl. Soc.* **11**, 603 (1968).
7. J. T. Mihalczo, "Prompt Neutron Time Behavior in Delayed Critical Coupled Uranium Metal Cylinders," *Proceedings of the International Conference on Fast Critical Experiments and Their Analysis,* ANL-7320, 237–241 (Oct. 1966).
8. 8. Mihalczo, J.T.; Lynn, J.J.; Taylor, J.R.; Hansen, G.E.; Pelowitz, D.B., "Delayed Critical ORNL Unreflected Uranium (93.20) Metal Sphere and the Pure Unreflected Uranium (93.80) Sphere Critical Mass," Annals of Nuclear Energy, v 29, n 5, March 2002, p 525-560 (2002).
9. 9. John Mihalczo, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF" ORNL Report, ORNL/TM-2012/32 (Sep 2012). [OSTI #1052246]

APPENDIX A. SUPPORT STRUCTURE

The support structure is described in this appendix. Figure A.1 represents the diaphragm and rings with its support structure. Figure A.2 represents the low-mass support structure. Both these structures can be seen in Figure 2. These support structures were used in many other critical experiments with oralloy at ORCEF.

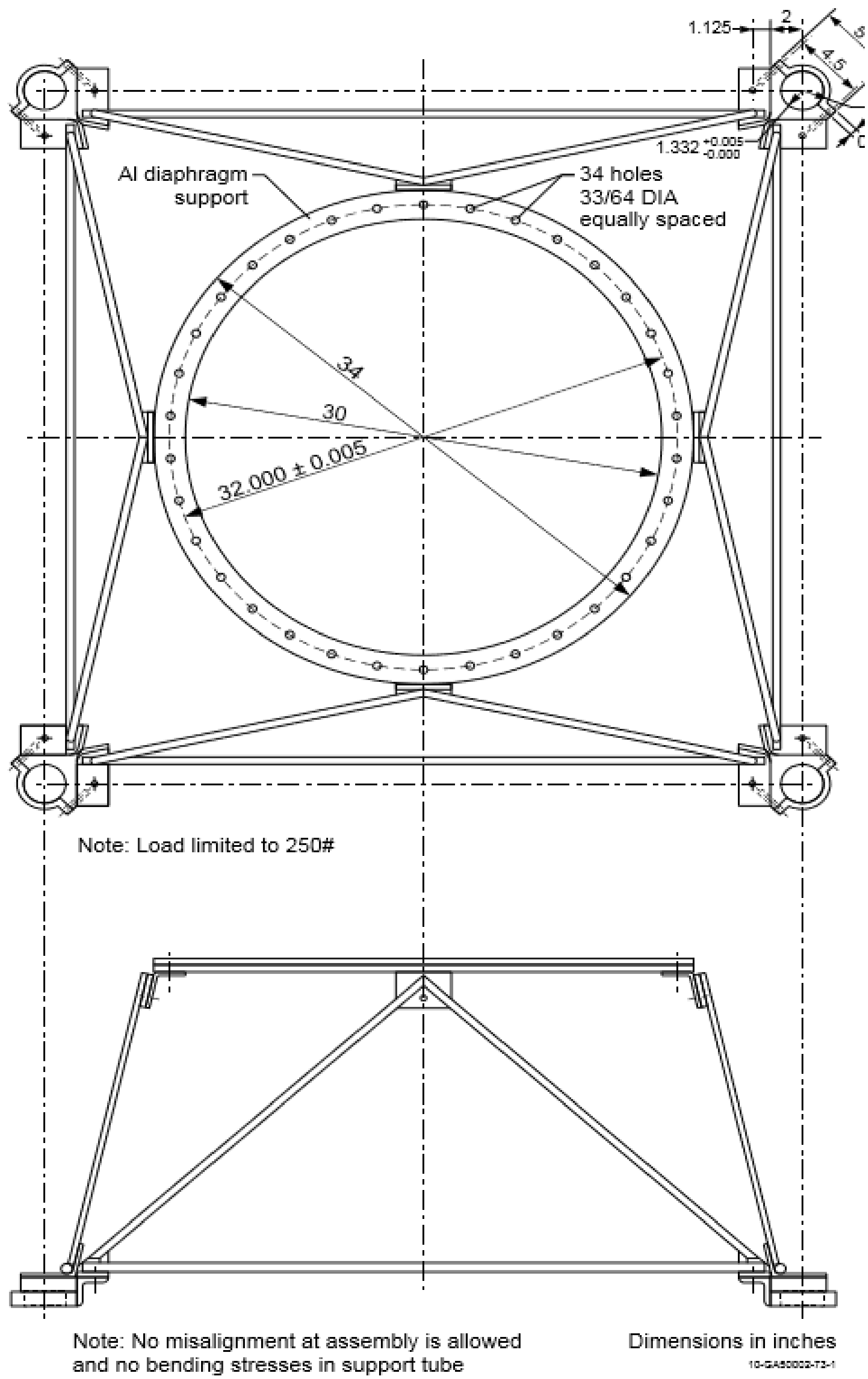

Figure A.1. Diaphragm support structure.

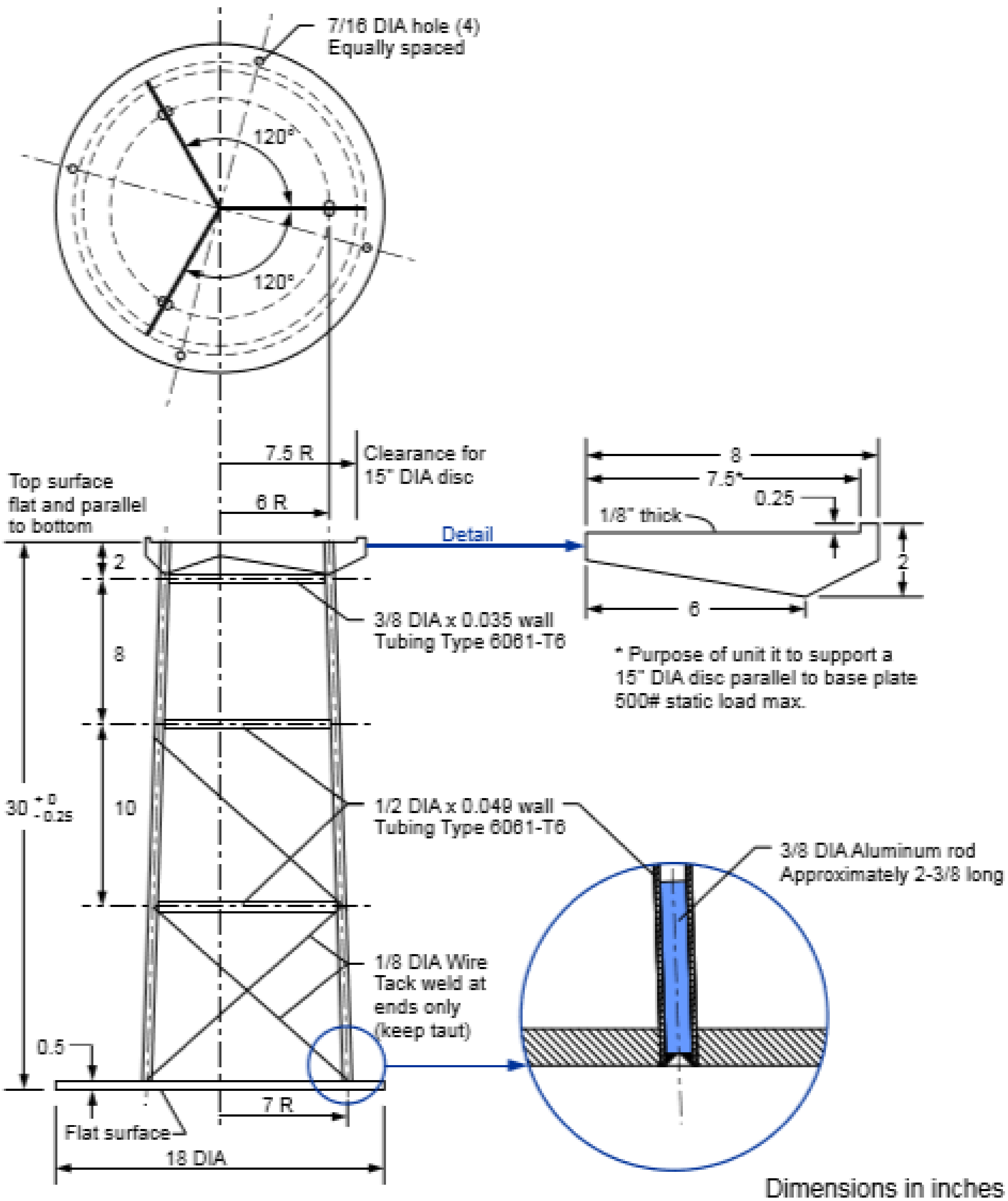

Figure A.2. Details of the lower support structure