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Critical Experiments with Uranium (93.14) Metal Annuli and Cylinders with Thick Polyethylene Reflectors and/or Internal Polyethylene Moderator

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Prepared by
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ABSTRACT

This report describes in detail delayed critical experiments with 93.14 wt ^{235}U enriched uranium metal and polyethylene that were performed at the Oak Ridge Critical Experiments Facility. Experiments with uranium metal annuli without polyethylene reflector and with thick polyethylene reflector with the central void region either empty or filled with polyethylene are described here. The outside diameters of the uranium annuli were 11, 13, and 15 in. In addition, there were uranium metal cylinders with diameters varying from 7 to 15 in. with complete reflection and reflection on one flat surface to simulate floor reflection. Most of the experiments were performed between February 1964 and April 1964. The one-side-reflected experiments were assembled in November 1967. This detailed accurate description makes these critical experiments suitable for criticality safety benchmarks.

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CRITICAL EXPERIMENTS WITH URANIUM (93.14) METAL ANNULI AND CYLINDERS WITH THICK POLYETHYLENE REFLECTORS AND/OR INTERNAL POLYETHYLENE MODERATOR

1 INTRODUCTION

A variety of critical experiments were constructed of enriched uranium metal during the 1960s and 1970s at the Oak Ridge Critical Experiments Facility in support of criticality safety operations at the Y-12 Plant [(1–7)]. The purpose of these experiments included the evaluation of storage, casting, 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 solid cylinders of various diameters, annuli of various inside and outside diameters, two and three interacting cylinders of various diameters, and graphite- and polyethylene-reflected cylinders and annuli.

Of these hundreds of delayed-critical experiments, the ones described here are (1) uranium metal annuli without reflector and polyethylene in the central void region, (2) 7- to 15-in.-diam uranium metal cylinders with "infinite" polyethylene reflector, (3) 7- to 15-in.-diam uranium metal cylinders with "infinite" polyethylene on one flat surface, and (4) uranium metal annuli with outside diameters of 11, 13, and 15 in. with "infinite" polyethylene reflector and the internal region moderated with polyethylene or containing air. Most of the experiments were performed between February 1964 and April 1964. The one-side-reflected experiments were assembled in November 1967. Because of the detailed accurate descriptions, the 25 experiments described are suitable for use as criticality safety benchmarks. In addition to the near delayed-critical configurations, the results of uranium height perturbation measurements are reported and also can be used to verify calculational methods.

Unreflected and unmoderated experiments with highly enriched uranium metal performed at the Oak Ridge Critical Experiments Facility in the 1960s are evaluated in HEU-MET-FAST-051[6]. Thin-graphite-reflected (2 in. or less) experiments also performed at the Oak Ridge Critical Experiments Facility are evaluated in HEU-METAL-FAST-071.[7]

2 DESCRIPTION AND RESULTS OF EXPERIMENTAL CONFIGURATIONS AND MEASURED REACTIVITIES

Information on the polyethylene reflected and/or moderated experiments was from Ref. 3 and experimental logbooks.[a] These experiments were performed in the 35 × 35 × 30-ft.-high East Cell, and the assemblies of uranium 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 experiments were highly enriched uranium metal annuli with outside diameters of 11, 13, and 15 in. with thick polyethylene reflectors. In addition, experiments were performed with annuli without external reflectors but with internal polyethylene moderators. Uranium metal cylinders were also assembled with complete polyethylene reflectors and with polyethylene reflector on one flat surface to simulate floor reflection. It should be noted that all dimensions were measured and recorded in inches. When dimensions are rounded to the nearest inch in this report, they are nominal dimensions; otherwise they are measured. The 25 experiments and their measured reactivities measured with support structures and uranium masses (including impurities) are summarized in Table 1.

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[a] Experimental data for Experiments 1–3 can be found in pages 71–81 of ORNL logbook 14R (East Cell—Logbook 3). Data for Experiments 9–13 can be found in pages 5–32 of ORNL logbook 17R (East Cell—Logbook 7). Data for all other experiments can be found in pages 184–249 of ORNL logbook 14R (East Cell—Logbook 3).

Table 1. Uranium metal mass and measured reactivity of delayed-critical annuli and cylinders with polyethylene thick reflector and/or internal moderator

	Description				Uranium mass (g)				
Experiment number	HEU OD (in.)	HEU ID (in.)	Material inside annulus	Reflector thickness (in.)	Lower section	Upper section	Total	Average measured reactivity (cents) [b]	Average period (s)
1	15	7	Poly	0	84,762	84,925	169,687	4.5	249
2	15	9	Poly	0	69,346	107,711	177,057	33.6	13.9
3	13	7	Poly	0	57,892	86,249	144,141	21.2	21.2
4	15	0	NA	∞	61,074	0	61,074	8.8	113
5	13	0	NA	∞	50,971	0	50,971	44.2	7.4
6	11	0	NA	∞	41,431	0	41,431	25.5	23.5
7	9	0	NA	∞	33,276	0	33,276	–1.25	–1062
8	7	0	NA	∞	26,893	0	26,893	5.8	185
9	15	0	NA	*a*	108,508	0	108,508	33.7	*c*
10	13	0	NA	*a*	89,144	0	89,144	29.9	*c*
11	11	0	NA	*a*	71,078	0	71,078	60	*d*
12	9	0	NA	*a*	56,121	0	56,121	12.8	68.4
13	7	0	NA	*a*	47,268	0	47,268	12.6	70.6
14	15	7	Void	∞	70,363	0	70,363	30.0	17.4
15	15	7	Poly	∞	76,330	0	76,330	24.3	24.8
16	15	9	Void	∞	73,709	0	73,709	8.9	111
17	15	9	Poly	∞	82,391	0	82,391	21.2	32.4
18	15	11	Void	∞	80,631	0	80,631	13.9	61
19	15	11	Poly	∞	91,656	0	91,656	20.9	33
20	13	7	Void	∞	60,548	0	60,548	27.9	20.0
21	13	7	Poly	∞	66,935	0	66,935	40	*e*
22	13	9	Void	∞	67,018	0	67,018	8.4	118.5
23	13	9	Poly	∞	75,626	0	75,626	13.2	66.2
24	11	7	Void	∞	54,770	0	54,770	23.4	118.5
25	11	7	Poly	∞	59,120	0	59,120	–2.0	–681

[a] Reflected on the flat top surface with 6.01-in.-thick polyethylene, 44.0-in.-square.
[b] Measured reactivity values listed here are for the assembled experiment with support structure present. These values can be converted to k_{eff} by using an effective delayed-neutron fraction of 0.0068. A reactivity of 100 cents or one dollar is equal to the effective delayed-neutron fraction. Reactivity values corrected for support structure and room return are given in Table 3. For experiments with infinite reflectors, there is no correction for support structure.
[c] The reactivity was determined with an analog computer system based on inverse kinetics, which uses point kinetics with six delayed neutron groups to obtain the reactivity from the fission density as a function of time (Ref. 8).
[d] The reactivity given was determined with an analog system, which was based on inverse kinetics with the point kinetics assumption with six delayed neutron groups to obtain the reactivity from the fission density as a function of time. This measured reactivity was +40 cents with a 0.020-in gap between the top of the uranium and the bottom of the reflector. This gap decreased the reactivity by 20 cents. Thus, the fully assembled reactivity was + 60 cents
[e] The reactivity of this assembly was obtained from a reactor period of 20.8 sec, which corresponds to a reactivity of 27.3 cents. The assembly had a ⅛-in. gap between side reflector parts G and H, which was worth 12.7 cents; thus the fully assembled reactivity is 27.3+12.7 = 40.0 cents

2.1 EXPERIMENTAL METHODOLOGY

Annuli with nominal outside diameters of 11, 13, and 15 in. with thick polyethylene reflectors were assembled to delayed criticality, with the center of the annuli void or containing polyethylene, at the Oak Ridge Critical Experiments Facility. In addition, non-reflected annuli with internal polyethylene moderators and no reflectors were assembled. Uranium metal cylinders with diameters varying from 7 to 15 in. with thick polyethylene reflector on all sides were also assembled. One-sided polyethylene-reflected uranium metal cylinders were also assembled to delayed criticality to simulate floor reflection. The experiments were performed in a deliberate and step-by-step manner, with observed data recorded. The assembly procedure was different for the non-reflected and thick-polyethylene-reflected experiments. The geometrical configurations of these experiments are depicted in the sketches of Figs. 1 to 5, where the upper and lower sections are illustrated. The polyethylene-moderated and -reflected uranium metal assemblies were constructed on a vertical assembly machine, as shown in Fig. 6, which primarily consisted of a hydraulic lift (22-in. vertical motion) to support the lower section and a stationary upper section.

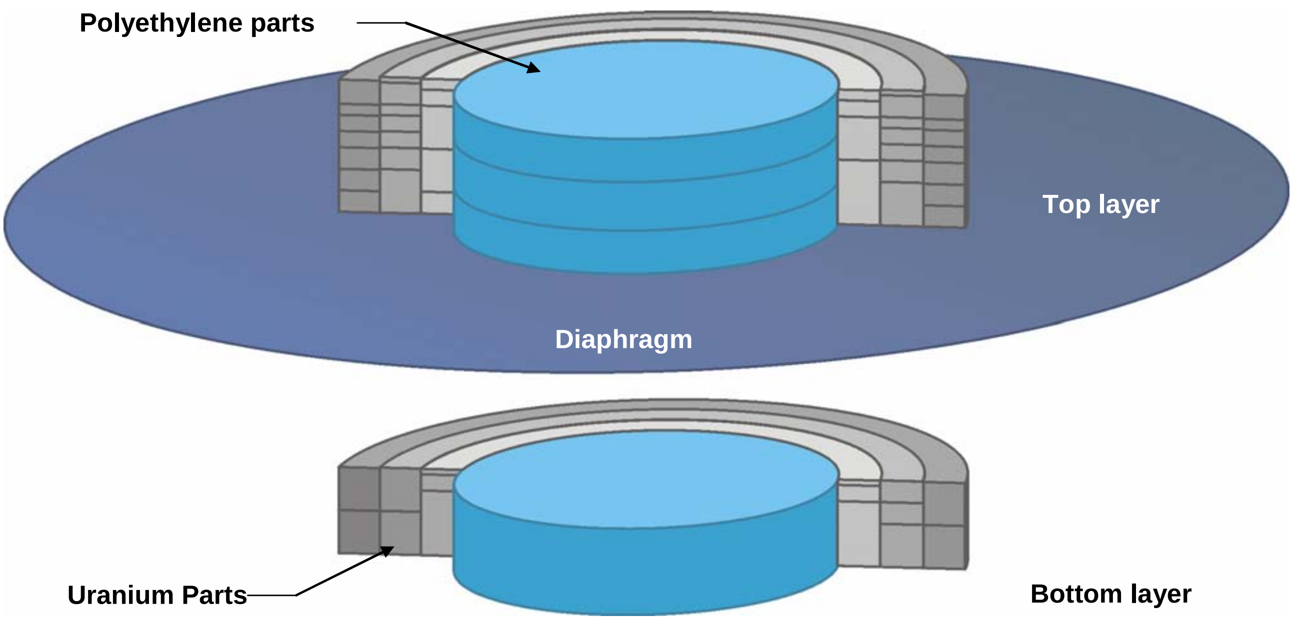

Fig. 1. Geometry of uranium metal annulus with internal polyethylene moderator for experiments 1–3[b].

[b]**Sketches in Figures 1–5 were provided by Christine E. White of Idaho National Laboratory**

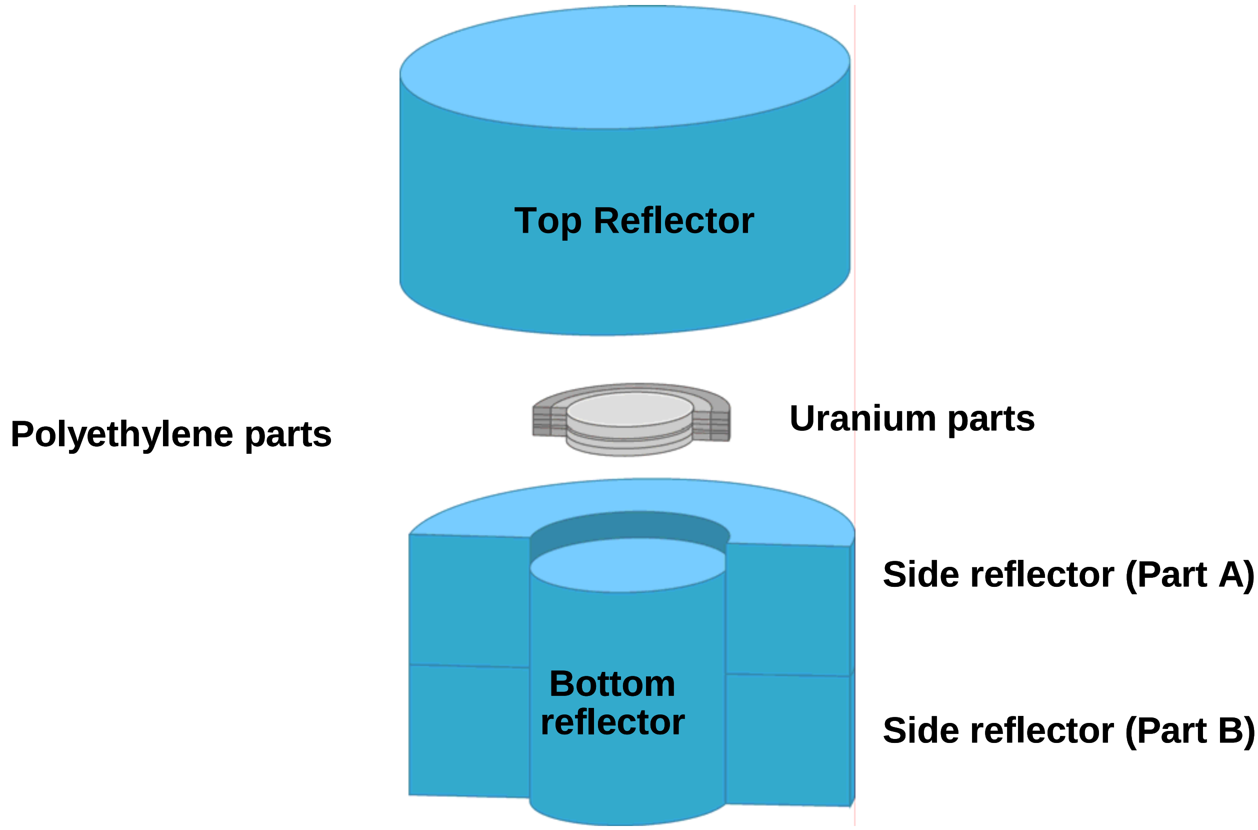

Fig. 2. Geometry of uranium metal cylinder with infinite polyethylene reflector for experiments 4–8.

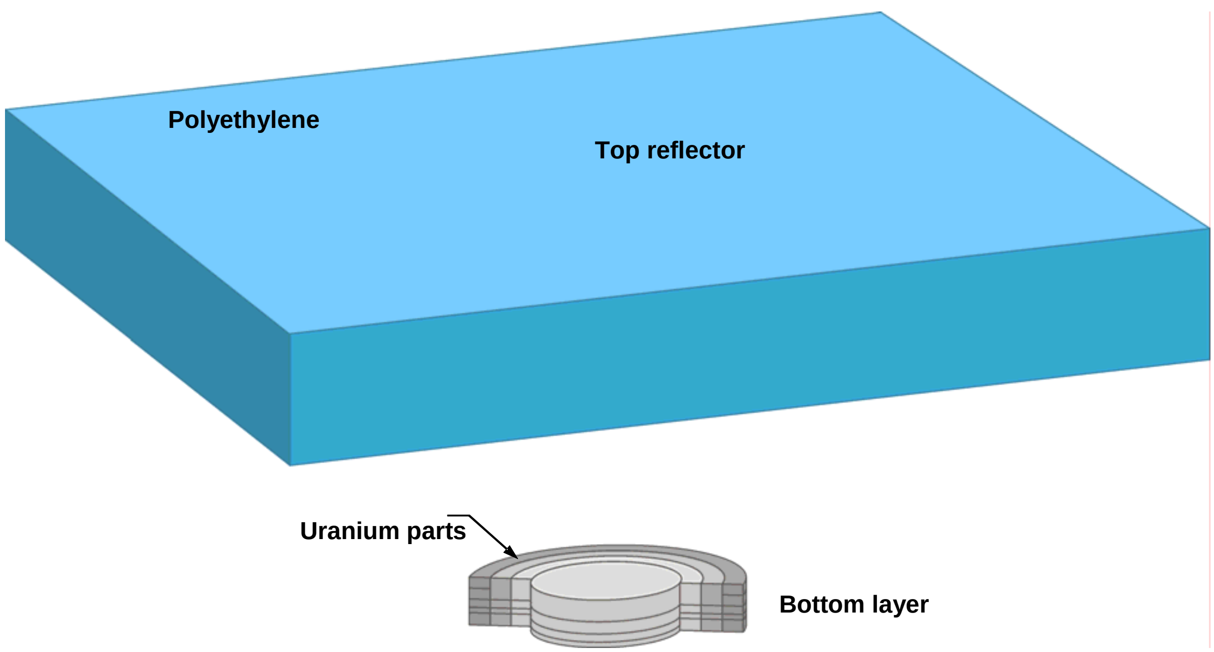

Fig. 3. Geometry of uranium metal cylinder with infinite polyethylene reflector on one flat surface for experiments 9–13.

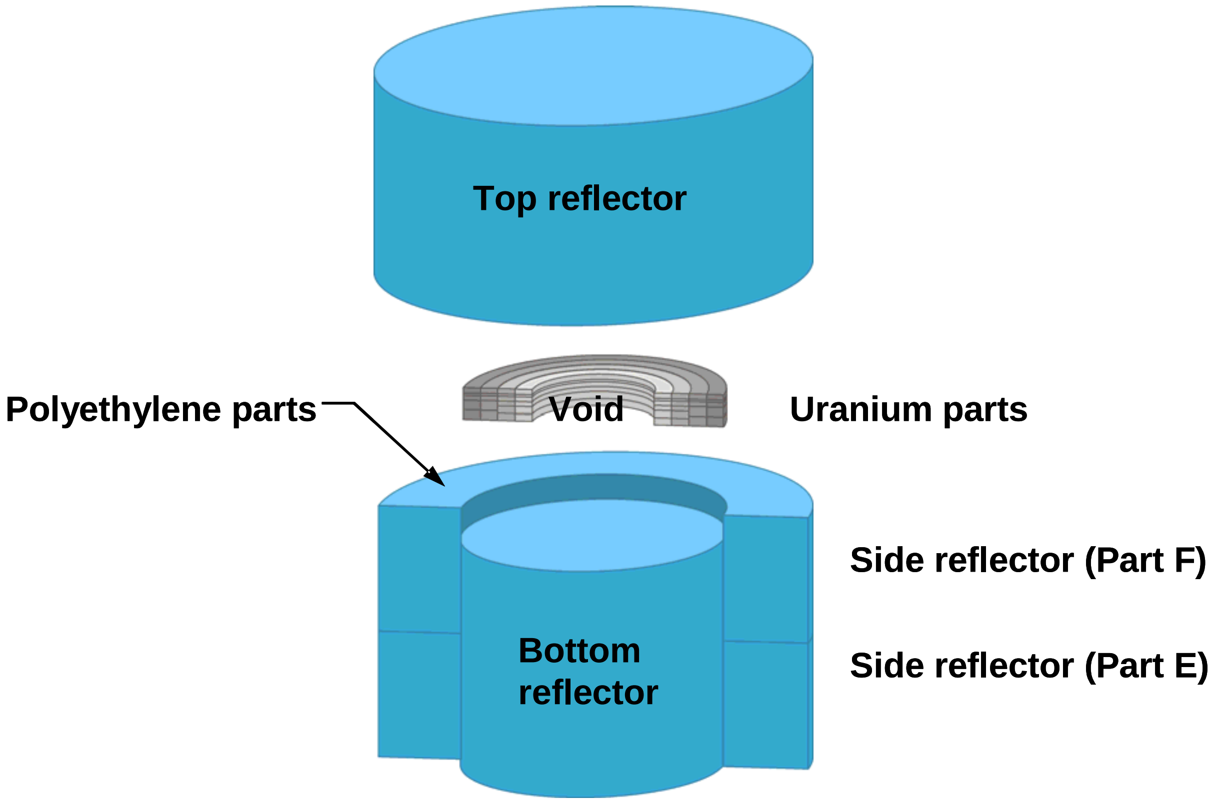

Fig. 4. Geometry of uranium metal annulus with infinite polyethylene reflector and void in the center of the annulus for experiments 14, 16, 18, 20, 22, and 24.

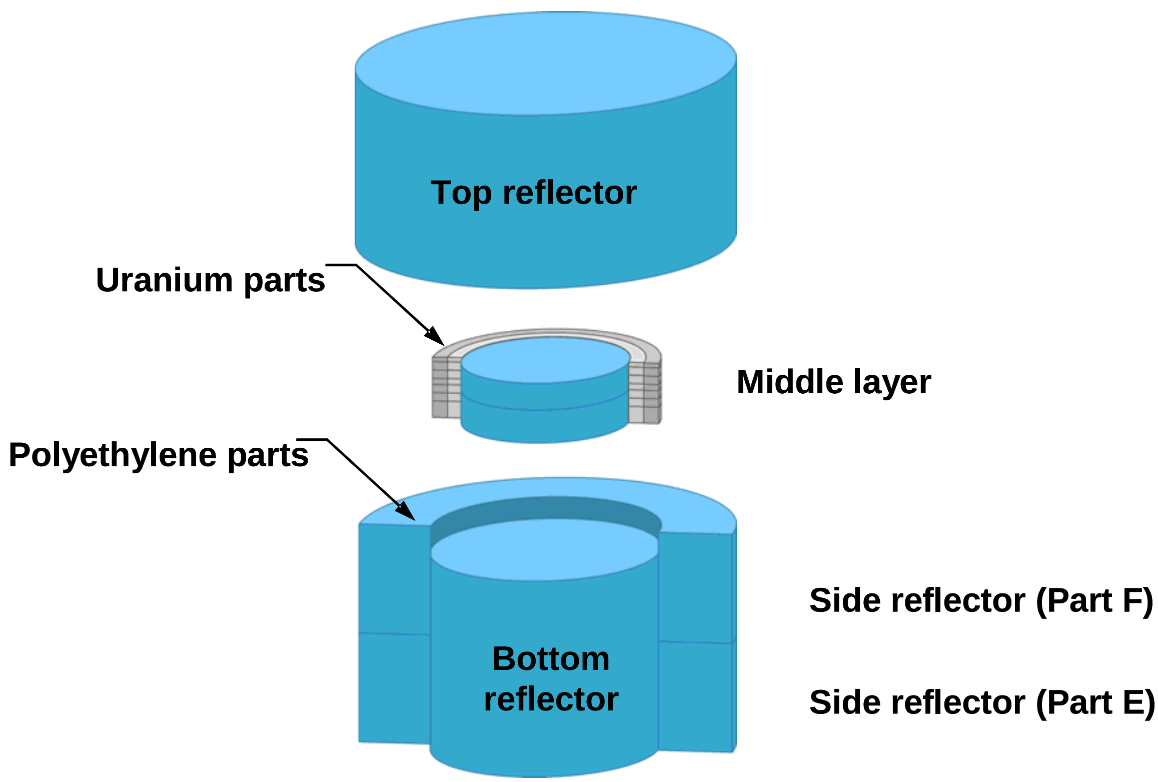

Fig. 5. Geometry of uranium metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus for experiments 15, 17, 19, 21, 23, and 25.

2.1.1 Unreflected Experiments

For the measurements with no reflector, the lower support structure supported the lower polyethylene moderator parts, and the uranium metal of the lower section. The lower section was supported on three 0.125-in.-thick aluminum edges, oriented vertically 120 degrees apart (visible in Fig. 7). Note that Fig. 7 shows an unreflected uranium metal assembly, but these internally moderated annular uranium metal critical experiments were assembled on the same vertical lift with the same support apparatus as shown in this figure. The edges were supported on a 36-in.-high, low-mass aluminum support tower mounted in the vertical position and is also shown in Fig. 7. The base of this 0.5-in.-thick, 18-in.-diameter aluminum support stand was bolted to the 1-in.-thick, 18-in.-diameter steel table of the vertical lift and supported the lower surface of the uranium 36-in. above the aluminum base. Lateral motion on the lower section was restrained by the small aluminum pieces bolted to the 120° vertical members, also visible in Fig 7**.** The lower support stand was bolted to the vertical lift as shown in Fig 7. The upper section was supported by four vertical posts with 48 in. between the centerlines of adjacent posts, which held a low-mass support consisting of two 30-in.-ID, 2-in.-wide,0.5-in.-thick aluminum clamping rings bolted (1/2-in.-diam SS304 bolts) together and supported off vertical poles by aluminum tubing; see Fig. 7. The 30-in.-ID clamping rings held a 0.010-in.-thick stainless steel (304L) diaphragm on which the uranium metal of the upper section and internal polyethylene moderator was supported. The clamping ring was supported by a lightweight aluminum structure supported by the four vertical poles. The arrangement of Fig. 7 was used for these three unreflected annuli experiments. These low-mass support structures were utilized so as to minimize the reactivity effects of the support structure for these unreflected experiments.

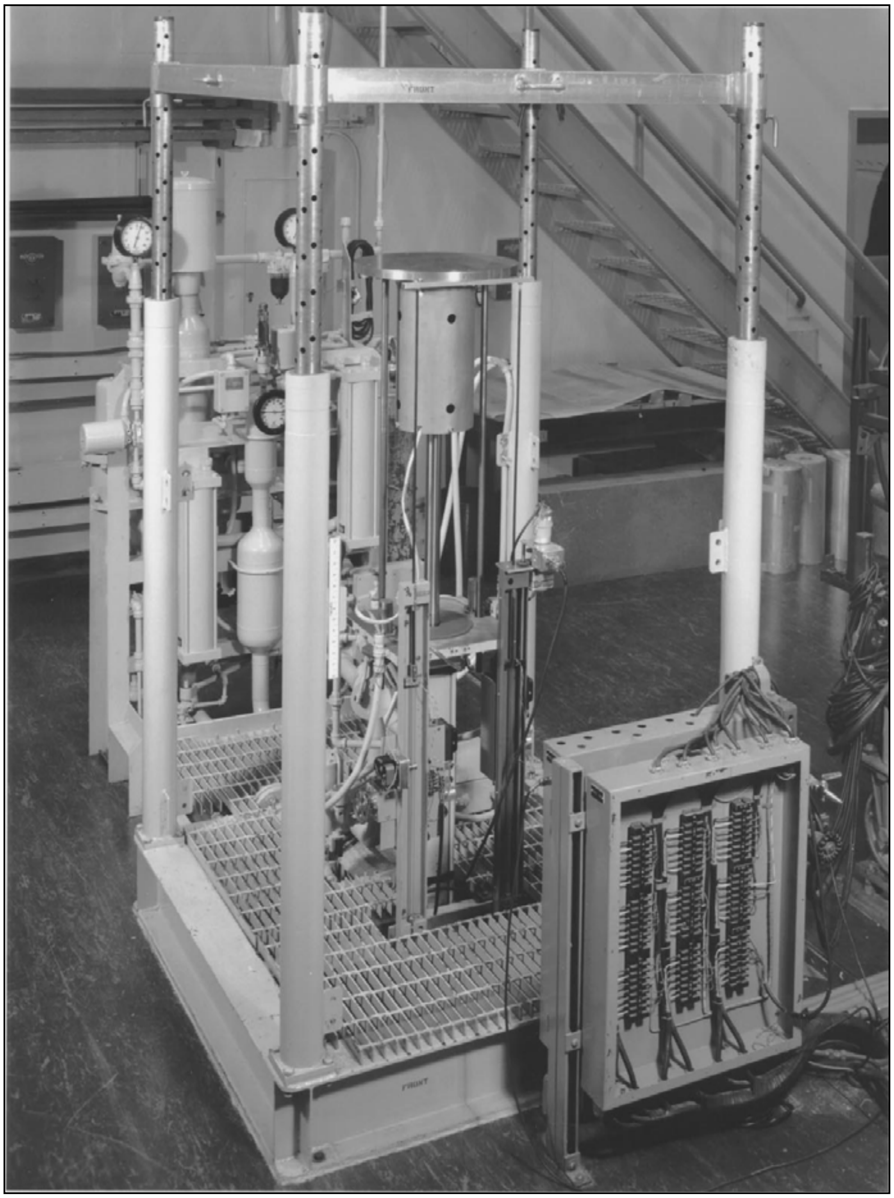

Fig. 6. Photograph of the vertical assembly machine with the movable table up. Upper and side reflector support structures for these reflected experiments are included in this photograph. Lower support stand is not shown.[c]

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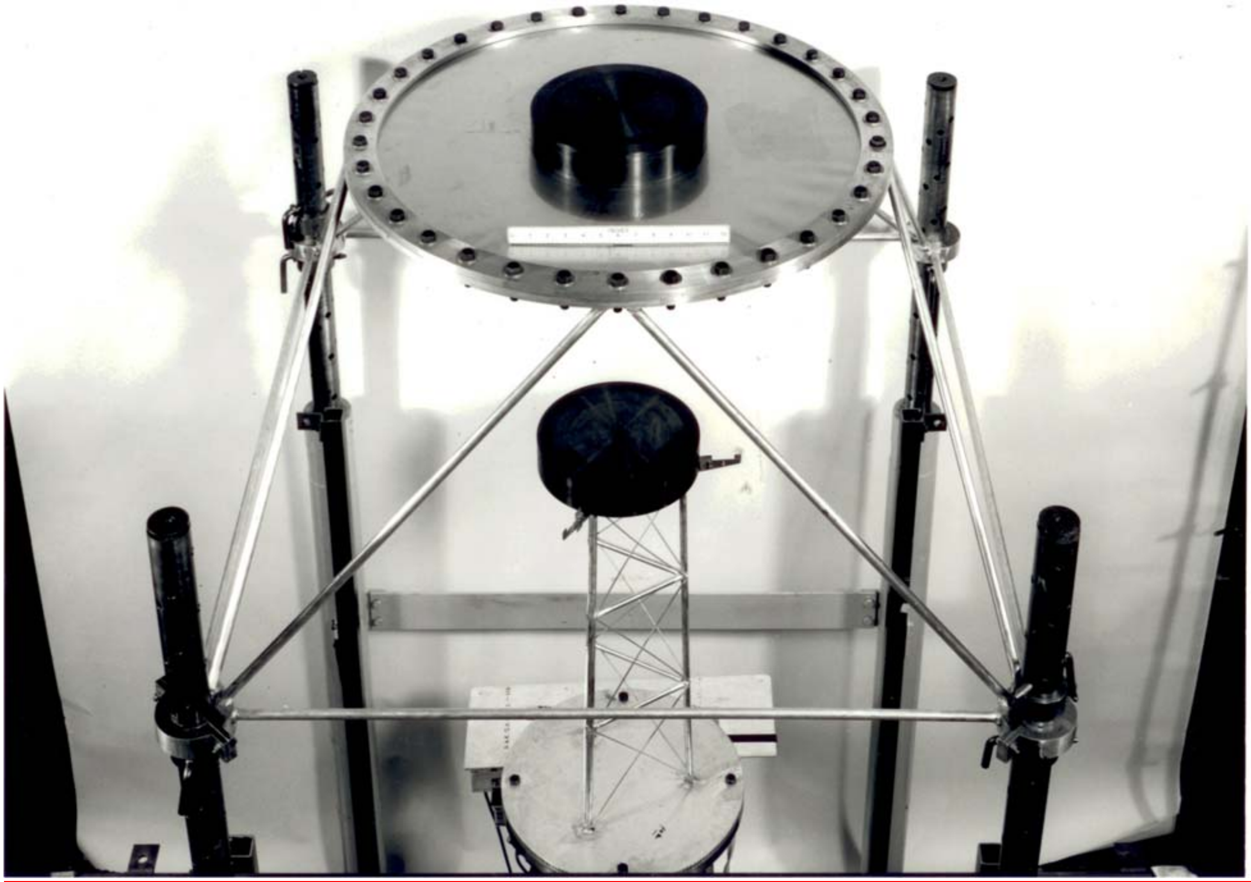
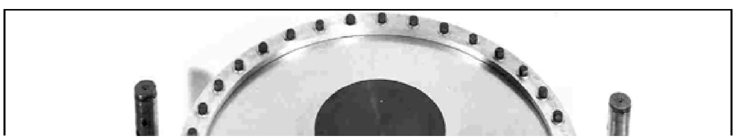
[c]**Safety Review of the Oak Ridge Critical Experiments Facility, Union Carbide Nuclear Corporation, Oak Ridge National Laboratory (1962).**





Experiments were assembled by mounting a fixed height of uranium metal parts on the lower section with the polyethylene moderator, and then uranium and polyethylene was added to the upper section until near delayed criticality was achieved. For these experiments, the lower section was raised until it made contact with the diaphragm and actually slightly lifted the upper section of material mounted on the diaphragm. This lifting of the top section slightly by the upward motion of the bottom section was to compensate for the sag of the diaphragm when the upper material was added. The lifting of the diaphragm was monitored to the nearest 0.001 in., and the lower section was moved up until the diaphragm was level. Because of the thickness of the smallest uranium parts, the system could rarely be adjusted to exactly delayed criticality. For most assemblies, the uranium mass of the upper section was adjusted until a self-sustaining fission chain reaction occurred with a measurable positive stable reactor period. For those assemblies that were slightly subcritical, an additional hydrogenous moderator (small piece of Plexiglas) was added as reflector to achieve a self-sustaining chain reaction. When the fission rate achieved a value from which a negative reactor period could be measured, the small plexiglas reflector was quickly removed (less than 0.5 seconds) to measure the resulting negative reactor period.

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[d]Photo 39380, Oak Ridge National Laboratory Photo of a bare uranium assembly. The same support structure was used for the uranium metal annuli without reflectors.

The reactivity was obtained from the stable period measurements using a 12-group-in-hour equation (six groups for ^{235}U and six groups for ^{238}U) with parameters from the delayed-neutron data of Keepin, Wimett, and Zeigler.[9] It was assumed that half the fissions that actually occurred in ^{234}U and ^{236}U occurred in ^{235}U and the other half in ^{238}U. This should result in an ~ 1% uncertainty in a measured reactivity, since the number of fissions in ^{234}U and ^{236}U is very low. Using an effective delayed-neutron fraction of 0.00680 ± 0.00005, the reactivity in cents can be converted to Δk_{eff} since one dollar or 100 cents equals a Δk_{eff} of 0.0068. The uncertainty in the effective delayed neutron fraction was based on the uncertainty in the value for the isotope. Since the difference between the delayed neutron fraction for the isotope and the effective value is small, the uncertainty in the effective value was taken as the uncertainty in the measurements for the isotope.

2.1.2 Reflected Experiments

For the uranium metal annuli and cylinders with thick reflectors on all sides, the uranium was mounted on top of the bottom polyethylene reflector on the vertical lift. The bottom reflector on the vertical lift rested on a 1-in.-thick 7.00-in.-diam. aluminum disc to ensure that for all assemblies that the uranium metal on the lift would make contact with the top reflector. This aluminum was necessary, since the one-in.-thick, 18-in.-diam. steel top of the lift was larger than the hole in the side reflector. The top and side polyethylene reflector was mounted on a fixed 0.5-in.-thick aluminum plate with a 20-in.-diam. hole supported by the four vertical poles of the fixed upper section, as shown in Fig. 8. The assembly shown in Fig. 8 is for a 9-in.-diam. uranium metal assembly with complete polyethylene reflection. For the fully reflected 7-in.-diam cylinder, a polyethylene annulus surrounded the sides of the uranium; and in this case, part of the side reflector was on the lower section moved by the vertical lift. Delayed criticality was achieved by raising the uranium with its partial polyethylene side and bottom reflector mounted on the vertical lift into the top and side reflector until contact was made with the top reflector. The position of the top reflector at completion of the assembly was monitored to 0.001 in. The lower section was raised by the vertical lift until the top reflector was raised 0.002 in. This ensured good contact between the uranium and the top reflector. The position of the top reflector was carefully monitored during assembly to ensure that the motion of the lower section was not lifting the upper section upon insertion of the lower section into the hole in the side reflector. For these measurements with thick polyethylene reflectors on all sides, any irregularities in the height of the uranium were at the surface of the uranium adjacent to the top reflector.

For the uranium metal cylinders with polyethylene reflector on one flat surface, the uranium metal was supported on a low mass support stand (like that shown in Fig. 7). The one-sided top reflector was fixed by an upper support structure similar to that shown in Fig. 8 but consisting of only the outer 3-in.-angle, ¼-in.-thick aluminum support structure. This aluminum frame supported the 44 × 44 -in.^{2} top reflector. To assemble the system to delayed criticality, the lower support stand mounted on the vertical lift was raised until the uranium metal made contact with the top polyethylene reflector. Again, the lower section was raised until the top reflector was lifted 0.002 in. to ensure good contact. For these one-sided reflected experiments the top surfaces of the uranium cylinders were flat, resulting in no gaps between the top of a radial incremented section of uranium and the bottom of the top reflector. This was done with the appropriate thickness of aluminum foil shims between the uranium and the lower support stand. Thus, any irregularities in the height of the uranium sections were at the bottoms of the uranium cylinders in a region of less importance.

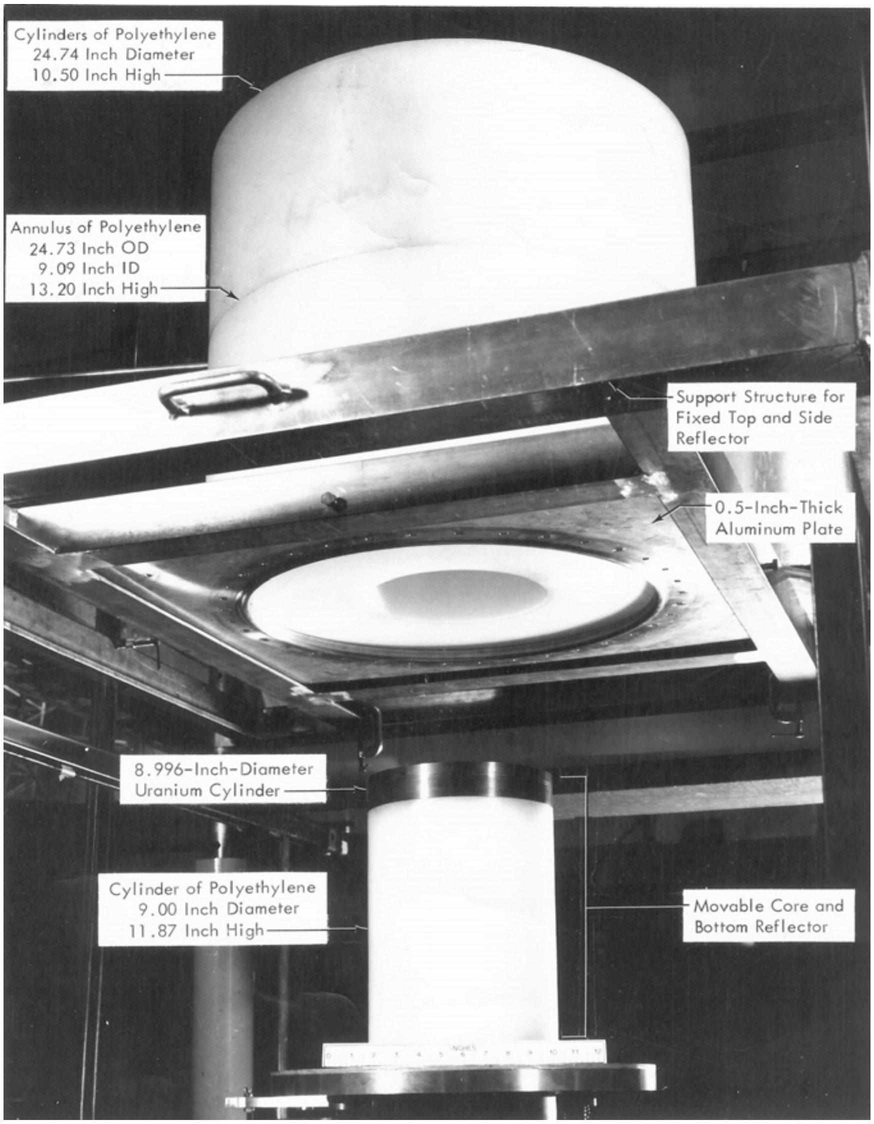

Fig. 8. Typical polyethylene-reflected 9-in.-diam. uranium metal cylinder in the disassembled condition.

2.1.3 Height of Annular and Disc Sections

The assembly heights of the annular-ring and disc sections for a given experiment were measured at 7 azimuthal locations with micrometers that read out to 0.001 in. and averaged. The measurements were performed as follows. For example, all of the 13-in.-OD, 11-in.-ID annular rings of an assembly were stacked on a precision flat surface, and the distance between the upper surface and the precision flat surface was measured. In stacking, all parts in the assemblies of the various annuli were in the same vertical order and orientation as in the critical experiment. The azimuth 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. This ensured reproducibility in restacking assemblies or parts of assemblies for height measurements or repeat measurements. The parts were always positioned on the surface with the scribed part numbers facing up. Thus, for the height measurements on the precision flat surface, the orientation of the uranium metal annuli was as in the assembly. The height of the total stack of a given 1-in.-wide radial increment was normally measured at azimuthal locations N, E, S, W, SW, and NE, and the values were averaged. This operation presented no criticality safety problems in hand stacking since the annuli were only 1 in. thick radially. This procedure allowed the safe measurement of the stacked height of the central disc and each concentric annulus.

For the one-side-reflected experiments with all the uranium metal accessible on the lower support stand, the heights were measured with the uranium on the lower support stand as the assemblies were disassembled. For example, for the 15-in.-OD cylinder, the height of the outer annulus (13–15 in.) was measured at several locations azimuthally. After the height measurements for this annular ring, it was removed from the support stand and the height of the 11- to 13-in. annular ring measured. This process continued until the height of the central 7-in.-diam. disc was measured. The average measured height of the uranium for each assembly is given in Table 2. The measure stack heights are accurate to ±0.001 in. Gap sizes between flat surfaces of uranium can be obtained by subtracting the height (from inspection reports) of each individual uranium part from the total measured height of the annular region and dividing by one less than the number of uranium parts in the annular region. The measured stack height had an uncertainty a factor of 10 larger than individual uranium metal parts. The individual part heights were measured to $\pm 1\times10^{-4}$ in. Because of the high uncertainty in the stack height, this process sometimes resulted in differences less than zero. For these cases, the average void thickness vertically between uranium metal parts is assumed to be zero.

Table 2. Measured heights of uranium metal for delayed-critical annuli and cylinders with polyethylene reflector and/or internal moderator

Experiment number	Description				Measured height of uranium (for annular rings diameters)				
	OD (in.)	ID (in.)	Material inside annulus[a]	Reflector thickness (in.)	15–13 (in.)	13–11 (in.)	11–9 (in.)	9–7 (in.)	7–0 (in.)
1	15	7	Poly (4.0232)	0	4.0088	4.0140	4.0215	4.0116	–
2	15	9	Poly (5.1487)	0	5.1360	5.1501	5.0786	–	–
3	13	7	Poly (5.0213)	0	–	5.0105	4.9501	5.0261	–
4	15	0	NA	∞	1.1252	1.1315	1.1320	1.1341	1.1313
5	13	0	NA	∞	–	1.2561	1.2520	1.2551	1.2535
6	11	0	NA	∞	–	–	1.4092	1.4170	1.4460
7	9	0	NA	∞	–	–	–	1.6938	1.6930 [b]
8	7	0	NA	∞	–	–	–	–	2.2574 [c]
9	15	0	NA	*d*	1.999	2.015	2.002	2.001	2.005
10	13	0	NA	*d*	0	2.195	2.193	2.191	2.191
11	11	0	NA	*d*	0	0	2.445	2.441	2.443
12	9	0	NA	*d*	0	0	0	2.879	2.881
13	7	0	NA	*d*	0	0	0	0	4.009
14	15	7	Air	∞	1.6640	1.6641	1.6577	1.6638	–
15	15	7	Poly (1.7588)	∞	1.7802	1.8218	1.7894	1.8196	–
16	15	9	Air	∞	2.1241	2.1306	2.1361	–	–
17	15	9	Poly (2.3821)	∞	2.3745	2.3814	2.3831	–	–
18	15	11	Air	∞	3.2200	3.2298	–	–	–
19	15	11	Poly (3.6335)	∞	3.6651	3.6700	–	–	–
20	13	7	Air	∞	–	2.0968	2.0972	2.1022	–
21	13	7	Poly (2.3146)	∞	–	2.3168	2.3160	2.3166	–
22	13	9	Air	∞	–	3.1648	3.1688	–	–
23	13	9	Poly (3.5668)	∞	–	3.5708	3.5708	–	–
24	11	7	Air	∞	–	–	3.1645	3.1660	–
25	11	7	Poly (3.3993)	∞	–	–	3.4150	3.4192	–

[a]The measured thicknesses (in.) of the polyethylene moderator on the interior of the annuli are given in parentheses. For the polyethylene thickness less than the uranium, the gap was between the center polyethylene and the top reflector.
[b]5.000×5.000 in.,[2] 0.031-in.-thick piece of uranium was centered on the upper surface of the uranium cylinder with the large flat surface in contact. A 2.500×2.500 in.,[2] 0.03125-in.-thick piece of uranium was located on the 5.00×5.00 in.[2] piece with its center 1.25 in. from the center of the larger square. The sides of both squares were parallel, and the large flat surfaces were in contact. The measured height does not include the square uranium plates on the top of the uranium cylinder.
[c]5.00×5.000-in.,[2] 0.031-in.-thick piece of uranium was located on top of this uranium cylinder. The measured height does not include the square uranium plate on top of the uranium cylinder.
[d]Reflected on the top flat surface with 44.0×44.0×6.01-in.-thick polyethylene.

3 ASSEMBLY ALIGNMENT FOR UNREFLECTED EXPERIMENTS

3.1 ASSEMBLY ALIGNMENT

Upper Section

For assembly of the upper section, uranium metal was added to the top of the type 304L stainless steel diaphragm. Uranium was located, with a ruler, at the appropriate distance from the inside of the aluminum clamping ring, which holds the 0.010-in.-thick stainless diaphragm. A layer of uranium metal for an 11-in.-diam. annulus typically consists of a 7-in.-ID/9-in.-OD annulus, and a 9-in.-ID/11-in.-OD annulus. About half or slightly more of the material was then added to the diaphragm. The location of the material was continuously adjusted with a precise high-quality level, with the level oriented in one direction and then rotated 90° on the uranium parts. If the assembly was not exactly centered on 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 uranium metal until it was aligned. An edge of the machined block was then 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 and rechecked 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 section was less than ±0.001 in.

Lower Section

For the lower section, uranium was centrally located on the lower support stand, and the same procedure was used except that the leveling of the parts was accomplished by shimming with aluminum foil (various thicknesses of aluminum foil were available). The foil was placed between the three 120° upper edges of the lower support stand and the bottom reflector, which was in contact with the lower support stand. After the uranium metal was laterally aligned (as described in the next section), the internal moderator was added to the upper and lower sections.

The uncertainty in radial alignment of the uranium metal parts on each half is ±0.001 in.

3.2 LATERAL ALIGNMENT OF UPPER SECTION WITH LOWER SECTION

For these experiments, the alignment of the upper and lower sections was adjusted and verified using the lateral alignment fixture shown in Fig. 9. Two identical fixtures (see Fig. 9) were used for lateral alignment between the upper and lower sections. They were U-shaped and were machined out of 0.375-in.-thick aluminum. The end pieces were carefully machined by the Y-12 shops to be perpendicular to the long direction of the fixture and coplanar with each other. When leveled properly, the front faces of the 4×4×½ in. end pieces were vertical and in the same plane to within ±0.001 in. This fixture was carefully machined and handled delicately when not in use so as to not damage it. 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 uranium metal annuli. The fixture was moved inward until it touched the uranium of the top section. The machine screws were adjusted until the fixture was level.

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 it was at the height of the lower leg of the U-shaped fixture. Then both fixtures were nearly adjusted properly. Removal or additions of material from the upper section sometimes required small leveling adjustments. The fixtures were moved in until they touched uranium (on either the upper 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. Finally, 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 upper section. This was a long and tedious procedure, which took 1 to 2 hours or more as needed but, it was always performed. After adjustment at these two angles, alignments at other angles were verified. Therefore, the uranium metal of the upper and lower sections was aligned within ±0.005 in. This value is a conservative estimate.

4 ASSEMBLY ALIGNMENT FOR THE REFLECTED MEASUREMENTS

The alignment procedures for the reflected experiments were much simpler, since all the uranium metal was mounted on the lower section. The uranium of the lower section was aligned in the same manner as for the unreflected experiments, but there was no need to use the elaborate fixture of Fig. 9. All that had to be assured was that the lower section could be inserted in the hole in the side reflector. This was accomplished by raising the lower section to the lower edge of the hole in the side reflector, observing the relationship of the lower section to the hole in the side reflector, and adjusting it appropriately by centering the material on the lower section until it could be inserted freely into the side reflector. To simplify the insertion of the lower section into the side reflector, the inside diameter of the side reflector was 0.090 in. larger than the outside diameter of the lower section. For the fully reflected assemblies, the unevenness of the uranium height was at the top of the uranium metal, whereas for the one-sided reflected assemblies, it was at the bottom of the uranium.

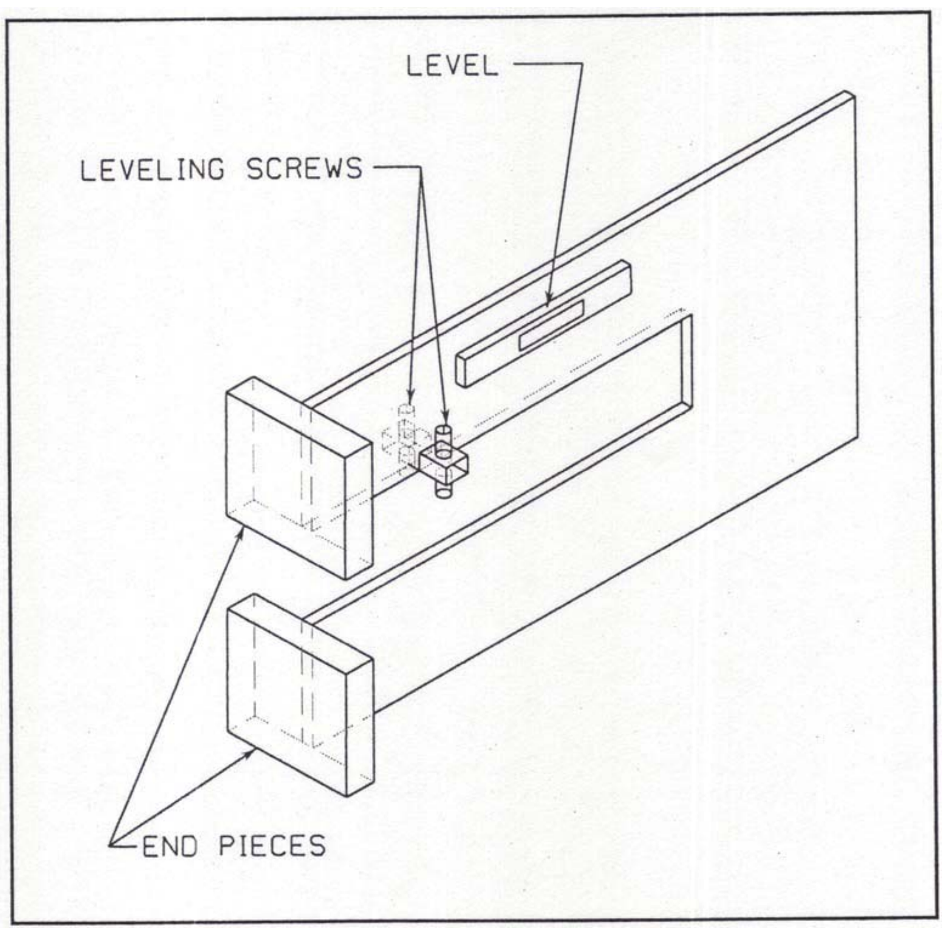

Fig. 9. Sketch of fixture for lateral alignment of uranium (93.14 wt. % ^{235}U) metal annuli with internal moderation and no reflection.

5 REACTIVITY EFFECTS OF THE SUPPORT STRUCTURE AND ROOM RETURN

5.1 UNREFLECTED EXPERIMENTS

The support structure that was used to assemble these delayed-critical experiments was made up of the 0.010-in.-thick type 304L steel stainless steel diaphragm, the low-mass aluminum support stand, and two 30-in.-diam, 2-in.-wide, 0.5-in.-thick annular diaphragm clamping rings bolted together. The support structure reactivity worth consisted primarily of the reactivity effects of the diaphragm, the diaphragm support rings, and the low-mass support stand. In some of the experiments, the removal of the support structure resulted in experimental k_{eff} values lower than unity. The reactivity worth of each of the three parts of the support structure was measured for each experiment. A positive reactivity effect means that the reactivity of the critical assembly increased as a result of the inclusion of that item in the assembly. Therefore, removing that particular item from the experiment resulted in a decrease in the neutron multiplication factor. A negative reactivity effect means that the reactivity of the assembly decreased because of the item's inclusion. Thus, removing that item from the experiment or assembly resulted in an increase in the neutron multiplication factor. The type 304L stainless steel diaphragm in all experiments reduced the k_{eff} of the system because it separated uranium metal parts. The presence of the diaphragm support ring and low-mass support stand of the lower section resulted in a positive reactivity addition. The presence of the support ring and low-mass stand provided neutron reflection to the system. The combined reactivity effect of all other supports, like the four vertical poles and tubing for the diaphragm support ring, was less than one 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 measured reactor period from the assembly with and without the additional support structure. To evaluate the effect of the lower support stand, an inverted support stand like that for the lower section was added to the top of the upper section. Care was taken in suspending it inverted on the upper section so that it would not compress the materials of the assembly. The thicknesses of the diaphragm and clamping ring were doubled. These effects were measured for each assembly and are listed in Table 3. In some cases, multiple detection systems for reactor period measurements were used. The reactivity worth of the entire support structure was obtained by adding up the worth of the three components of the support structure, which are additive: annular diaphragm rings, stainless steel diaphragm, and low-mass support stand. For most of the delayed-critical experiments presented here, multiple measurements of the reactivity effects of the support structure were not performed. In the instances in which multiple measurements of the reactivity effects of the support structure were performed, average values are listed. When the logbooks indicate a single value of the reactivity worth of each of the three parts of the support structure, the standard deviation for each measurement was conservatively assumed as 10% of the mean value.

The effects of support structure are given in Table 3, where a β_{eff} value of 0.0068 was used to convert reactivity to Δk units.

5.2 REFLECTED EXPERIMENTS

For the fully polyethylene-reflected experiments, the corrections for the support structure were assumed to be zero because all of these materials were outside the thick reflector.

For the one-sided-reflected cylinders, the reactivity effect of the lower support stand was evaluated experimentally. This was done by adding aluminum adjacent to the vertical members of the lower support structure to essentially double the amount of aluminum. Steel was added to the base of the support stand to essentially double the thickness of steel. In some cases, the addition of steel for the full 18-in. diameter of the support table was too large to measure directly. In these cases, a fraction of the material was added

Table 3. Reactivity effects of support structure and room return on neutron multiplication factor

Experiment number	Experimental reactivity (cents)	Reactivity of support structure (cents)	Room return	Total reactivity (cents) [a]	Assembly reactivity corrected for support structure	Neutron multiplication factor
1	4.5	3.55, –18.0, 15.8[b]	11.6	–8.45	–5.74E-4	0.9994
2	33.6	5.42, –16.84,10.03	10.9	24.1	1.64E-3	1.0016
3	21.2	4.15, –17.53, 11.68	7.9	15.0	1.02E-3	1.0010
4	8.8	NA, NA, NA	0	8.8	5.98-4	1.0006
5	44.2	NA, NA, NA	0	44.2	3.01E-3	1.0030
6	25.5	NA, NA, NA	0	25.5	1.73E-3	1.0017
7	–1.25	NA, NA, NA	0	–1.25	–8.5E-5	0.9999
8	5.8	NA, NA, NA	0	5.8	3.94E-4	1.0004
9	33.7	NA, NA, 129	7.4	–102.7	–6.98E-3	0.9930
10	29.9	NA, NA, 127	6.3	–103.4	–7.03E-3	0.9930
11	60.0	NA, NA, 73	5.6	–18.6	–1.26E-3	0.9987
12	12.8	NA, NA, 63	2.8	–53.0	–3.60E-3	0.9964
13	12.6	NA, NA, 38	2.9	–28.3	–1.92E-3	0.9980
14	30.0	NA, NA, NA	0	30.0	2.04E-3	1.0020
15	24.3	NA, NA, NA	0	24.3	1.65E-3	1.0017
16	8.9	NA, NA, NA	0	8.9	6.05E-4	1.0006
17	21.2	NA, NA, NA	0	21.2	1.44E-3	1.0014
18	13.9	NA, NA, NA	0	13.9	9.45E-4	1.0009
19	20.9	NA, NA, NA	0	20.9	1.42E-3	1.0014
20	27.9	NA, NA, NA	0	27.9	1.89E-3	1.0019
21	40	NA, NA, NA	0	40	2.72E-3	1.0027
22	8.4	NA, NA, NA	0	8.4	5.92E-4	1.0006
23	13.2	NA, NA, NA	0	13.2	9.00E-4	1.0009
24	23.4	NA, NA, NA	0	23.4	1.60E-3	1.0016
25	–2.0	NA, NA, NA	0	–2.0	1.36E-4	0.9999

[a]Total reactivity equals experimental reactivity minus the reactivity correction for support structure and room return.
[b]Values listed from left to right are for diaphragm support ring, stainless steel diaphragm, and lower support stand.

and the measured result increased appropriately. The increase in the reactivity associated with the addition of the materials was assumed to be the reactivity worth of the support structure. These values are given in Table 3 also. These values are much larger than for the three internally moderated assemblies because most of the neutron leakage is out the bottom of the one-side-reflected experiments.

5.3 ROOM RETURN[e]

For the fully reflected experiments 4–8 and 14–25, the room return effects are zero because of the presence of the thick reflector. For experiments 1–3 and 9–13, the reactivity effects of neutrons reflected from the experimental cell walls, floor, and ceiling were obtained from Monte Carlo calculations where the calculations were performed with and without the surrounding concrete. Models were created using both Oak Ridge and Magnuson Concrete for the walls, floor, and ceiling. The difference in the room

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[e]These calculations were performed by Tyler Sumner, a student at Georgia Institute of Technology, on contract with Idaho National Laboratory

return reactivity correction for the two types of concrete was insignificant. For the one-side-reflected experiments, the values varied from 2.9 cents for Experiment 13 to 7.4 cents for Experiment 9. The larger-diameter assemblies have a larger room return effect because neutrons reflecting off the surrounding concrete see a larger target because of the larger size of the assembly. The calculated value for the 7-in.-diam cylinder is close to the 3 cents obtained from the indoor/outdoor measurements for GODIVA at Los Alamos National Laboratory (LANL) because the diameter of GODIVA is also approximately 7 in. The larger calculated values for the three unreflected experiments are also because of their larger size. The effects of room return and neutron multiplication factors corrected for effects of support structure and room return are summarized in Table 3. A βeff value of 0.0068 was used to convert reactivity to Δk units.

6 DRAWINGS OF EXPERIMENTAL CONFIGURATIONS

The assembly of each experiment is illustrated in Figures 10–34.[f]

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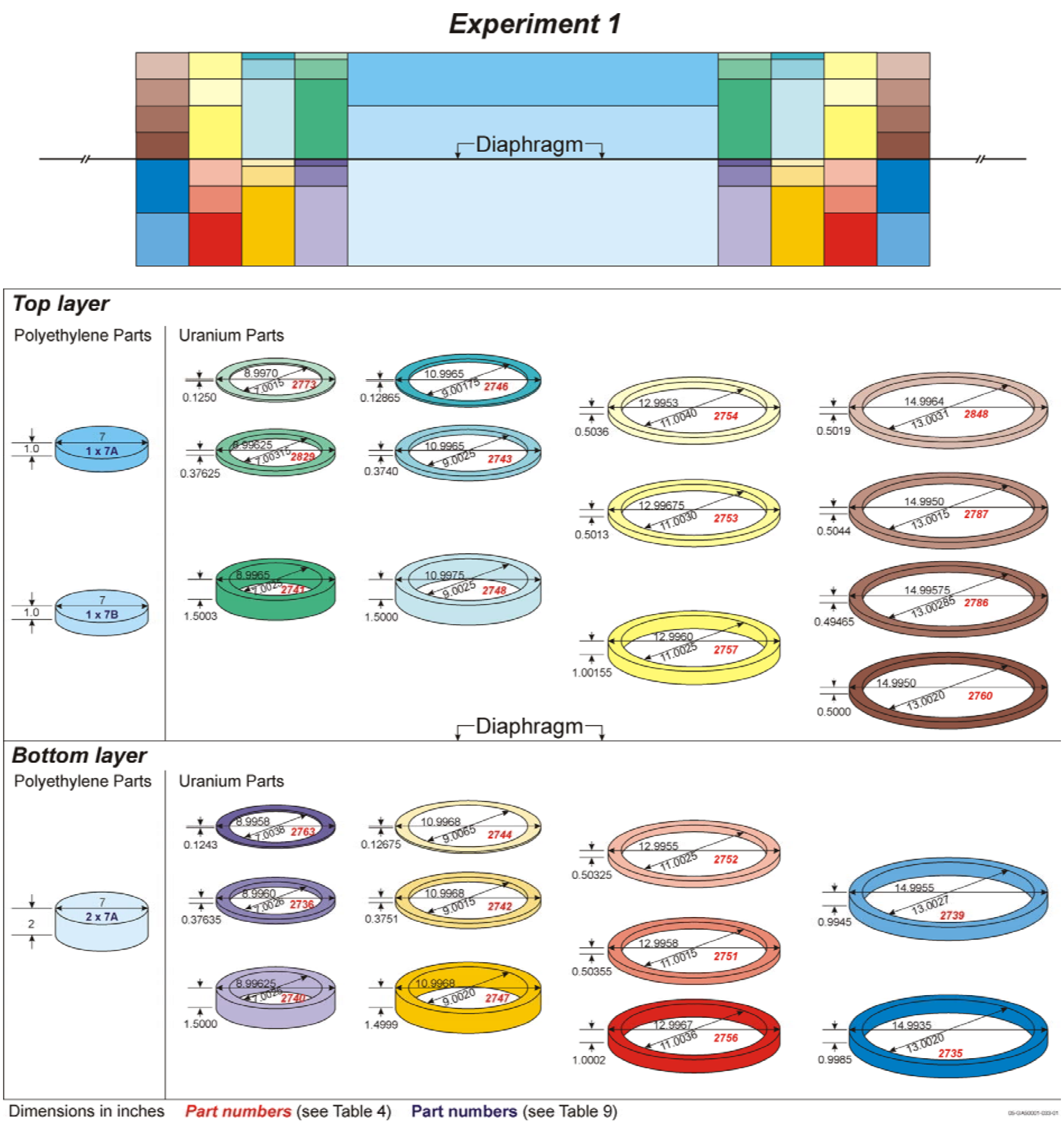
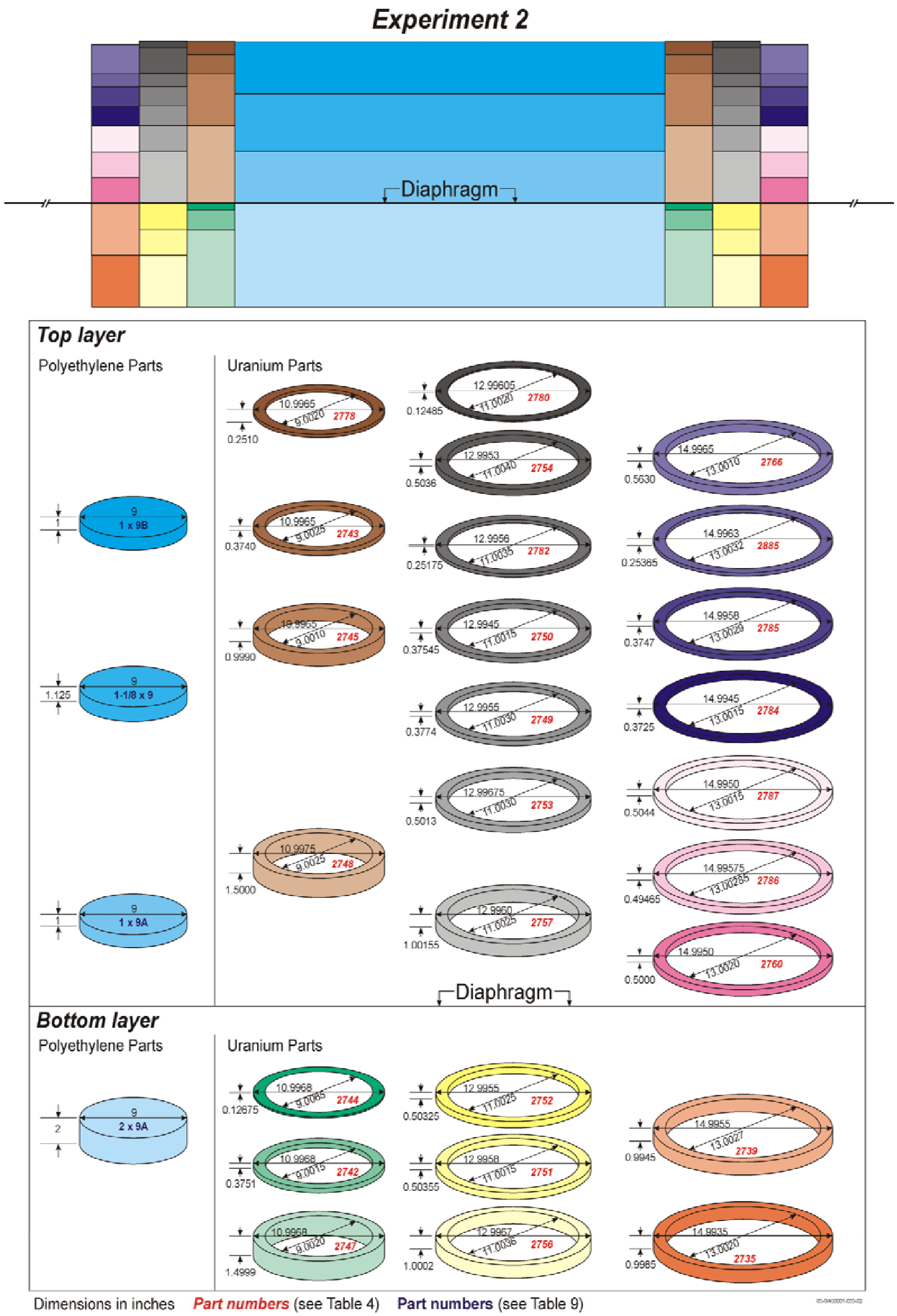
[f]The electronic version of this report should be used to obtain the dimensions of these uranium parts if they are not readable in the figures or from the tables in section 7. These sketches were provided by Christine E. White of Idaho National Laboratory.



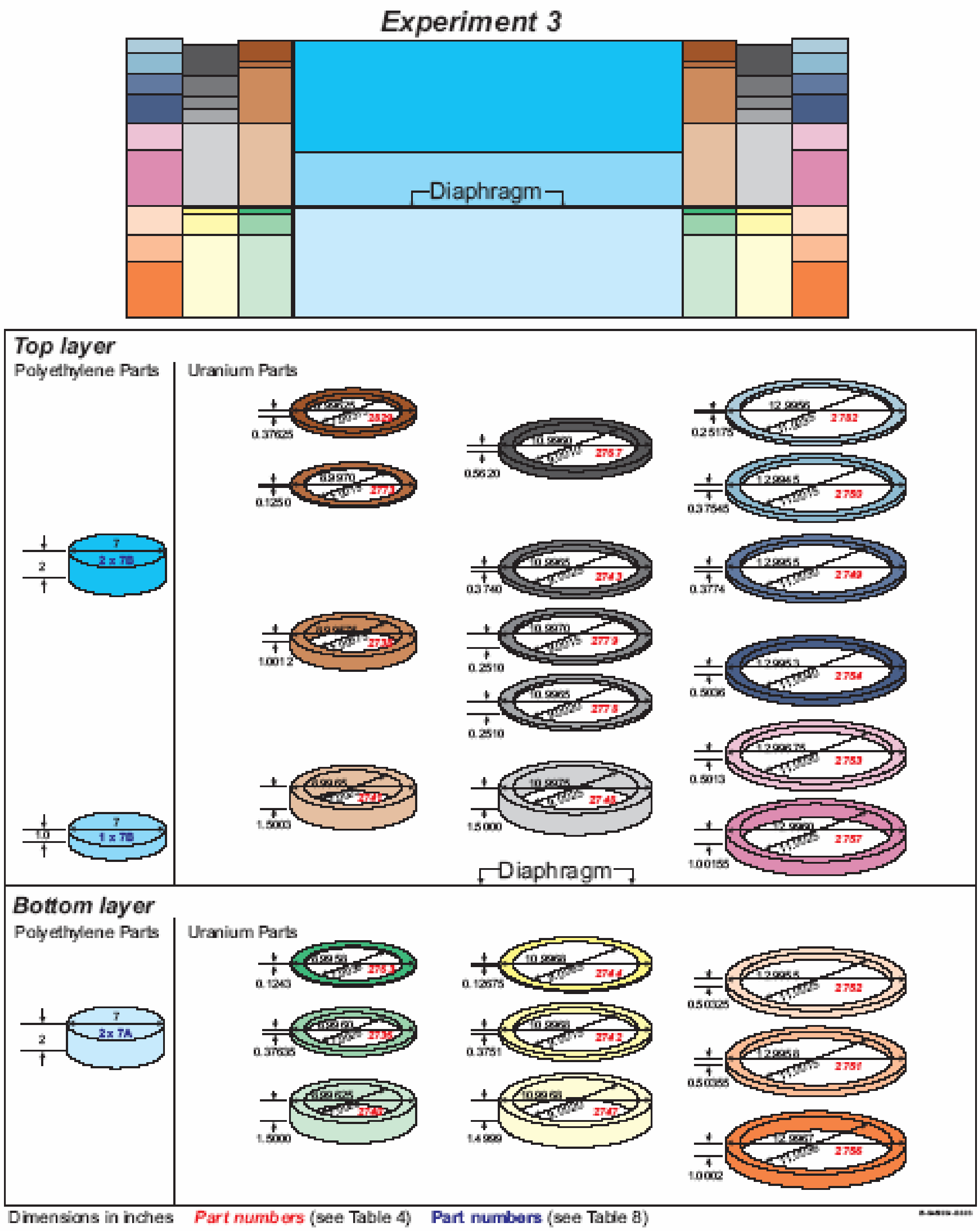
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	4.0088
U height, 11" ID, 13" OD region	4.0140
U height, 9" ID, 11" OD region	4.0215
U height, 7" ID, 9" OD region	4.0116
Polyethylene inside annulus	4.0232

Fig. 10. Experiment 1—Configuration of a delayed-critical, 15-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with internal polyethylene moderator.



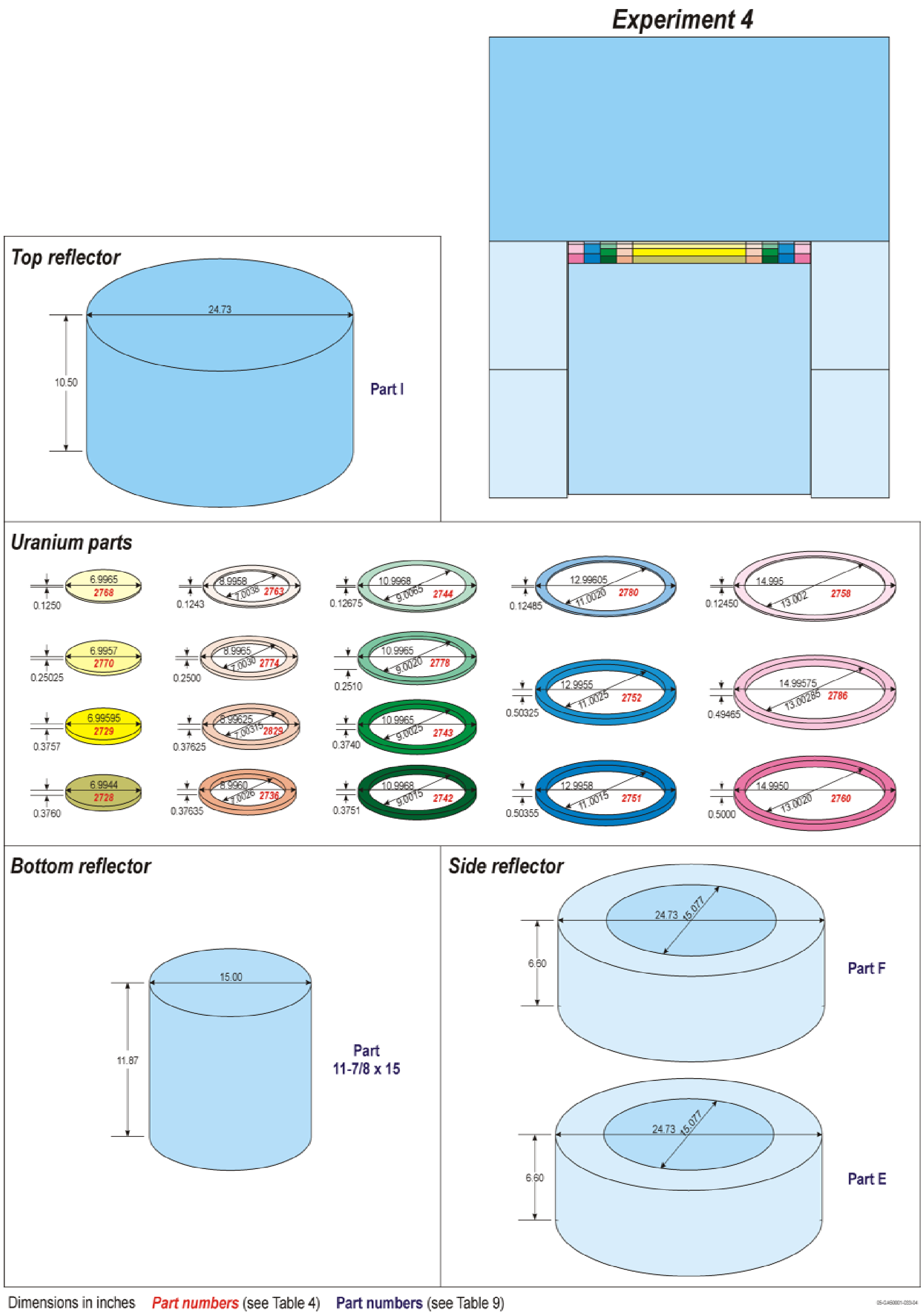
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	5.1360
U height, 11" ID, 13" OD region	5.1501
U height, 9" ID, 11" OD region	5.0786
Polyethylene inside annulus	5.1487

Fig. 11. Experiment 2—Configuration of a delayed-critical, 15-in.-OD, 9-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with internal polyethylene moderator.



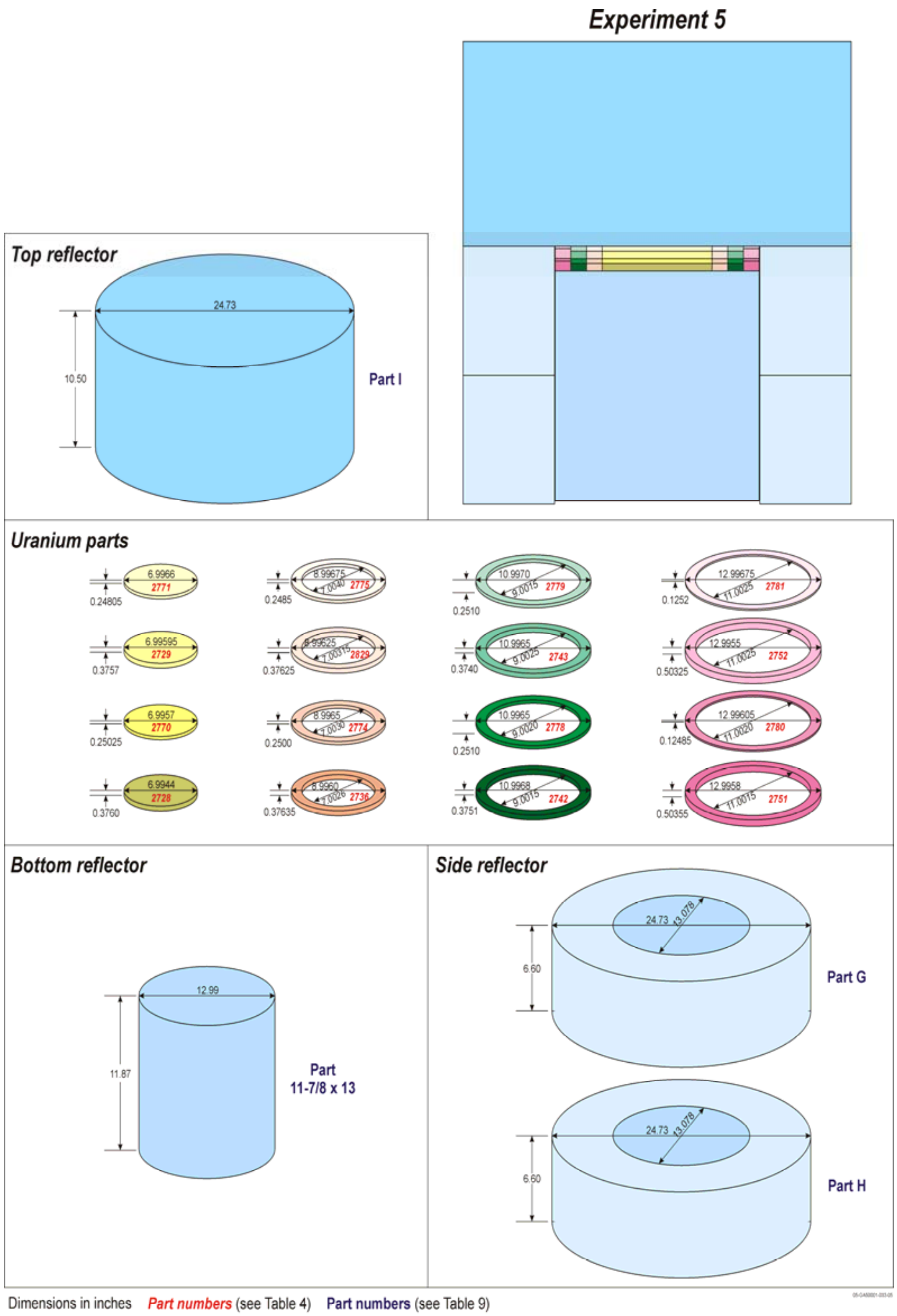
Region	Measured Height (in.)
Fuel height, 11" ID, 13" OD region	5.0105
Fuel height, 9" ID, 11" OD region	4.9501
Fuel height, 7" ID, 9" OD region	5.0261
Polyethylene inside annulus	5.0213

Fig. 12. Experiment 3—Configuration of a delayed-critical, 13-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with internal polyethylene moderator.



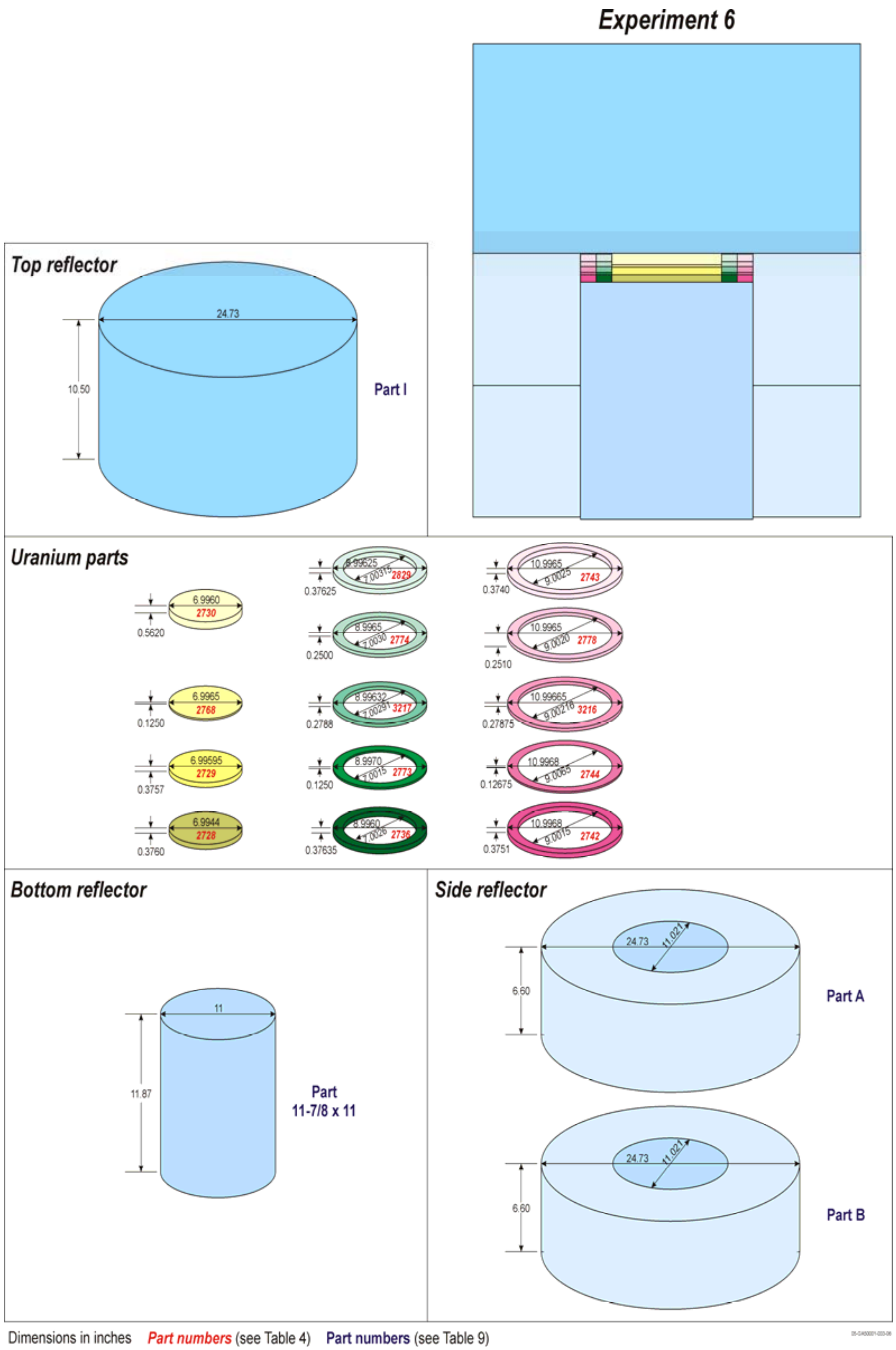
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	1.1252
U height, 11" ID, 13" OD region	1.1315
U height, 9" ID, 11" OD region	1.1320
U height, 7" ID, 9" OD region	1.1341
U height, 7" OD region	1.1313

Fig. 13. Experiment 4—Configuration of a delayed-critical, 15-in.-OD, uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector.



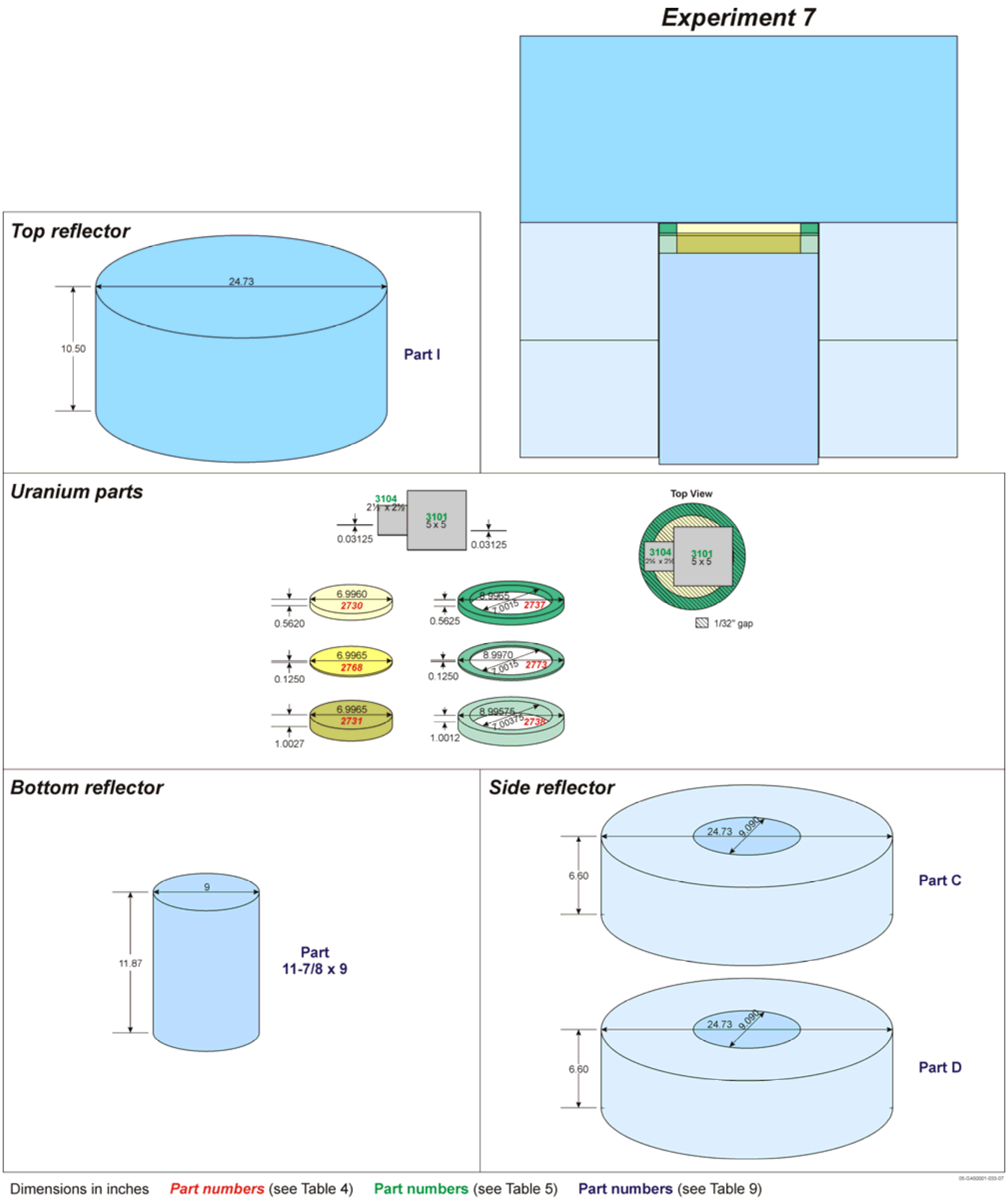
Region	Measured Height (in.)
U height, 11" ID, 13" OD region	1.2561
U height, 9" ID, 11" OD region	1.2520
U height, 7" ID, 9" OD region	1.2551
U height, 7" OD region	1.2535

Fig. 14. Experiment 5—Configuration of a delayed-critical, 13-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector.



Region	Measured Height (in.)
U height, 9" ID, 11" OD region	1.4092
U height, 7" ID, 9" OD region	1.4170
U height, 7" OD region	1.4460

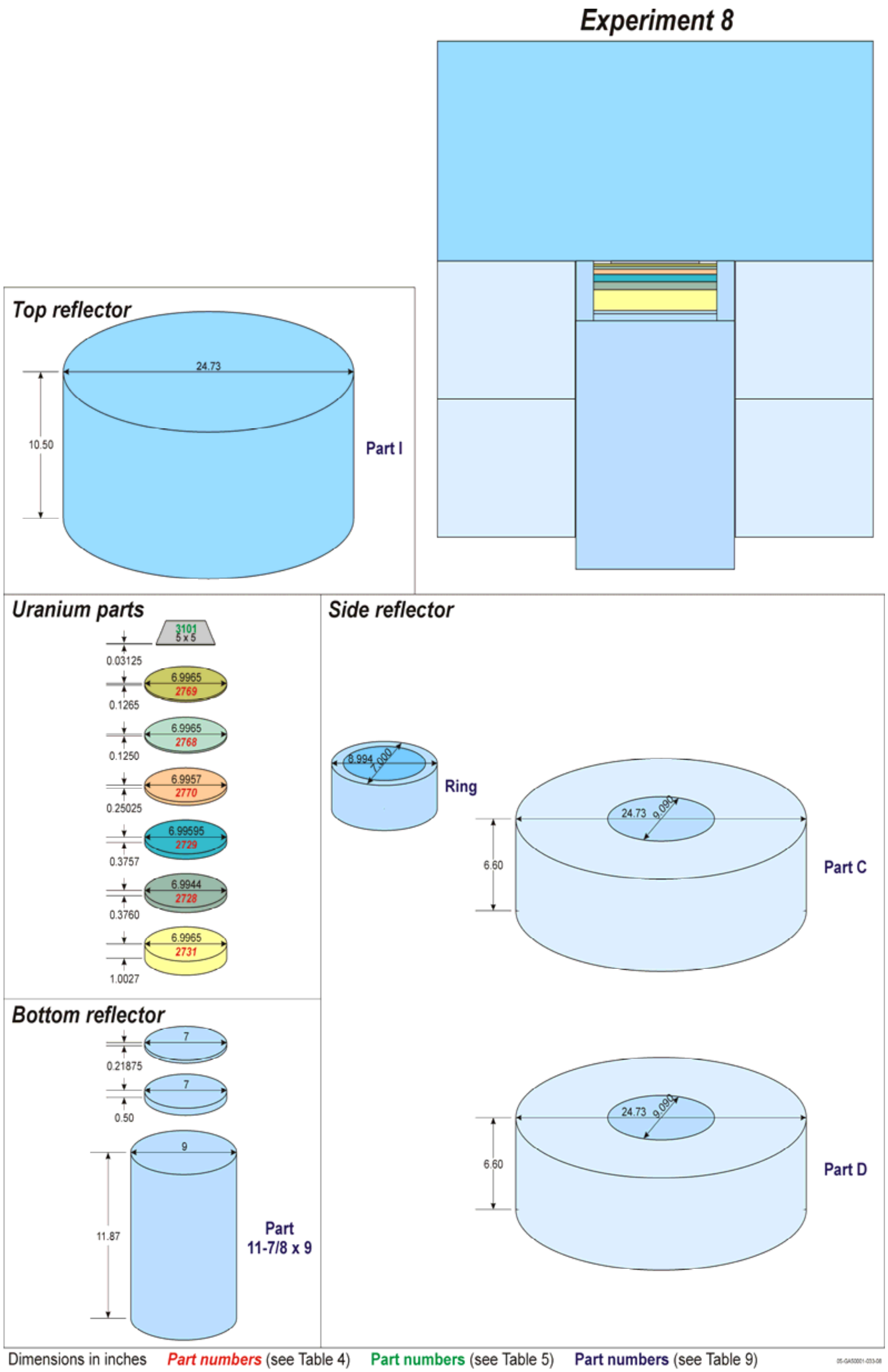
Fig. 15. Experiment 6—Configuration of a delayed-critical, 11-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector.



Region	Measured Height* (in.)
U height, 7" ID, 9" OD region	1.6938
U height, 7" OD region	1.6930

*Measured height does not include square uranium parts on top.

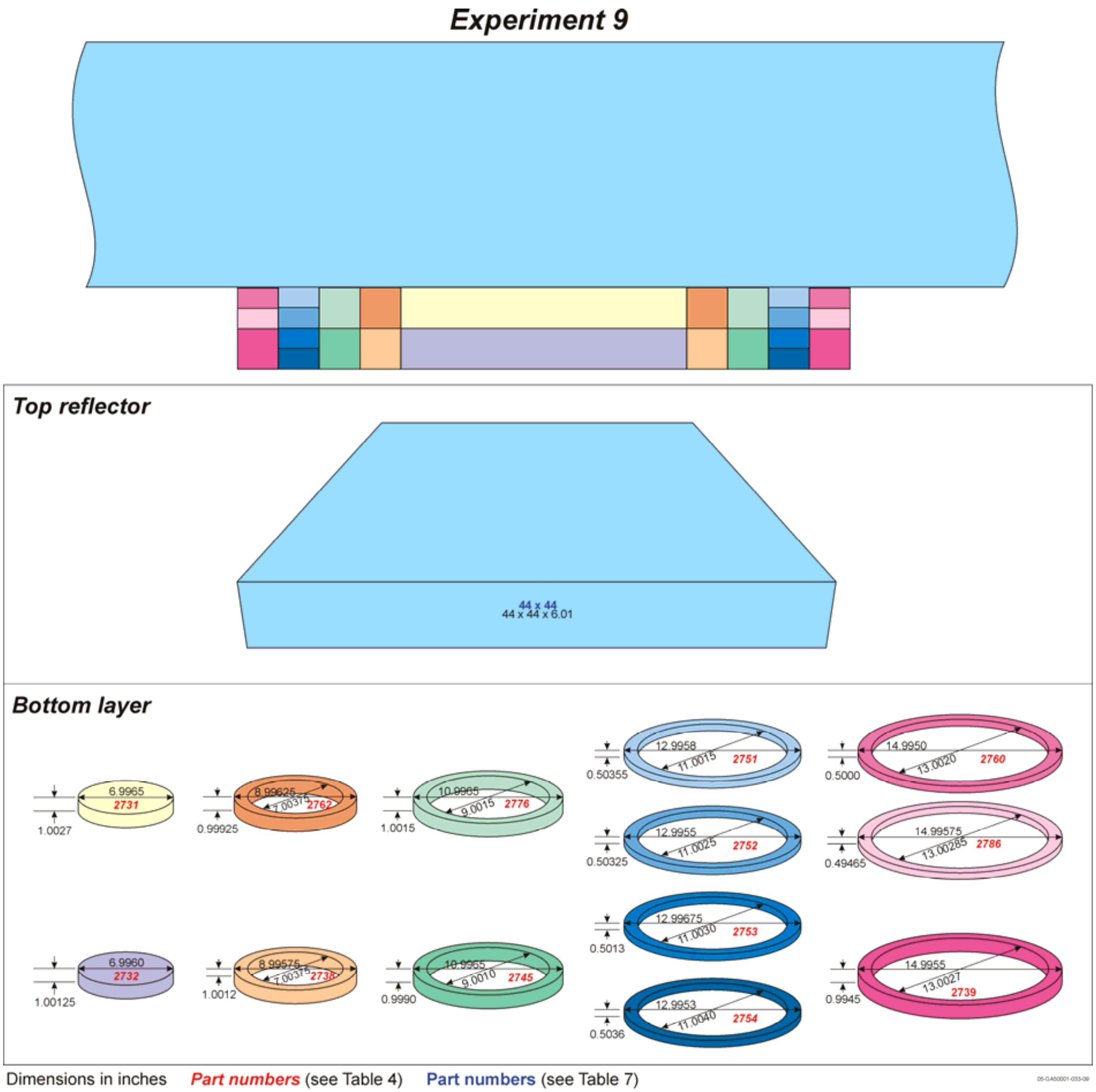
Fig. 16. Experiment 7—Configuration of a delayed-critical, 9-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector.



Region	Measured Height* (in.)
U height, 7" OD region	2.2574

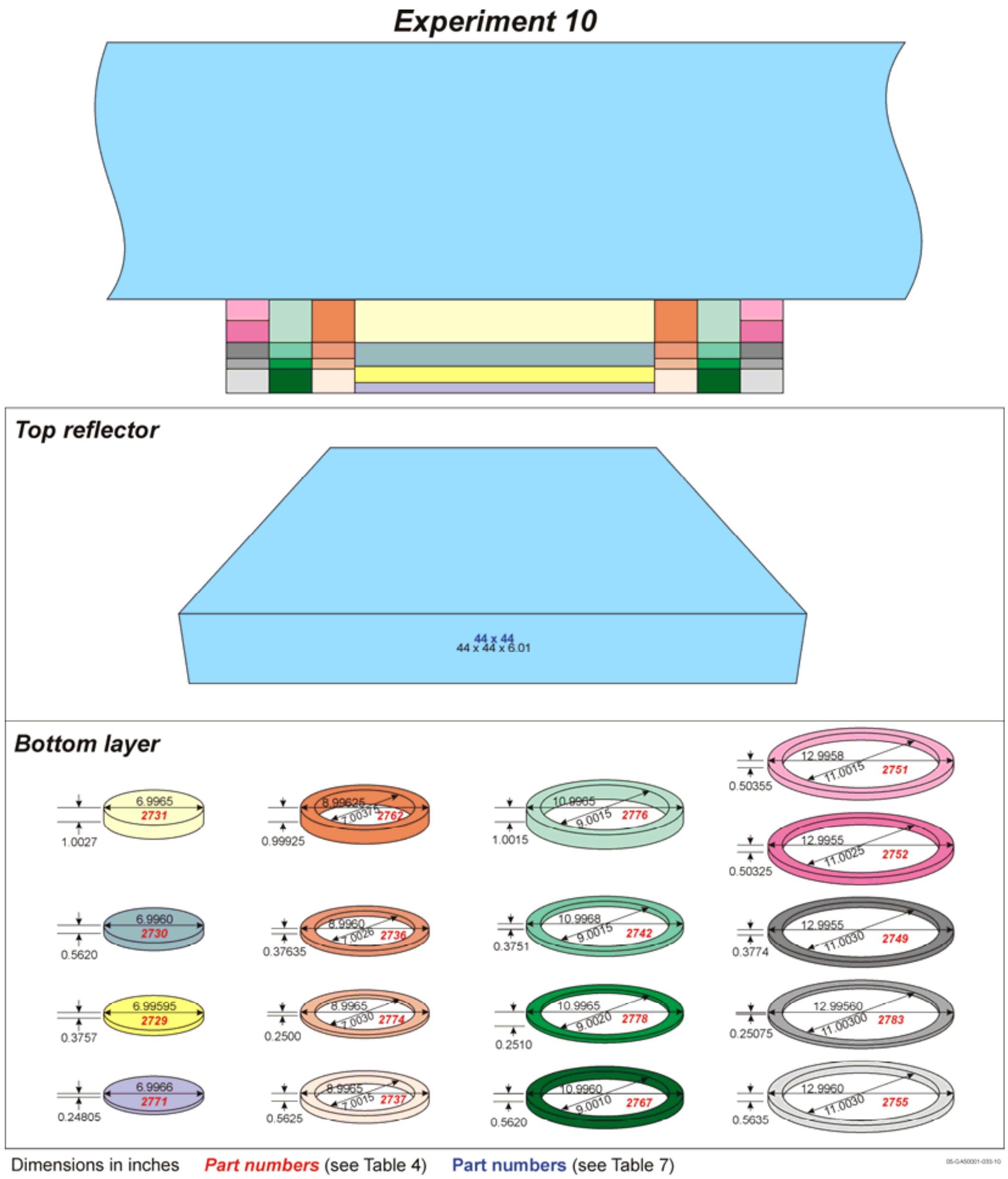
*Measured height does not include square uranium part on top.

Fig. 17. Experiment 8—Configuration of a delayed-critical, 7-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector.



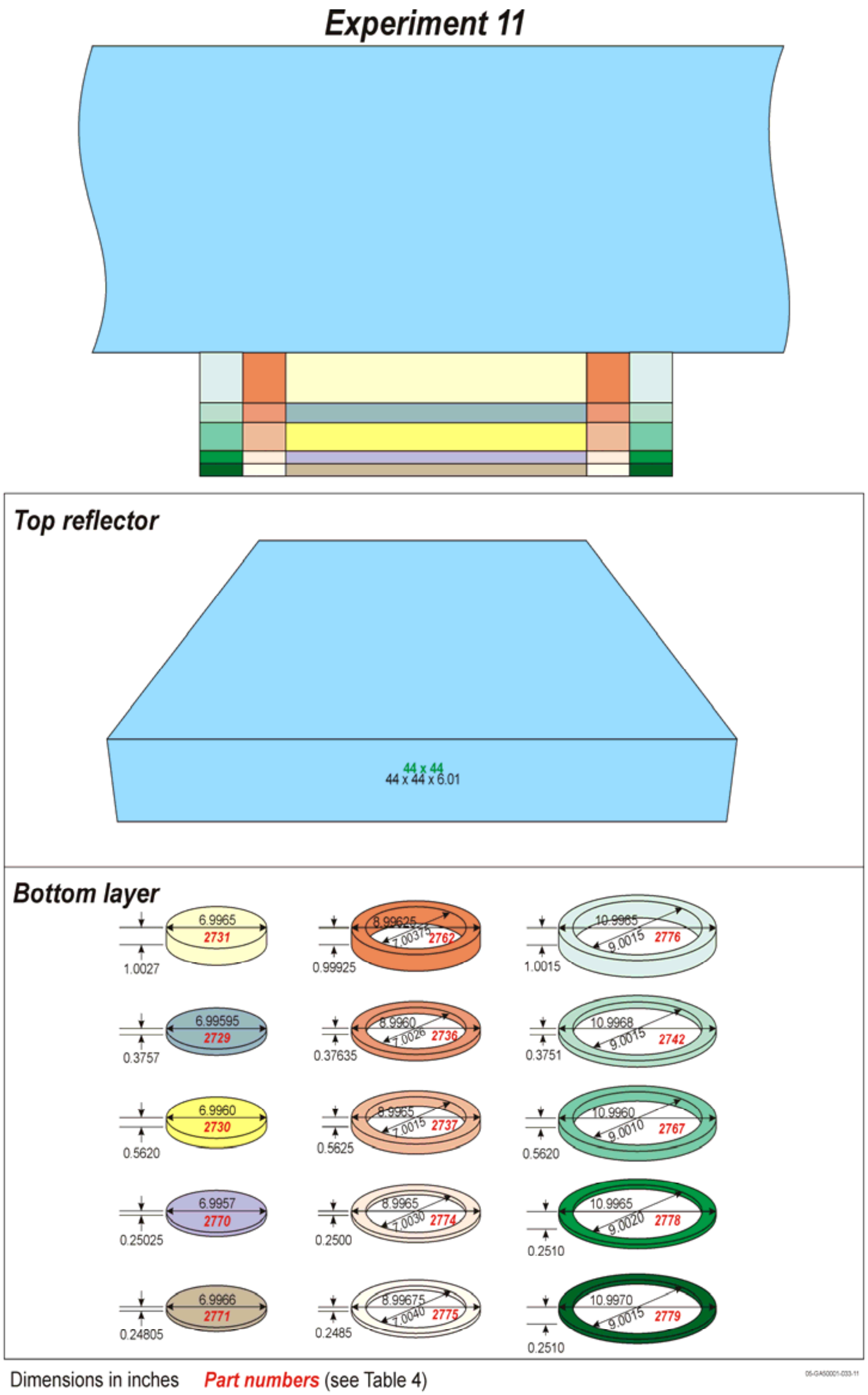
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	1.999
U height, 11" ID, 13" OD region	2.015
U height, 9" ID, 11" OD region	2.002
U height, 7" ID, 9" OD region	2.001
U height, 7" OD region	2.005

Fig. 18. Experiment 9—Configuration of a delayed-critical, 15-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector on one flat surface.



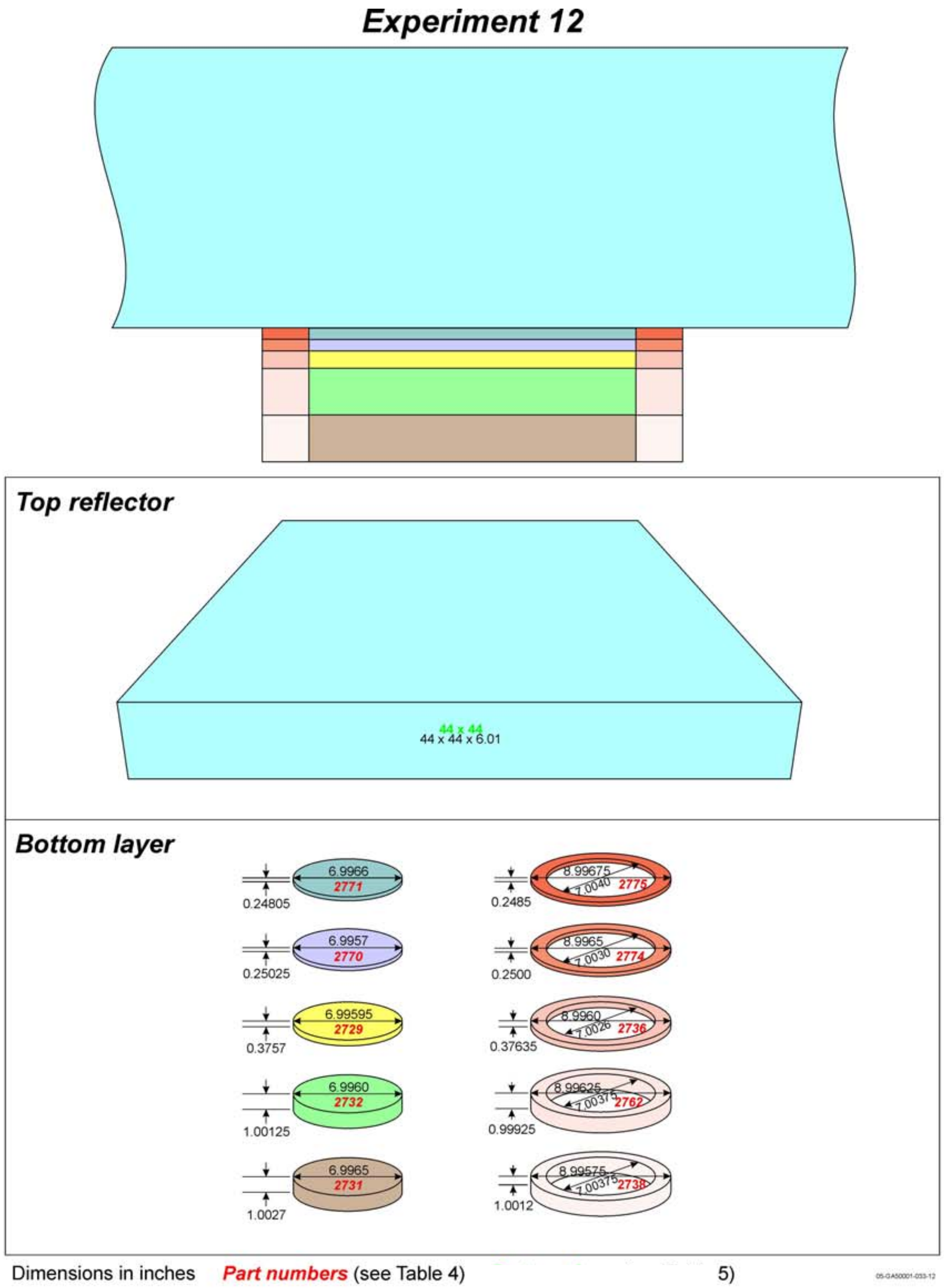
Region	Measured Height (in.)
U height, 11" ID, 13" OD region	2.195
U height, 9" ID, 11" OD region	2.193
U height, 7" ID, 9" OD region	2.191
U height, 7" OD region	2.191

Fig. 19. Experiment 10—Configuration of a delayed-critical, 13-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector on one flat surface.



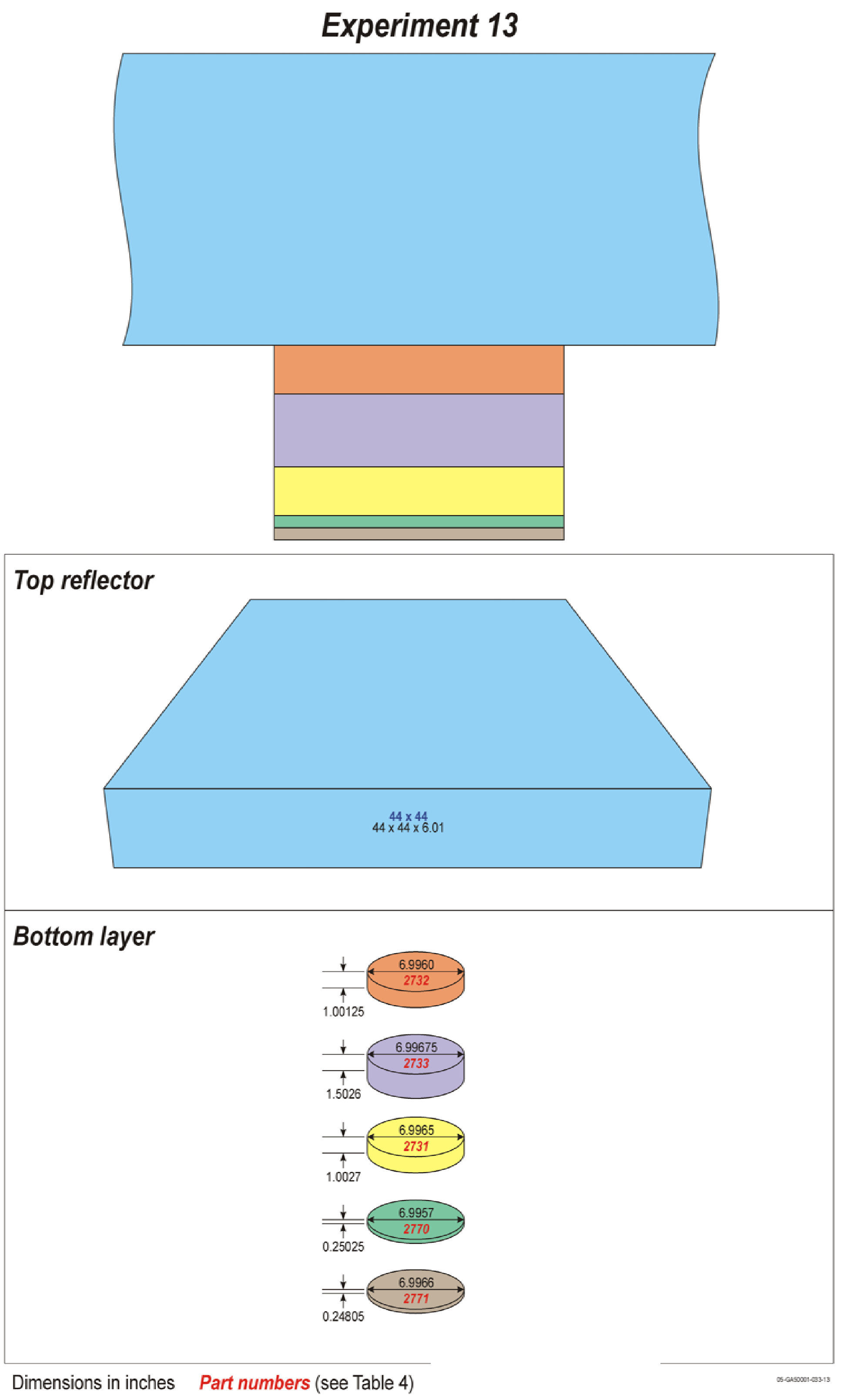
Region	Measured Height (in.)
U height, 9" ID, 11" OD region	2.445
U height, 7" ID, 9" OD region	2.441
U height, 7" OD region	2.443

Fig. 20. Experiment 11—Configuration of a delayed-critical, 11-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector on one flat surface.



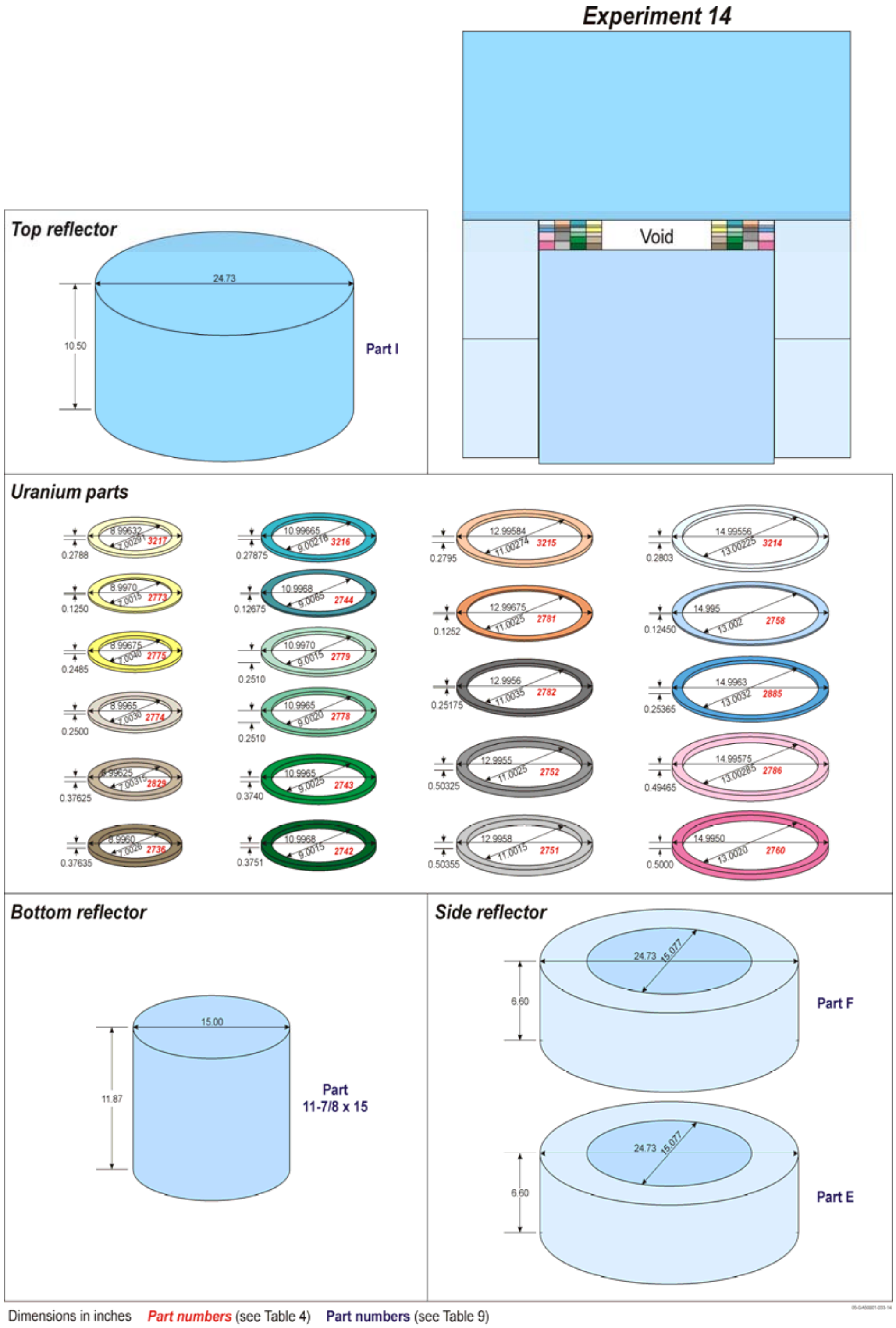
Region	Measured Height (in.)
Fuel height, 7" ID, 9" OD region	2.879
Fuel height, 7" OD region	2.881

Fig. 21. Experiment 12—Configuration of a delayed-critical, 9-in.-diam uranium (93.14 wt %^{235}U) metal cylinder with infinite polyethylene reflector on one flat surface.



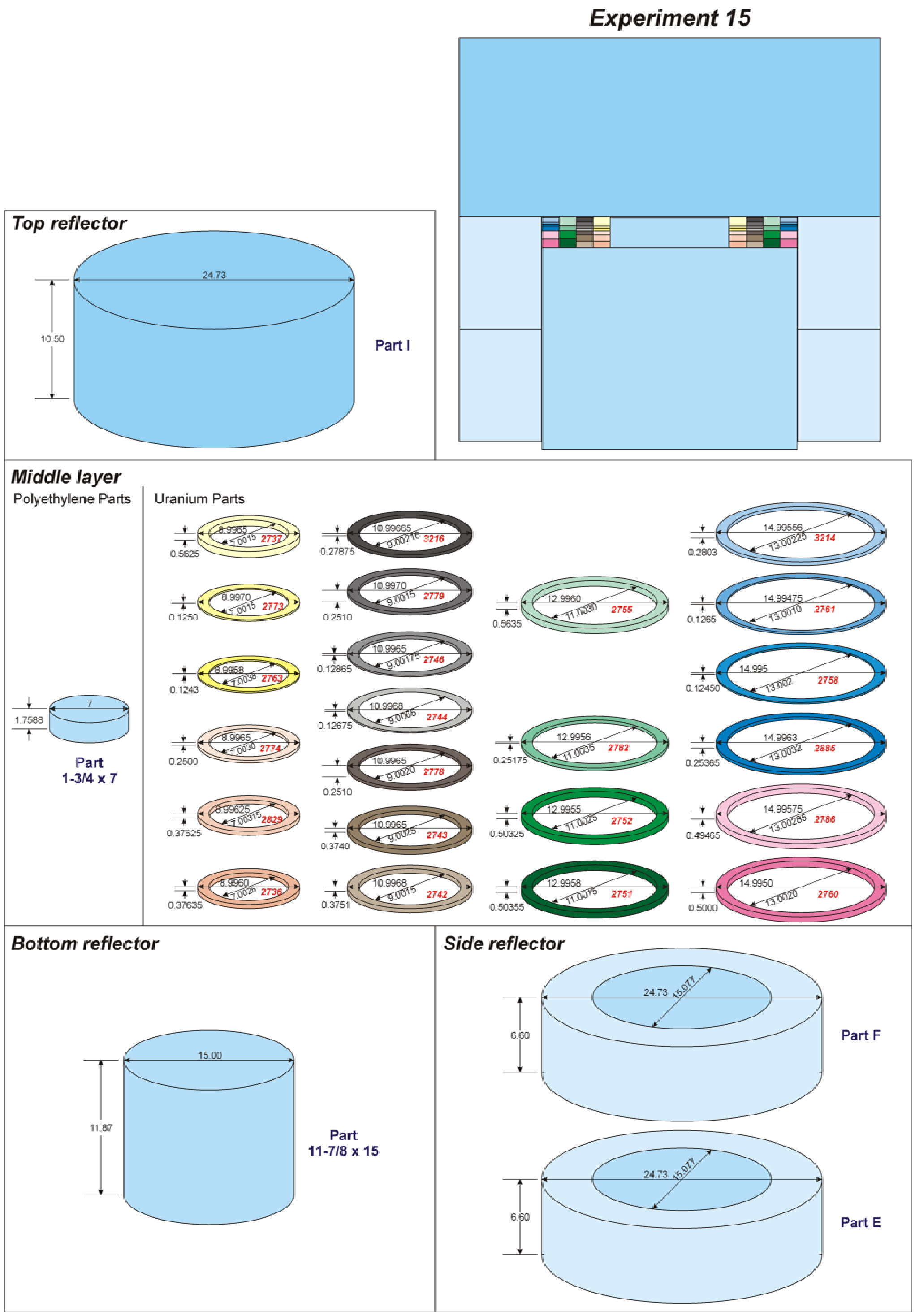
Region	Measured Height (in.)
U height, 7" OD region	4.009

Fig. 22. Experiment 13—Configuration of a delayed-critical, 7-in.-diam uranium (93.14 wt % ^{235}U) metal cylinder with infinite polyethylene reflector on one flat surface.



Region	Measured Height (in.)
U height, 13" ID, 15" OD region	1.6640
U height, 11" ID, 13" OD region	1.6641
U height, 9" ID, 11" OD region	1.6577
U height, 7" ID, 9" OD region	1.6638

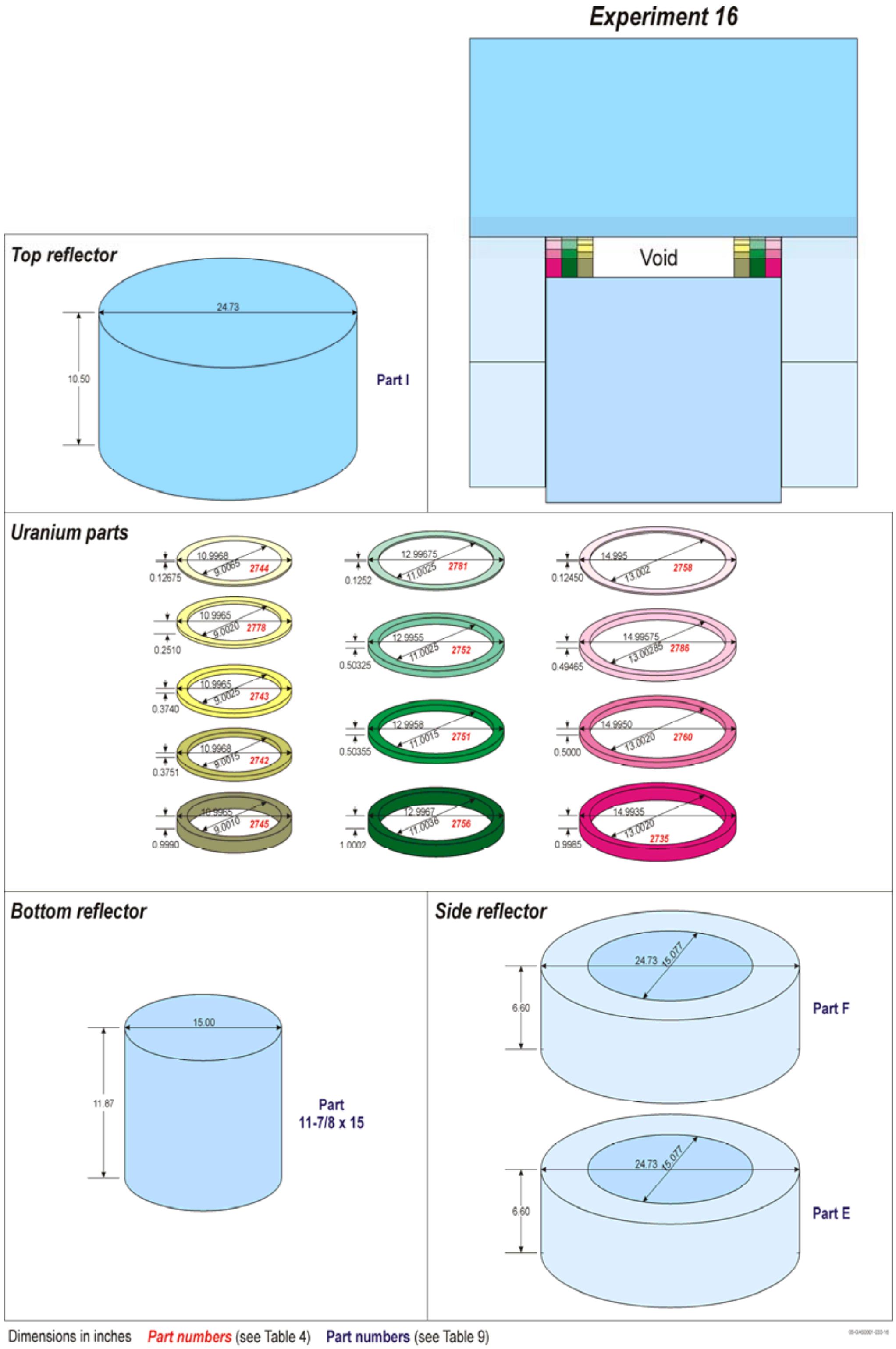
Fig. 23. Experiment 14—Configuration of a delayed-critical, 15-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



Dimensions in inches *Part numbers* (see Table 4) **Part numbers** (see Table 9)

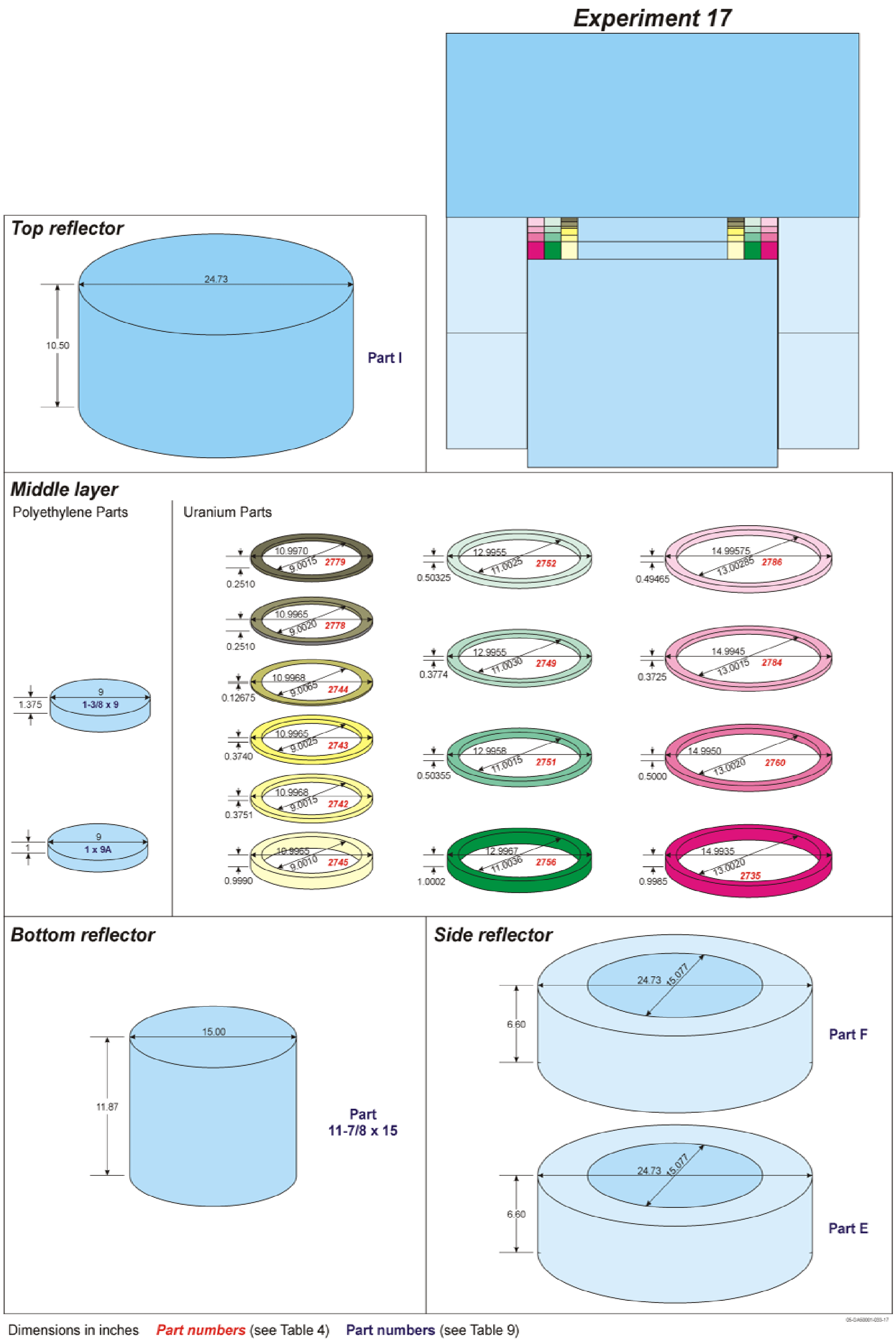
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	1.7802
U height, 11" ID, 13" OD region	1.8218
U height, 9" ID, 11" OD region	1.7894
U height, 7" ID, 9" OD region	1.8195
Polyethylene inside annulus	1.7588

Fig. 24. Experiment 15—Configuration of a delayed-critical, 15-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.



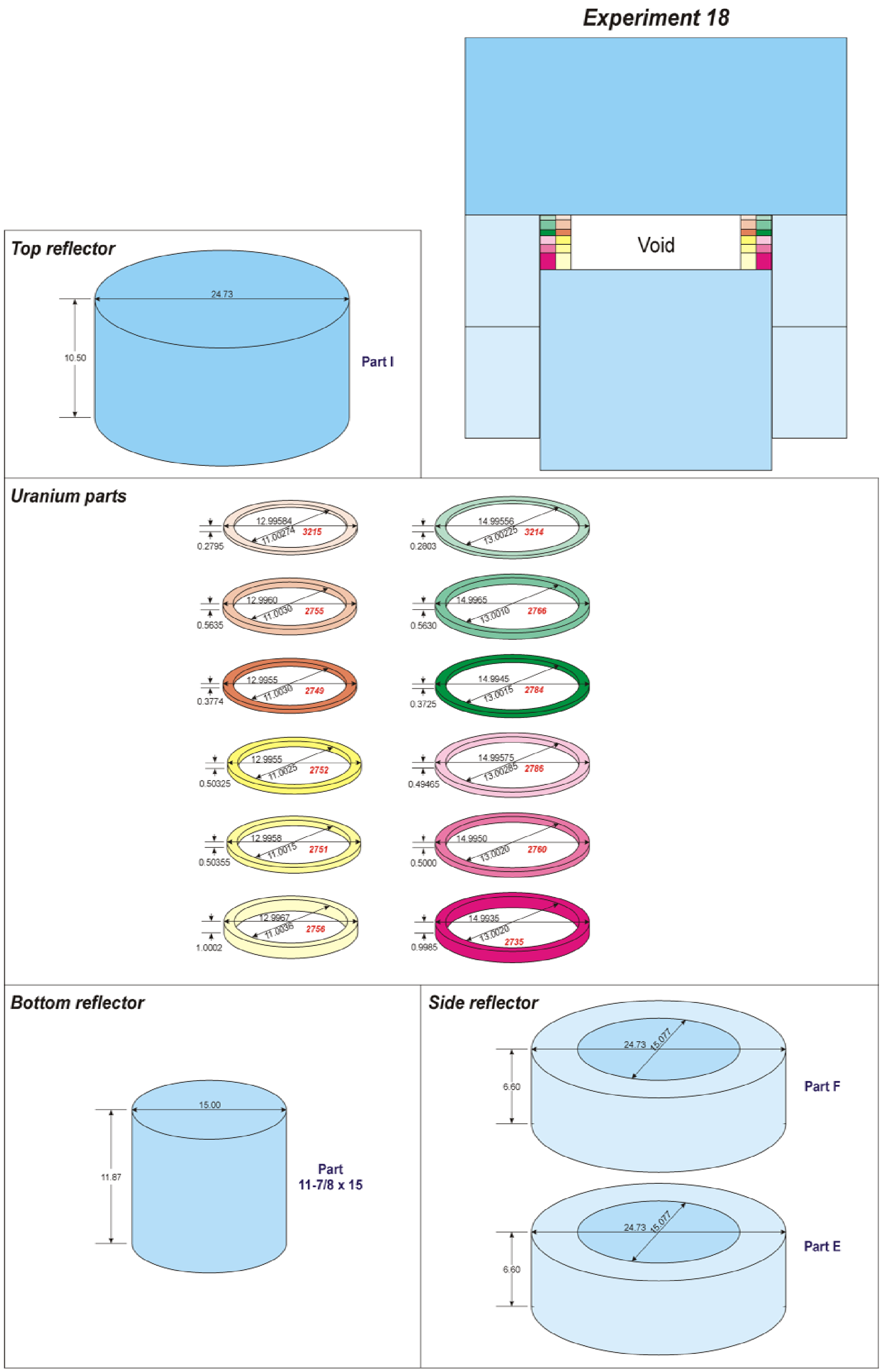
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	2.1241
U height, 11" ID, 13" OD region	2.1306
U height, 9" ID, 11" OD region	2.1361

Fig. 25. Experiment 16—Configuration of a delayed-critical, 15-in.-OD, 9-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



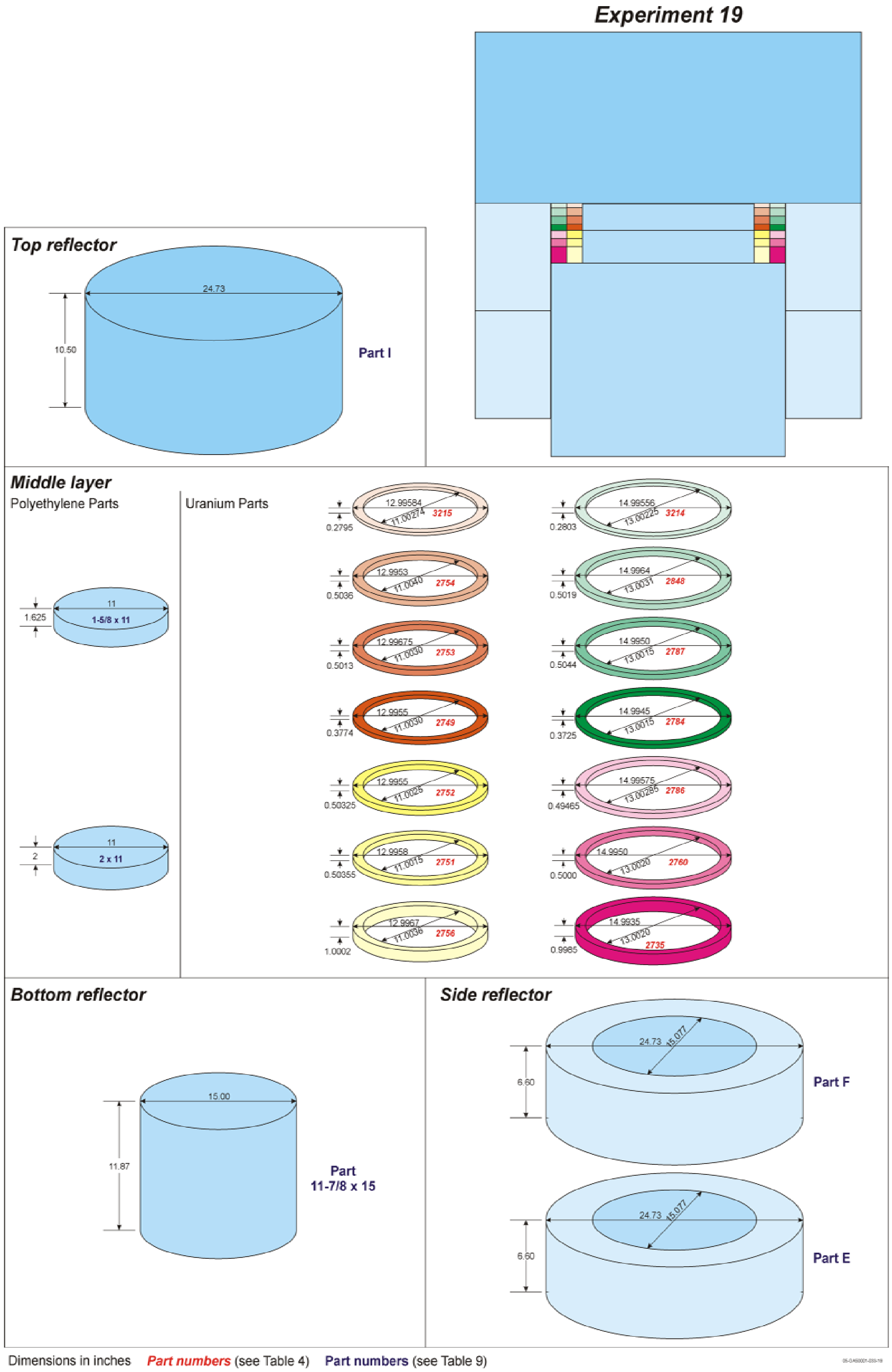
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	2.3745
U height, 11" ID, 13" OD region	2.3814
U height, 9" ID, 11" OD region	2.3831
Polyethylene inside annulus	2.3821

Fig. 26. Experiment 17—Configuration of a delayed-critical, 15-in.-OD, 9-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.



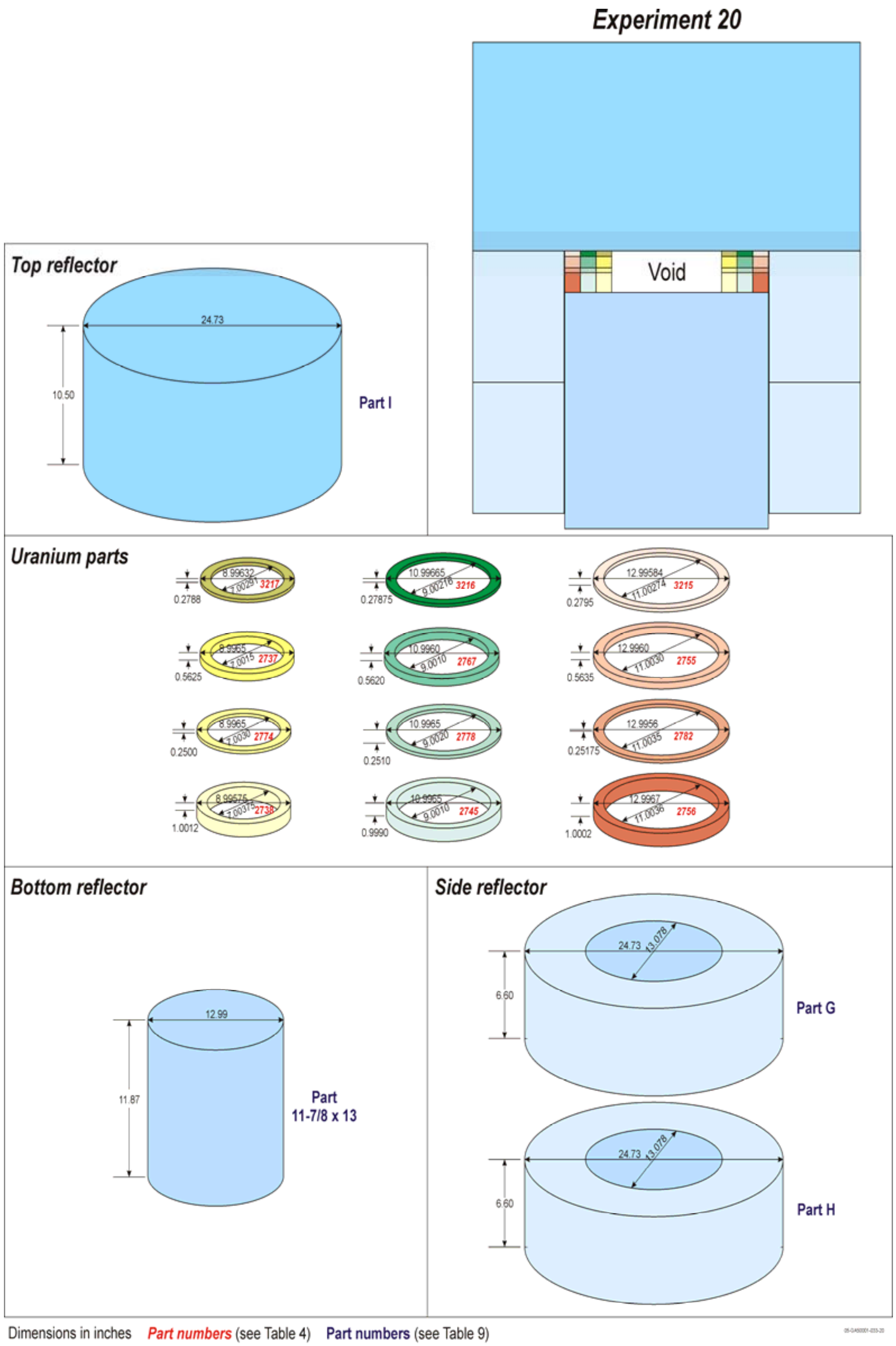
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	3.2200
U height, 11" ID, 13" OD region	3.2298

Fig. 27. Experiment 18—Configuration of a delayed-critical, 15-in.-OD, 11-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



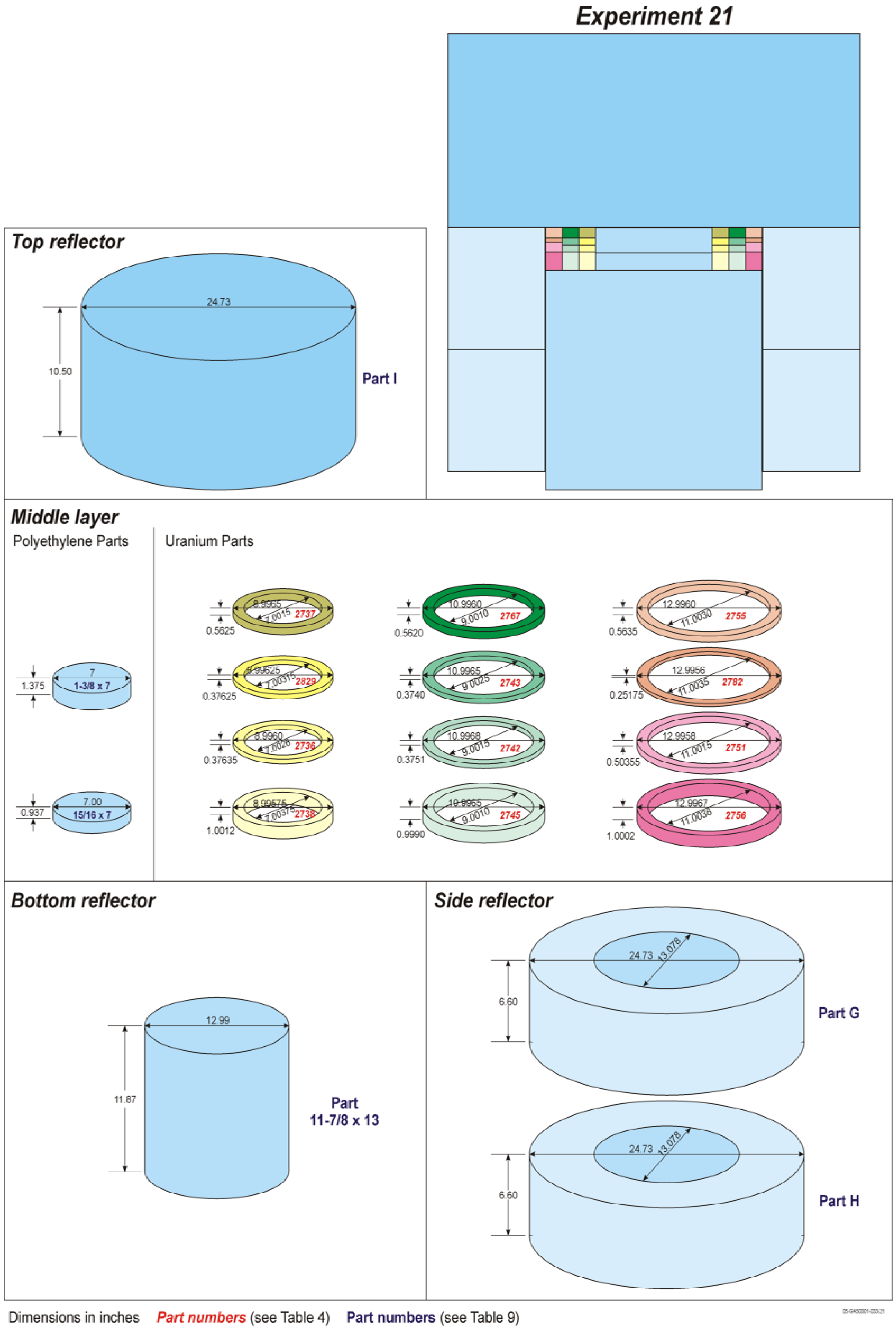
Region	Measured Height (in.)
U height, 13" ID, 15" OD region	3.6651
U height, 11" ID, 13" OD region	3.6700
Polyethylene inside annulus	3.6335

Fig. 28. Experiment 19—Configuration of a delayed-critical, 15-in.-OD, 11-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.



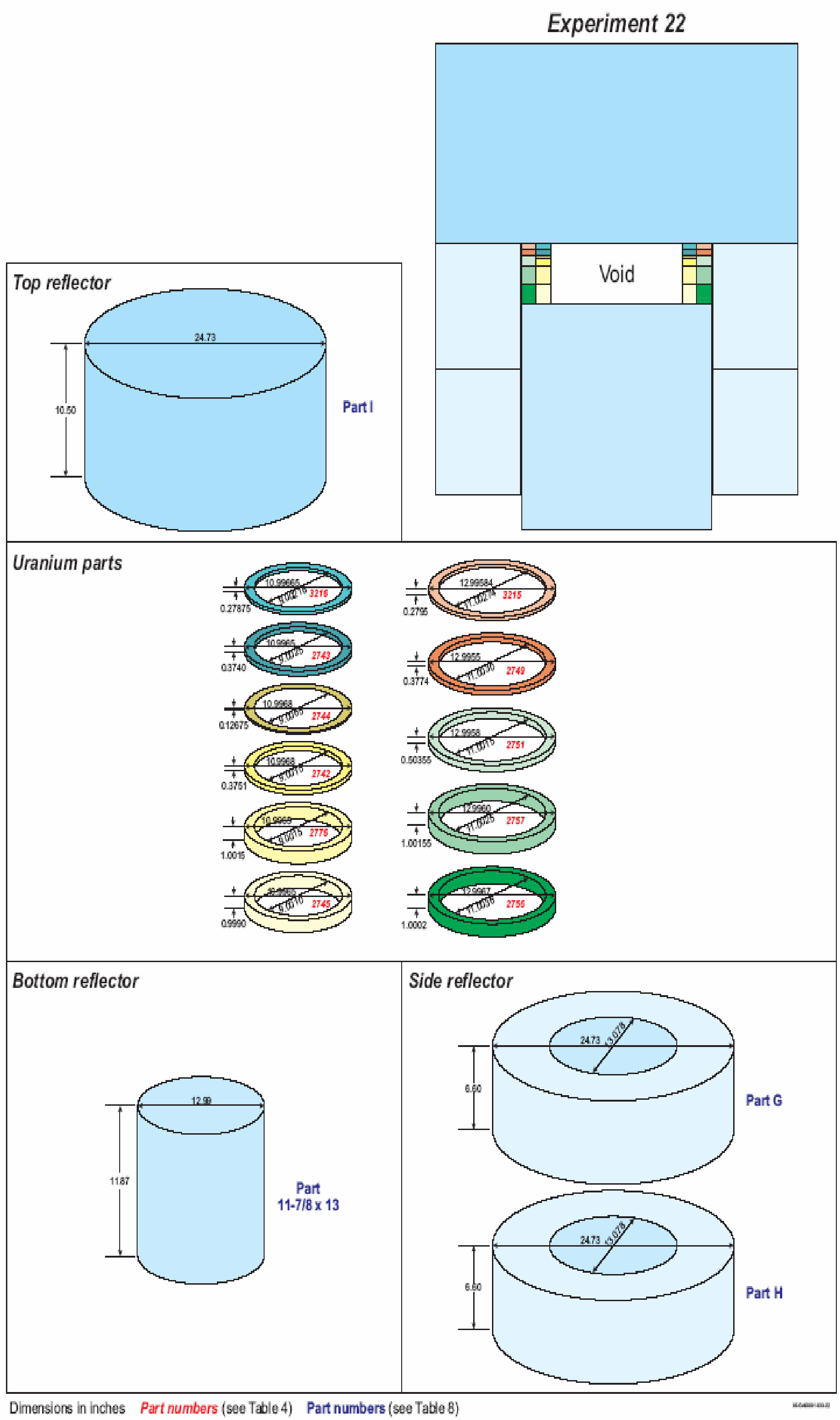
Region	Measured Height (in.)
U height, 11" ID, 13" OD region	2.0968
U height, 9" ID, 11" OD region	2.0972
U height, 7" ID, 9" OD region	2.1022

Fig. 29. Experiment 20—Configuration of a delayed-critical, 13-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



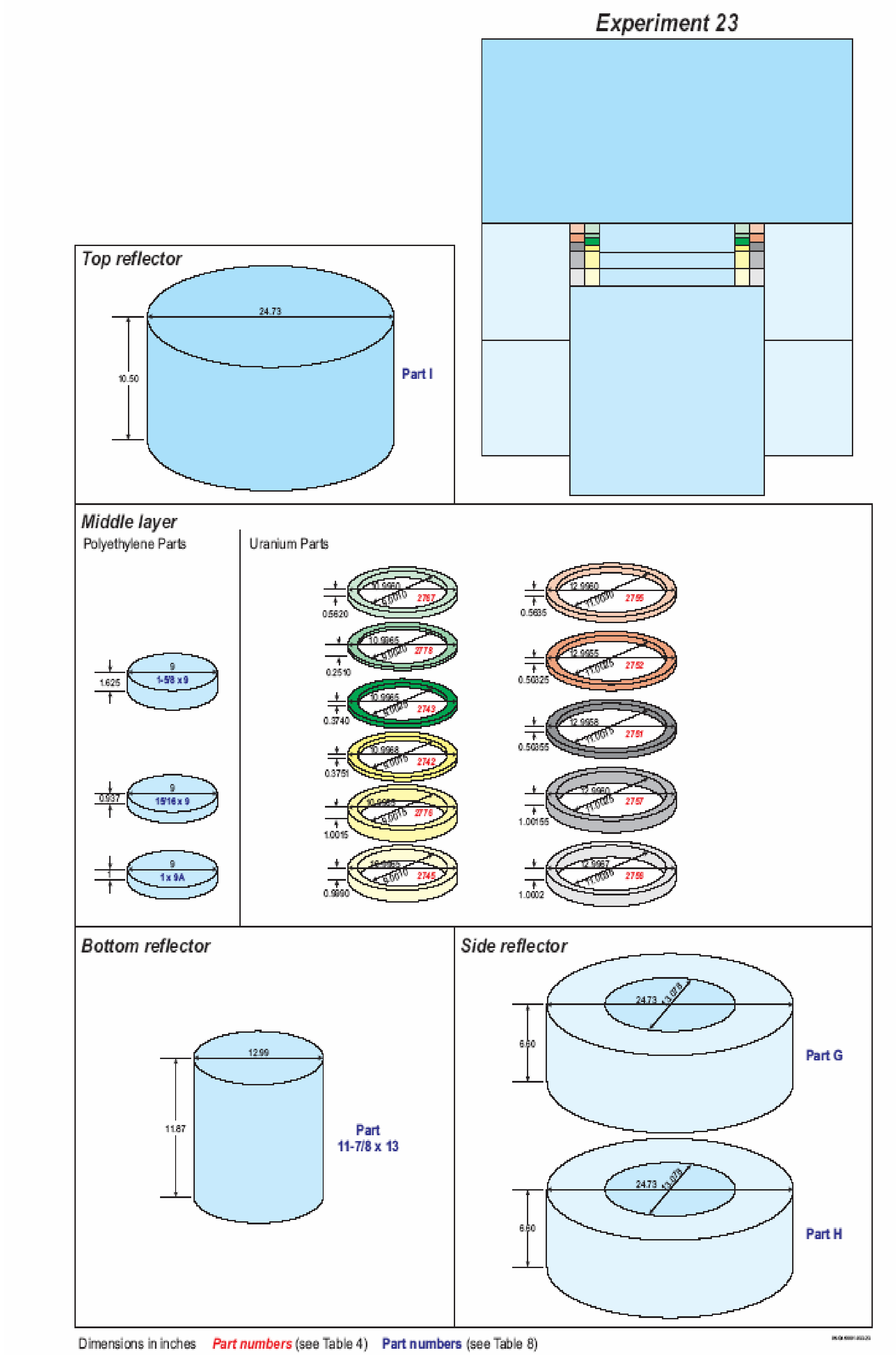
Region	Measured Height (in.)
U height, 11" ID, 13" OD region	2.3168
U height, 9" ID, 11" OD region	2.3160
U height, 7" ID, 9" OD region	2.3166
Polyethylene inside annulus	2.3146

Fig. 30. Experiment 21—Configuration of a delayed-critical, 13-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.



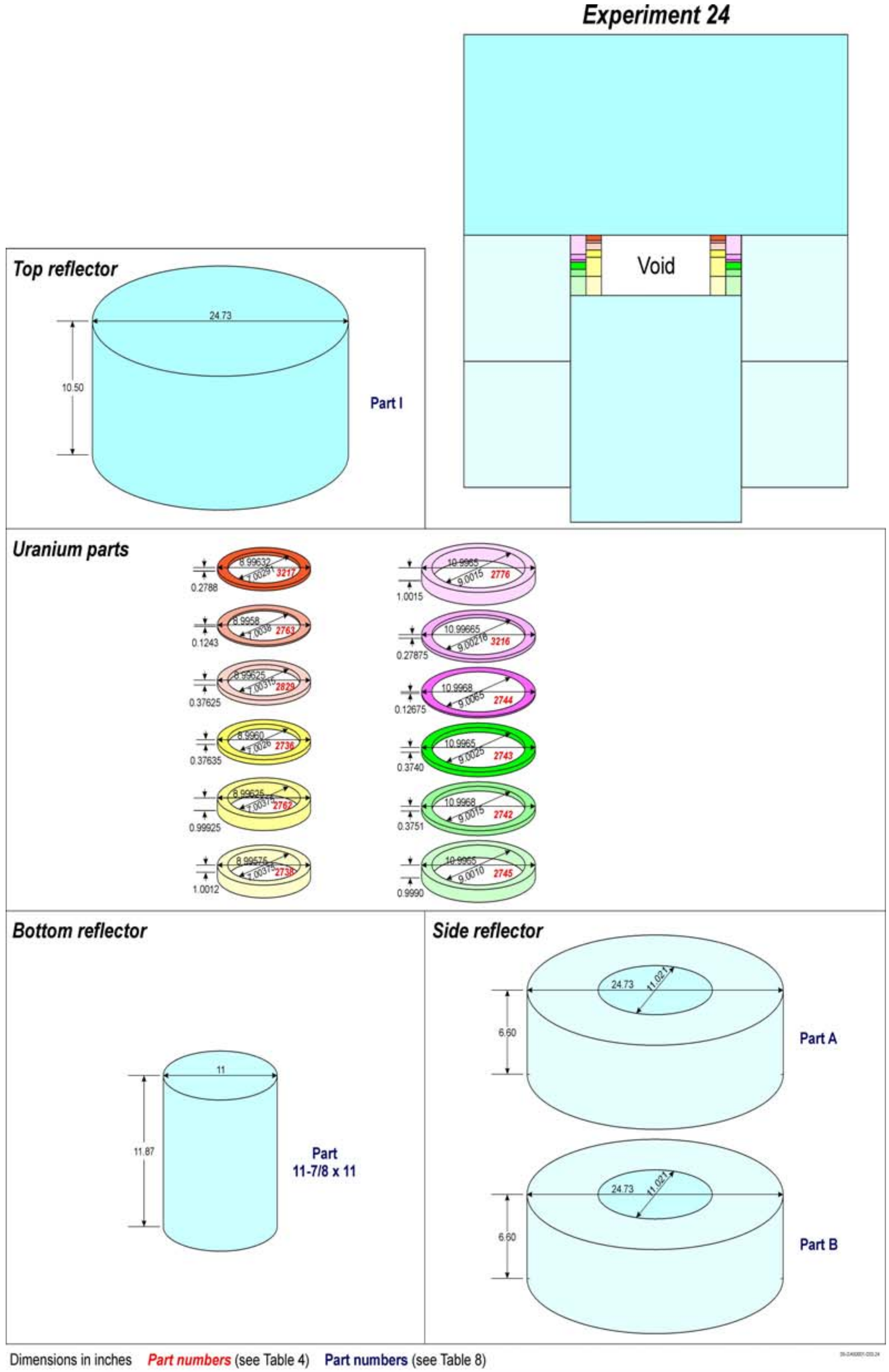
Region	Measured Height (in.)
Fuel height, 11" ID, 13" OD region	3.1648
Fuel height, 9" ID, 11" OD region	3.1688

Fig. 31. Experiment 22—Configuration of a delayed-critical, 13-in.-OD, 9-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



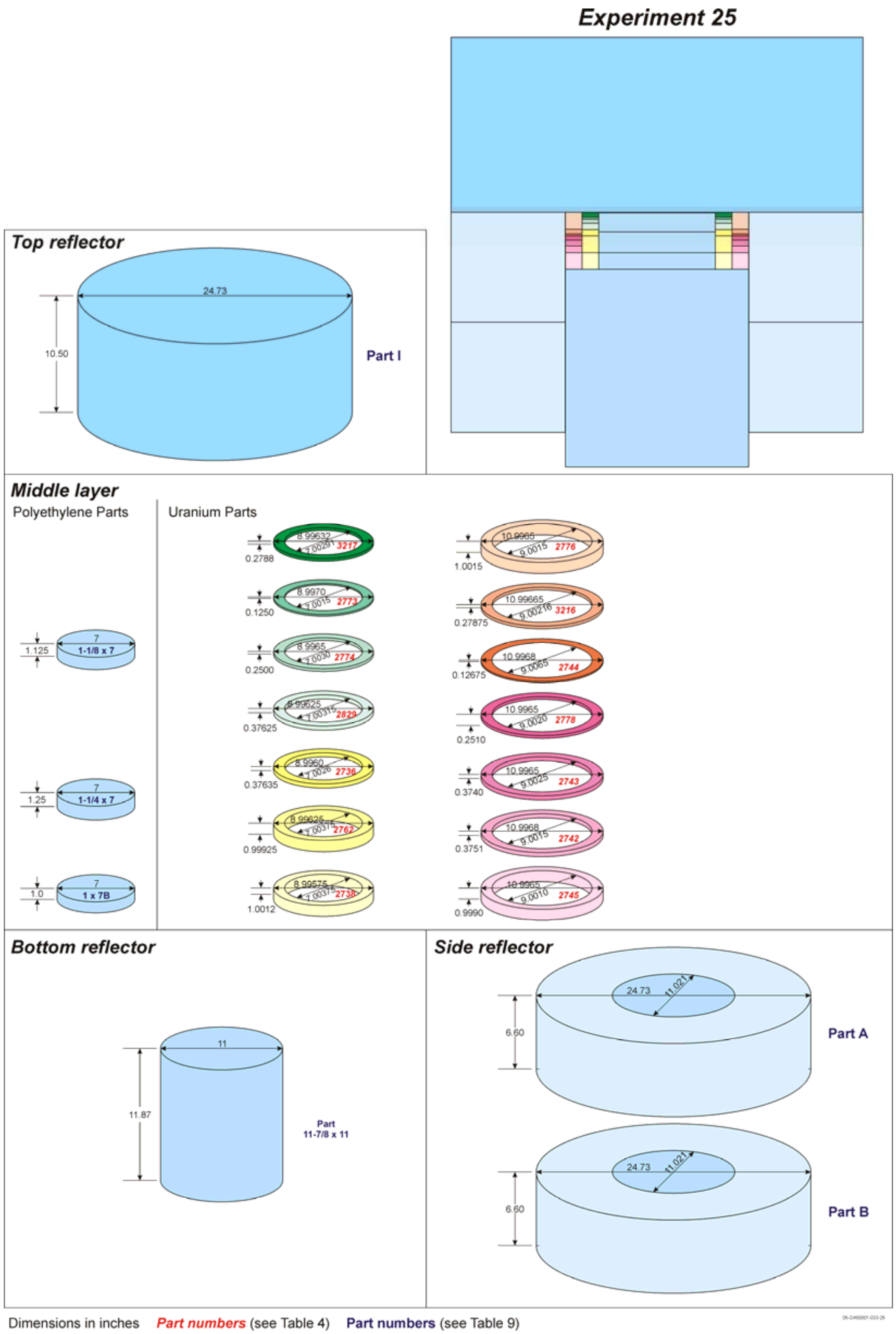
Region	Measured Height (in.)
Fuel height, 11" ID, 13" OD region	3.5708
Fuel height, 9" ID, 11" OD region	3.5708
Polyethylene inside annulus	3.5668

Fig. 32. Experiment 23—Configuration of a delayed-critical, 13-in.-OD, 9-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.



Region	Measured Height (in.)
Fuel height, 9" ID, 11" OD region	3.1645
Fuel height, 7" ID, 9" OD region	3.1660

Fig. 33 Experiment 24—Configuration of a delayed-critical, 11-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector with void in the center of the annulus.



Region	Measured Height (in.)
U height, 9" ID, 11" OD region	3.4150
U height, 7" ID, 9" OD region	3.4192
Polyethylene inside annulus	3.3993

Fig. 34. Experiment 25—Configuration of a delayed-critical, 11-in.-OD, 7-in.-ID uranium (93.14 wt % ^{235}U) metal annulus with infinite polyethylene reflector and with polyethylene in the center of the annulus.

7 DESCRIPTION OF MATERIALS

7.1 URANIUM PARTS

The uranium metal parts for these critical experiments were carefully fabricated at the Oak Ridge Y-12 Plant in the early 1960s. Each uranium metal part was a separate casting that was then machined. Dimensions, masses, uranium isotopics, and impurity content were measured. The dimensions were measured at 70°F.

The average dimensions and masses of the uranium metal parts for these experiments are given in Table 4, and the dimensions are measured with an accuracy of 1×10^{-4} in. with an uncertainty of 5×10^{-5} in. The masses of the parts given in Table 4 are accurate to 0.5 g. For some of the parts, 3214 to 3217, the measured dimensions were not available. For these parts, the inside and outside diameters were the average IDs and ODs of the other parts of the same radial dimensions. For the thickness or height, the dimensions were inferred from the measured stack heights of Table 2 but with average vertical heights for similar stacks with most of the same parts. This was done to obtain the best estimates of the vertical gaps in order to obtain good estimates of the thickness for these parts. The dimensions and masses of square plates of uranium are given in Table 5.

The average vertical gaps between uranium metal annular parts can be obtained from the measured stack heights given in Table 2 by subtracting the sum of the thickness of the individual parts given in Table 4 and dividing by the number of parts, less one, in the stack.

The uranium isotopics obtained from spectrographic analyses are given in Table 6. The average isotopic contents of the uranium metal discs and annuli are 0.97 wt % ^{234}U, 93.14 wt % ^{235}U and 0.25 wt % ^{236}U. For the parts not measured, a weighted average of other isotopic measurements was used, and they are noted on Table 6. The uncertainty in the measured values for ^{234}U, ^{235}U, and ^{236}U is 5×10^{-3} wt. %. The ^{238}U values were obtained by subtracting the sum of the other three from unity. For parts where measured isotopics are not now available, average values of parts of similar radial dimension were used. The average isotopic content of the uranium rectangular plates from Ref. 10 are 1.07 wt of ^{234}U, 93.15 wt of ^{235}U, and 0.68 wt of ^{236}U.

The impurities in these uranium metal discs and annuli from the 11 spectrographic analyses performed are given in Table 7; only average and range information exist (Ref. 3). These 11 randomly sampled uranium parts include discs as well as annular parts. Therefore, the information presented is a representative average of the impurity content in these uranium parts. These values are consistent (489 ppm) with the nominal impurity content 500 ppm by weight of highly enriched uranium metal at the Oak Ridge Y-12 Plant at the time the parts were made (i.e., 99.95 g of uranium per l00 g of material). The major impurities from spectrographic analyses for the uranium rectangular plates are A1—10 ppm, C—400 ppm, Fe—40 ppm, Mo—50 ppm, Si—40 ppm (from Ref. 10).

7.2. POLYETHYLENE PARTS

The dimension and masses or densities of the polyethylene parts are given in Table 8. The average density of the polyethylene was 0.916 g/cm^3; it was used where masses of parts were not given. The impurities in the polyethylene from mass spectroscopy are given in Table 9 and are the results of a single spectrographic analysis. Thus, the uncertainty in the values from this single analysis is a factor of 2. The main impurity in the polyethylene is silicon at 200 ppm. All polyethylene was obtained from the same manufacturer at the same time so this should minimize variations.

Table 4. Masses and dimensions of uranium (93.14 wt. % ^{235}U) metal cylinders and annuli for delayed-critical experiments with cylinders and annuli reflected and/or internally moderated with polyethylene

Part number	Measured mass (a)	Measured height (in.)	Measured inner diameter (in.)	Measured outer diameter (in.)
2728	4435	0.3760	–	6.9944
2729	4440	0.3757	–	6.99595
2730	6646	0.5620	–	6.9960
2731	11841	1.0027	–	6.9965
2732	11814	1.00125	–	6.9960
2733	17742	1.5026	–	6.99675
2735	13409	0.9985	13.0020	14.9935
2736	2895	0.37635	7.0026	8.9960
2737	4336	0.5625	7.0015	8.9965
2738	7710	1.0012	7.00375	8.99575
2739	13461	0.9945	13.0027	14.9955
2740	11568	1.5000	7.0025	8.99625
2741	11568	1.5003	7.0025	8.9965
2742	3617	0.3751	9.0015	10.9968
2743	3621	0.3740	9.0025	10.9965
2744	1223	0.12675	9.0065	10.9968
2745	9634	0.9990	9.0010	10.9965
2746	1238	0.12865	9.00175	10.9965
2747	14436	1.4999	9.0020	10.9968
2748	14462	1.5000	9.0025	10.9975
2749	4360	0.3774	11.0030	12.9955
2750	4336	0.37545	11.0015	12.9945
2751	5822	0.50355	11.0015	12.9958
2752	5811	0.50325	11.0025	12.9955
2753	5782	0.5013	11.0030	12.99675
2754	5826	0.5036	11.0040	12.9953
2755	6514	0.5635	11.0030	12.9960
2756	11567	1.0002	11.0036	12.9967
2757	11575	1.00155	11.0025	12.9960
2758	1685	0.5000	13.0020	14.9950
2760	6743	0.5000	13.0020	14.9950
2762	7703	0.99925	7.00375	8.99625
2763	953	0.1243	7.0038	8.9958
2766	7605	0.5630	13.0010	14.9965
2767	5410	0.5620	9.0010	10.9960
2768	1481	0.1250	–	6.9965
2769	1495	0.1265	–	6.9965
2770	2955	0.25025	–	6.9957
2771	2916	0.24805	–	6.9966
2773	962	0.1250	7.0015	8.9970
2774	1930	0.2500	7.0030	8.9965
2775	1917	0.2485	7.0040	8.99675
2776	9644	1.0015	9.0015	10.9965
2778	2411	0.2510	9.0020	10.9965
2779	2417	0.2510	9.0015	10.9970
2780	1440	0.12485	11.0020	12.99605
2781	1449	0.1252	11.0025	12.99675
2782	2914	0.25175	11.0035	12.9956

Table 4. Masses and dimensions of uranium (93.14 wt. % ^{235}U) metal cylinders and annuli for delayed-critical experiments with cylinders and annuli reflected and/or internally moderated with polyethylene

2784	5039	0.3725	13.0015	14.9945
2785	5043	0.3747	13.0029	14.9958
2786	6717	0.3747	13.00285	14.99575
2787	6788	0.5044	13.0015	14.9950
2829	2895	0.37625	7.00315	8.99625
2848	6748	0.5019	13.0031	14.9964
2885	3415	0.25365	13.0032	14.9963
3214	3797	0.2803[c]	13.00225[d]	14.99556[d]
3215	3259	0.2795[c]	11.00274[d]	12.99584[d]
3216	2708	0.27875[c]	9.00216[d]	10.99665[d]
3217	2167	0.2788[c]	7.00291[d]	8.99632[d]

[a] Masses traceable back to U.S. Bureau of Standards to less than 0.5 grams accuracy and rounded to the nearest 1 gram.
[b]The dimensions were measured to 0.0001 in. accuracy at 8 azimuthal locations and averaged. All dimensions were measured at 70°F and traceable back to the U.S. Bureau of Standards.
[c]Inferred from measured stack heights and other part thicknesses and averaged over several estimates.
[d]Average of parts of similar diameter.

Table 5. Dimensions of rectangular uranium (93.14 wt % ^{235}U) metal plates for delayed-critical experiments with cylinders reflected with polyethylene

Part number	Measured mass (g)	Measured height (in.)	Measured length (in.)	Measured width (in.)
3101	240	0.03125	5.0000	5.0000
3104	60.3	0.03125	2.5000	2.5000

Table 6. Summary of uranium isotopics of metal cylinders, annuli, and plates for delayed-critical experiments reflected and/or internally moderated with polyethylene[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
2735	93.12	0.98	0.25	5.65
2736	93.17	1.01	0.21	5.61
2737	93.08	0.99	0.29	5.64
2738	93.15	0.98	0.24	5.63
2739	93.16	0.96	0.25	5.63
2740	93.17	0.97	0.24	5.62

Table 6. Summary of uranium isotopics of metal cylinders, annuli, and plates for delayed-critical experiments reflected and/or internally moderated with polyethylene[a] (continued)

2741	93.18	0.96	0.25	5.61
2742	93.14	0.98	0.23	5.65
2743	93.14	0.98	0.23	5.65
2744	93.14	0.98	0.23	5.65
2745	93.20	0.96	0.22	5.62
2746	93.09	1.00	0.22	5.69
2747	93.16	0.98	0.19	5.67
2748	93.09	1.00	0.22	5.69
2749	93.19	0.98	0.25	5.58
2750	93.12	0.95	0.25	5.68
2751	93.13	0.98	0.24	5.65
2752	93.13	0.98	0.24	5.65
2753	93.12	0.95	0.25	5.68
2754	93.10	0.96	0.28	5.66
2755	93.10	0.96	0.28	5.66
2756	93.18	0.93	0.25	5.64
2757	93.20	0.96	0.23	5.61
2758	93.16	0.98	0.27	5.59
2760	93.13	0.99	0.24	5.64
2761	93.12	0.96	0.27	5.65
2762	93.13	0.97	0.27	5.63
2763	93.18	0.96	0.25	5.61
2766	93.16	0.98	0.27	5.59
2767	93.14	0.96	0.26	5.64
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	93.14	0.97	0.25	5.64
2773	93.17	0.97	0.24	5.62
2774	93.08	0.99	0.29	5.64
2775	93.15	0.98	0.24	5.63
2776	93.16	0.96	0.23	5.65
2778	93.16	0.96	0.23	5.65
2779	93.16	0.96	0.23	5.65
2780	93.13	0.98	0.25	5.64
2781	93.19	0.98	0.25	5.58
2782	93.20	0.96	0.23	5.61
2783	93.18	0.93	0.25	5.64

Table 6. Summary of uranium isotopics of metal cylinders, annuli, and plates for delayed-critical experiments reflected and/or internally moderated with polyethylene[a] (continued)

2784	93.11	0.99	0.26	5.64
2785	93.14	0.98	0.24	5.64
2786	93.14	0.98	0.24	5.64
2787	93.14	0.98	0.24	5.64
2803	93.14	1.00	0.23	5.63
2820	93.14	0.98	0.24	5.64
2821	93.14	0.98	0.24	5.64
2829	93.10	0.99	0.24	5.67
2848	93.18	0.99	0.24	5.59
2885	93.11	0.99	0.26	5.64
2886	93.11	0.99	0.26	5.64
3078	93.14	0.97	0.25	5.64
3101	93.14	0.97	0.25	5.64
3102	93.14	0.97	0.25	5.64
3103	93.14	0.97	0.25	5.64
3104	93.14	0.97	0.25	5.64
3105	93.14	0.97	0.25	5.64
3214[c]	93.14	0.98	0.25	5.63
3215[d]	93.15	0.96	0.25	5.64
3216[e]	93.15	0.98	0.22	5.65
3217[f]	93.15	0.97	0.25	5.63

[a]Mass spectrographic analysis; These values for 234, 235, and 236 are accurate to ±0.0005 and the ^{238}U value is by difference from unity.
[b]By difference from 100%.
[c]Values are weighted average of parts: 2848, 2885, 2886, 27784, 2785, 2786, 2787, 2766, 2758, 2760, 2762,2739, 2735
[d]Values are weighted average of parts: 2749, 2750, 2752, 2752, 2753, 2754, 2755, 2756, 2757, 2780, 2781, 2782, 2783.
[e]Values are weighted average of parts: 2742, 2743, 2744, 2745, 2746, 2747, 2748, 2767, 2776, 2778, 2779.
[f]Values are weighted average of parts: 2736, 2737, 2738, 2740, 2741, 2762, 2763, 2773, 2774, 2775, 2829.

Table 7. Average measured impurity content of uranium metal cylinders, annuli, and plates for delayed-critical experiments with uranium metal reflected and/or internally moderated with polyethylene.[a]

Element	Average parts per million by weight (ppm)	Range (ppm)	Standard deviation (ppm) [b]
Ag	8	3–25	3.2
Ba	< 0.01	–	0.005
Bi	164	81–311	52.9
C	< 10	–	2.4
Ca	0.1	–	0.05
Cd	< 1	–	0.5
Co	5	2–15	1.9
Cr	7	4–12	1.9
Cu	25	10–40	8
K	< 0.2	0.2–0.8	0.1
Li	< 2	–	1
Mg	3	2–3	1.7
Mn	56	25–89	17.1
Mo	< 1	< 1–1	0.5
Na	27	15–50	7.7
Ni	100	–	10
Sb	38	10–80	17.4
Ti	1	–	0.5

[a]Mass spectrographic analysis except for oxygen and nitrogen using data in Reference 4. Oxygen and nitrogen content was assumed to be 20 and 30 ppm, respectively, consistent with highly enriched uranium produced at the time of these experiments. Total impurity content is consistent with stated values at that time of 500 ppm, which gives 99.95 grams of U per 100 grams of material. Minor differences in the impurities exist between values listed in Table 10 and the impurity values provided in HEU-MET-FAST-051.

[b]Personal communication, J. A. Mullens to John Mihalczo, June 2004. With the assumption that the individual values for each of the impurities are normally distributed, the uncertainty can be obtained from the average values.

2.1

Table 8. Masses or density and dimensions of polyethylene parts for delayed-critical experiments of reflected and/or moderated annuli and cylinders

Polyethylene part number	Actual dimensions (in)[a]			Density g/cm^3
	Outside diameter	Inside diameter	Thickness [a]	
11⅞ × 11	11	0	11.87	0.916
11⅞ × 13	12.99	0	11.78	0.916
11⅞ ×15	15	0	11.87	0.916
11⅞ × 9	9	0	11.87	0.916
A	24.73	11.021	6.6	0.916
B	24.73	11.021	6.6	0.916
C	24.73	9.09	6.6	0.916
D	24.73	9.09	6.6	0.916
E	24.73	15.077	6.6	0.916
F	24.73	15.077	6.6	0.916
G	24.73	13.078	6.6	0.916
H	24.73	13.078	6.6	0.916
I	24.73	0	10.5	0.916
15/16 × 7	7	0	0.937	0.916
1×7A	7	0	1	*b*
1×7B	7	0	1	*b*
1⅛ × 7	7	0	1.125	0.916
1¼ × 7	7	0	1.25	0.916
1¾ × 7	7	0	1.759	0.916
2×7A	7	0	2	0.922
2×7B	7	0	2	0.913
15/16 × 9	9	0	0.937	0.916
1×9A	9	0	1	*c*
1×9B	9	0	1	0.90
1⅛ × 9	9	0	1.125	0.92
1⅜ × 9	9	0	1.375	0.916
1⅝ × 9	9	0	1.625	0.916
2×9A	9	0	2	0.916
1⅝ × 11	11	0	1.625	0.916
44×44	N/A	N/A	6.01	0.916
Ring	8.994	7	3	0.916
2×11	11	0	2	0.916
Disc 5 [c]	7	0	0.71875	0.916

[a]Dimensional uncertainty in polyethylene is ±0.010 in.
[b]Masses for part 1×7A, 1×7B and 1×9A are 581, 582, and 947 grams, respectively.
[c]Disc 5, which was used in Experiment 8, consisted of two discs resting on top of each other. The lower disc had a thickness of 0.5 in., and the upper disc had a thickness of 7/32 in. The diameter and density of disc 5 were assumed to be the same as parts of similar dimensions.

Table 9. Impurities in the polyethylene

Element	Impurity content (ppm)[a]	Element	Impurity content (ppm)[a]
Ag	<1	Mn	<2
Al	<5	Mo	<1
B	<1	Na	<10
Ba	<20	Ni	<3
Be	<1	Pb	<3
Bi	<3	Rb	<10
Ca	<30	Sb	<10
Cb	<10	Si	200
Cd	<10	Sn	<3
Co	<10	Ta	30
Cr	<10	Ti	3
Cu	<1	V	<3
Fe	3	W	<30
K	<10	Zn	<50
Li	1	Zr	<10
Mg	3	-	-

[a]These are the results of spectrographic analyses reported as parts (mass) of impurity per million parts of the materials. "Less than" indicates lower limit of measurements and not necessarily that the impurity is present.

8 SUPPLEMENTAL EXPERIMENTAL MEASUREMENTS

The reactivity effect of changing the height of various-diameter annular uranium metal rings was measured. The measurements were performed as follows: the system was assembled to near delayed criticality and the stable reactor period measured. The system was disassembled, height-perturbed, and reassembled to measure the stable reactor period. The height was perturbed by removing an annular ring of uranium metal, replacing it with one of increased height of 1/16 or 1/32 in. The excess reactivity was then measured and recorded. The reactivities were obtained from the two reactor period measurements, and the difference in reactivities is the worth of the uranium height perturbation. These values, shown in Table 10, were also used in evaluating the uncertainty associated with height.

Height perturbation measurements were not practical for the one-side-reflected uranium metal cylinders with diameters larger than 9 in., since the large reactivity changes could not be measured directly with the uranium metal parts available. However, for experiments 10 – 13, measurements were performed with a 1×1×0.125-in.-thick uranium metal plate added to the bottom of the uranium metal cylinders. This was done by raising the uranium metal cylinder ¼ in. off the lower support stand with small aluminum shims as needed and placing the 1×1×0.125-in.-thick uranium metal on the lower surface. A measurement of the exponential change in the fission rate was performed without the additional uranium and then with the 1×1×0.125.-in.-thick piece of aluminum at various radial positions on the lower surface of the cylinders. The reactivity differences obtained from two (with and without the 1×1×0.125-in -thick square exponential increases of the fission rate. The mass of this uranium metal sample was 38 grams. These values are given in Table 11.

Height perturbation measurements can also be used to verify calculational methods. Calculational changes in experiments can usually be calculated move accurately than absolute values. However, if height perturbation measurements are lower than measured, then it would be expected that the calculated k_{eff} of the assembly would be lower than measured and visa versa.

Table 10. Height perturbation measurements for uranium metal cylinders and annuli reflected and/or internally moderated with polyethylene

Description of experiment					Height change (in.)	Measured reactivity change (cents) for uranium annuli [a]				Total
Experiment number	**HEU OD (in.)**	**HEU ID (in.)**	**Material inside annulus**	**Reflector thickness (in.)**		**15–13 (in.)**	**13–11 (in.)**	**11–9 (in.)**	**9–7 (in.)**	**Δρ/ΔH (cents/mil)**
1	15	7	Poly	0	1/16	12.6 (0.202)	26.6 (0.425)	33.2 (0.531)	29.0 (0.46)	1.630
2	15	7	Poly	0	1/16	11.65 (0.186)	23.5 (0.376)	24.6 (0.394)	–	0.956
3	15	7	Poly	0	1/16	--	11.6 (0.185)	27.4 (0.438)	26.9 (0.430)	1.054
4	15	0	NA	∞	1/32	10.5 (0.335)	14.3 (0.459)	21.0 (0.674)	26.8 (0.859)	–
5	13	0	NA	∞	1/32	–	15.4 (0.493)	22.0 (0.703)	24.0 (0.768)	–
6	11	0	NA	∞	1/32	–	–	20.3 (0.650)	27.5 (0.879)	–
9	15	0	NA	*b*	1/32	6.2 (0.198)	13.0 (0.416)	19.5 (0.624)	23.3 (0.746)	–
10	13	0	NA	*b*	1/32	–	9.3 (0.300)	12.0 (0.384)	15.8 (0.506)	–
11	11	0	NA	*b*	1/32	–	–	–	14.7 (0.470)	–
12[c]	9	0	NA	∞	1/32	–	–	–	11.4 (0.374)	2.102[c]
14	15	7	Void	∞	1/32	20.5 (0.656)	23.9 (0.766)	30.0 (0.960)	21.2 (0.680)	3.062
15	15	7	Poly	∞	1/32	21. 2(0.679)	24.8 (0.794)	20.7 (0.663)	21.8 (0.698)	2.834
16	15	9	Void	∞	1/32	23.3 (0.744)	23.2 (0.743)	23.1 (0.740)	–	2.227
17	15	9	Poly	∞	1/32	18.3 (0.585)	25.8 (0.824)	23.0 (0.738)	–	2.147
18	15	11	Void	∞	1/32	17.9 (0.572)	14.1 (0.452)	–	–	1.024
19	15	11	Poly	∞	1/32	17.8 (0.570)	15.1 (0.482)	–	–	1.052
20	3	7	Void	∞	1/32	–	23.1 (0.740)	27.9 (0.893)	26.2 (0.839)	2.471
21	3	7	Poly	∞	1/32	–	23.7 (0.758)	24.4 (0.780)	22.2 (0.709)	2.248
22	13	9	Void	∞	1/32	12.8 (0.410)	22.2 (0.711)	–	–	1.122
23	13	9	Poly	∞	1/32	15.6 (0.499)	16.6 (0.530)	–	–	1.0228
24	11	7	Void	∞	1/32	–	–	2501 (0.802)	23.4 (0.749)	1.551
25	11	7	Poly	∞	1/32	–	–	17.0 (0.544)	18.0 (0.575)	1.119

[a]These data are for the uranium parts only. Central 7-in.-diam. height perturbations were too large to measure directly for experiments 9 – 11.. Values in parentheses are cents per thousandth of an inch (cents/0.001 in.) or cents/mil.
[b]Reflected on the top of that surface by 6.01-in.-thick polyethylene 44.0 in. square.
[c]For this experiment, a height perturbation measurement was practical for the central 7-in.-diam system and a change in height of 1/32 in. was worth 54 cents in reactivity. A similar value for a change in height of 1/16 in. for Experiment 13 was 62.3 cents and thus, a total value of 0.997 cents/mil.

Table 11. Reactivity worth of a 1×1×0.125-in.-thick uranium 38-g metal plate as a function of radial position for one-sided-reflected, various diameter up to 13-in.-OD uranium metal cylinders

Exp. 10.: 13-in OD		Exp. 11.: 11-in OD		Exp. 12: 9-in. OD		Exp. 13: 7-in. OD	
Radius (in.)	**Reactivity (cents)**	**Radius (in.)**	**Reactivity (cents)**	**Radius (in.)**	**Reactivity (cents)**	**Radius (in.)**	**Reactivity (cents)**
0	9.26	0	10.49	0	10.67	0.	9.10
0.5	8.95	1.0	9.45	0.5	10.08	0.5	8.40
1.5	7.63	2.0	7.61	1.0	9.07	1.0	7.23
2.5	6.04	3.0	5.22	2.0	6.25	2.0	4.63
3.5	4.30	4.0	3.34	3.0	3.31	3.0	1.66
4.5	2.84	5.0	1.65	4.0	0.98	–	–
5.5	1.44	–	–	–	–	–	–
6.5	0.60	–	–	–	–		

9 CONCLUSIONS

The detailed accurate data presented in this report allow these delayed-critical experiments with polyethylene and 93.14 wt % ^{235}U enriched uranium metal to be used for testing and benchmarking calculational methods and data for nuclear criticality safety. These data served as a basis for handling enriched uranium metal at the Oak Ridge Y-12 Plant in the 1960s.

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