ORNL/TM-2021/2234

Uranium–Molybdenum Alloy Critical Experiments for the Design of the Health Physics Research Reactor

John T. Mihalczo

December 2021

OAK RIDGE National Laboratory

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Physics Division

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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ACRONYMS

ORNL	Oak Ridge National Laboratory
ORCEF	Oak Ridge Critical Experiments Facility
HPRR	Health Physics Research Reactor
U-Mo	Uranium Molybdenum
ICSBEP	International Criticality Safety Benchmark Program
NEA	Nuclear Energy Agency
INL	Idaho National Laboratory
USDOE	United States Department of Energy
HEU	Highly Enriched Uranium
OD	Outside Diameter
k_{eff}	Effective neutron multiplication factor
ID	Inside Diameter

ACKNOWLEDGEMENTS

The photograph were provided by the Y-12 Photography Department. The sketches of the configurations were provided by Daniel Campbell of Idaho National Laboratory.

ABSTRACT

Critical experiments with a uranium–molybdenum alloy (average of 10.1616 wt. % Mo with a density of 17.08 g/cm^3) were performed at the Oak Ridge Critical Experiments Facility (ORCEF) in 1961 with minimal incidental reflection from support structure. These measurements supported the design of the Health Physics Research Reactor (HPRR). The HPRR was similar to the Godiva burst reactor at Los Alamos National Laboratory and was designed to produce a 50 μs burst of 10^{17} fissions for dosimetry measurements, initially in support of the determination of the doses from the nuclear detonations in Japan during World War II. The experiments reported here were used to verify the calculational methods used to design the HPRR. The following delayed critical measurements were performed:

1. A solid unreflected and unmoderated 8-in.-diameter U–Mo alloy cylinder

2. An unmoderated and unreflected annulus with an 8-in. outside diameter, 2-in. inside diameter cylinder with a central void;

3. An unmoderated and unreflected annulus with 8-in. outside diameter, 2-in. inside diameter cylinder with a central void filled with stainless steel

4. This measurement was the same as (3) but with a 3-in.-thick Plexiglas reflector on top with and without cadmium between the reflector and the U–Mo alloy assembly with steel in the center; and

5. An unmoderated and unreflected annulus that was a modification of the second but with the lower 5 in. of the central hole enlarged to 3.5 in. with various reflector conditions

The reflector conditions included a 1-in.-thick Plexiglas on all outer surfaces with a void in the center; 1-in.-thick Plexiglas on all outer surfaces with Plexiglas in the center; 2-in.-thick Plexiglas on the radial surface with a void in the center; 6-in.-thick Plexiglas on the bottom only with Plexiglas in the center; and 6-in.-thick Plexiglas on bottom, 1-in.-thick Plexiglas on the top and on the lower 3.125-in.-section of the radial surface with a void in the center. For some of these reflector conditions, 0.010-in.-thick cadmium was located between the reflector and the U–Mo alloy. The uranium contained 93.17 wt. % ^{235}U. Reflection was a safety concern for this unmoderated and unreflected reactor, and reduction of reflection effects was also investigated by insertion of neutron absorber around the U–Mo alloy. The stainless steel 304 contained 18% nickel and 8% chromium, and the rest was iron. The reflector material was a methacrylate plastic (Plexiglas) containing 5.8×10^{22} atoms/cm^3 of hydrogen and 3.6×10^{22} atoms/cm^3 of carbon with a density of 1.20 g/cm^3. The purpose of this report is to document the experimental information for the measurements performed so that at a later date researchers could perform the required uncertainty and calculational analyses and documentation to use these data for an International Nuclear Criticality Safety Benchmark Program (ICSBEP) or a Nuclear Energy Agency (NEA) benchmark. Once the uncertainty analysis is completed, the data from these experiments should be acceptable for use as criticality safety benchmark experiments for the ICSBEP and the NEA nuclear criticality safety benchmark program. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainties in k_{eff} could be as low as ±0.0002 for some configurations.

Preparation of the present report is part of a larger cooperative effort between Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) to document more than 15 undocumented critical and subcritical experiments enumerated in ORNL/TM-2019/18 and performed by ORNL at ORCEF and other USDOE critical experiments facilities using more than 500 operational days of critical facility time.

1. INTRODUCTION

The United Nuclear Corporation, under a contract with Oak Ridge National Laboratory (ORNL), designed the ORNL Health Physics Research Reactor (HPRR) [1, 2]. The HPRR was an unmoderated and unreflected reactor containing about 100 kg of U–Mo alloy that was designed to produce 50 μs bursts of 10^{17} fissions. It was also capable of operation at 10 kW thermal power for 10 minutes with forced air cooling or steady-state operation at 1 kW with natural convection cooling. The HPRR was used as a research tool at ORNL for radiobiological, dosimetry, material testing, and radiochemical research. The principal differences between the HPRR and the previous Godiva burst reactor [3] was the use of a U–Mo alloy (average of 10.1616 wt. % Mo) with greater strength and improved physical properties, which allowed the production of bursts larger than those of Godiva II. The better dimensional stability of the alloy under thermal cycling increased the operational lifetime. The reactor design at the time was an 8-in.-diameter annulus of U–Mo alloy about 7.5 in. high with a movable 2-in.-diameter steel core. The lower section of the magnetically supported steel core was attached to a 3.38-in.-outside-daimeter annulus of U–Mo alloy, which served as a safety device. These critical experiments at the Oak Ridge Critical Experiments Facility (ORCEF) in 1961 were used to validate the calculational methods for reactor design. In addition, they evaluated the effects of hydrocarbon reflectors, which were useful for safety studies, and the use of neutron absorbers around the U–Mo alloy to reduce reflection effects. In recent years, the use of U–Mo as a high-density alloy of low (<20 % ^{235}U) enrichment for research reactors has been used to reduce proliferation concerns.

The following delayed critical measurements were performed:

1. A solid unreflected and unmoderated 8-in.-diameter U–Mo cylinder

2. An unmoderated and unreflected annulus with an 8-in. outside diameter, 2-in. inside diameter cylinder with a central void;

3. An unmoderated and unreflected annulus with 8-in. outside diameter, 2-in. inside diameter cylinder with a central void filled with stainless steel

4. This measurement was the as (3) but with a 3-in.-thick Plexiglas reflector on top with and without cadmium between the reflector and the U–Mo alloy assembly with steel in the center; and

5. An unmoderated and unreflected annulus that was a modification of the second but with the lower 5 in. of the central hole enlarged to 3.5 in. with various reflector conditions

The following reflector conditions were used: 1-in.-thick Plexiglas on all outer surfaces with void in the center; 1-in.-thick Plexiglas on all outer surfaces (Plexiglas in the center); 2.00-in.-thick Plexiglas on the radial surface (void in the center); 6-in.-thick Plexiglas on the bottom only (Plexiglas in the center); and 6.00-in.-thick Plexiglas on bottom, 1-in.-thick on top, and on the lower 3.5-in.-section of the radial surface (void in the center). For some of these reflector conditions 0.010-in.-thick cadmium sheet was located between the radial reflector and the U–Mo alloy. The fissile material was an alloy of 10 wt. % Mo and 90 wt. % U (93.17 wt. % ^{235}U). The stainless steel 304 contained 18% nickel and 8% chromium and the rest iron. The reflector material was a methacrylate plastic (Plexiglas) with a density of 1.20 g/cm^3. The purpose of this report is to document the experimental information for the measurements performed so that at a later date researchers could perform the required uncertainty and calculational analyses and documentation to use these data for an International Nuclear Criticality Safety Benchmark Program (ICSBEP) or a Nuclear Energy Agency (NEA) benchmark. The data from the experiments described here should be acceptable for use as criticality safety benchmark experiments once the uncertainty analysis is

completed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainties in k_{eff} could be as low as ±0.0002 for some configurations.

Preparation of the present report is part of a larger cooperative effort between Idaho National Laboratory (INL) and ORNL to document more than 15 undocumented critical and subcritical experiments enumerated in ORNL/TM-2019/18 [4] and performed by ORNL at ORCEF and other USDOE critical experiments facilities using more than 500 operational days of critical facility time.

2. DESCRIPTION OF THE MEASUREMENTS

2.1 OVERVIEW OF THE EXPERIMENT

A variety of critical experiments were constructed with unreflected and unmoderated highly enriched uranium metal during the 1960s and 1970s at the Oak Ridge Critical Experiments Facility (ORCEF) in support of criticality safety of the Y-12 CNS [5]–[11]. Highly enriched uranium (HEU) metal experiments with 7, 9, 11, 13, and 15 in. diameter HEU metal cylinders have been reported and analyzed in HEU-MET-FAST-051 [12]. Other HEU metal experiments at ORCEF already in the NEA benchmark database include HEU-MET-FAST-059, -069, -071, and -100 [12], among others. Of these hundreds of delayed critical assemblies, the experiments described in this report are the only critical experiments with highly enriched (93.17 wt. % ^{235}U) U–Mo alloy (10.1616 wt. % Mo). The experiments with minimal reflection from support structure were performed from March 1961 through part of June 1961. They were performed to verify the calculational methods used to design the HPRR, which was an unmoderated and unreflected reactor designed to produce fission bursts of 10^{17} fissions. In addition to unmoderated and unreflected configurations of U–Mo alloy, a variety of critical configurations were assembled with hydrocarbon reflectors for evaluation of the safety concerns associated with hydrocarbon reflector.

The data from most of these 14 experiments described should be acceptable for use as criticality safety benchmark experiments in 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 because the procedure for assembly and detailed description of the materials and configurations are the same as measurement with HEU uranium metal.

2.2 DESCRIPTION OF THE EXPERIMENTAL CONFIGURATIONS

These experiments were performed in the 35 x 35 x 30-ft high east cell of ORCEF. The assemblies of uranium metal alloy were located approximately 11.7-t 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. They were performed using the vertical assembly machine of the East cell of the ORCEF. A brief description of the assemblies is given in Table 2.1 along with the critical masses and critical heights as well as reference to the appropriate logbook page.

Table 2.1. Summary of experimental configurations.

Experiment identification	Description	ORCEF Logbook E-6-page number	Reactor period (s) & reactivity (cents)	Neutron multiplication factor, k_{eff} [a]	Mass (grams of U-Mo)	Nominal U–Mo height of parts (in.)
A	Solid U–Mo alloy cylinder (Additional U–Mo alloy on top)	100	−167 & −10.3	0.99932	81,260	5.78125[b]
B	U–Mo alloy annulus with 2.0.-diameter axial hole (Additional U–Mo alloy on top)	112	Infinite & 0	1.0000	102,170	7.71875
C	U–Mo alloy annulus with 2.0-in.-diameter axial hole filled with steel (Additional U–Mo alloy on top)	50	−154 & −11.67	0.9992	97,574	7.375
D	U–Mo alloy annulus with 2.0-in.-diameter steel core and 3.0-in.-thick Plexiglas on top	86	Period not documented & +15.8	1.00105	85,772	6.500
E	U–Mo alloy annulus with 2.0-in.-diam. steel core and 3.0-in.-thick Plexiglas on top with cadmium between Plexiglas & U–Mo alloy,	88	+52.9 & +15.5	1.00103	89,850	6.8125
G[c]	U–Mo alloy annulus with 1-in.-thick Plexiglas radial reflector with Plexiglas center	138	+33.3 & +21.9	1.00144	63450	5.500
H[c]	U–Mo alloy annulus with 1-in.-thick Plexiglas radial reflector, void in the center, Cadmium between core and reflector	142	-304 & -4.9	0.9997	84,507	7.09375
I[c]	U–Mo annulus with 2-in.-thick Plexiglas radial reflector, void in center	146	+25 & +24.6	1.00162	56,893	5.000
J[c]	U–Mo annulus with 2-in.-thick Plexiglas radial reflector, void in center, cadmium between core and reflector	150	+75.45 & −12.15	1.00089	73,402	6.250

Table 2.1. Summary of experimental configurations (continued).

Experiment identification	Description	ORCEF Logbook E-6-page number	Reactor period (s) & reactivity (cents)	Neutron multiplication factor, k_{eff} [a]	Mass (grams of U-Mo)	Nominal U–Mo height of parts (in.)
K[c]	U–Mo alloy annulus with 2-in.-thick Plexiglas radial reflector, Plexiglas core, cadmium metal between the U–Mo and radial reflector	152	+260 & +4.41	1.00029	65,214?	5.21875
L[c]	U–Mo alloy annulus with 6-in.-thick bottom reflector, void center	153	Infinite & 0	1.00000	89,457	7.71875
M[c]	U–Mo alloy annulus with 6-in.-thick bottom reflector, Plexiglas center	155	+468 & +2.57	1.00017	83,268	7.000
N[c]	U–Mo alloy annulus with 6-in.-thick bottom reflector, 1.0-in.-thick top reflector, 1-in.-thick radial reflector around bottom 3.125 in. of U–Mo alloy	157	Infinite & 0	1,0000	89,860	7.500

[a] Reactivity in cents converted to neutron multiplication factor using a value of beta effective of 0.0066
[b] Central plugs 1/16 inch lower than annular plates.
[c] Lower portion of the assembly has an enlarged central hole 3.5-in.-diameter in the lower 5 in. and Plexiglas as internal moderator and/or reflector

2.3 EXPERIMENTAL METHODOLOGY

The cylinders or annuli comprised layers of U–Mo alloy with dimensions machined to precise tolerances. The experiments were performed in a deliberate and step-by-step manner and observed data were recorded.[1] The assembly was approximately divided in half, including a fixed upper section and a movable lower section.

2.3.1 General Assembly Procedure

The assemblies were constructed on a vertical assembly machine that primarily consisted of a hydraulic lift (22 in. vertical motion) to support the lower section (see Figure 2.3.1) and a stationary upper half consisting of four vertical posts spaced 4 feet apart, which held a support for the upper section of critical experiments. The upper U–Mo alloy section of an experiment was supported by a 24-in.-inner-diameter clamping ring that held a 0.010-in.-thick, stainless steel (304) diaphragm in tension. The diaphragm clamping ring had a total thickness of 1 in., part of which was a 30-in. square, 1/2-in.-thick aluminum plate. The other part of the clamping apparatus was a 24-in.-diameter, 2-in.-wide, 1/2-in.-thick ring bolted to the aluminum plate by thirty-four 0.375-in.-diameter 1.5-in.-long stainless steel bolts with appropriate

[1] All Rossi-α data for these measurements which are not reported here are stored in Records Management Services Department at ORNL and at the ICSBEP at Idaho National Laboratory. In the title line of the data for each measurement, the first entry is the date of each measurement, which can be correlated with the dates in the east cell of ORCEF logbooks.

nuts. The mating surfaces between the ring and the plate were not flat, so when the nuts were tightened, the diaphragm would be held in tension (see Figure 2.3.2). The plate was supported by a welded 4-in.by 3-in. right angle aluminum framework mounted in a larger framework that was supported by the four vertical poles. The framework attached to the four poles was composed of welded 3/8-in.-thick, 4-in. right angle aluminum support. The U–Mo alloy parts of the upper and lower section were 8-in.-OD cylindrical annuli of two different inside diameters depending on the experiment. In the center of the annular fissile parts were U–Mo alloy, stainless steel, or Plexiglas. Another photograph of the solid U–Mo alloy cylinder showing more details of the lower section and its supports is given in Figure 2.3.3. The lower section was supported on a low-mass aluminum support tower mounted on the vertical lift platform, also shown in Figure 2.3.3. The vertical member of the lower support stand was a 3-in.-square tube, 30-in.-high with 1/8-in.-thick wall thickness. The 1/2-in.-thick, 18-in.-diameter aluminum base of the support stand was bolted to a 1-in.-thick, 18-in.-diam. stainless steel support table of the vertical lift. An external reflector was added around, above, and below the U–Mo alloy, as appropriate.

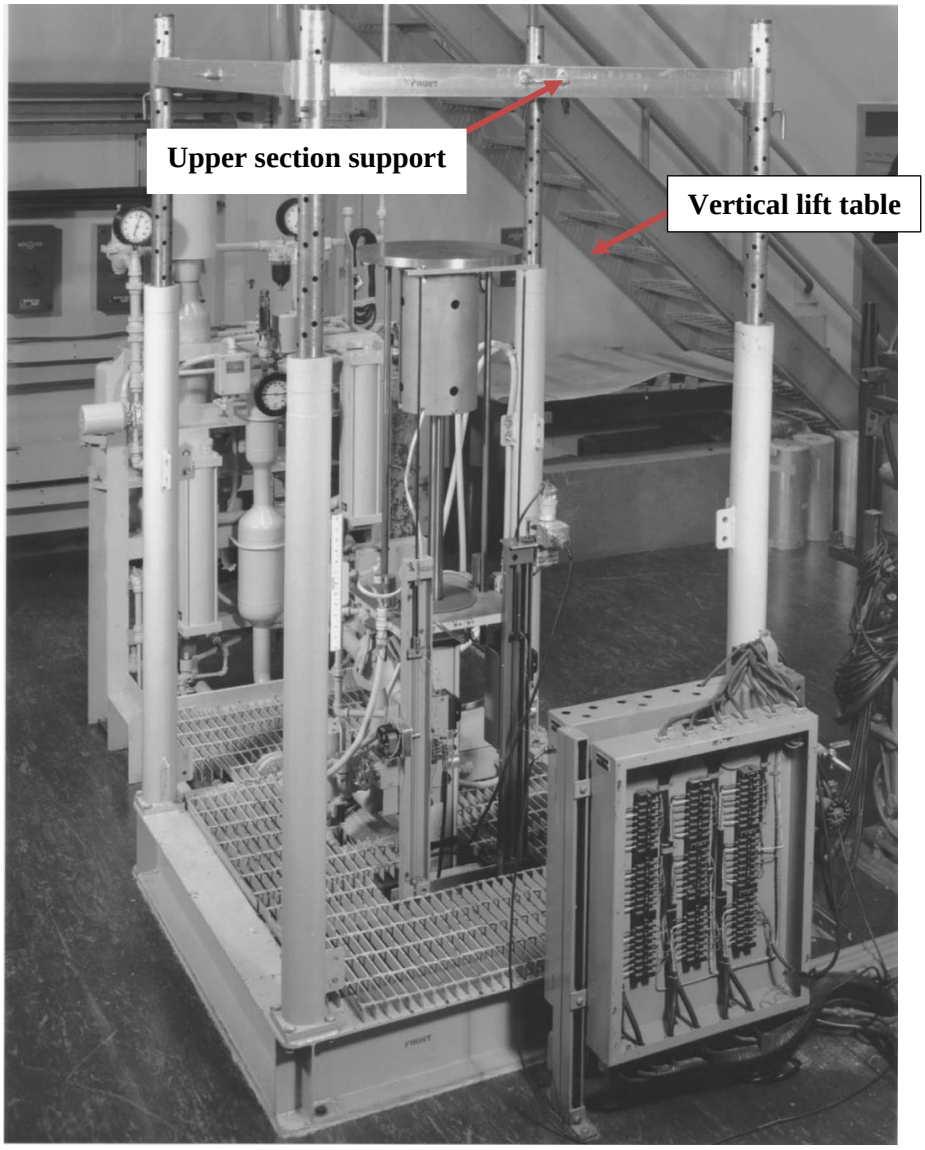

Figure 2.3.1. Photograph of the vertical assembly machine with the movable table up. (No lower support structures are in this photograph except for the vertical lift table which is in the upward position).

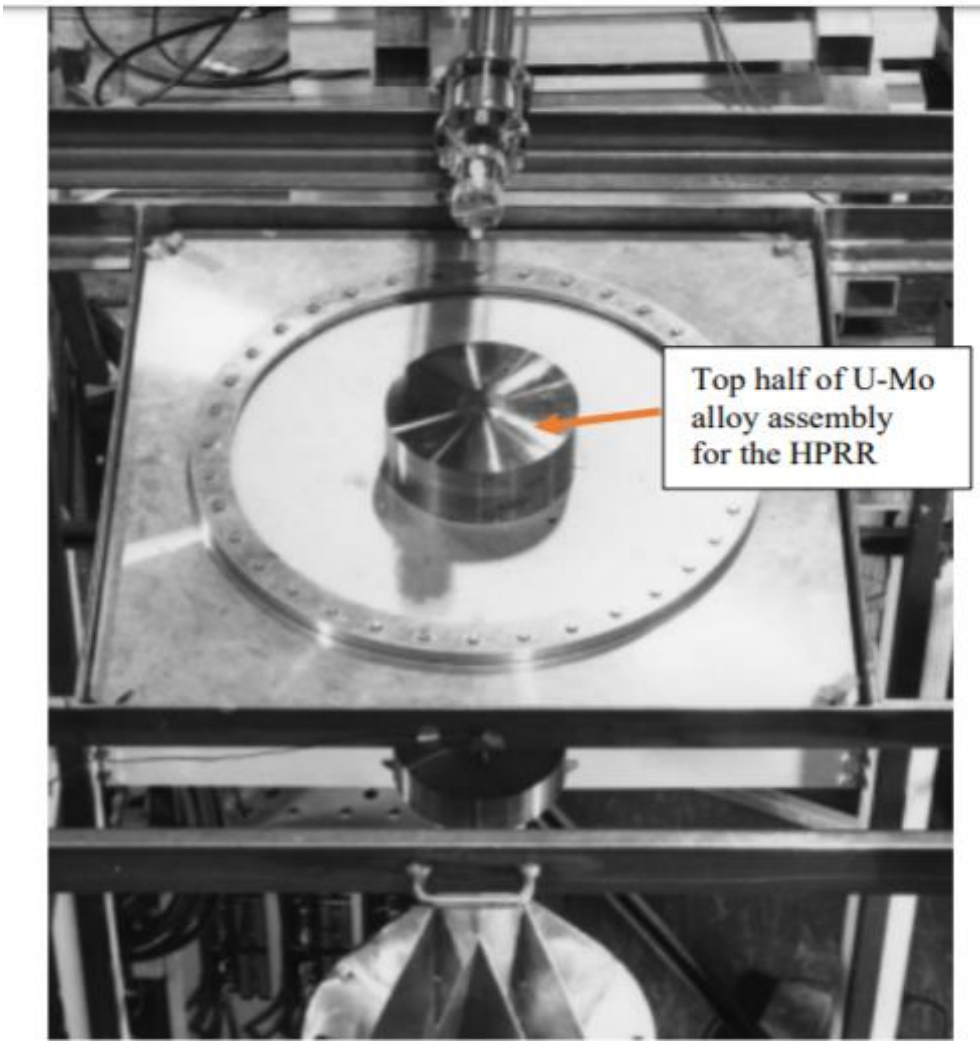

Figure 2.3.2. Photograph of the vertical assembly showing the support structure for the upper half of the U–Mo alloy solid cylinder configuration. (Upper section is supported on a stainless steel diaphragm held in position by a 24-in.-diameter clamping ring supported by a 30-in.-square aluminum plate; a pulsed neutron producing accelerator target assembly is shown above the upper U–Mo alloy section.)

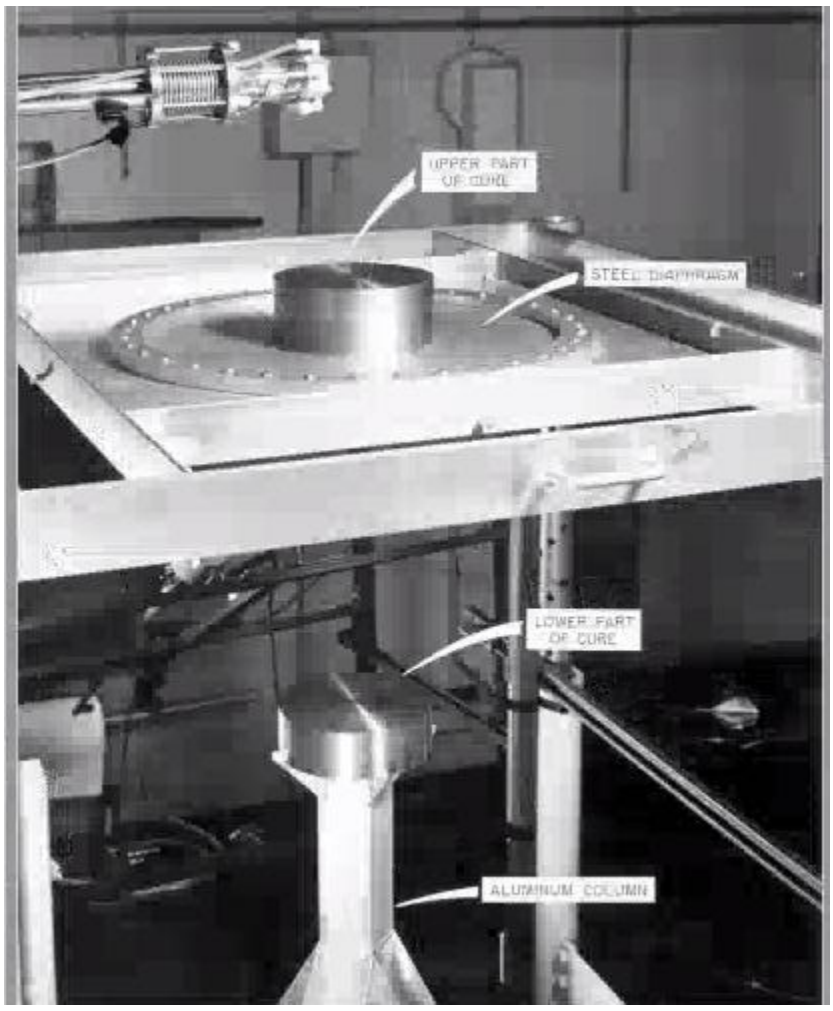

Figure 2.3.3. Vertical split table configuration of a solid U–Mo alloy cylinder showing upper section on a 0.010-in.-thick diaphragm and the lower section on a low mass support stand in its disassembled location. (The water-cooled target of a Cockcroft–Walton accelerator is shown about 12 in. above the top of the U–Mo alloy on the diaphragm; note the lack of oxidation on the outer surface of the U–Mo alloy compared to uranium metal, which looks much darker.)

2.3.2 Alignment of Each Half

The upper and lower sections were aligned using the processes described below. Uncertainty in radial alignment of top U–Mo alloy section with respect to the bottom U–Mo alloy section is ±0.031 in.

2.3.2.1 Upper Section

For assembly of the upper section, U–Mo metal was added to the top diaphragm. The U–Mo was positioned with a ruler the appropriate distance from inside the aluminum ring, which held the stainless diaphragm. Usually an annulus of U–Mo alloy was placed on the diaphragm, and additional material was stacked on it after alignment. After it was aligned with the material on the vertical lift as described below, the rest of the U–Mo fissile material was then added to the top annulus. 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. Two precisely machined steel blocks (±0.0001 in.) were used to squeeze the material at the outer radial surfaces 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 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 are adjusted, the positions at 180° and 270° can be off only by the difference in the outside diameters of the parts. Each major U–Mo alloy part had a part number scribed on one surface. This surface with the part number scribed was positioned facing up for all configurations. To enhance reproducibility, the part was oriented on the assembly machine upper or lower section with the part number toward the north wall of the facility.

2.3.2.2 Lower Section

For the lower section, the same procedure was used except that the parts were leveled by shimming appropriately at selected locations on the underside of the bottom U–Mo annulus with aluminum foil. The foil was placed between the support stand and the lowest U–Mo part so that the upper surface of the lower annulus was level.

2.3.3 Lateral Alignment of the Upper Section with the Lower Sections

Some material was loaded on the support structure for the bottom and on the diaphragm. The lower support structure was raised until it was about 0.375 in. from the diaphragm. The distance between the outer radial surface of the U–Mo alloy and the inside circular surface of the support structure for the diaphragm was measured with a micrometer at four locations 90° apart. The U–Mo alloy material on the diaphragm was adjusted so that its radial outer surface was the same distance from the inside radial surface of the upper part of the support ring at the same four locations. This aligned the upper and lower section of U–Mo allow within 1/32 in. After alignment, the location of the upper U–Mo annulus was marked by a circle on the diaphragm and tape on the diaphragm at several locations at the outer diameter of the U–Mo annulus.
For assembly, the lower section was raised by the vertical lift until it supported the weight of the upper section with the diaphragm level at its position with any material on it. This compensated for the sag of the diaphragm (measured on page 10 of the ORCEF E-6 logbook), and the diaphragm was approximately level in the completed assembly.

2.3.3.1 Lateral Alignment Accuracy Summary for the Upper and Lower Section of the Assembly

For the upper and lower assembly, the lateral alignment of the upper and lower section uncertainty was 0.031 in.

3. DESCRIPTION OF THE EXPERIMENTS

3.1 EXPERIMENT A: SOLID U–MO ALLOY CYLINDER

This experiment was assembled on April 28, 1961, and is described on page 100 of ORCEF logbook E-6. This unreflected and unmoderated U–Mo solid assembly was nominally 8-in.-outside-diameter right circular cylinder and consisted of the U–Mo annular plates with nominal 2-in.-diameter U–Mo alloy plugs in the center. The plugs usually had same thickness as the U–Mo alloy annuli that they were placed inside. The configuration of the U–Mo alloy parts is given in Figure 3.1.1, and a description of the parts is given in Figure 3.1.2. All the sketches in this report for the configuration of the assemblies are two dimensional. The configured total U–Mo alloy mass of the system was 81,260 g. The nominal height of the U–Mo annular plates was 5.78125 in. and that for the central U-Mo alloy central plugs was 1/16

inches less. One of the parts, 1366 (the last four digits of the process batch number), had a diametral hole for insertion of the source and use for fission rate spatial distribution measurements. The central U–Mo alloy plug (part 1381) used inside this annulus also had a similar diametral hole. These holes were at the vertical center of the annular plate and U–Mo alloy center plug and the alignment of these two parts was accomplished by a 1 g key of U–Mo alloy. These diametral holes were filled with U–Mo alloy inserts (one 3-in.-long, two 1.5-in. long, four 1/2-in.-long and two 1/4-in.-long) and are included in the total mass. The configuration of the parts with the diametral hole are given in Figure 3.1.3. The reactivity of the assembled configuration was – 10.3 cents (reactor period of −167 seconds) with a corresponding k_{eff} of 0.99932 using a beta effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metals systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration has the lowest uncertainties and includes all of the support structure and the 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. In another variation of this assembly, seven 1/32-in.-thick, 1.996-in.-diameter discs of U–Mo alloy were arranged across the top of the U–Mo alloy cylinder as shown in Figure 3.1.4. For this configuration with the additional U–Mo alloy discs across the top, the reactivity was + 6.9 cents (reactor period of +155.2 seconds) with a neutron multiplication factor of 1.00045. The reactivity of the additional U–Mo discs on top of the assembly was 17.2 cents or a Δk_{eff} of 0.001135. To evaluate the reactivity effect of the diaphragm an 11 × 12 × 0.005-in.-thick sheet of stainless steel was added between the top and bottom sections. The logbook entries are not complete enough to document the reactivity effects of the diaphragm.

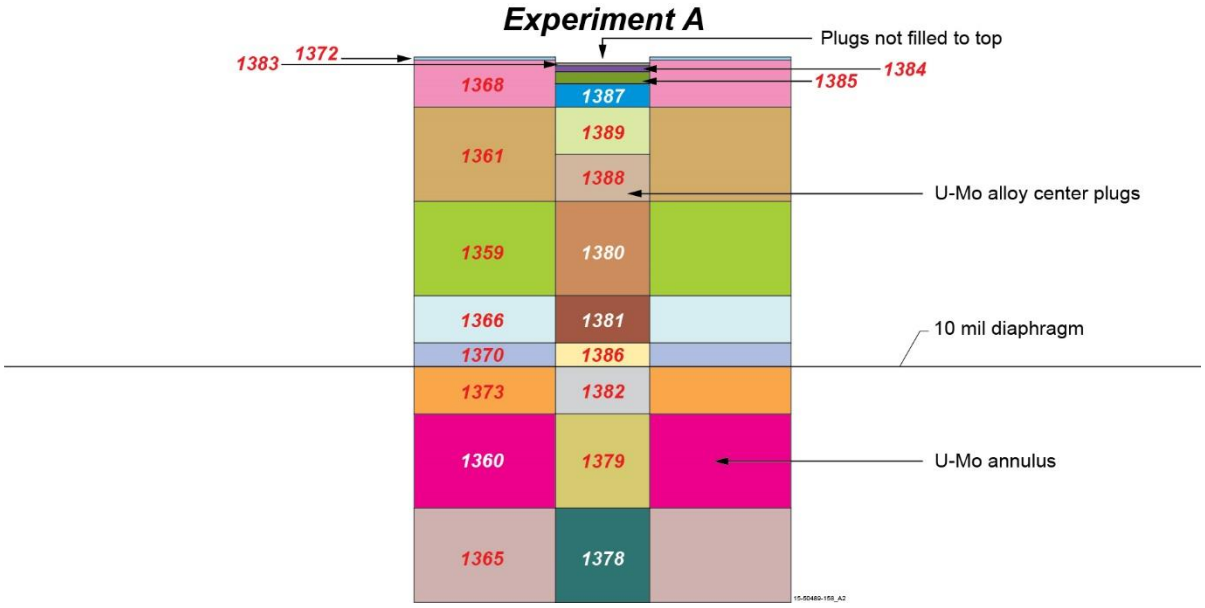

Figure 3.1.1. Configuration of the U–Mo alloy annular assembly with central cylindrical U–Mo alloy plugs, Experiment A. (Two-dimensional cross section along diameters; only the last four digits of part numbers are given)

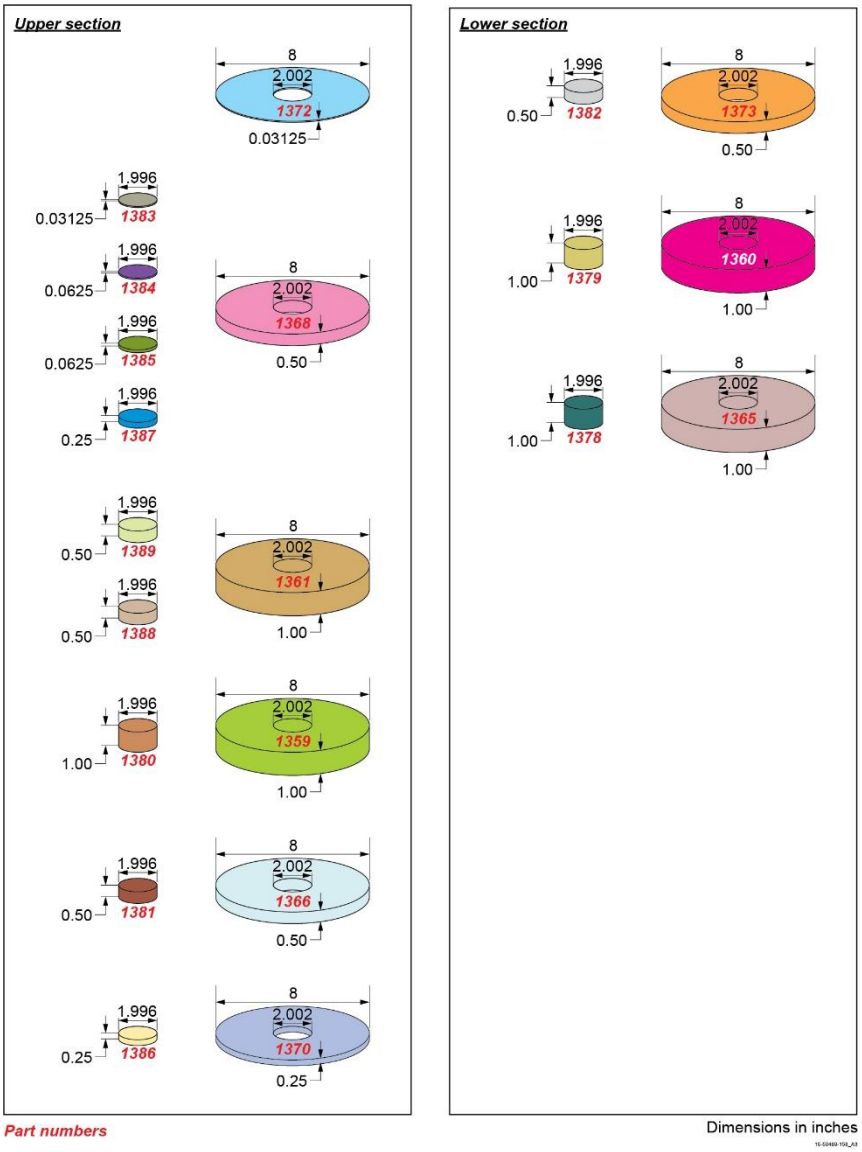

Figure 3.1.2. Description of the U–Mo alloy parts for the U–Mo alloy annular assembly with central cylindrical U–Mo alloy plugs, Experiment A. (Only the last four digits of part numbers are given in the figure; additional 2-in.-diameter discs on top, see Figure 3.1.4.) Part

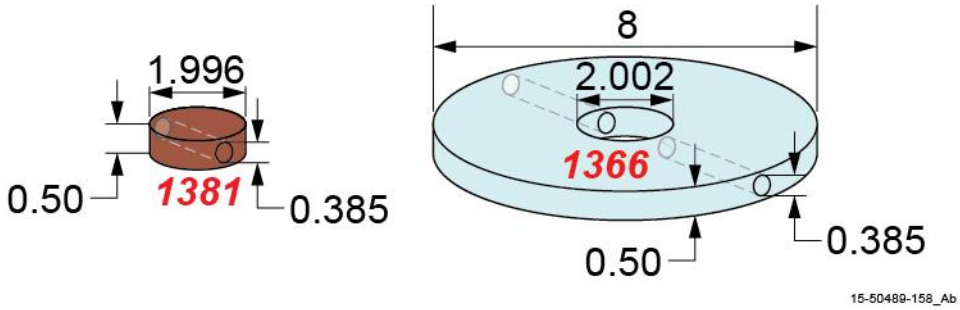

Figure 3.1.3. Configuration of the U–Mo annulus and central plug with a diametral hole. Experiment A. (Only the last four digits of part numbers are given in the figure)

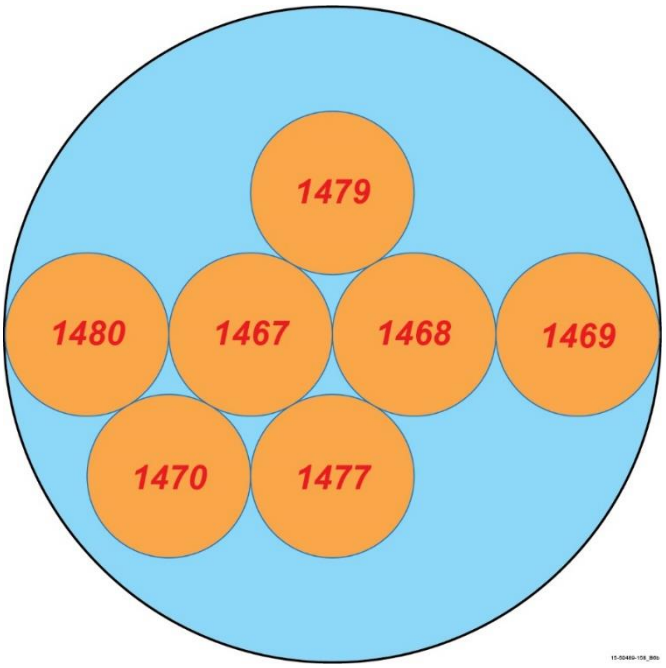

Figure 3.1.4. Arrangement of 1.996-in.-diameter U–Mo alloy discs (1/32-in. thick) on top of the fissile assembly, Experiment A. (Only the last four digits of part numbers are given in the figure.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.2 EXPERIMENT B: U–MO ALLOY ANNULUS WITH 2-IN.-DIAMETER AXIAL HOLE

This unreflected and unmoderated U–Mo alloy nominal 8-in.-diameter cylindrical annulus with a nominal 2-in.-diameter axial hole consisted of the U–Mo alloy annular plates and was assembled on May 4, 1961. In addition to the annular plates, there were thin 2-in.-diameter cylindrical discs of U–Mo alloy distributed across the top. The configuration of the U–Mo alloy annular plates is given in Figure 3.2.1. The description of the U–Mo alloy annular parts is given in Figure 3.2.2. The nominal height of the U–Mo alloy assembly was 7.7188 in. plus some U–Mo alloy cylindrical discs on top. The distribution of the eight thin discs across the top is shown in Figure 3.2.3. The configured total U–Mo alloy mass of the system was 102,170 g including the grams associated with the eight discs on top (one was 1/8 in. thick, one was 1/16 in. thick, and the other six were 1/32 in. thick). One of the parts, 1366 (last four digits of the process batch number), had a diametral hole for insertion of the source and was used for fission rate spatial distribution measurements. This hole was at the vertical center of the plate. The diametral hole was filled with U–Mo alloy inserts, which are included in the total mass. The reactivity of the assembled configuration was extremely close to zero (reactor period of −7,602 seconds) with a corresponding k_{eff} of 1.0000. This configuration had the lowest uncertainties and included all of the support structure and the 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. The reactivity of the upper and lower supports was measured by increasing the support structures and measuring the change in reactivity or a configuration with a different arrangement of U–Mo alloy discs on the top surface. Addition of a 0.005-in.-thick stainless steel sheet under the

diaphragm reduced the reactivity 6.04 cents (change in reactor period from +258.5 to −851 seconds). This sheet was removed, and the addition of a 0.010-in.-thick stainless steel sheet reduced the reactivity 10.8 cents (change in reactor period from +258.5 to −242.2 seconds). The change in reactivity is not linear since the first 0.005-in.-thickness was worth 6.04 cents and the next 0.005-in.-thickness was worth 4.8 cents. To get a more reliable estimate of the reactivity worth of the diaphragm, first step is to verify the ability to calculate the negative reactivity effects of adding these stainless steel sheets. If the calculation accurately predicts these measurements, then they can be used to estimate the worth of the diaphragm which will be larger because of the nonlinearity. In previous benchmark documentation, it was assumed that the reactivity of the added diaphragm thicknesses was equal to the reactivity of the original thickness and this work indicates that that would have been an underestimate. For this configuration, the reactivity of the lower support was +7.7 cents (addition increased the reactor period from −688.5 to +194.4 seconds) and is not as ambiguous. After the diaphragm worth is obtained, the neutron multiplication factor corrected for support structure could be obtained.

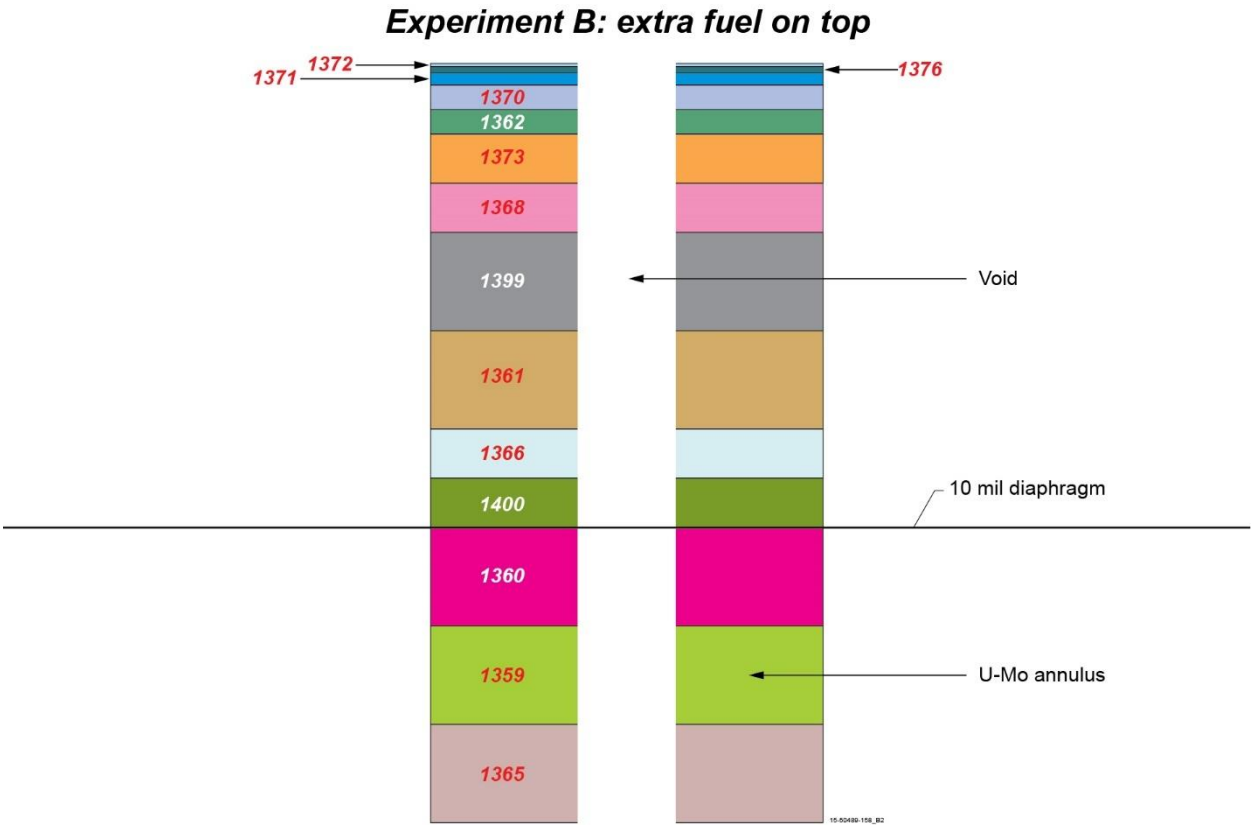

Figure 3.2.1. Configuration of the U–Mo alloy annular assembly with central void, Experiment B. (Two-dimensional cross section along diameters; only the last four digits of part numbers are given in the figure; additional U–Mo alloy on top; see Figure 3.2.3.)

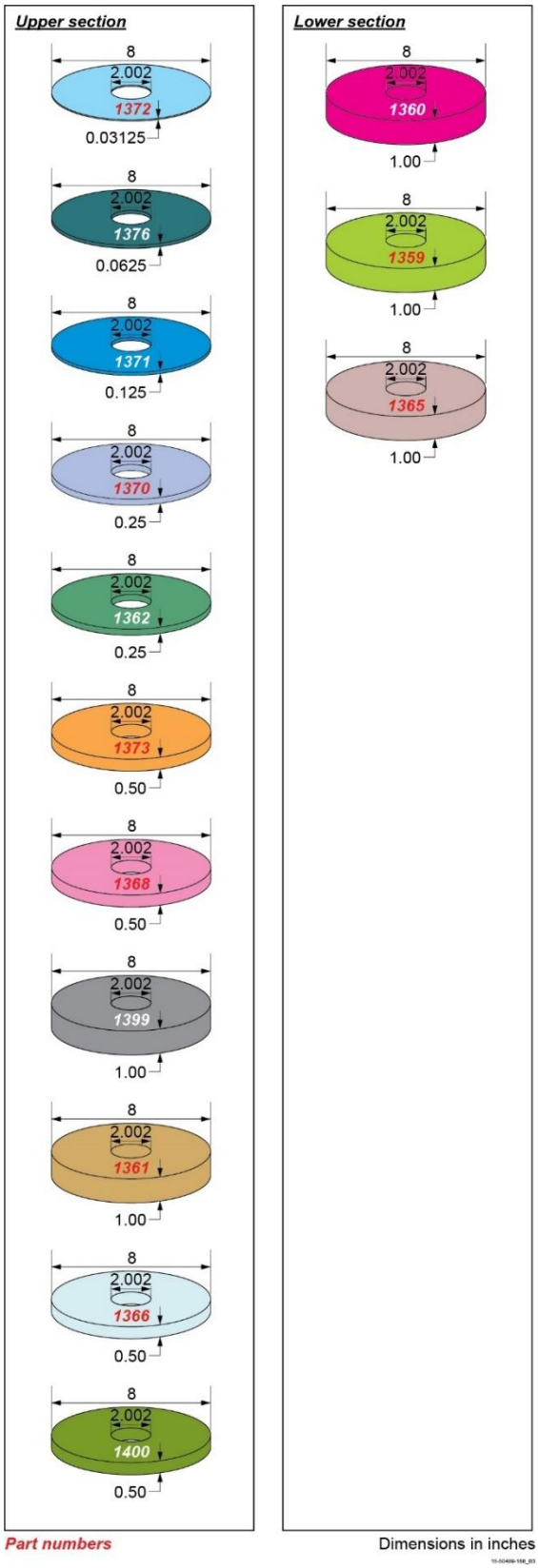

Figure 3.2.2. Description of the U–Mo alloy annular parts for the U–Mo alloy annular assembly with central void, Experiment B. (Only the last four digits of part numbers are given in the figure.)

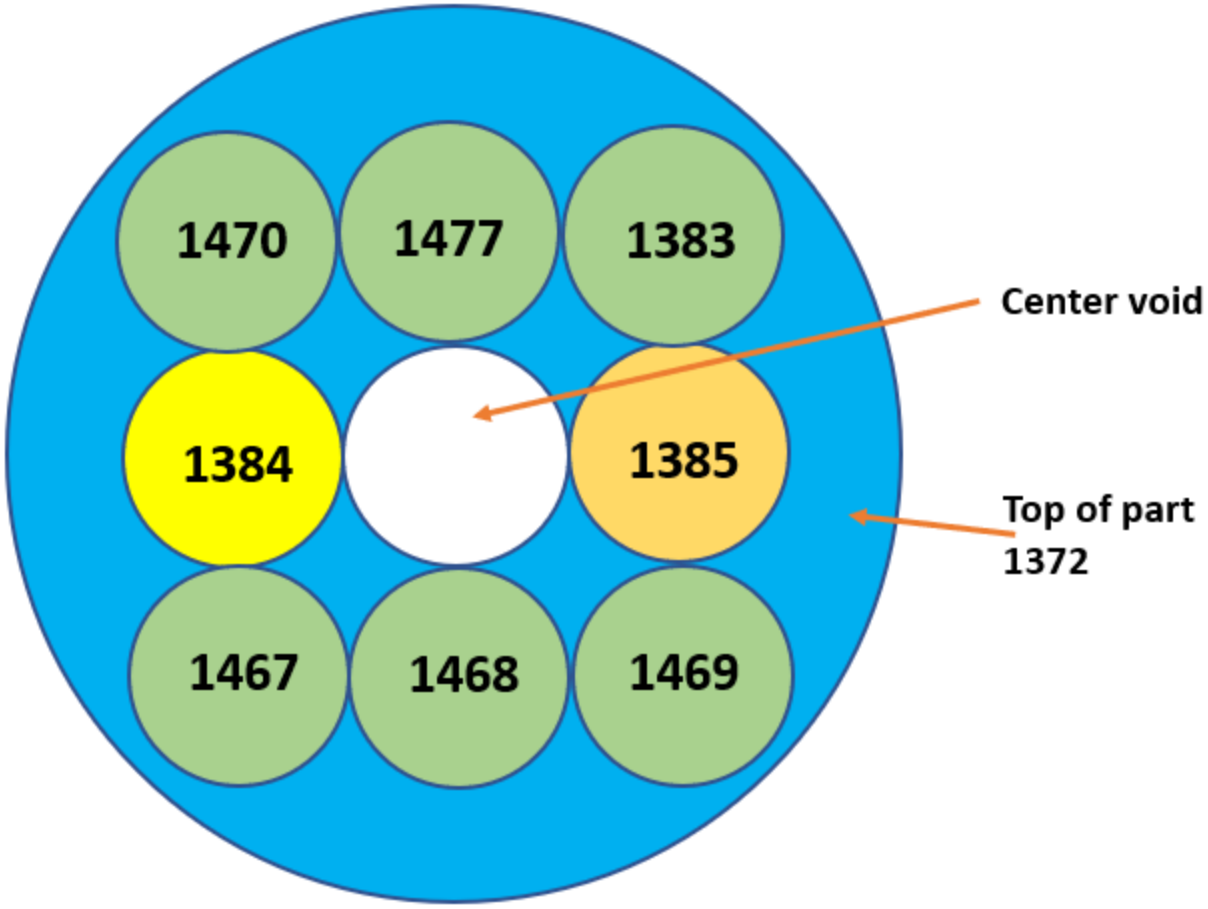

Figure 3.2.3. Arrangement of 2-in.-diameter U–Mo alloy discs on top of the fissile assembly for Experiment B. (Discs 1384 and 1385 are 1/16 and 1/8-in. thick. All others are 1/32 in. thick; only the last four digits of part numbers are given in the figure.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.3 EXPERIMENT C: U–MO ALLOY ANNULUS WITH 2-IN.-DIAMETER AXIAL HOLE FILLED WITH STEEL CORE

This unreflected and unmoderated U–Mo solid nominal 8-in.-OD right circular annular configuration and a 2.0-in.-ID (assembled on March 28, 1961) consisted of the U–Mo annular plates with nominal 2-in.-diameter stainless steel plugs in the center usually of the same thickness as the U–Mo alloy annuli that they were within. The exact diameter of the central cylindrical steel plugs was 1.996 in. The configuration of the U–Mo alloy parts is given in Figure 3.3.1 and a description of the U–Mo alloy parts is given in Figure 3.3.2. The nominal height of the U–Mo alloy assembly of annular plates was 7.375 in. One of the complete U–Mo alloy annular parts, 1366 (last four digits of the process batch number), on the diaphragm had a diametral hole for insertion of the source and use for fission rate spatial distribution measurements. This hole was at the vertical center of the annular plate. This diametral hole in the U–Mo alloy annulus

was filled with U–Mo alloy inserts and are included in the total U–Mo alloy mass. The total U–Mo alloy mass of 97,574 g. The reactivity of the assembled configuration was minus 11.67 cents (reactor period of −154 seconds) with a corresponding k_{eff} of 0.9992 using a ß effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metals systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration had the lowest uncertainties and included all of the support structure and the 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.

The reactivity effects of the addition of 1/32-in.-thick U–Mo alloy annular quarter sections were evaluated. The addition of the first U–Mo alloy annular quarter section was worth +4.36 cents (reactor period change from −154 to −217 seconds). The addition of the second and third U–Mo alloy annular quarter section was worth +8.35 cents (reactor period change from –217 to +1,213 seconds). The addition of the fourth U–Mo alloy annular quarter section was worth +4.48 cents (reactor period change from +1,213 to +202 seconds). The mass of the 1/32-in.-thick U–Mo annular plate was 416 g before it was cut into quarters, and after the cut into quarter sections, it was 412 g. Each quarter section totaled 103 g instead of 104 g.

The reactivity effect or the diaphragm was evaluated. The first 0.005 in. added was worth −6.0 cents (reactor period change from +195.4 seconds to slightly below delayed critical and the second 0.005 in. was worth –4.8 cents). The reactivity effect of the lower support structure was +3.82 cents. In addition, there were two 2 × 10-in. wooden planks mounted on the north and south of the vertical assembly apparatus about 4.5 feet below the assembly on which the experimenters stood on to adjust the upper section of the assembly. These supports for personnel added 0.62 cents to the assembly reactivity.

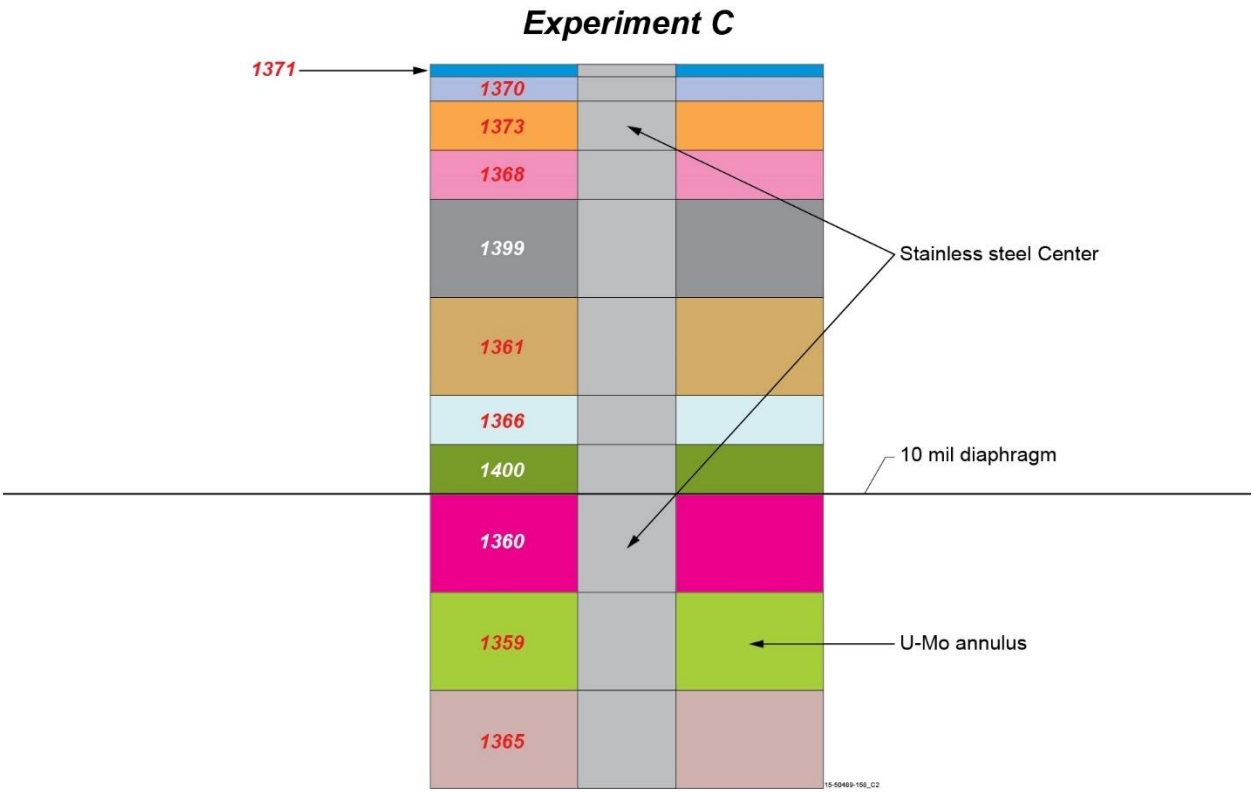

Figure 3.3.1. Configuration of the U–Mo alloy annular assembly with central cylindrical stainless steel plugs, Experiment C. (Two-dimensional cross section along diameters; only the last four digits of part numbers are given in the figure; additional U–Mo alloy on top; see Figure 3.3.3.)

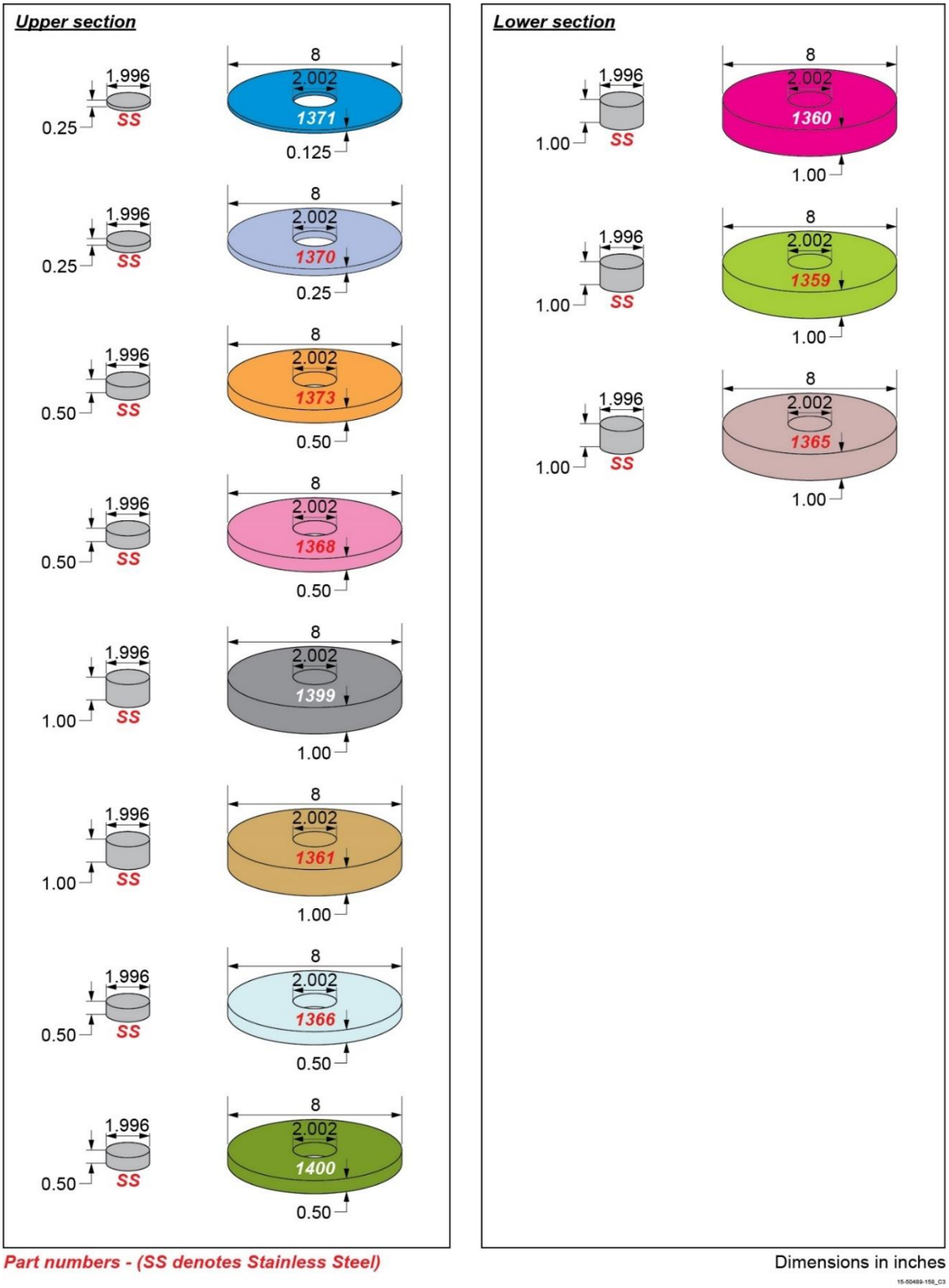

Figure 3.3.2. Description of the U–Mo alloy Parts for the annuli for the U–Mo alloy annular assembly with central cylindrical stainless steel plugs Experiment C. (Only the last four digits of part numbers are given in the figure. For additional U–Mo alloy parts on top, see Figure 3.3.3.)

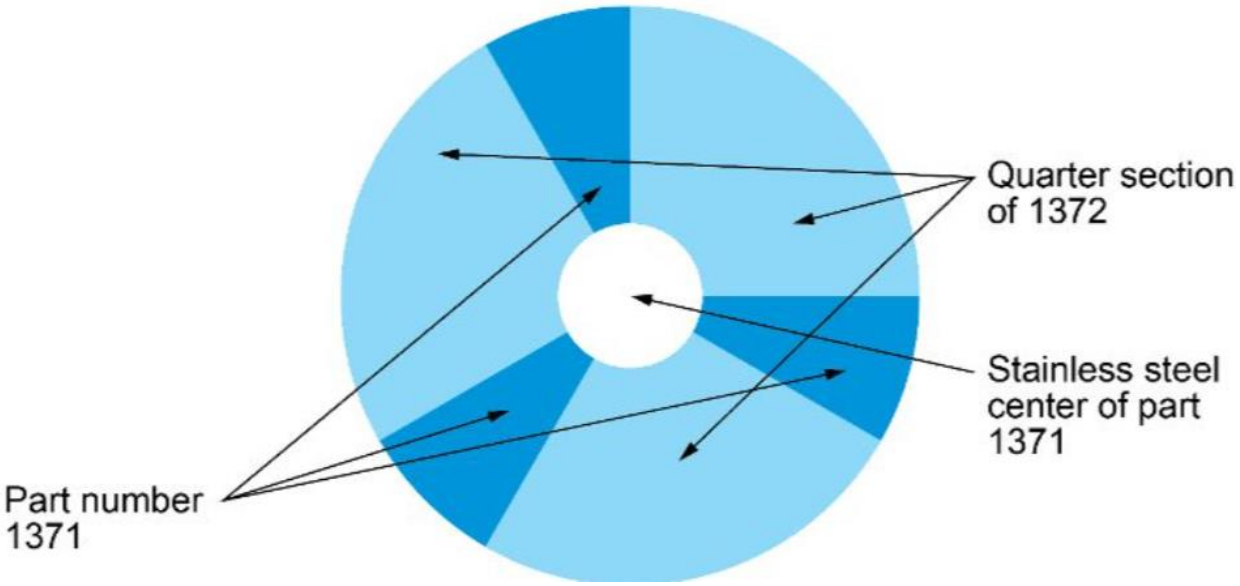

Figure 3.3.3. Top view of configuration of three-quarter sections of part 1372 on top of part number 1371. (The angular segment of each quarter section was 89.1°; only the last four digits of part numbers are given in the figure.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.4 EXPERIMENT D: U–MO ALLOY ANNULUS WITH 2-IN.-DIAMETER STEEL CORE AND 3.00-IN.-THICK PLEXIGLAS ON TOP

This unreflected and unmoderated U–Mo solid nominal 8-in.-OD right circular annular configuration and a 2.0-in. ID consisted of the U–Mo annular plates with nominal 2-in.-diameter stainless steel plugs in the center of the same thickness as the U–Mo alloy annuli that they were inside. The configuration of the U–Mo alloy parts is given in Figure 3.4.1 and was assembled on April 17, 1961. The nominal height of the U–Mo alloy assembly was 6.500 in. and the configured total U–Mo alloy mass of the system was 85,722 g. The configuration of the U–Mo alloy parts is given in Figure 3.3.1 and a description of the U–Mo alloy parts is given in Figure 3.4.2. One of the parts, 1366 (last four digits of the process batch number), had a diametral hole for insertion of the source and use for fission rate spatial distribution measurements. This hole was at the vertical center of the plates. This diametral hole in the U–Mo alloy annulus was filled with U–Mo alloy inserts that are included in the total U–Mo alloy mass of 85,728 g. The reactivity of the assembled configuration was +15.8 cents and a corresponding k_{eff} of 1.00105 using a beta effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metals systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration had the lowest uncertainties and included all of the support structure and the 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, and support structure effects were not measured.

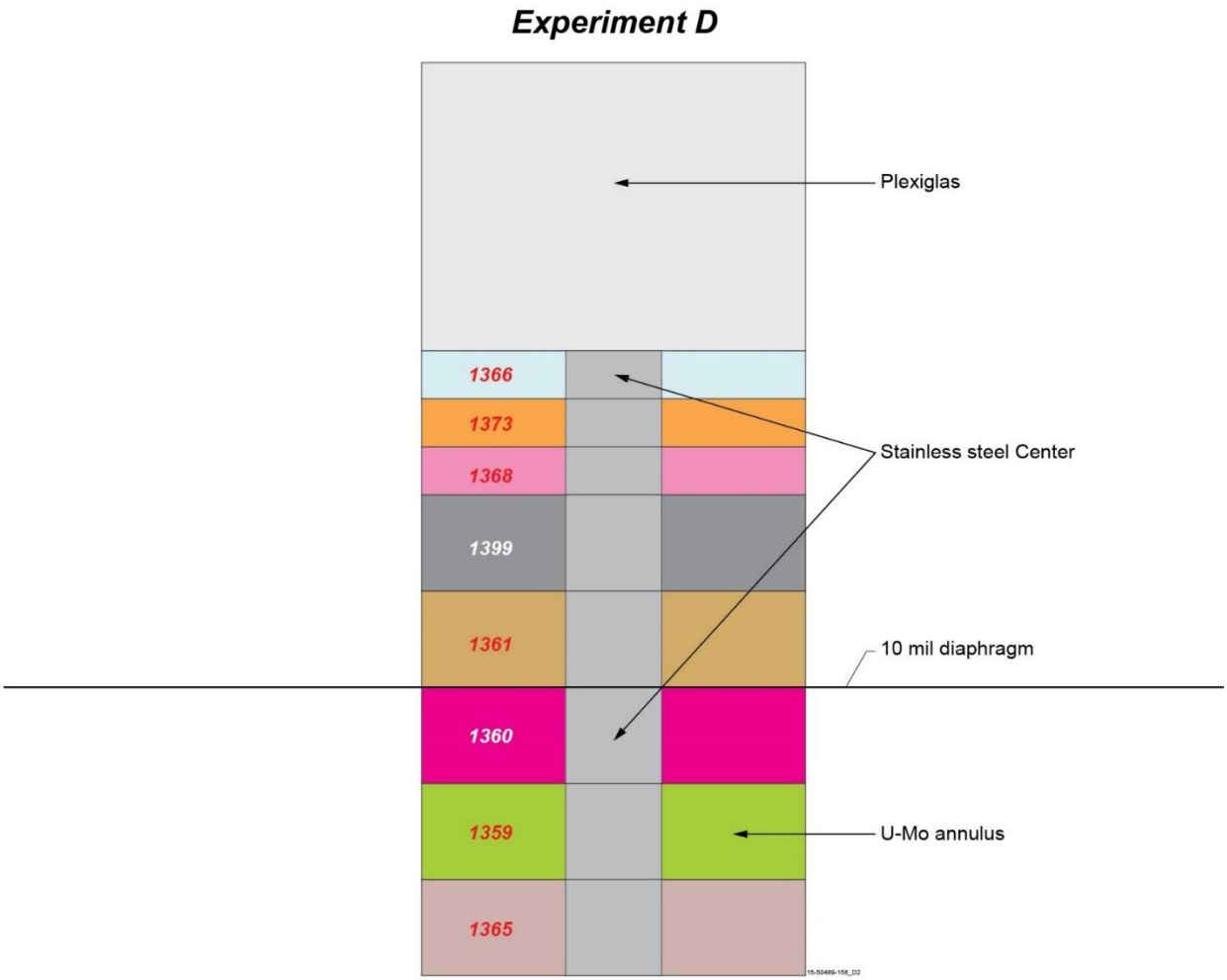

Figure 3.4.1. Configuration for the U–Mo alloy annular assembly with central cylindrical stainless steel plugs and 3-in.-thick top reflector, Experiment D. (Two-dimensional cross section along diameters; only the last four digits of part numbers are given in the figure.)

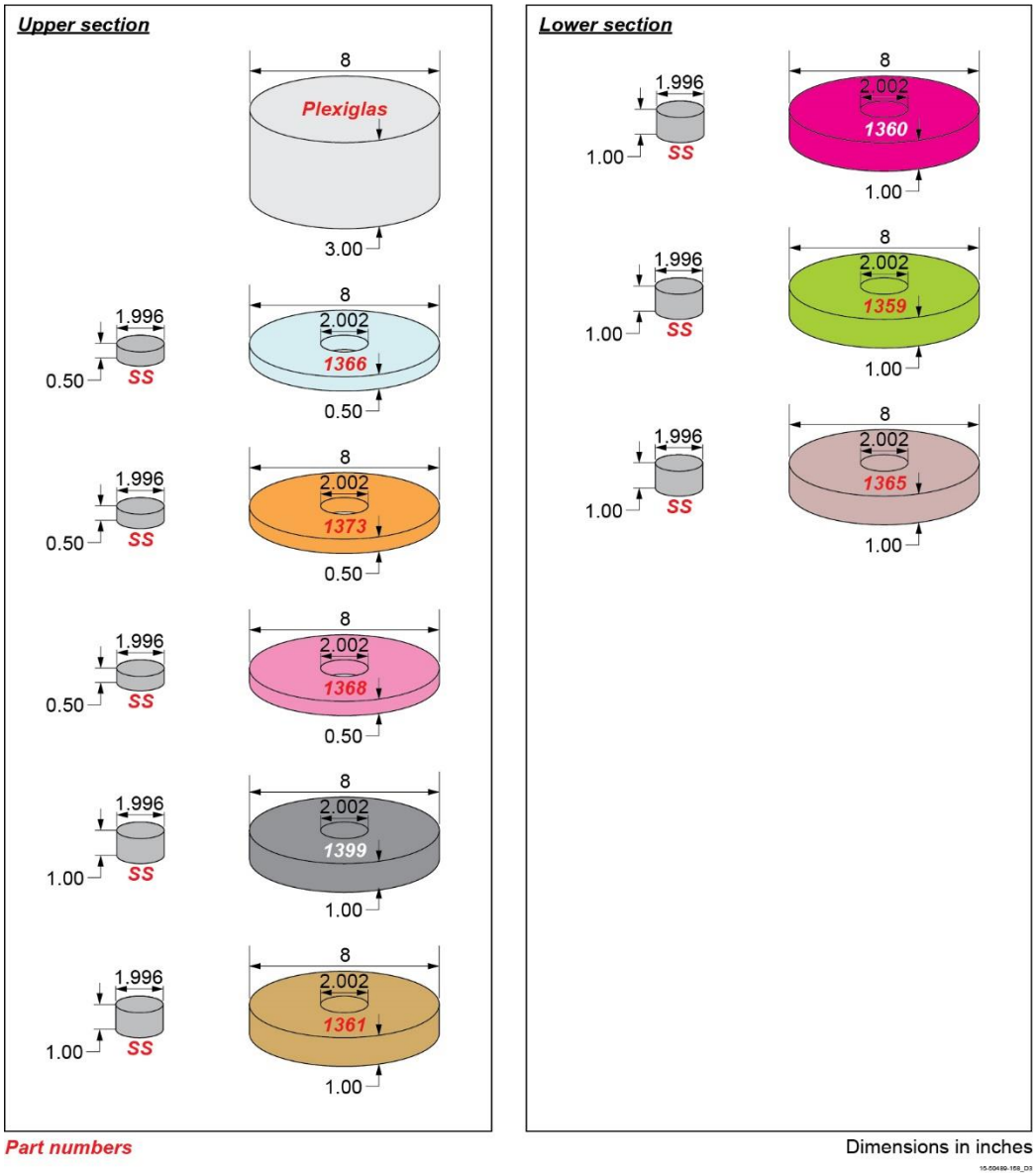

Figure 3.4.2. The U–Mo alloy and Plexiglas parts for the annular assembly with central cylindrical stainless steel plugs and 3-in.-thick top reflector, Experiment D. (Only the last four digits of part numbers are given.)

If the geometry of the experimental cell is not included in the calculations, the effects of room return should be calculated using Monte Carlo simulations assuming the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate.

3.5 EXPERIMENT E: U–MO ALLOY ANNULUS WITH 2.0-IN.-DIAM. STEEL CORE AND 3.0-IN.-THICK PLEXIGLAS REFLECTOR ON TOP WITH CADMIUM BETWEEN PLEXIGLAS AND U–MO ALLOY

This unreflected and unmoderated U–Mo alloy nominal 8-in.-OD right circular annular configuration and a 2.0-in.-ID consisted of the U–Mo annular plates with nominal 2-in.-diameter stainless steel plugs in the center of the same thickness as the U–Mo alloy annuli that they were inside. This was a variation of this Experiment D by the insertion of cadmium metal between the top reflector and the fissile configuration. This system was assembled on April 17, 1961. The cadmium metal sheet was 0.026-in. thick and was

coated with 0.0015-in.-thick Glyptal on both sides. This results in an increase in the height of the assembly at delayed criticality of about 5/16 in. A sketch of this configuration with a total U–Mo alloy mass of 89,850 g is given in Figure 3.5.1, and the U–Mo alloy parts are described in Figure 3.5.2. The reactivity of the assembled configuration was +15.5 cents with a corresponding k_{eff} of 1.00103 using a beta effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration had the lowest uncertainties and included all of the support structure and the 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, and support structure effects were not measured.

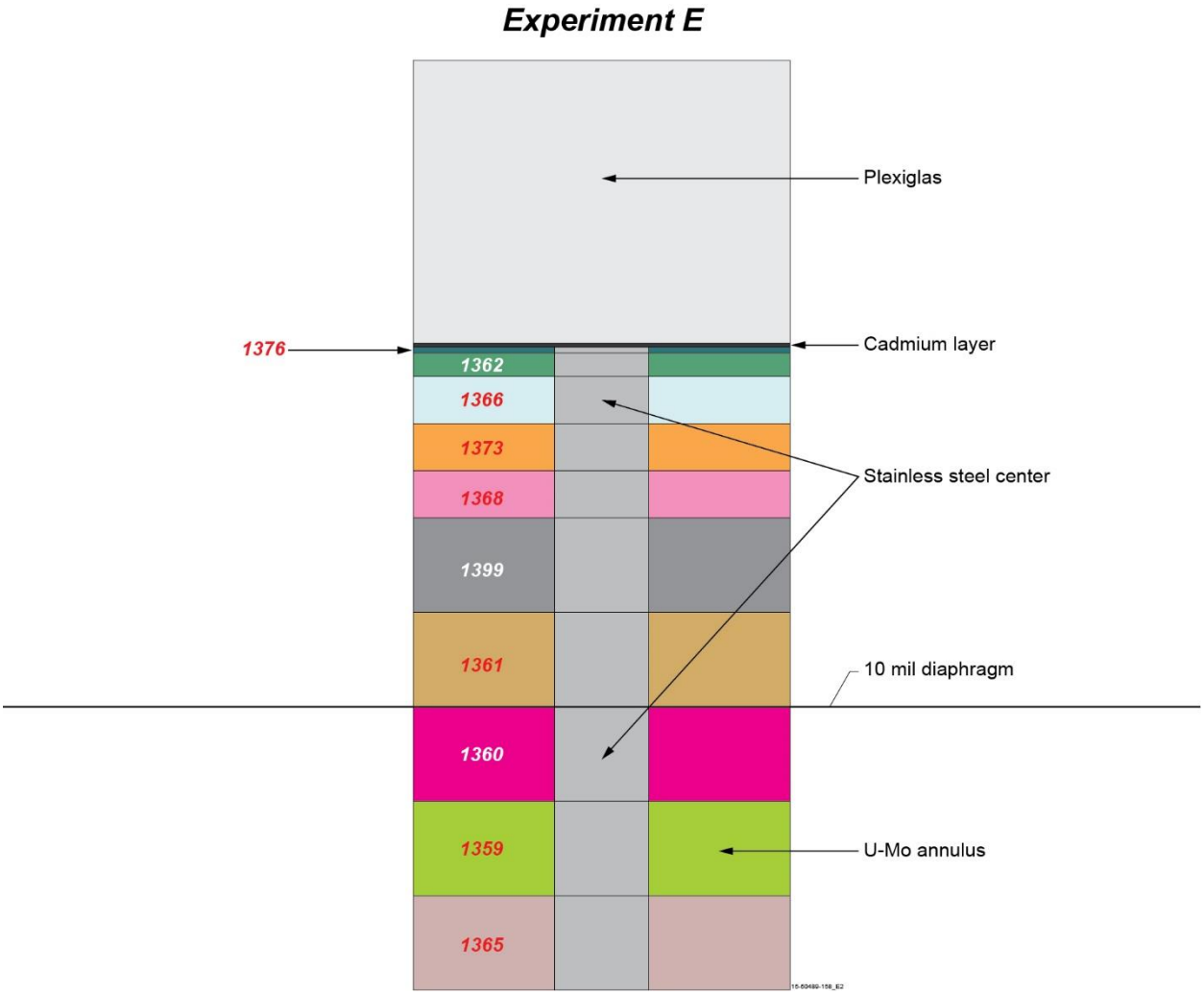

Figure 3.5.1. Configuration for the U–Mo alloy annular assembly with central cylindrical stainless steel plugs with cadmium between the 3-in.-thick top reflector and the U–Mo alloy/stainless steel assembly, Experiment E. (Two-dimensional cross section along diameters; only the last four digits of part numbers are given in the figure.)

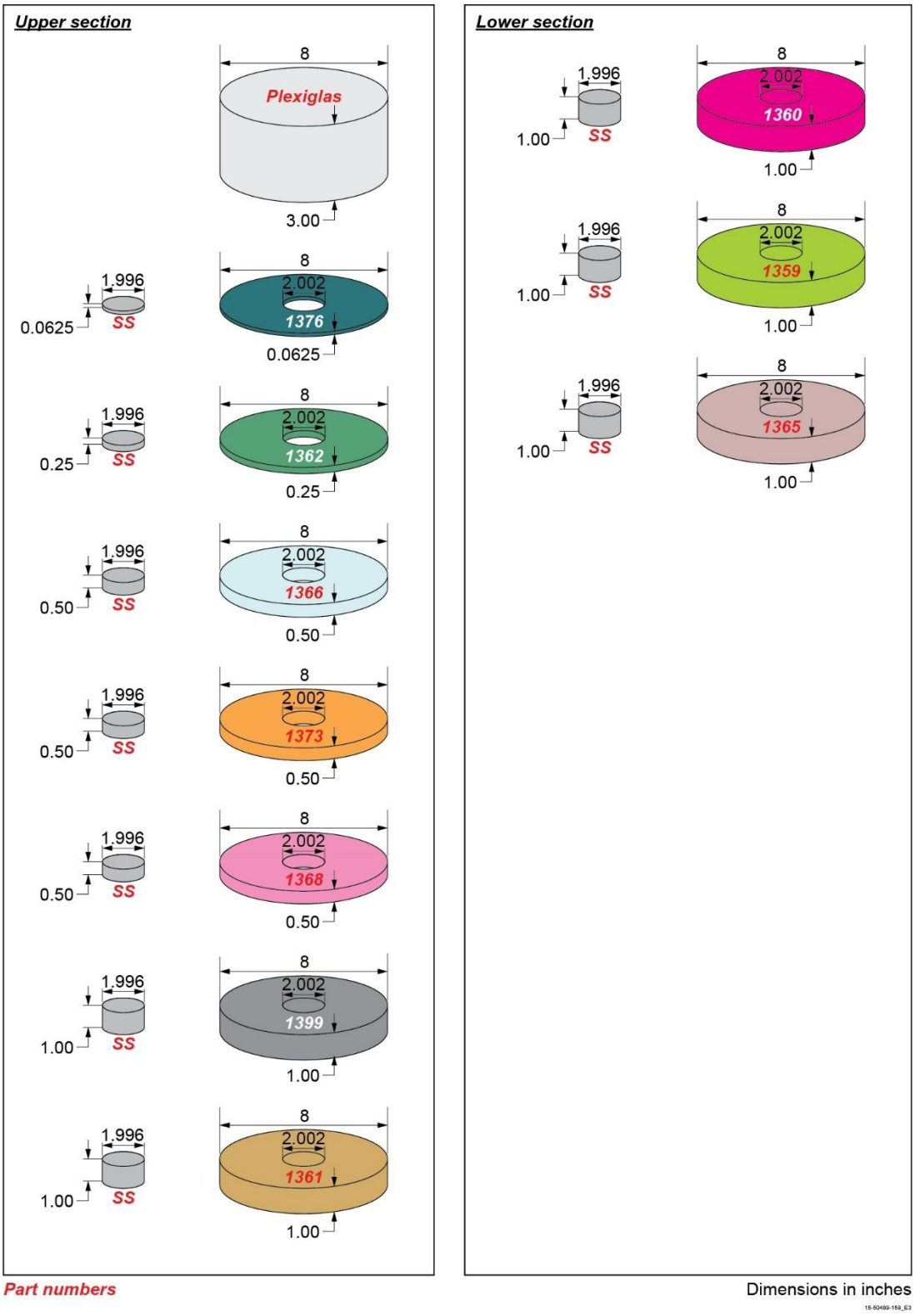

Figure 3.5.2. The U–Mo alloy, stainless steel, and Plexiglas parts for the annular assembly with central cylindrical stainless steel plugs with cadmium between the 3-in.-thick top reflector and the U–Mo alloy/stainless steel, Experiment E. (Only the last four digits of part numbers are given in the figure.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.6 EXPERIMENT F: U–MO ALLOY ANNULUS WITH 1-IN.-THICK PLEXIGLAS REFLECTOR ON ALL OUTER RADIAL SURFACES WITH VOID CENTER

This U–Mo alloy nominal 8-in. OD right circular annular configuration had two different axial-hole diameters: nominal 3.5 in. diameter for the lower 5 in. (3 in. on the lower support and 2 in. on the diaphragm, nominal 2-in.-diameter for the rest of the upper section on the diaphragm. This experiment was performed on May 31, 1961, to evaluate the effects of hand reflection by using an external hydrocarbon reflector. A sketch of this configuration with a total U–Mo alloy mass of 80,415 g is given in Figure 3.6.1. This thickness of reflector was to simulate the addition of hand reflection to the radial surface. The nominal height of the U–Mo alloy annular assembly was 6.78125 in. The Plexiglas radial reflector on the bottom section was 3 in. high. The Plexiglas reflector pieces were the same height as the annular plates they surrounded, and their inside diameters were 8.020 in. The Plexiglas (in all experiments) was shimmed underneath as necessary with thin aluminum foil so that the top surface of all parts on the lower section were in the same plane. The reactivity of the assembled configuration was −10.2 cents (reactor period of −167 seconds) with a corresponding k_{eff} of 0.99933 using a beta effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration had the lowest uncertainties and included all of the support structure and the 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.

The reactivity addition of adding a 1/32-in.-thick U–Mo alloy annular plate to the top was 26.7 cents (reactor period change from −167 to +4,922 seconds). There is some ambiguity for the measurement of 0.005-in.-thick diaphragm and all results are not presented. The reactivity change from changing the thickness from 0.005 to 0.010-in.-thickness was 4.6 cents (reactor period change from +78.7 to +214 seconds).

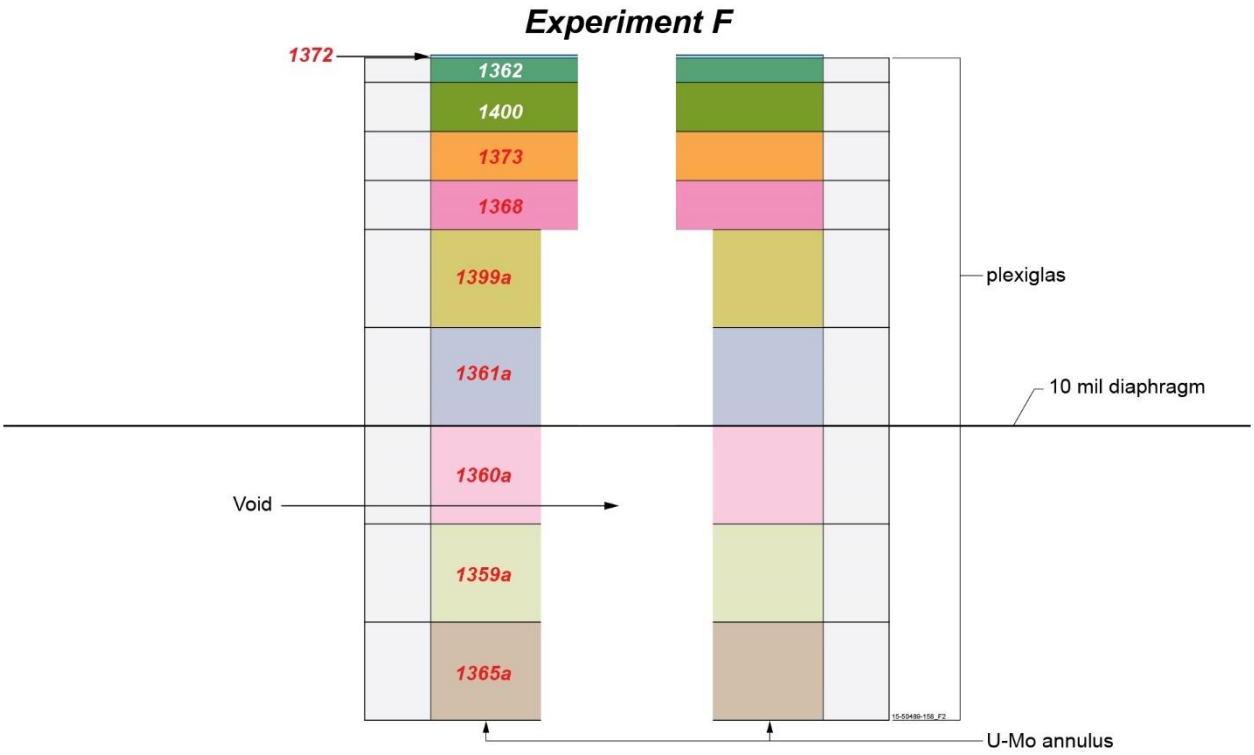

Figure 3.6.1. Configuration of U–Mo alloy annulus with 1-in.-thick Plexiglas reflector on all outer surfaces with void center, Experiment F. (Only the last four digits of part numbers are given in the figure. The inside and outside diameter of the radial reflector are 8.020 and 10.020 in., respectively.)

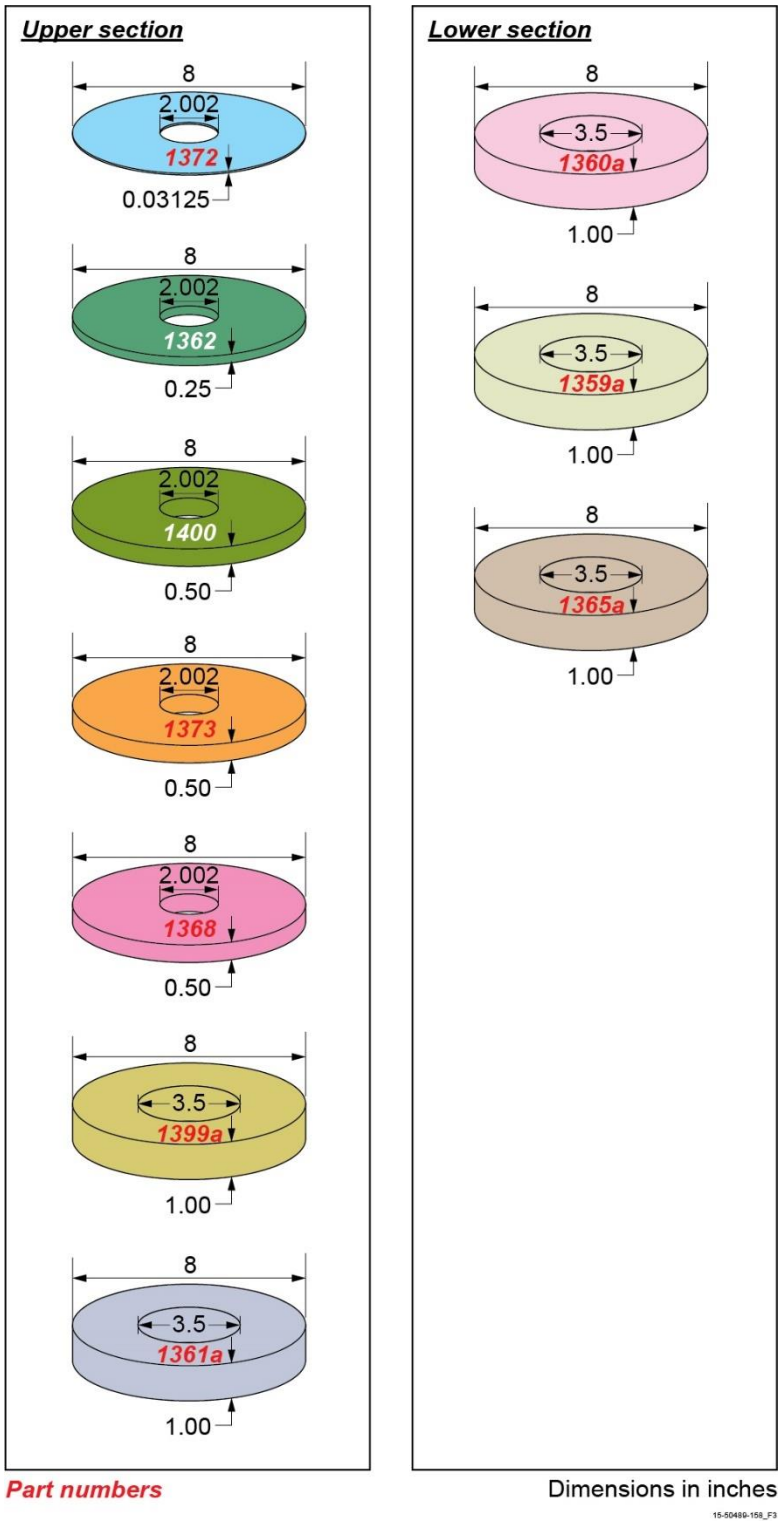

Figure 3.6.2. The U–Mo alloy parts for the annular assembly with central void and 1-in.-thick Plexiglas on radial surface, Experiment F. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.020 and 10.020 in., respectively.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the

measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.7 EXPERIMENT G: U–MO ALLOY ANNULUS WITH 1-IN.-THICK PLEXIGLAS REFLECTOR ON ALL OUTER SURFACES WITH PLEXIGLAS CENTER

This experiment was performed to verify calculation of the effects of internal hydrocarbon moderator and was performed on May 31, 1961. This U–Mo alloy nominal 8-in.-OD right circular annular configuration with a 3.500-in.-ID (except for the upper plate) consisted of the U–Mo annular plates with nominal 3.5-in.-diameter Plexiglas plugs in the center of the same thickness as the U–Mo alloy annuli that they were inside. This system was assembled on May 31, 1961, with a height of 5.5 in. The upper half inch of the assembly had an inside diameter of 2.002 in. with Plexiglas central plugs of 1.995 in. The lower 5 in. of the assembly had an inside diameter of 3.500 in., and the internal Plexiglas plugs had an outside diameter of 3.490 in. The configuration of the U–Mo alloy parts and Plexiglas is given in Figure 3.7.1 and Figure 3.7.2, and the configured total U–Mo alloy mass of the system was 63,459 g. The nominal height of the assembly was 5.50 in. The top annular plate (1366, last four digits of the process batch number) had a diametral hole for insertion of the source and use for fission rate spatial distribution measurements. This hole was at the vertical center of the plates. This diametral hole in this U–Mo alloy annulus was filled with U–Mo alloy inserts and are included in the total U–Mo alloy mass. The reactivity of the assembled configuration was +21.9 cents (reactor period of +33.3 seconds) with a corresponding k_{eff} of 1.00144 using a ß effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration had the lowest uncertainties and included all of the support structure and the 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.

Addition of 0.005-in.-thick stainless steel to the bottom of the diaphragm reduced the reactivity 8.93 cents (reactor period change from +33.3 to 69.5 seconds). Another addition of 0.005-in.-thick stainless steel to the diaphragm reduced the reactivity another 9.1 cents (reactor period change from +69.5 to +310.5 seconds).

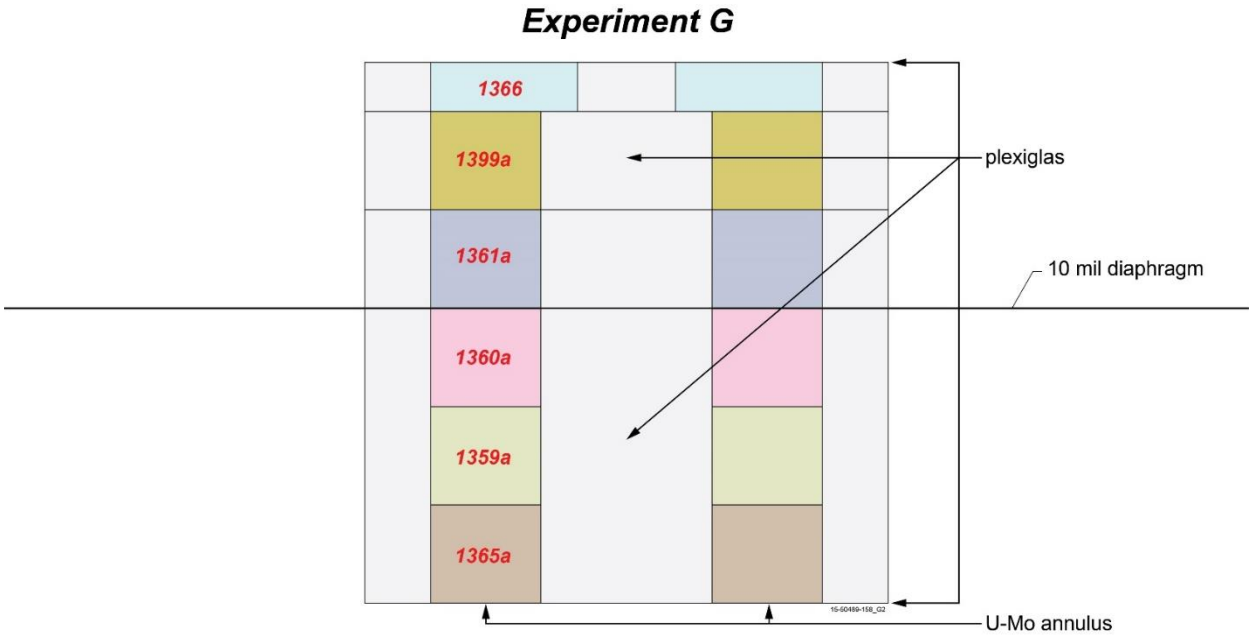

Figure 3.7.1. Configuration of the U–Mo annulus with 1-in.-thick Plexiglas reflector on all outer radial surfaces with Plexiglas center, Experiment G. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.020 and 10.020 in., respectively. Outside diameters of inner Plexiglas are 3.480 and 1.980 in.)

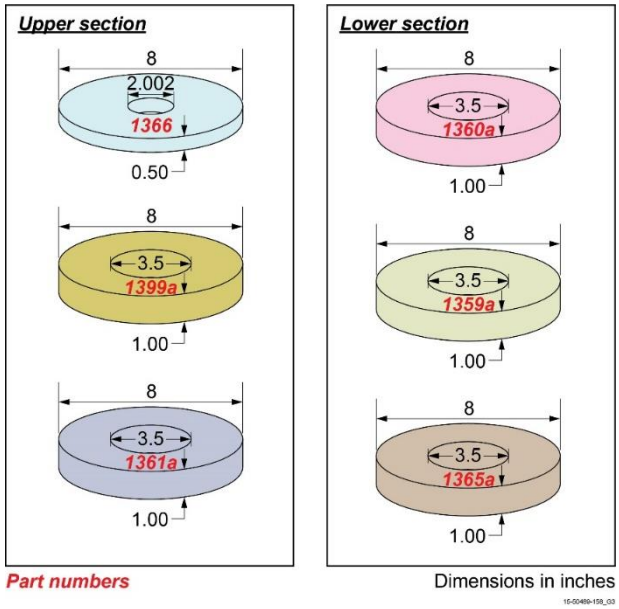

Figure 3.7.2. The U–Mo alloy parts for U–Mo annulus with 1-in.-thick Plexiglas reflector on all outer radial surfaces with Plexiglas center, Experiment G. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.020 and 10.020 in., respectively. Outside diameters of inner Plexiglas are 3.480 and 1.980 in.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the mix.

3.8 EXPERIMENT H: U–MO ALLOY ANNULUS WITH 1-IN.-THICK PLEXIGLAS RADIAL REFLECTOR, VOID IN THE CENTER, CADMIUM BETWEEN THE U-MO AND REFLECTOR

This U–Mo alloy nominal 8-in.-OD right circular annular configuration with a 3.5-in.-ID consisted of the U–Mo annular plates and was assembled on June 1, 1961, with 1-in.-thick radial reflector and cadmium between the U–Mo alloy annulus and the reflector. The configuration of the U–Mo alloy parts is given in Figure 3.8.1, and the configured total U–Mo alloy mass of the system was 84,507 g. The nominal height of the assembly was 7.09375 in. The lower 5 in. of height has a nominal 3.5-in.-inside diameter, and the annular U–Mo alloy plates at the top of the assembly had an inside diameter of 2 in. The U–Mo alloy parts are described in Figure 3.8.2. The reactivity of the assembled configuration was −4.9 cents (reactor period of −304 seconds) with a corresponding k_{eff} of 0.9997 using a ß effective of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration has the lowest uncertainties and includes all of the support structure and the 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.

The reactivity associated with the addition of 1/32-in.-thick U–Mo alloy annular plate on the top was +27.2 cents (reactor period change from −304.4 to +31 seconds). The reactivity change from adding 0.005-in.-thick stainless steel to the bottom of the diaphragm was −3.98 cents (reactor period change from +31 to +43.4 seconds). The reactivity effect of adding an additional 0.005-in.-thick stainless steel was −3.83 cents (reactor period change from 43.4 to 59.3 seconds).

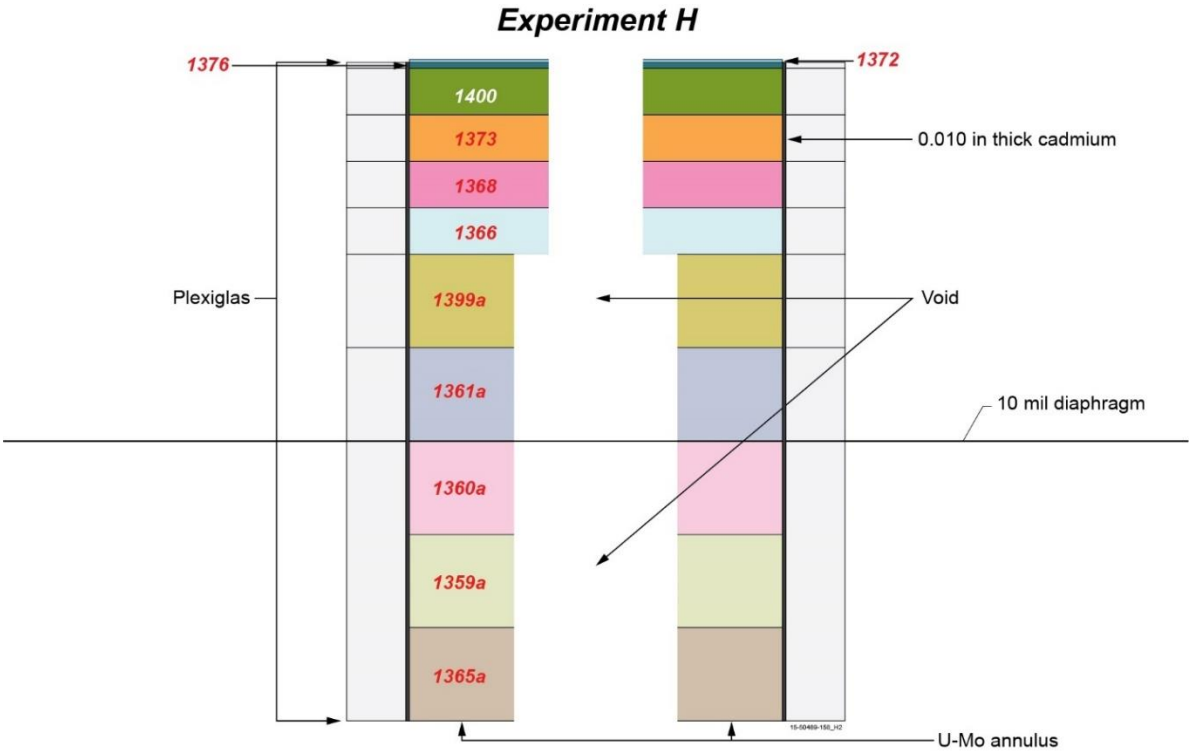

Figure 3.8.1. Configuration of the U–Mo annulus with 1-in.-thick Plexiglas reflector on all outer radial surfaces with void center and cadmium between the U-Mo alloy and the reflector, Experiment H. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.040 and 10.040 in., respectively.)

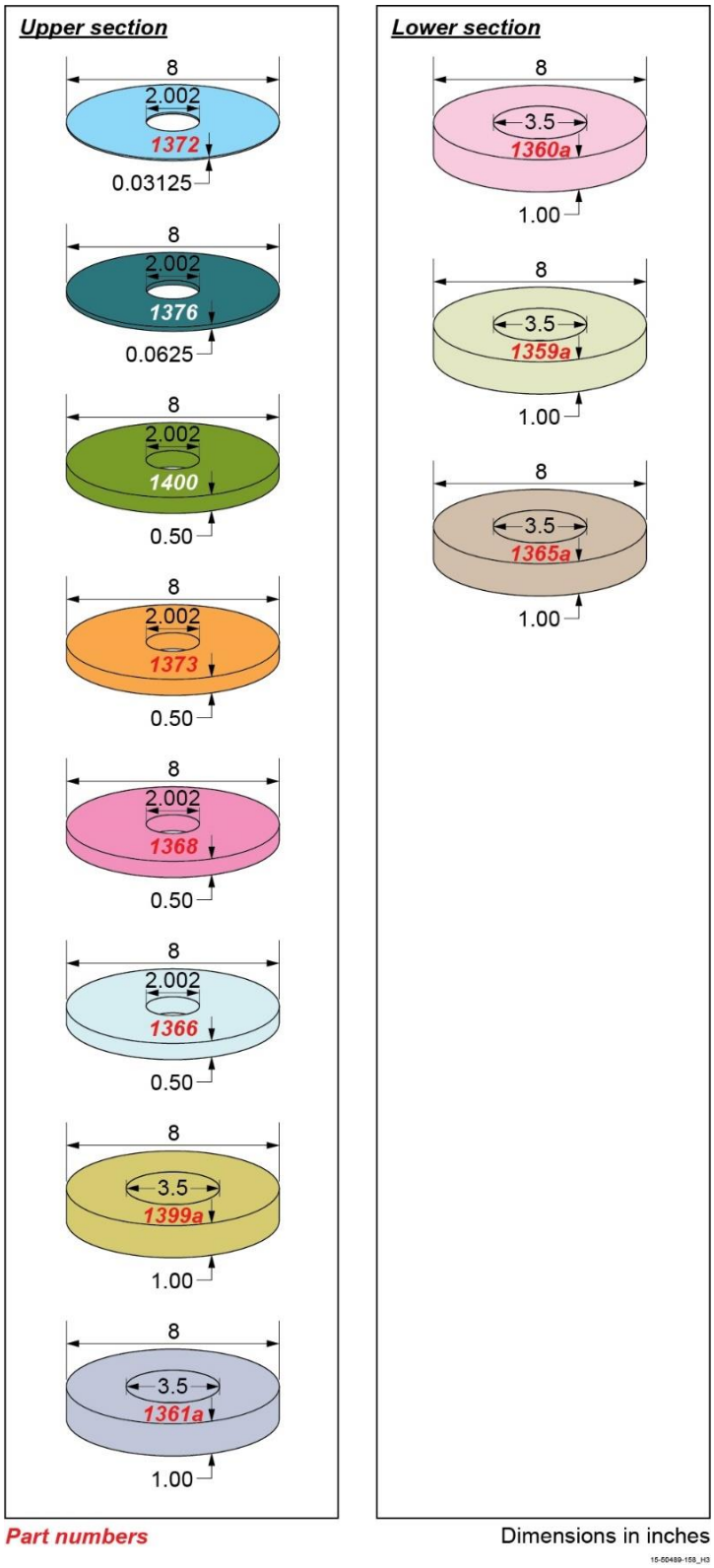

Figure 3.8.2. The U–Mo alloy parts for the annular assembly with central void and 2-in.-thick Plexiglas on radial surface with cadmium between the U-Mo and the reflector, Experiment H. (Only the last four digits of part numbers are given in the figure. Inside and outside diameter or radial reflector are 8.020 and 10.020 in., respectively.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.9 EXPERIMENT I: U–MO ANNULUS WITH 2-IN.-THICK PLEXIGLAS RADIAL REFLECTOR AND VOID IN CENTER

This configuration of a U–Mo alloy annulus with 2-in.-thick radial reflector and 3.5-in.-diameter void in the center had a nominal height of 5.0 in. and was assembled on June 1, 1961, with a mass of 56,893 g. This assembly has a 3.500-in.-diameter central hole. This experiment was performed to evaluate the effects of a thicker reflector. The configuration of the U–Mo alloy parts and Plexiglas is given in Figure 3.9.1 and Figure 3.9.2. The system had a +25 second reactor period and thus a reactivity + 24.6 cents (k_{eff} = 1.00162) with the lower section 0.020 in. from completely up. It is clear that with the sag of the diaphragm, the lower section is in contact with the upper section and the system is completely assembled. This configuration has the lowest uncertainties and includes all of the support structure and the 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 that were not measured. This experiment may not be benchmark quality because of the ambiguity of the separation.

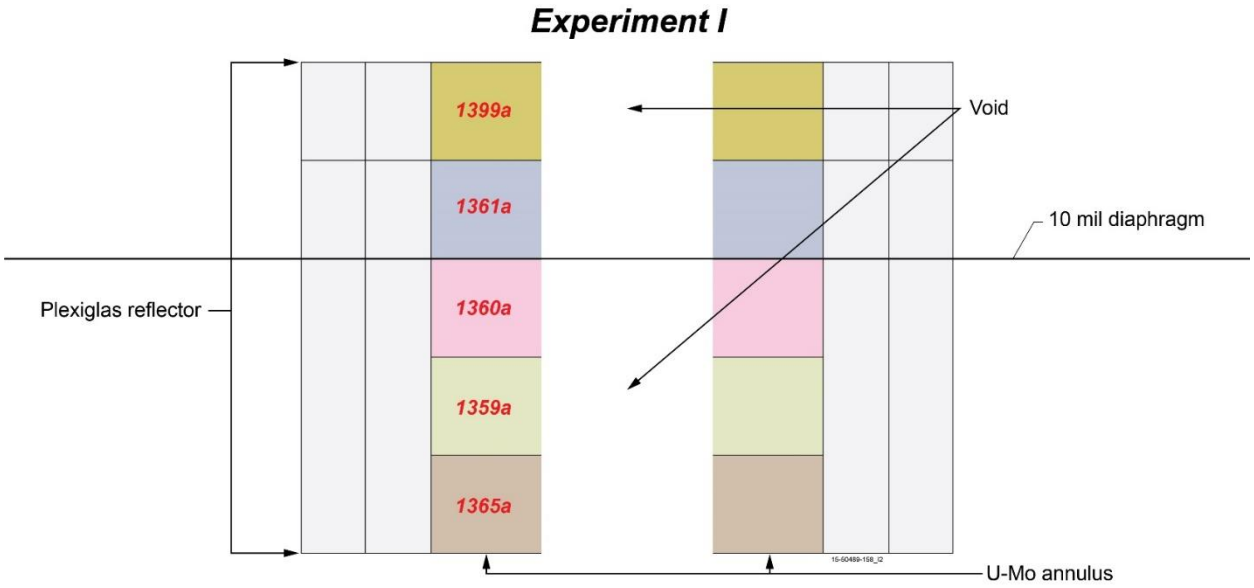

Figure 3.9.1. Configuration of the U–Mo annulus with 2-in.-thick Plexiglas radial reflector with void center, Experiment I. (Only the last four digits of part numbers are given in the figure; inside and outside diameter or radial reflector are 8.020 and 10.020 in. and 10.040 and 12.040 in., respectively.)

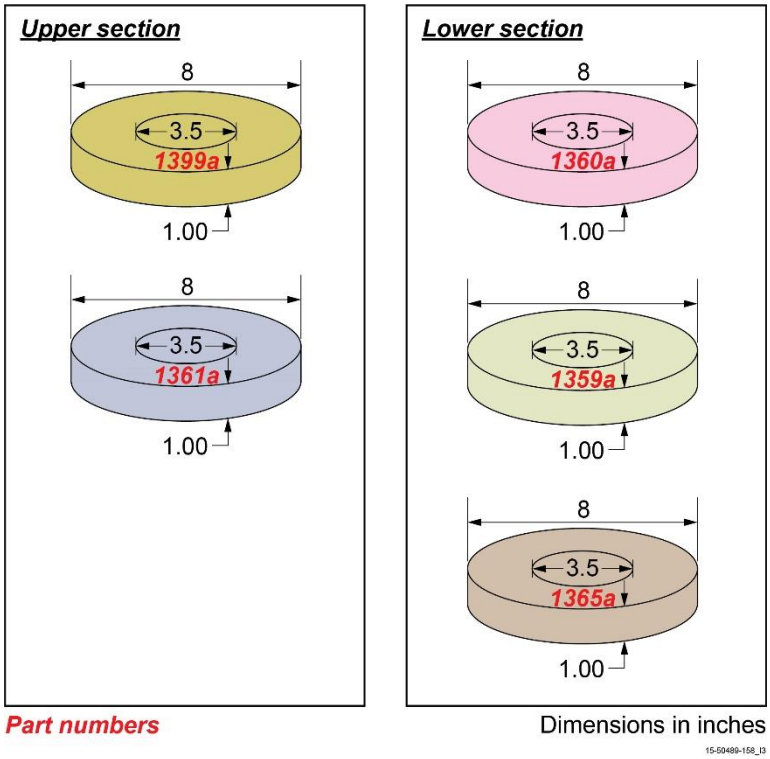

Figure 3.9.2. The U–Mo alloy parts for the U–Mo annulus with 2-in.-thickPlexiglas radial reflector with void center, Experiment I. (Only the last four digits of part numbers are given in the figure. The inside and outside diameter or radial reflector are 8.020 and 10.020 in. and 10.040 and 12.040 in., respectively.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.10 EXPERIMENT J: U–MO ALLOY ANNULUS WITH 2-IN.-THICK PLEXIGLAS RADIAL REFLECTOR, VOID IN THE CENTER AND CADMIUM BETWEEN THE RADIAL REFLECTOR AND THE U–MO ALLOY ANNULUS

This experiment was assembled on June 2, 1961, with a height of 6.25 in. The lower 5 in. of the assembly has a 3.500-in.-diameter central hole. The upper 1.25 inches of the assembly has a 2.002-in.-diameter central hole. This experiment was performed to evaluate the effects of reduction of external hydrocarbon reflector using neutron absorber. The configuration of the U–Mo alloy parts and Plexiglas is given in Figure 3.10.1 with a mass of 73,402 g and a description of the U–Mo alloy parts are given in Figure 3.10.2. The reactivity of this configuration was −12.15 cents (reactor period of −75.45 seconds) with a corresponding k_{eff} = 0.9992. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration has the lowest uncertainties and includes all of the support structure and the 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.

The reactivity effect of adding 0.010-in.-thich stainless steel under the diaphragm reduced the reactivity 4.35 cents (change in the reactor period from +75.45 to +134 seconds).

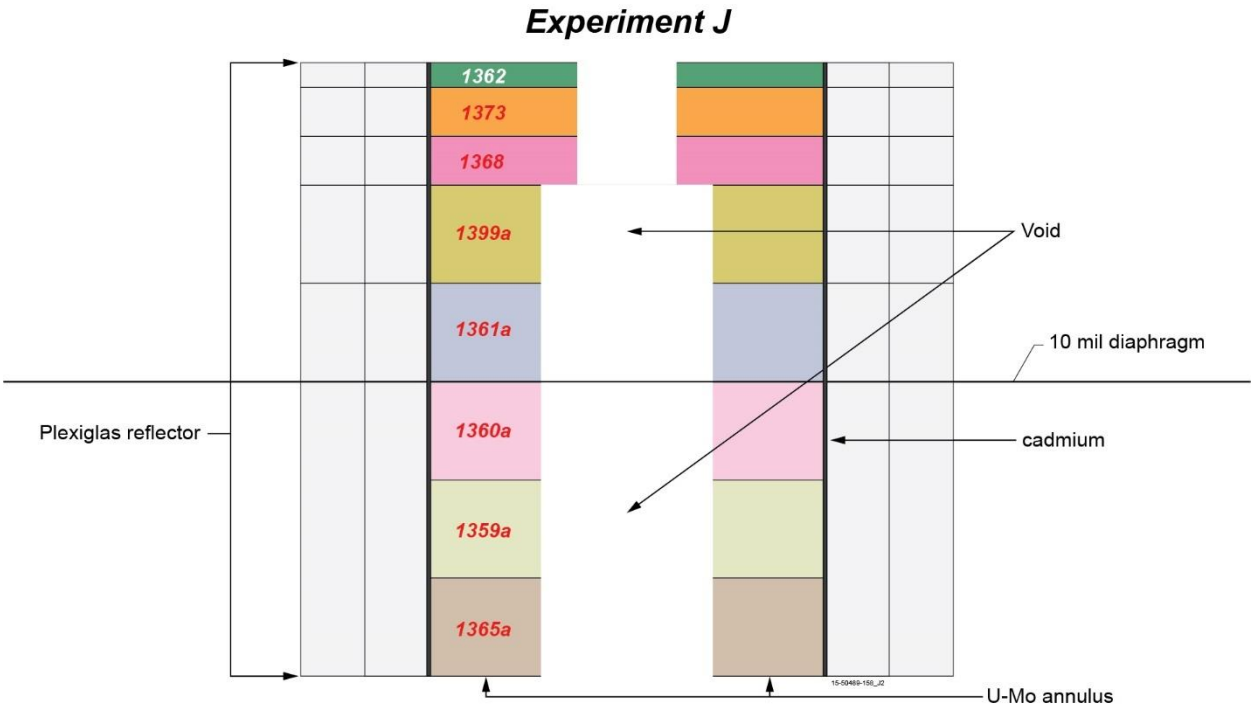

Figure 3.10.1. Configuration of the U–Mo annulus with 2-in.-thick Plexiglas radial reflector, void center and cadmium between the radial reflector and the U–Mo alloy annulus Experiment J. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.040 and 10.040 in. and 10.060 and 12.060 in., respectively.)

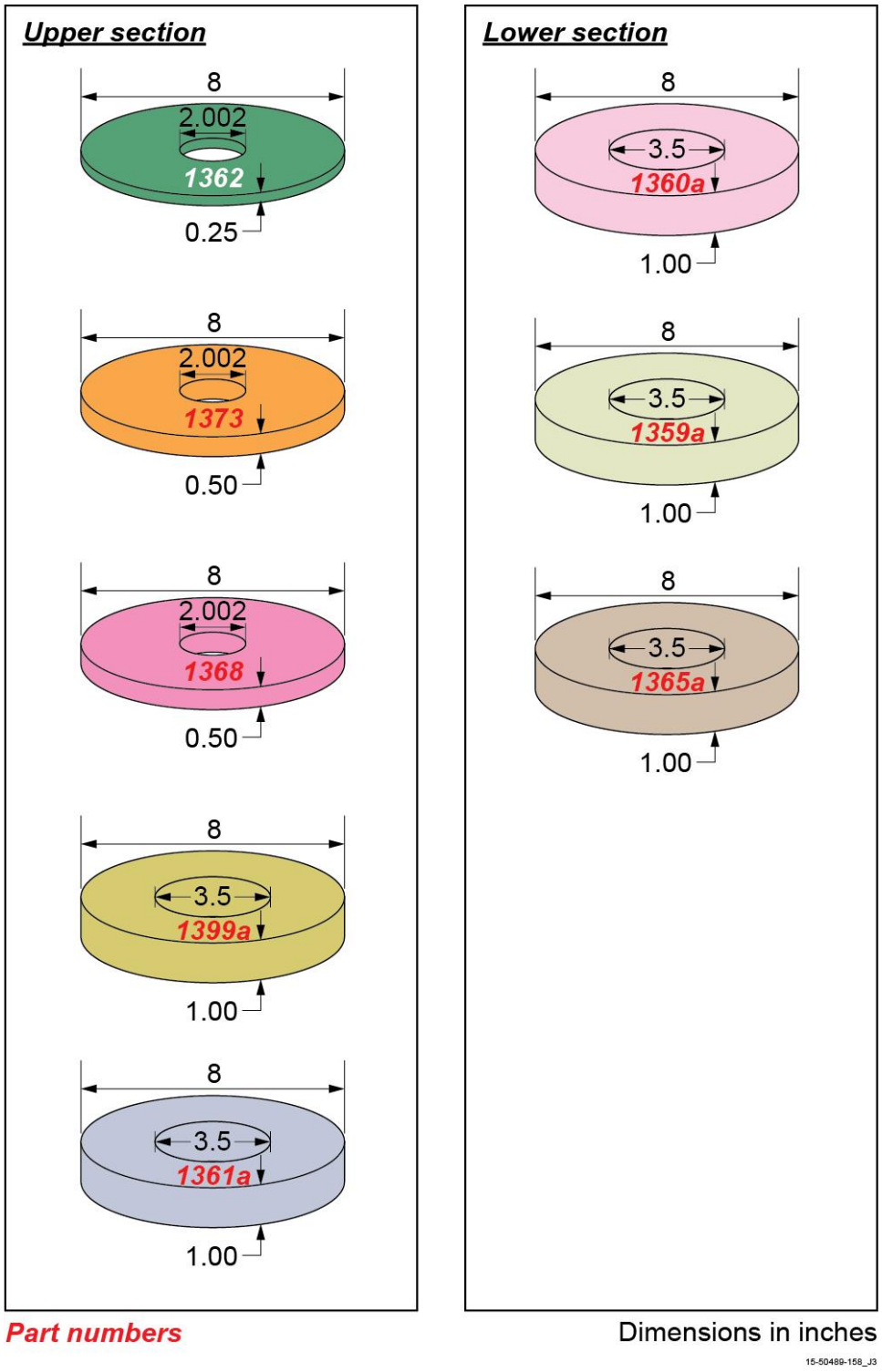

Figure 3.10.2. The U–Mo alloy parts for the U–Mo annulus with 2-in.-thick Plexiglas reflector, void center, and cadmium between the radial reflector and the U–Mo alloy annulus. Experiment J. (Only the last four digits of part numbers are given in the figure. The inside and outside diameters of the radial reflector are 8.040 and 10.040 in., and 10.060 and 12.060 in., respectively.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.11 EXPERIMENT K: U–MO ANNULUS WITH 2-IN.-THICK PLEXIGLAS RADIAL REFLECTOR, PLEXIGLAS CENTER, AND CADMIUM BETWEEN THE RADIAL REFLECTOR AND THE U–MO ALLOY ANNULUS SURFACES

The nominal height of this configuration was 5.21875 inches and was assembled on June 2, 1961, with a mass of 59781 g. It was a U–Mo alloy annulus with 2-in.-thick radial reflector with cadmium between the U–Mo alloy annulus and the radial reflectors with a Plexiglas in the center, The configuration of the U–Mo alloy parts and Plexiglas is given in Figure 3.11.1 and the U–Mo alloy parts are described in Figure 3.11.2. The reactivity of this configuration was +4.41cents (reactor period of 260 seconds) with a corresponding k_{eff} = 1.00029 using an effective delayed neutron fraction of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. This configuration has the lowest uncertainties and includes all of the support structure and the 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. The reduction in the reactivity from the insertion of 0.010-in.-thick stainless steel under the diaphragm was 7.05 cents (reactor period change from +260 to −528 seconds).

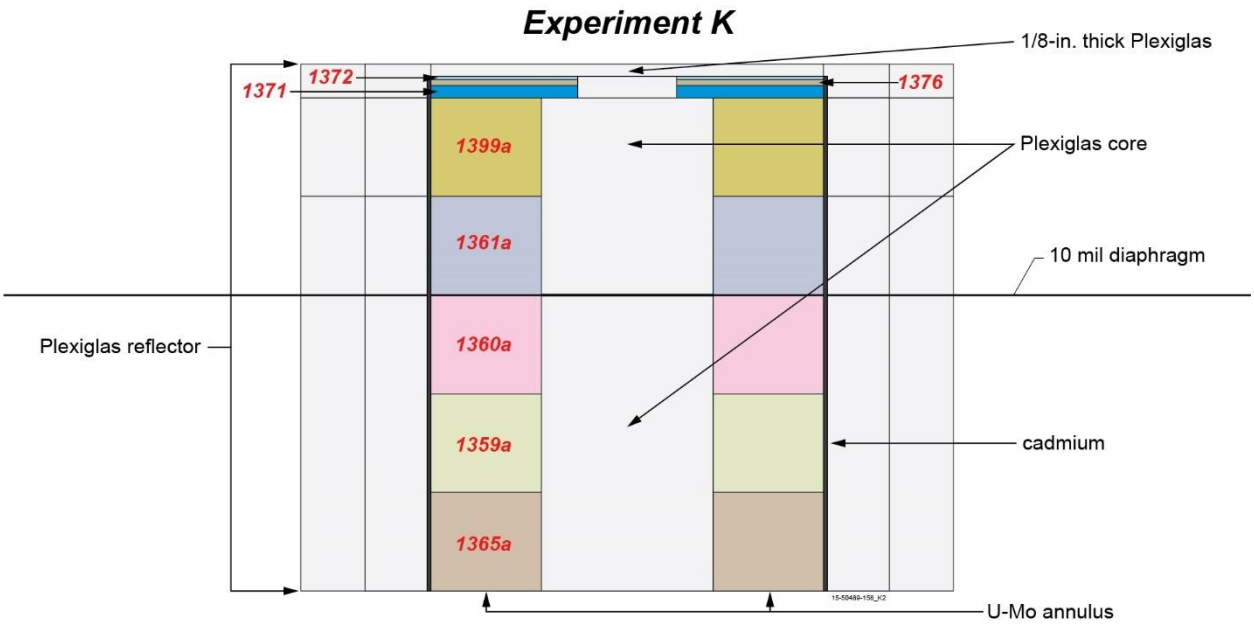

Figure 3.11.1. Configuration of the U–Mo annulus with 2-in.-thick Plexiglas reflector on all outer surfaces with cadmium between the radial reflector and the U–Mo alloy with Plexiglas center, Experiment K. (Only the last four digits of the part number are given in the figure. The inside and outside diameters of the radial reflector are 8.040 and 10.040 in., and 10.060 and 12.060 in., respectively.)

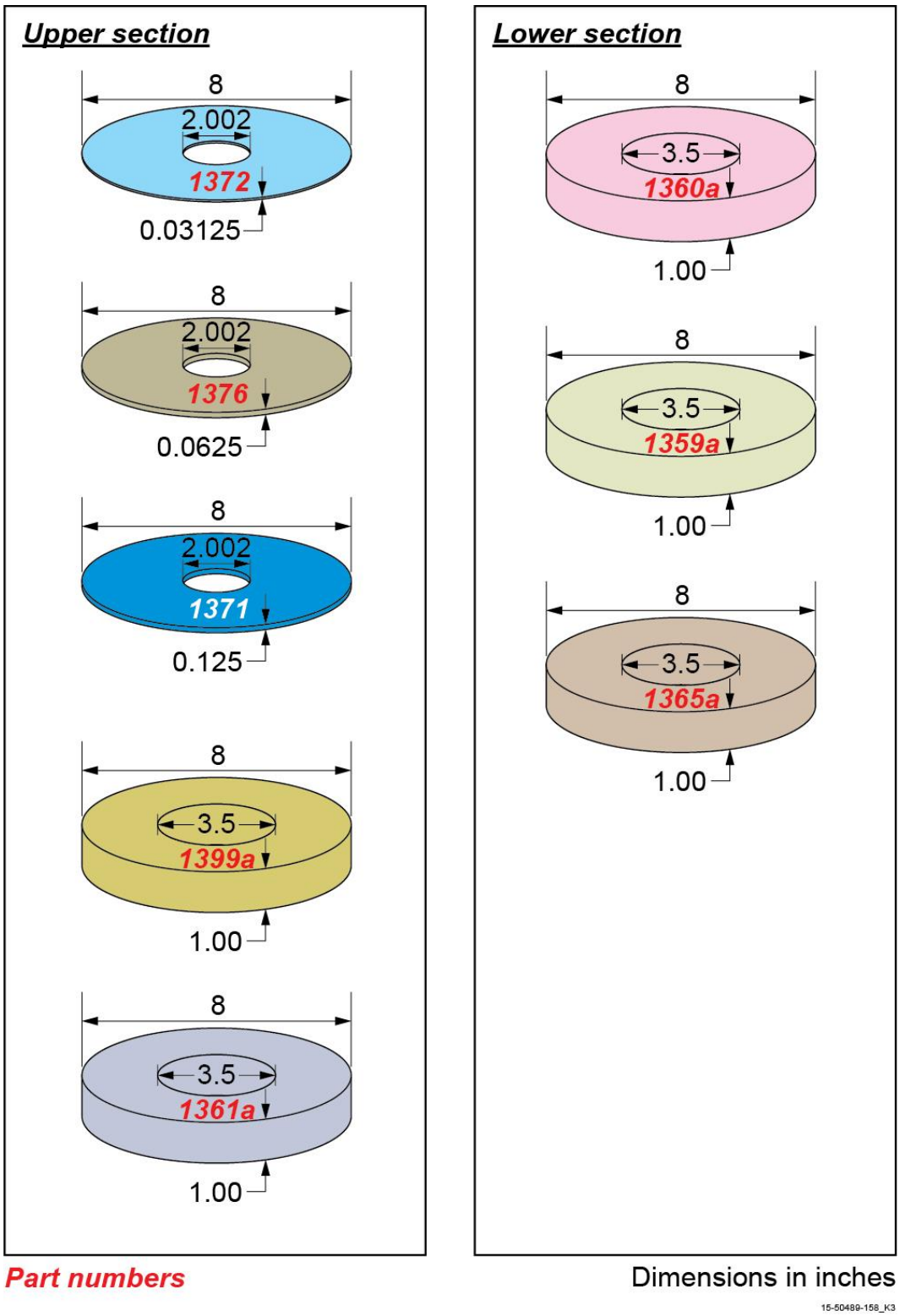

Figure 3.11.2. The U–Mo alloy parts for the annular assembly with Plexiglas center and 2-in.-thick Plexiglas on radial surface and cadmium between the radial reflector and U–Mo alloy, Experiment K. (Only the last four digits of the part number are given in the figure. The inside and outside diameters of the radial reflector are 8.040 and 10.040 in. and 10.060 and 12.060 in., respectively.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.12 EXPERIMENT L: U–MO ALLOY ANNULUS WITH 6-IN.-THICK BOTTOM REFLECTOR, VOID CENTER

This U–Mo alloy assembly with nominal 8-in.-OD right circular annular configuration consisted of the U–Mo annular plates and was assembled on June 5, 1961, to estimate the effects of floor reflection with 6-in.-thick bottom reflector with void in the center. The height of the assembly was 7.71875 in. with a mass of 89457 g and the reactivity of the assembled configuration was assumed to be exactly delayed critical. There is no indication in the logbook of the resulting reactivity, and this may result in this experiment not being benchmark quality. (This may be judged by a comparison with calculations. If the agreement is comparable to the other 11 experiments with Plexiglas then the assumption of the reactivity condition may be valid.) The lower 5 in. of U–Mo alloy had an inside diameter of 3.500 in., and the annular plates above that had an inner diameter of 2.002 inches. The configuration of the parts is given in Figure 3.12.1, and a description of the parts is given in Figure 3.12.2.

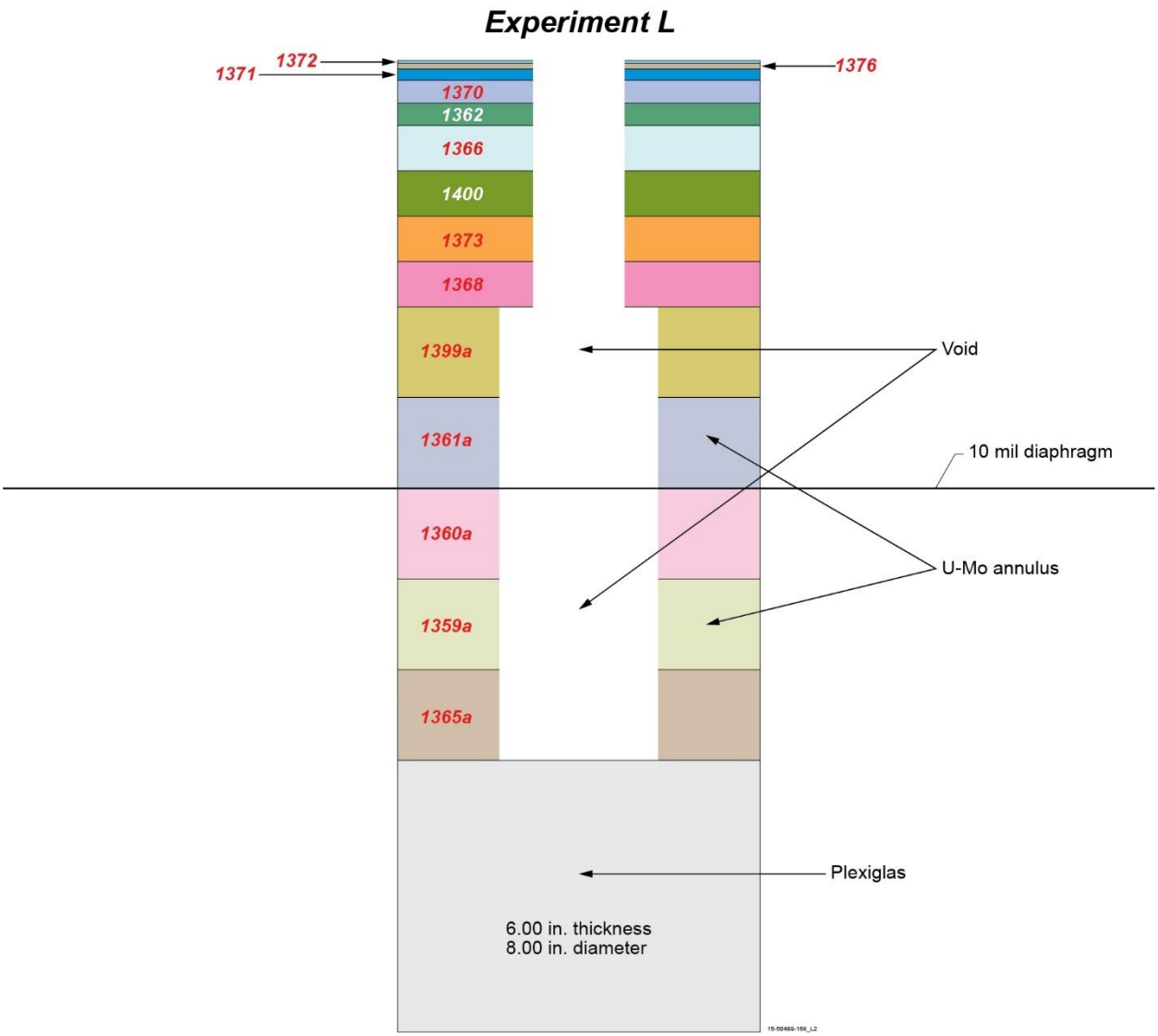

Figure 3.12.1. Configuration of U–Mo alloy annulus with 6-in.-thick bottom reflector and void center, Experiment L. (Only the last four digits of part numbers are given in the figure.)

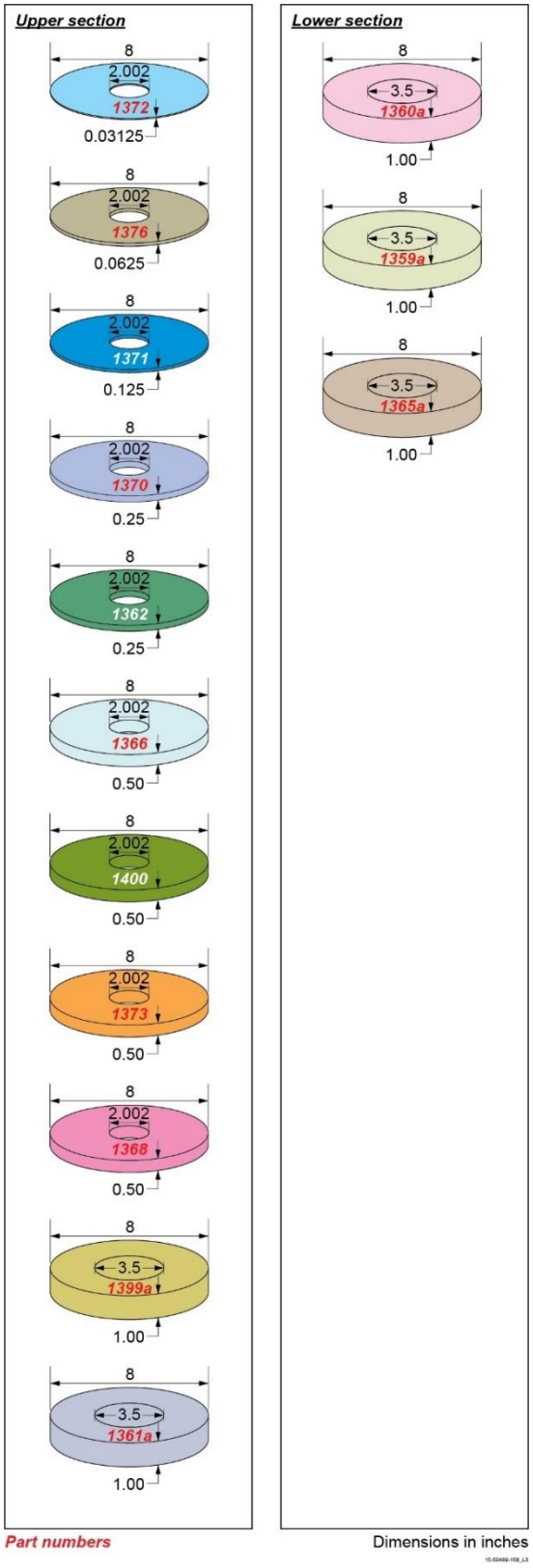

Figure 3.12.2. Description of U–Mo alloy parts for Experiment L. (Only the last four digits of part numbers are given in the figure.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.13 EXPERIMENT M: U–MO ALLOY ANNULUS WITH 6-IN.-THICK BOTTOM REFLECTOR, PLEXIGLAS IN THE CENTER

This U–Mo alloy assembly with nominal 8-in.-OD right circular annular configuration consisted of the U–Mo annular plates and was assembled on June 5, 1961, with 6-in.-thick bottom reflector with Plexiglas in the center. The configuration of the parts is given in Figure 3.13.1 and a description of the parts in Figure 3.13.2. The height of the assembly was 7.00 inches with a mass of 83,268 g and the reactivity of the assembled configuration was +2.57 cents (reactor period of 468 seconds) with a corresponding k_{eff} = 1.00017 using a delayed neutron fraction of 0.0066. This effective delayed neutron fraction was assumed and is more appropriate for unreflected uranium metal systems, and in the final analysis of this experiment, the effective delayed neutron fraction should be calculated for a U–Mo alloy system for a U–Mo alloy system and used to convert reactivity in cents to k_{eff} units. The lower 5 in. of the U–Mo alloy plates had an inside diameter of 3.500 in., and the annular plates above that had an inner diameter of 2.002 in. This configuration has the lowest uncertainties and includes all of the support structure and the 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.

The addition of one quarter section of the 1/32-in.-thick U–Mo alloy annulus on top increased the reactivity to 6.7 cents, and the reactivity addition of this quarter section increased the reactivity 4.13 cent. The addition of 0.005-in.-thick stainless steel under the diaphragm deceased the reactivity 6.7 cents (change in the reactor period from 260 seconds to near infinite).

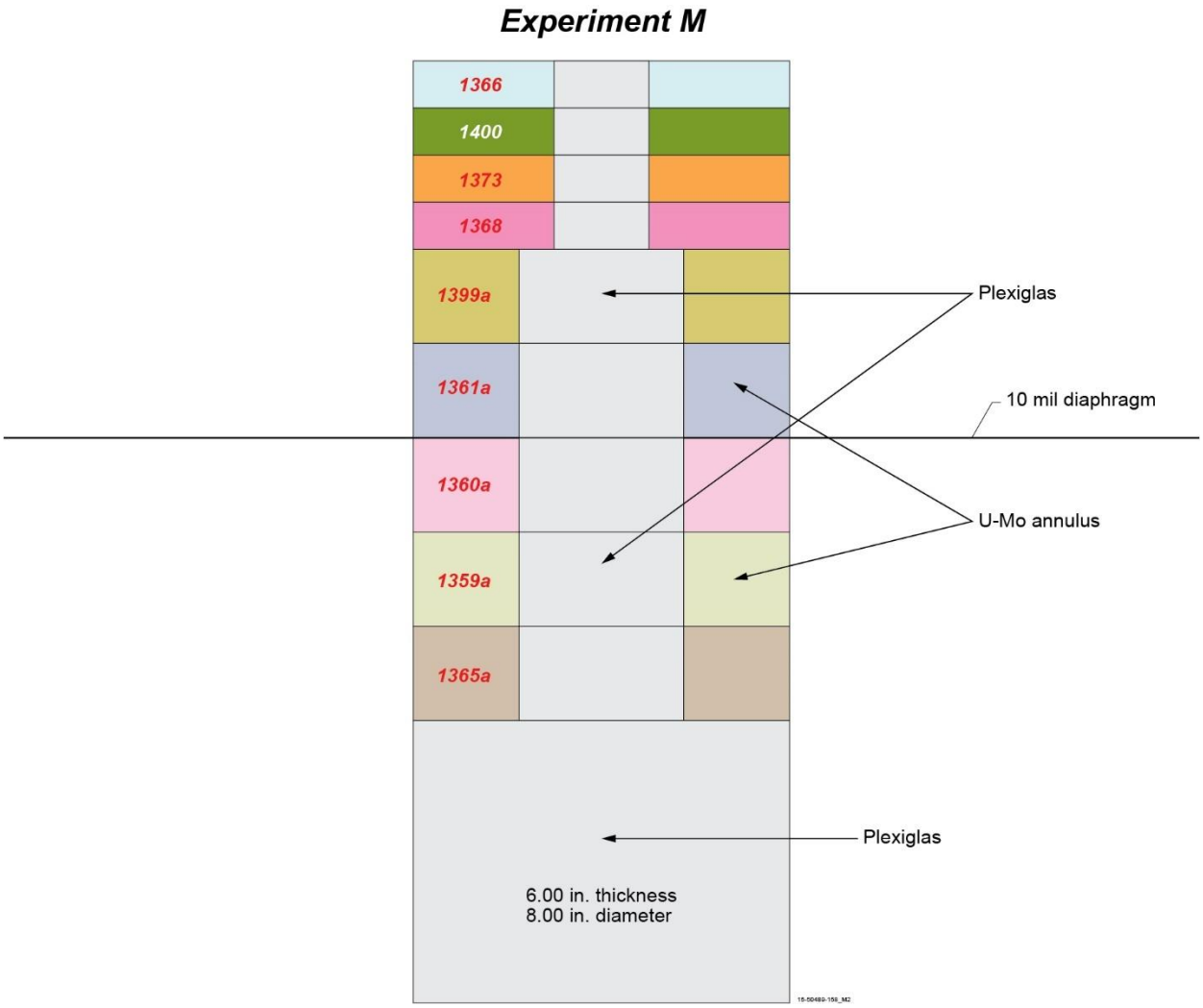

Figure 3.13.1. Configuration of U–Mo alloy annulus with 6-in.-thick bottom reflector and Plexiglas in the center, Experiment M. (Only the last four digits of the part number are given in the figure. The outside diameters of the inner Plexiglas are 3.480 and 1.980 in.)

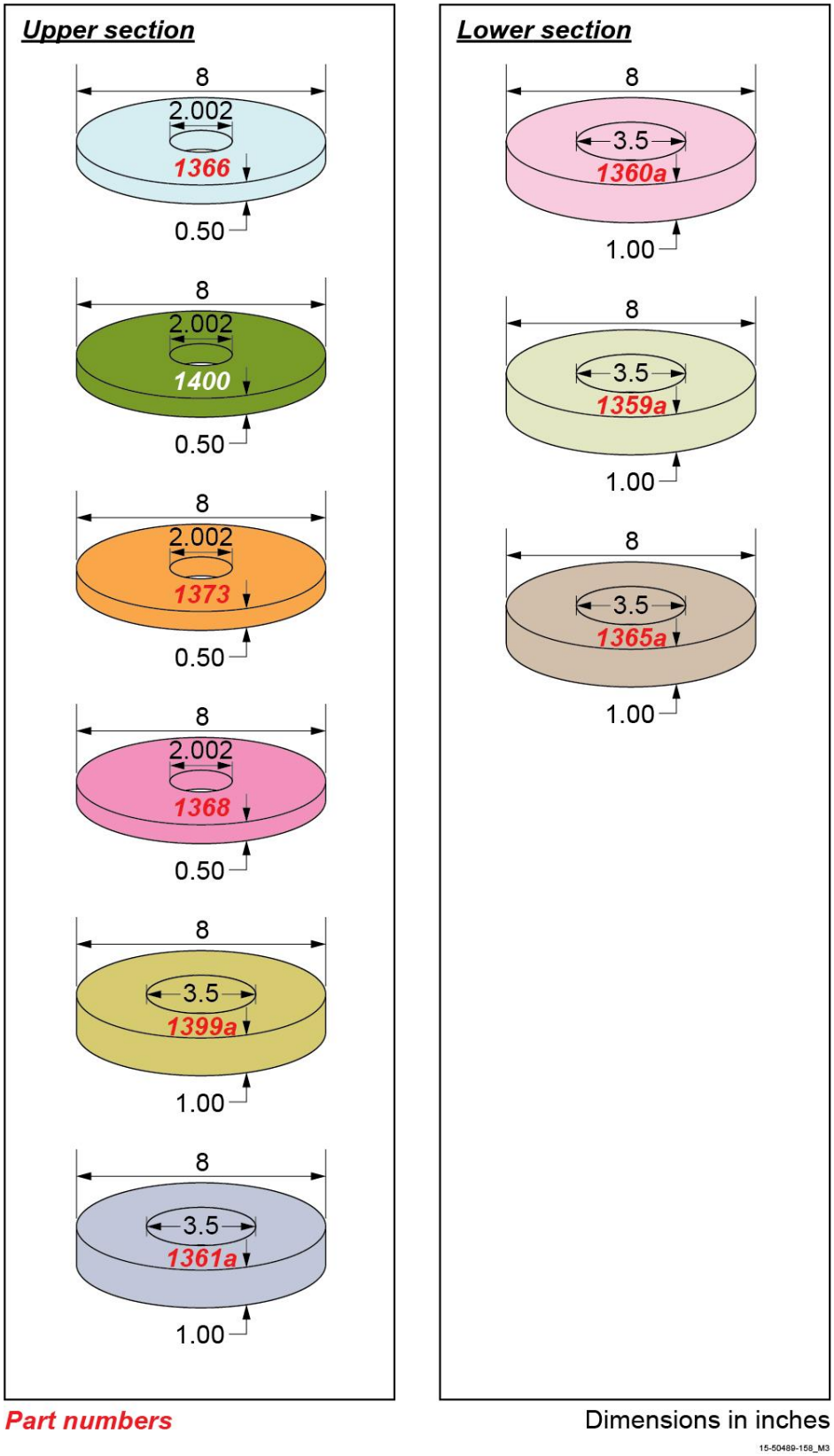

Figure 3.13.2. Description of U–Mo alloy parts for Experiment M. (Only the last four digits of part numbers are given in the figure. The outside diameters of the inner Plexiglas are 3.480 and 1.980 in.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration.

3.14 EXPERIMENT N: U–MO ALLOY ANNULUS WITH 6-IN.-THICK BOTTOM REFLECTOR, 1.0-IN.-THICK TOP REFLECTOR, 1-IN.-THICK RADIAL REFLECTOR AROUND BOTTOM 3.125 IN. OF U–MO ALLOY, PLEXIGLAS CENTER

This U–Mo alloy assembly with nominal 8-in.-OD right circular annular configuration consisted of the U–Mo annular plates and was assembled on June 5, 1961, with 6-in.-thick bottom reflector, 1-in.thick top reflector and 1-in.-thick radial reflector around the lower 3.125 in. of U–Mo alloy. The configuration of the U–Mo alloy parts is given in Figure 3.14.1, and the configured total U–Mo alloy mass of the system was 89,860 g. The nominal height of the assembly was 7.5 in. The U–Mo alloy parts are described in Figure 3.14.2. The U–Mo alloy annular plates had two different inside diameters: 3.500 in. for the 5 in. of lower plates and 2.002 in. for the upper 2.5 in. of U–Mo alloy. The reactivity of the assembled configuration was exactly delayed critical with a corresponding k_{eff} of 1.0000. This configuration has the lowest uncertainties and includes all of the support structure and the 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 that were not measured.

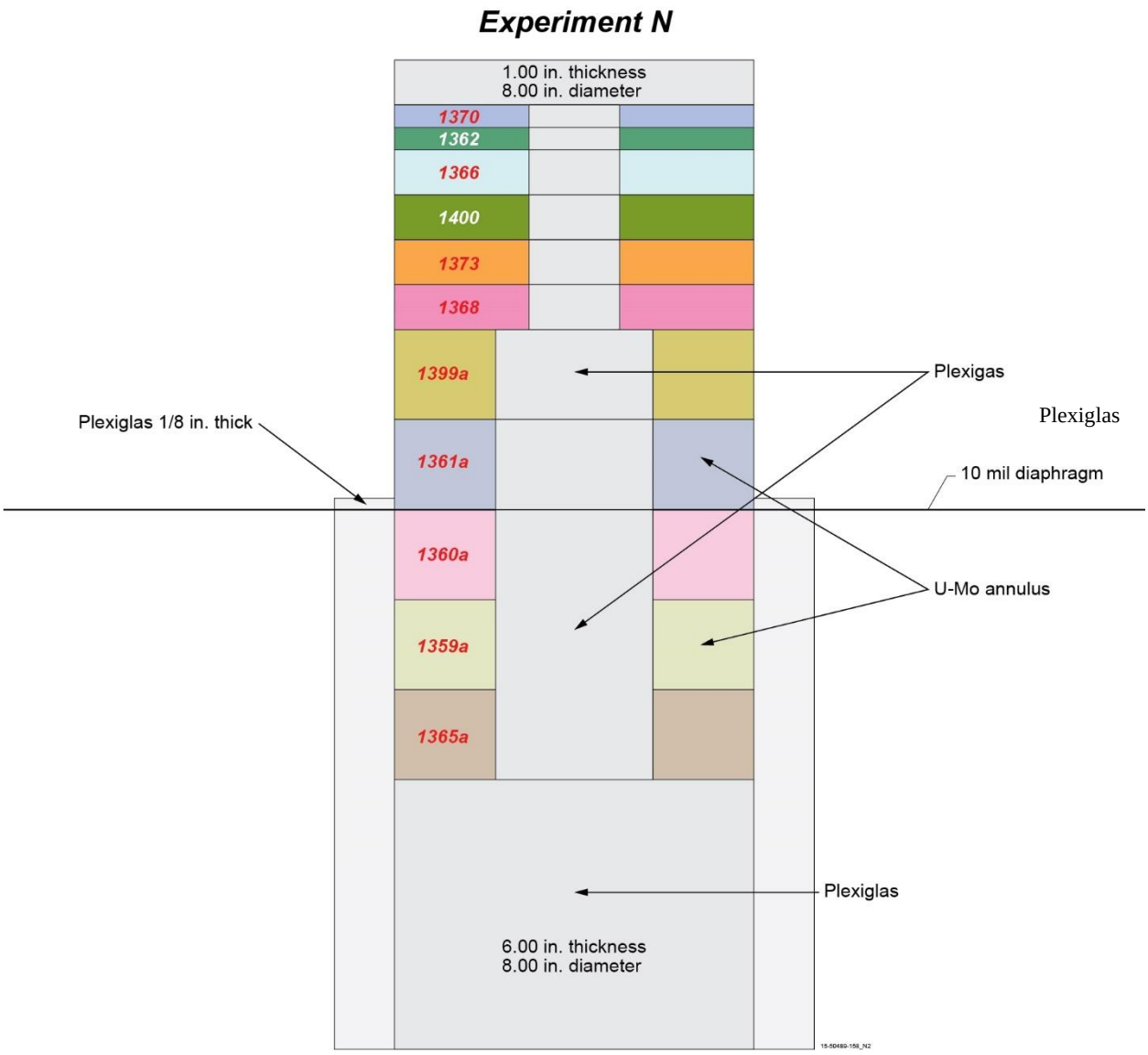

Figure 3.14.1. Configuration of U–Mo alloy annulus with top and bottom and partial radial reflector, Plexiglas center, Experiment N. (Only the last four digits of part numbers are given in the figure. The outside diameters of the inner Plexiglas are 3.480 and 1.980 in.)

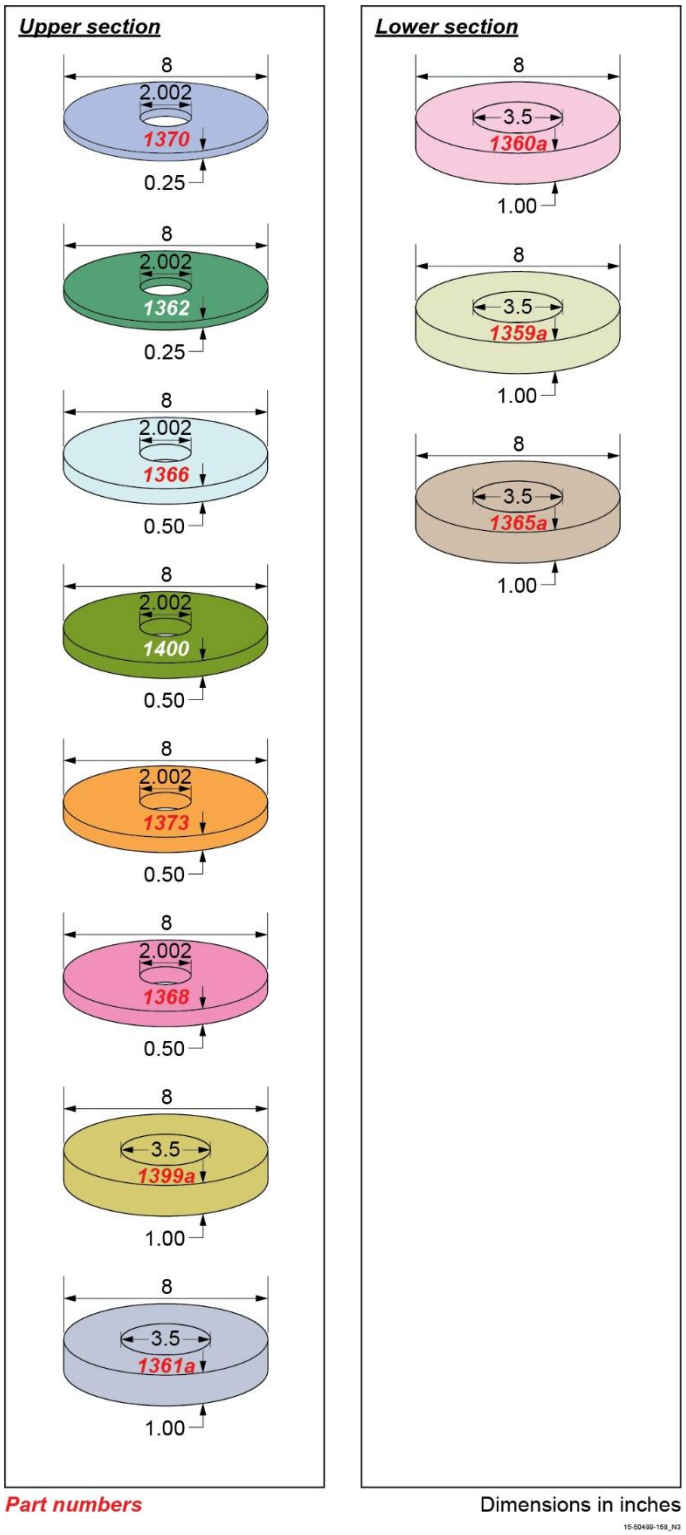

Figure 3.14.2. Description of U–Mo alloy Parts for Experiment N. (Only the last four digits of part numbers are given in the figure; outside diameters of the inner Plexiglas are 3.480 and 1.980 in.)

If the room is not included in the comparison of calculations with experiments, the effects of room return should be calculated using Monte Carlo simulations, and this effect should be subtracted from the

measured neutron multiplication factor. These calculations should assume the wall and floor were 2-ft-thick, and the concrete was Oak Ridge concrete, which used crushed limestone instead of sand in the aggregate. This thickness is sufficient because neutrons that penetrate deeper into the walls and floor have little chance of returning to the critical configuration

4. DESCRIPTION OF MATERIALS

4.1 URANIUM–MOLYBDENUM ALLOY

The fissile U–Mo alloy materials were nominal 8-in. OD. Nominal 2-in. ID annuli of a variety of thicknesses varying from 1/32 in. to 1 in. For each annulus, there were nominal 2-in.outside diameter cylindrical U–Mo alloy plugs with the same thicknesses as the annuli. Since the dimensional inspection reports were not yet retrieved from the Y-12 Plant, several assumptions were made that were consistent with HEU metal fabricated in the same machine shop as the U–Mo alloy. The outside diameters of the U–Mo central plugs were assumed to be 0.004 in. less than the nominal 2-in.-diameter or 1.996 in., which is consistent with other HEU metal parts fabricated at the Y-12 CNS that were intended to be used inside other HEU metal parts. The outside diameters of the annuli were assumed to be 8.000 in., and the inside diameters were 0.002 in. more than the nominal diameter or 2.002 in. Until the inspection reports are obtained from the Y-12 CNS, these assumptions about the part dimensions are the best estimates. After initial measurements, part number 1372 was cut into four ~90° pie-shaped parts with a loss a mass of 4 g or 103 g per pie-shaped part with a reduction of annular section to 89.1°. These pie-shaped parts were used for fine adjustments of the reactivity. The actual thickness of the parts was determined using the dimensions in Table 4.1 and a measured U–Mo density of 17.08 g/cm^3. The diametral holes in part numbers 1366 and 1381 were 0.385 in. in diameter. The inserts had a diameter of 0.375 in. One of the parts, 1396, was a 1 g key used to align the diametral hole in the U–Mo annulus with the diametral hole in the central U–Mo plug. The mass of the five thickest annuli varied only by 31 g of 13,190 g, which is extremely small. After the first five experiments were performed, these annuli were sent back to the machine shop to have the inside diameters increased to 3.500 in. (approximate diameter of the lower annuli in the HPRR). These annuli were then used with Plexiglas in a variety of measurements evaluating the effects of reflection by Plexiglas

Table 4.1. Uranium–molybdenum alloy parts.

Process batch number	Outside diameter (in.)	Inside diameter (in.)	Thickness (in.)	Mass (g)	Description
883 40 1359	8.000 (20.32) [a]	2.002 (5.0808)	1.000 [1.0004][b]	13,209	Annulus(17.0866)[c]
883 40 1359 [d]	8.000 (20.32)	3.500	1.000	11394	Annulus modified (17.0866)
883 40 1359	8.000 (20.32)	2.002 (5.0808)	1.000 [0.9988]	13,188	Annulus(17.0595)
883 40 1360 [d]	8.000 (20.32)	3.500	1.000	11376	Annulus modified (17.0595)
883 40 1361	8.000 (20.32)	2.002 (5.0808)	1.000 [0.9990]	13,194	Annulus(17.06729)
883 40 1361 [d]	8.000 (20.32)	3.500	1.000	11381	Annulus modified (17.06729)

Table 4.1. Uranium–molybdenum alloy parts (continued).

Process batch number	Outside diameter (in.)	Inside diameter (in.)	Thickness (in.)	Mass (g)	Description
883 38 1362	8.000 (20.32)	2.002 (5.0808)	0.250 [1.0000]	3,301	Annulus(17.08022)
883 40 1365	8.000 (20.32)	2.002 (5.0808)	1.000 [0.9986]	13,178	Annulus(17.05658)
883 40 1365 [d]	8.000 (20.32)	3.500	1.000	11367	Annulus modified (17.05658)
883 39 1366	8.000 (20.32)	2.002 (5.0808)	0.500	6390	Annulus(17.0109) source hole
883 39 1368	8.000 (20.32)	2.002 (5.0808)	0.500 [0.5009]	6614	Annulus(17.11126)
883 38 1370	8.000 (20.32)	2.002 (5.0808)	0.250 [0.2492]	3,291	Annulus(17.02848)
883 37 1371	8.000 (20.32	2.002 (5.0808)	0.125 [0.1248]	1,649	Annulus(17.0646)
883 35 1372	8.000 (20.32)	2.02 (5.0808)	1/32	416	Four 90^0 sections—after cutting into fourths each piece weighed 104 g
883 39 1373	8.000 (20.32)	2.002 (5.0808)	0.500 [0.49920]	6592	Annulus (17.054295)
883 36 1376	8.000 (20.32)	2.002 (5.0808)	1/16 [0.0626]	827	Annulus(17.1164)
883 46 1378	1.996 (4.990)	0	1.000 [1.0012](a)	876	Center plug (17.1011)
883 46 1379	1.996 (4.990)	0	1.000 [1.0024]	877	Center plug (17.1207)
883 46 1380	1.996 (4.990)	0	1.000 [1.0024]	877	Center plug (17.1207)
883 45 1381	1.996 (4.990)	0	0.500	376	Center plug (17.2239)
883 45 1382	1.996 (4.990)	0	0.500 1.31128 0.516 [0.4994]	438	Center plug (17.10118)
883 41 1383	1.996 (4.990)	0	1/32 [0.02979]	28	Center plug (17.4916)
883 41 1467 to 1470, 1477, to 1479 & 1481	1.996 (4.990)	0	1/32 [0.02979]	28	Center plug (17.4916) Masses not recorded in the logbook so each of the masses were assumed to be the same as part ending in 1383
883 42 1384	1.996 (4.990)	0	1/16 [0.06286]	55	Center plug(17.17927)
883 43 1385	1.996 (4.990)	0	0.125 [0.12428]	110	Center plug(17.17927)
883 44 1386	1.996 (4.990)	0	0.250 [0.24969]	219	Center plug(17.10118)

Table 4.1. Uranium–molybdenum alloy parts (continued).

Process batch number	Outside diameter (in.)	Inside diameter (in.)	Thickness (in.)	Mass (g)	Description
883 44 1387	1.996 (4.990)	0	0.250 [0.24969]	219	Center plug (17.10118)
883 45 1388	1.996 (4.990)	0	0.500 [0.5006]	438	Center plug (17.10118)
883 45 1389	1.996 (4.990)	0	0.500 [0.4982]	439	Center plug (17.140228)
883 47 1392	0.365 (0.9271)	0	0.125 [0.12463]	584	80 foil pieces(17.0296)
883 481393	0.365 (0.9271)	0	0.500 [0.5036]	59	4 foil pieces (17.2046)
883 49 1394	0.365 (0.9271)	0	1.500 [1.5023]	88	Diametral hole plugs (17.107)
883 50 1395	0.365 (0.9271)	0	3.000 [3.0047]	80 [e]	Diametral hole plug (17.107)
883 51 1396	1/8 (0.3175)	0	0.250	1	Key for aligning 1366 and 1381
883 40 1399	8.000 (20.32)	2.002 (5.0808)	1.000 [0.9988]	13,181	Annulus (17.0605)
883 40 1399 [d]	8.000 (20.32)	3.500	1.000	11370	Annulus modified (17.0866)
883 39 1400	8.000 (20.32)	2.002 (5.0808)	0.500 [0.5004]	6603	Annulus (17.0929)

[a] Numbers in parentheses are dimensions in centimeters.
[b] The numbers in brackets are dimensions calculated assuming the diameters were correct, and the density was 17.08 g/cm^3.
[c] The numbers in parentheses in this column are the U–Mo density in grams per cm^3.
[d] The masses for these parts were not recorded in the logbook.
[e] The mass of this part cannot be correct because it gives an impossible density. Thus, the mass was assumed to be 88 g, twice the mass of the 1.5-in.-long hole plugs.

In determining the U–Mo alloy stack heights, both the nominal heights and the numbers in brackets were used to determine the height of the assembled parts without gaps, and the difference was assumed to be the uncertainty.

Lacking the inspection reports for the ^{234}U and ^{236}U content, the average values of ^{234}U and ^{236}U for HEU metal parts fabricated at the Y-12 Plant in early 1961 with ^{235}U contents of 93.17 wt. % were used. Thus, the isotopic content of the uranium was 93.17 wt. % ^{235}U, 0.97 ^{234}U wt. %, and 0. 24 wt. % ^{236}U and by difference from 100 wt. % 5.62 wt. % for ^{238}U.

The chemical analysis determined the impurities given in Table 4.2. The chemical analysis was for samples drilled at the top and bottom of each casting after removing material from the surface. It is a good assumption that the impurity content varied linearly from the top of the part to the bottom (personal communication from Alan Moore, Y-12 National Security Complex, February, 2021). The remarks “cast with another process number” means cast simultaneously in different molds with the same liquid metal pour. The higher carbon content compared to HEU metal is attributable to the affinity of the U–Mo alloy for carbon during the casting process. Where parts were made as a batch, the impurity content of the

group is given. The properties of the individual parts such as molybdenum and impurity content should be used in any detailed neutron multiplication calculations.

Table 4.2. Chemical analysis if impurities for U–Mo alloy.

Mark Number	Part Size* Thickness in.	Process Batch No.	Molybdenum Content %	Alkali Metals Li, Na, K	Carbon	Gases O, N, H	Zr	Maximum Total Impurities	Remarks
1	1/32	883-35-1372	Top 10.180	<7.2 ppm	306 ppm	150 ppm	<20 ppm	796 ppm	Cast with 883-1368
			Bottom 10.220	<7.2	229	150	<20	718	
2	1/16	883-36-1376	Top 10.040	<8.2	258	75	<20	577	
			Bottom 9.992	<7.2	224	75	<20	737	
3	1/8	883-37-1371	Top 10.220	<7.2	172	140	<20	703	Cast with 883-1370
			Bottom 10.181	<7.2	220	140	<20	711	
4	1/4	883-38-1362	Top 10.170	<7.2	236	104.8	<20	784	Cast with 883-1366
			Bottom 10.173	<7.2	210	104.8	<20	647	
4	1/4	883-38-1370	Top 10.040	<7.2	149	140	<20	684	Cast with 883-1371
			Bottom 10.220	<7.2	172	140	<20	703	
5	1/2	883-39-1366 (with drill thru)	Top 10.200	<7.2	222	104.8	<20	681	Cast with 883-1362
			Bottom 10.170	<7.2	236	104.8	<20	784	
5	1/2	883-39-1368	Top 9.893	<7.2	236	150	<20	726	Cast with 883-1372
			Bottom 10.180	<7.2	306	150	<20	796	
5	1/2	883-39-1373	Top 10.190	<7.2	228	90	<20	650	
			Bottom 10.090	<7.2	203	90	<20	653	
5	1/2	883-39-1400	Top 10.261	<7.2	257	720	<20	682	
			Bottom 10.284	<7.2	266	720	<20	749	
7	1	883-40-1359	Top 9.872	<8.2	153	113.2	<20	732	
			Bottom 9.823	<7.2	156	113.2	<20	778	
7	1	883-40-1360	Top 10.196	<7.2	144	102.3	<20	724	
			Bottom 10.337	<7.2	203	102.3	<20	781	
7	1	883-40-1361	Top 10.470	<7.2	204	166	<20	750	
			Bottom 10.040	<7.2	211	166	<20	769	
7	1	883-40-1365	Top 10.090	<7.2	151	470	<20	578	
			Bottom 10.240	<7.2	139	470	<20	831	
7	1	883-40-1399	Top 10.230	<7.2	238	290	<20	683	
			Bottom 10.080	<7.2	200	290	<20	751	

* All Mark Numbers 1-7 are 8" OD discs with a 2" central hole

Mark Number	Part Size* Thickness in.	Process Batch No.	Molybdenum Content %	Alkali Metals Li, Na, K	Carbon	Gases O, N. H	Zr	Maximum Total Impurities	Remarks
11	1/32	883-41-1383							
11	1/32	883-41-1467							
11	1/32	883-41-1468							
11	1/32	883-41-1469							
11	1/32	883-41-1470							
11	1/32	883-41-1477							
11	1/32	883-41-1478							
11	1/32	883-41-1479	Top 10.335	<7.2 ppm	500 ppm	110 ppm	<20 ppm	1,125 ppm	A Casting Group
			Bottom 10.065	<7.2	490	110	<20	1,086	
11	1/32	883-41-1481							
12	1/16	883-42-1384							
13	1/8	883-43-1385							
14	1/4	883-44-1386							
15	1/2	883-45-1382							
15	1/2	883-45-1388							
15	1/2	883-45-1389							
17	1	883-53-1480							

* All Mark Numbers 11-17 are 2" diameter discs.

Table 4.2. Chemical analysis if impurities for U–Mo alloy (continued).

Mark Number	Part Size* Thickness in.	Process Batch No.	Molybdenum Content %	Alkali Metals Li, Na, K	Carbon	Gases O, N, H	Zr	Maximum Total Impurities	Remarks
17	1	883-46-1378							
17	1	883-46-1379							
17	1	883-46-1380	Top 10.157	<7.2 ppm	311 ppm	80 ppm	<20 ppm	811 ppm	A Casting Group
15	1/2	883-45-1381	Bottom 10.395						
14	1/4	883-44-1387							
30		883-47-1392	(80 pieces)						
31		883-48-1393	(4 pieces)						
32		883-49-1394	Top 10.230	<7.2	532 ppm	370 ppm	<20	955	A Casting Group
			Bottom 10.230	<7.2	324	370	<20	694	
33		883-50-1395							
50		883-51-1396							

Mark Numbers 14-17 are 2" diameter discs

Mark Numbers 30-33 are .365" OD rods with lengths as follows:

30 - 1/4"
31 - 1/2
32 - 1-1/2
33 - 3

The alkali metals were assumed to total 3.6 ppm with 1.2 ppm each. The gas impurities were assumed to be split equally between O, N, and H, and the Zr was 10 ppm. It was also assumed that the difference between the total in the table and those listed was equally split between Fe and Si. Additional information from reference [1] stated that the Si content was 60–300 ppm, and the Fe content was 10–300 ppm, which is consistent with these assumptions.

4.2 URANIUM METAL FOILS

In addition, uranium metal foils (0.010-in.-thick) were available for fine adjustment to achieve the critical condition. These foils were arrayed on top of the U–Mo fissile material. The larger foils had an outside diameter of 2.875 in. and an inside diameter of 0.199 in. with an average mass of 18.06 g. The smaller foils had an outside diameter of 1.437 in. and an inside diameter of 0.199 in. with an average mass of 5.25 g. In the configurations described here, these foils were not used. These foils were not used in these 14 experiments but are presented here since they were used in other measurements not reported here.

4.3 PLEXIGLAS REFLECTOR MATERIAL

The Plexiglas material, which was used as a top, bottom, and radial reflector and internal to the U–Mo annulus, was a methacrylate plastic (Plexiglas was available at the time from the Rohm & Haas Corporation of Knoxville, TN, $C_5O_2H_8$) that contained 5.8×10^{22} atoms of hydrogen per cubic centimeter, 3.6×10^{22} atoms of carbon per cubic centimeter and 1.45×10^{22} atoms of oxygen per cubic centimeter. The density of the Plexiglas was 1.20 g/cm^3.

4.4 STAINLESS STEEL 304

There were stainless steel cylindrical plugs with the same thicknesses as the annuli that were used in the center of the annuli. These were used for the annular U–Mo assembly with a central steel core. Stainless steel was also the material of the diaphragm on which the upper portion of the critical assembly and the 36 nuts and bolts that supported the diaphragm. The composition of the stainless steel 304 was 18 wt. % chromium, 8 wt. % nickel, and the rest was iron with less than 0.03 wt. % carbon. Other impurities are

Mn < 2.0, P <0.045, S < 0.03, Si < 0.75, and N = 0.10 wt. %. The density of 18/8 stainless steel 304 from the literature is 7.93 g/cm^3. It is one of the oldest stainless steels and was used in these experiments. The outside diameters of the cylindrical central stainless steel plugs were 0.004 in. less than the nominal 2-in.-diameter or 1.996 in., which is consistent with other material fabricated at the Y-12 Plant to be inside HEU metal parts,

4.5 GLYPTAL

Glyptal was a coating on both sides of the piece of cadmium metal used between the top Plexiglas reflector and the U–Mo alloy. Its density is 1.03 g/cm^3, and its chemical composition is $C_6H_4(CO)_2O$.

4.6 CADMIUM

Two different thicknesses were used 0.010- and 0.026-in.-thick with the later coated with 0.0015 in. of Glyptal on both sides. The density of cadmium was 8.65 g/cm^3. Cadmium metal sheets have a minimum cadmium content of 99.5 wt. %. It should be assumed that the uncertainty in the thickness of cadmium metal sheet was ± 1%.

5. UNCERTAINTY ANALYSIS

The uncertainty analysis should include the reactivity effect associated with uncertainties in the configurations and materials [13] on the neutron multiplication factor. Estimates of the uncertainties in the specification of the experiments are given in this section. The uncertainties in the various items need to be each reflected in the uncertainty on the measured experimental neutron multiplication factor. The initial masses and only one of the inspection reports was available and it was the chemical analysis. The Y-12 Plant Records Department may have additional information as to the physical properties, uranium isotopic analysis, masses, and dimensional analysis. These U–Mo alloy parts were fabricated at Building 9215 in February or early March 1961and shipped to the ORNL Oak Ridge Critical Experiments Facility (ORCEF) in Building 9213 at the Y-12 Plant. Five major parts were shipped from ORCEF at Building 9213 back to building 9215 for remachining (most likely one working day after May 18, 1961) and then shipped back to Building 9213. These transfers occurred between May 19 and May 28, 1961; to Building 9215 at the beginning of this time period and back to Building 9213 at the end of the time period. (Most likely one working day before May 29, 1961). The masses and dimensions of the remachined parts are needed and may be on nuclear material control and accounting records for the shipments as well as inspection reports. These known dates for the machining and shipments and the part number should facilitate the search for these records. Availability of these records will reduce the uncertainties in these materials for the final benchmark analysis.

Since these experiments are cylindrically symmetric, the required uncertainty analysis can be performed by two-dimensional transport theory calculation like the S_n method and of course by Monte Carlo neutron transport methods. Some of the uncertainties may be sufficiently small that direct calculations are not practical. In these cases a larger change in the calculation is used and the result is then multiplied by the ratio of the actual uncertainty to that used in the calculation. This sections contains some suggestions as the uncertainties for the various parameters the affect the neutron multiplication factor.

5.1 UNCERTAINTY IN URANIUM ISOTOPES

The ^{235}U content of the uranium was given as 93.17 wt. % with no statement as to the content of ^{234}U and ^{236}U. The uncertainty in the ^{235}U content was assumed to be 0.005 wt. %. To estimate the content of these other uranium isotopes, isotopic analysis for other metal HEU samples [13] were used. All isotopic analysis available to the author with 93.17 wt. % ^{235}U were tabulated and the ^{234}U and ^{236}U values were

averaged. There were 10 uranium isotopic measurements with ^{235}U content of 93.17 wt. %. In these 10 measurements the ^{234}U contents were 0.95, 0.97, 0.97, 0.97, 0.97, 097, 0.98, 1.01, 1.01 and 1.02 wt. %, and the ^{236}U contents were 0.21, 0.24, 0.24, 0.24, 0.24, 0.24, 0.24, 0.21, 0.21, and 0.21 wt. %. The average ^{234}U and ^{236}U contents are 0.98 ± 0.022 wt. % and 0.228 ± 0.015 wt. %, respectively. Thus, the isotopic contents are: 93.17 ± 0.005 wt.% for ^{235}U, 0.98 ± 0.022 wt.% for ^{234}U, 0.228 ± 0.015 wt. % for ^{236}U, and 5.622 ± 0.027 wt. % for ^{238}U. The ^{238}U content is estimated by difference from 100 wt. % and was not measured.

5.2 U–MO ALLOY DENSITY AND HEIGHT

The density of the U–Mo for all the parts are given in Table 4.1. The dimensions were calculated in two ways. The first was to use the nominal dimensions and the stated U–Mo alloy density of 17.08 g/cm^3. The other was to use the radial dimensions and the stated masses of the parts and calculate the height of the part that gives that density. These heights are given in Table 2.1. In the uncertainty analysis the neutron multiplication factor with the density of 17.08 g/cm^3 and the nominal heights need to be calculated. Also perform a calculation with the alternate heights given in Table 2.1 and the separate densities for each part. The difference is an uncertainty due to density and height.

5.3 MOLYBDENUM CONTENT OF THE ALLOY

The molybdenum content was measured for each of the parts fabricated from samples at the top and bottom of the casting and are given in Table 4.2. The density varied linearly from the top to the bottom of each casting. The average measured molybdenum for all parts is 10.1616 ± 0.1393 wt. %. In the specification of each part for calculation, the density could be varied linearly from the top to the bottom of the part given in Table 4.2 or an average for each part could be used.

5.4 STACKING HEIGHT OF U–MO ALLOY

The height of the fissile assemblies was not measured. Based on Y-12 fabricated HEU metal assemblies of similar diameter the gap between parts was assumed to be zero with an uncertainty of −0 and +0.001 in. Calculate the neutron multiplication factor with the assembled system and with a 0.001-in. gap between the parts vertically. The difference will be the uncertainty in the experimental neutron multiplication factor resulting from uncertainty in height.

5.5 STACKING ORDER

It is not quite clear what the stacking order was for all experiments. In general, the heavier parts of the top sections were on the closest to the diaphragm and the lower part numbers were usually below higher part numbers except for part 1366 in Experiments A, B, and C where spatial fission density distributions were measured. The way to determine the sensitivity to stacking order is to vary the location of the parts and calculate the change in the neutron multiplication factor.

5.6 RADIAL DIMENSIONS OF U–MO ALLOY PARTS

Based on other measurement with radially nested uranium metal parts fabricated at Y-12, the inner diameters were 0.002 in. over nominal and the outer diameters were 0.004 in. under nominal. Thus, the outer diameter of the central U–Mo alloy plugs was assumed to be 2.002 in. and the inner diameter of the annuli were assumed to be 1.996 in. Since the outer diameter of the annuli did not need to fit inside anything it was assumed to be 8.000 in. The uncertainty in these dimensions was assumed to be ±0.001 in. The neutron multiplication factor needs to be calculated for the nominal radial dimension and then for a reduced dimension based on this dimensional uncertainty,

5.7 PLEXIGLAS DIMENSIONS

The Plexiglas parts for the central core were 0.010 in. less on the outside diameter that the inner diameter of the U–Mo fissile parts they were inside. Thus, the outside diameters were 1.990 and 3.490 in. with an uncertainty of 0.005 in. on the diameters. For many of the reflector Plexiglas parts radial thicknesses were 1.000 in. The heights of the Plexiglas reflector parts were usually the same thickness as the U–Mo alloy parts they surrounded. There were two sets of parts with nominal outside diameters of 10 and 12 in. Since 0.010-in.-thick cadmium had to be inserted around the outer radial surface of the U–Mo alloy annuli inside the radial reflector, the inside diameter of the nominal 10-in.-OD as slightly larger than 8.00 in. It is assumed the inside diameter was 8.030 in. to allow for the insertion of the cadmium. Thus, the outside diameter was 10.030 in. The inner diameter of the outer parts used for the two-in.-thick reflector assemblies on the outside of the inner reflector was 10.050 in and the outer diameter was 12.050 in. The uncertainty in the diameters of the reflector parts was 0.010 in. The uncertainty in the thicknesses was assumed to be 0.005 in.

5.8 STACKING OF PLEXIGLAS

It is assumed that the gaps in stacking of the Plexiglas parts was 0.003 in. with an uncertainty of +0 and −0.003 in.

5.9 PLEXIGLAS DENSITY

It is assumed the uncertainty in the Plexiglas density (1.20 g/cm^3) was +0 and −0.01 g/cm^3 because the density given in the literature is given as 1.19 g/cm^3. Neutron multiplication factor calculation need to be performed for each delayed critical configuration containing Plexiglas with a density of 1.19 and 1.20 and the difference in the neutron multiplication factor contributes to the uncertainty in the experimental neutron multiplication factor.

5.10 STAINLESS STEEL 304 DENSITY

Stainless steel density was 7.93 g/cm^3. Its uncertainty is assumed to be +0 and −0.08 g/cm^3. The difference in the calculated neutron multiplication factor of the configuration with stainless steel with the variation in density is the uncertainty in the experimental neutron multiplication factor from stainless steel 304 density uncertainty.

5.11 STAINLESS STEEL 304 DIMENSIONS

It is assumed that the machining of the stainless steel 304 parts at the Y-12 Plant had the same tolerances as the uranium parts. For the uncertainty analysis ± 0.001 in. can be assumed for the dimensions. The difference in the calculated neutron multiplication factor of the configuration with stainless steel and those increased by 0.001 in. is the uncertainty in the experimental neutron multiplication factor from the uncertainty in stainless steel 304 dimensions. The uncertainty in the vertical gaps between stainless steel is as good as for the uranium and an estimate is 0.000 in to 0.001 in.

5.12 VERTICAL GAP BETWEEN STAINLESS STEEL CENTRAL PLUGS

The gap between stainless steel plugs was assumed to be zero. The assumed uncertainty in the gap between each stainless steel part is assumed to be +0.001 in. and −0. The difference in the calculated neutron multiplication factor of the configuration with stainless steel gaps of 0 and 0.001 in. is the uncertainty in the experimental neutron multiplication factor from stainless steel 304L gap uncertainty.

5.13 LATERAL ALIGNMENT OF THE UPPER AND LOWER SECTIONS

The estimated lateral misalignment of the upper and lower sections was assumed to be 1/32 in. Perform neutron multiplication factors for each assembly with the sections aligned and misaligned and the difference in calculated values will be a good estimate of the alignment uncertainty.

6. SUPPLEMENTAL EXPERIMENTAL MEASUREMENTS

There were a variety of experimental measurements needed for reactor design and include fission density distributions, void coefficients as a function of radius, ratio of ^{235}U to ^{238}U fissions, and prompt neutron time decay. The fission density distributions are needed to predict the highest temperature location in the reactor. The void coefficients needed to assess the effect of the axial holes in the reactor associated with the control rod locations. The fission density spatial distributions and void coefficients are given in ORNL CF Number 61-8-71 [1]. Pulsed neutron measurements were performed with a 150KV Cockcroft–Walton accelerator and are not reported here. These measurements determined the ability of calculational methods at the time used for the HPRR design.

7. CONCLUSIONS

These accurate descriptions of the configurations and materials may allow many of these experiments to be incorporated into to the International Criticality Safety Benchmark Program (ICSBEP). Uncertainty analysis needs to be performed to determine the accuracy of the neutron multiplication actors, k_{eff}. This analysis should mimic that performed for other ICSBEP nuclear criticality safety benchmarks already documented 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 measured k_{eff} values for some of the assemblies could be as low as ±0.0002 for some configurations.

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