ORNL/TM-2022/2481

# Delayed Critical Enriched Uranium Metal, 7-in.-diam. Cylinder with Thin Stainless Steel Top and Bottom Reflectors

John T. Mihalczo

**July 2022**

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

**DOCUMENT AVAILABILITY**

Reports produced after January 1, 1996, are generally available free via US Department of Energy (DOE) SciTech Connect.

**_Website_** www.osti.gov

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
**_Telephone_** 703-605-6000 (1-800-553-6847)
**_TDD_** 703-487-4639
**_Fax_** 703-605-6900
**_E-mail_** info@ntis.gov
**_Website_** http://classic.ntis.gov/

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
**_Telephone_** 865-576-8401
**_Fax_** 865-576-5728
**_E-mail_** reports@osti.gov
**_Website_** http://www.osti.gov/contact.html

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**ORNL/TM-2022/2481**

Physics Division

# DELAYED CRITICAL ENRICHED URANIUM METAL, 7-IN.-DIAM. CYLINDER WITH THIN STAINLESS-STEEL TOP AND BOTTOM REFLECTORS

John T. Mihalczo

July 2022

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

# CONTENTS

FIGURES .......... v
TABLES .......... v
ABSTRACT .......... 1
1. INTRODUCTION .......... 1
2. DESCRIPTION OF MEASUREMENTS .......... 2
  2.1 OVERVIEW OF EXPERIMENTS .......... 2
  2.2 EXPERIMENTAL METHODOLOGY .......... 2
3. DESCRIPTION OF ASSEMBLIES .......... 6
  3.1 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 0.5 IN. THICK TOP AND BOTTOM REFLECTOR .......... 7
  3.2 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 1 IN. THICK TOP AND BOTTOM REFLECTOR .......... 10
  3.3 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 2 IN. THICK TOP AND BOTTOM REFLECTOR .......... 15
4. DESCRIPTION OF MATERIAL .......... 18
  4.1 URANIUM METAL .......... 19
5. ADDITIONAL MEASUREMENTS .......... 20
6. CONCLUSIONS .......... 21
ACKNOWLEDGMENTS .......... 22
REFERENCES .......... 22
APPENDIX A. RECENT REPORTS DOCUMENTING PAST ORCEF UNDOCUMENTED EXPERIMENTS .......... A-1
APPENDIX B. EXPERIMENTS DOCUMENTED IN THE NUCLEAR ENERGY AGENCY INTERNATIONAL HANDBOOK OF EVALUATED CRITICALITY SAFETY BENCHMARK EXPERIMENTS .......... B-1
APPENDIX C. SUPPORT STRUCTURE .......... C-1
APPENDIX D. ROSSI ALPHA DATE FOR THIN STAINLESS STEEL REFLECTED CRITICAL EXPERIMENTS .......... D-1

## FIGURES

Figure 2.1. Vertical assembly machine with the movable vertical lift table in the up position. ...................3
Figure 2.2. The 7 in. diameter uranium metal cylinder with 1 in. thick top and bottom reflectors in the disassembled condition on the vertical assembly machine at ORCEF. ....................................4
Figure 2.3. Sketch of the fixture for lateral alignment of upper and lower uranium metal cylinders...........6
Figure 3.1. Configuration of the uranium metal and steel material for the experiment with 0.5 in. thick top and bottom reflectors. ........................................................................................7
Figure 3.2. Description of the uranium metal and steel parts for the experiment with 0.5 in. thick top and bottom reflectors. ........................................................................................9
Figure 3.3. Top view of the configuration of the top uranium parts for the uranium cylinder with 0.5 in. thick top and bottom reflectors. ........................................................................................9
Figure 3.4. Configuration of the uranium and steel material for the experiment with 1 in. thick top and bottom reflectors and unfilled holes in the uranium metal.....................................................11
Figure 3.5. Description of the uranium metal and steel parts for the experiment with 1 in. thick top and bottom reflectors and unfilled holes in the uranium metal. ..............................................13
Figure 3.6. Configuration of the fissile material for the experiment with 1 in. thick top and bottom reflectors and filled holes in the uranium metal.............................................................................13
Figure 3.7. Description of the uranium metal parts for the experiment with 1 in. thick top and bottom reflectors and filled holes in the uranium metal. ................................................................15
Figure 3.8. Configuration of the fissile material for the experiment with 2 in. thick top and bottom reflectors. ........................................................................................................................16
Figure 3.9. Description of the uranium metal parts for the experiment with 2 in. thick top and bottom reflectors. ........................................................................................................................18

## TABLES

Table 4.1. Dimensions and masses of reflector parts.....................................................................18
Table 4.2. Composition of stainless steel 316.................................................................................19
Table 4.3. Mass, dimensions, and isotopics for uranium metal 7 in. diameter cylindrical parts ................19
Table 4.4. Measured average impurity content[a] of uranium metal cylinders for delayed critical experiments with two 7 in. diameter interacting cylinders ...........................................................20
Table 5.1 Prompt neutron decay constant of uranium metal cylinder with thin top and bottom steel reflectors ..........................................................................................................................21

# ABSTRACT

Three 7 in. diameter highly enriched uranium (HEU; 93.17 wt % $^{235}U$) metal cylinders were assembled on the vertical assembly machine of the Oak Ridge Critical Experiments Facility (ORCEF) with thin stainless steel reflectors (0.5, 1, and 2 in. thick) on the top and bottom. These experiments were performed during January 13–25, 1965, and used seven operational days at ORCEF. Before these experiments, unreflected and unmoderated 7 in. diameter HEU metal cylinders had been assembled to delayed criticality at ORCEF, and the results were benchmarked in HEU-MET-FAST-051. In addition to the critical experiments, the prompt neutron decay constant was measured via the Rossi-α technique, and those results are also presented in this report. To achieve near-delayed-critical systems, 5 × 5 × 0.03125 in. rectangular uranium metal parts were used on top of 7 in. diameter cylinders inside the top reflector. The delayed critical configuration from the three experiments described herein are acceptable for use as criticality safety benchmark experiments for the International Criticality Safety Benchmark Evaluation Program (ICSBEP), coordinated by the Nuclear Energy Agency, once the uncertainty analysis is completed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainty in $k_{eff}$ is expected to be as low as ±0.0002. The prompt neutron time decay data could be the basis of an International Reactor Physics Evaluation Program benchmark.

This report was prepared as part of an effort at the US Department of Energy's (DOE's) 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 DOE critical experiments facilities using more than 500 operational days of critical facility time. The publication of this report was supported by the Nuclear Criticality, Radiation Transport, and Safety Section of ORNL.

# 1. INTRODUCTION

A variety of critical experiments were constructed with unreflected and unmoderated highly enriched uranium (HEU; 93.15 wt % $^{235}U$) metal during the 1960s and 1970s at the Oak Ridge Critical Experiments Facility (ORCEF) at the US Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) in support of criticality safety of the Y-12 National Security Complex [1–8]. Of these hundreds of delayed critical assemblies, three assemblies of 7 in. diameter unmoderated HEU metal cylinders were assembled to delayed criticality with 0.5, 1, and 2 in. thick stainless steel type 304 top and bottom reflectors [9]. The experiments were performed during January 13–25, 1965. Experiments with unmoderated and unreflected 7 in. diameter HEU metal cylinders have been reported and analyzed in HEU-MET-FAST-051 [10]. Other HEU metal experiments at ORCEF already in the Nuclear Energy Agency benchmark (NEA) database are HEU-MET-FAST-059, -061, -071, and -100 [11]. The prompt neutron decay constant was measured via the Rossi-α technique [12], and the results of fitting the data to obtain the prompt neutron decay constants are summarized. Co-experimenters in these measurements in 1965 were J. J. Lynn and R. G. Taylor.

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 Evaluation Program (ICSBEP) benchmark. The data from the experiments described should be acceptable for use as criticality safety benchmark experiments for the ICSBEP and the NEA nuclear criticality safety benchmark program once the uncertainty analysis is completed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainty in $k_{eff}$ could be as low as ±0.0002 for some configurations. The prompt neutron time decay data could be the basis of an International Reactor Physics Evaluation Program benchmark.

This report was prepared as part of an effort at ORNL to document more than 15 undocumented critical and subcritical experiments enumerated in ORNL/TM-2019/18 [13] and performed by ORNL at ORCEF and other DOE critical experiments facilities using more than 500 operational days of critical facility time. The publication of this report was supported by the Nuclear Criticality, Radiation Transport and Safety Section of ORNL. Other reports in the series are listed in Appendix A, and benchmarks of ORNL experiments in the ICSBEP Handbook are listed in Appendix B.

# 2. DESCRIPTION OF MEASUREMENTS

## 2.1 OVERVIEW OF EXPERIMENTS

The critical experiments described in this report are clean critical experiments with HEU (93.17 wt % $^{235}U$) metal with thin (0.5, 1, and 2 in.) top and bottom reflectors. The experiments were performed in January 1965 to evaluate the effect of thin-metal reflection on the prompt neutron decay constant and to determine its effect on the kinetics of fast burst reactors such as the Health Physics Research Reactor [14].

The data from these three experiments should be acceptable for use as criticality safety benchmark experiments in ICSBEP once the uncertainty analysis is performed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainty in $k_{eff}$ is expected to be as low as ±0.0002 because the procedure for assembly and detailed description of the materials and configurations are the same as other measurements with HEU metal.

## 2.2 EXPERIMENTAL METHODOLOGY

The cylindrical assemblies comprised uranium metal cylinders with dimensions machined to precise tolerances. The experiments were performed in a deliberate and step-by-step manner, and observed data were recorded. The assemblies were approximately divided into a fixed upper section on a 0.010 in. (10 mil) thick diaphragm and a movable lower section mounted on a low-mass 30 in. high aluminum support tower. These supports are described in Appendix C.

### 2.2.1 General Assembly Procedure

The assemblies were constructed on a vertical assembly machine [15] that primarily consisted of a hydraulic lift (up to 22 in. vertical motion) to support the lower section (Figure 2.1) and a stationary upper half consisting of four vertical posts spaced 4 ft. apart, which held a support for the upper section of critical experiments. The upper support shown in Figure 2.1 was not used in these experiments. Instead, the upper section of each experiment was supported by a 30 in. inner diameter, 1.0 in. thick, 2.0 in. wide aluminum clamping ring that held in tension a 0.010 in. thick stainless steel (304L) diaphragm. The diaphragm clamping apparatus had a total thickness of 1 in. and was bolted together using 34 stainless steel bolts (0.375 in. diameter, 1.5 in. long) with appropriate nuts. The clamping ring was supported by the four vertical poles (on 4 ft centers) with a low-mass aluminum support structure. The mating surfaces of the clamping ring were not flat so that when the nuts were tightened, the diaphragm would be held in tension (Figure 2.2). The lower section was supported on a low-mass aluminum 30 in. high support tower mounted on the vertical lift platform, also shown in Figure 2.2. The lower support stand supported the uranium metal assemblies with 0.125 in. thick aluminum edges, oriented vertically and 120° apart. Lateral motion on the lower section was restrained by small aluminum pieces bolted to the 120° vertical members. These are visible in Figure 2.2. The low-mass support stand's 0.50 in. thick aluminum base was bolted to the vertical lift, as shown in Figure 2.2.

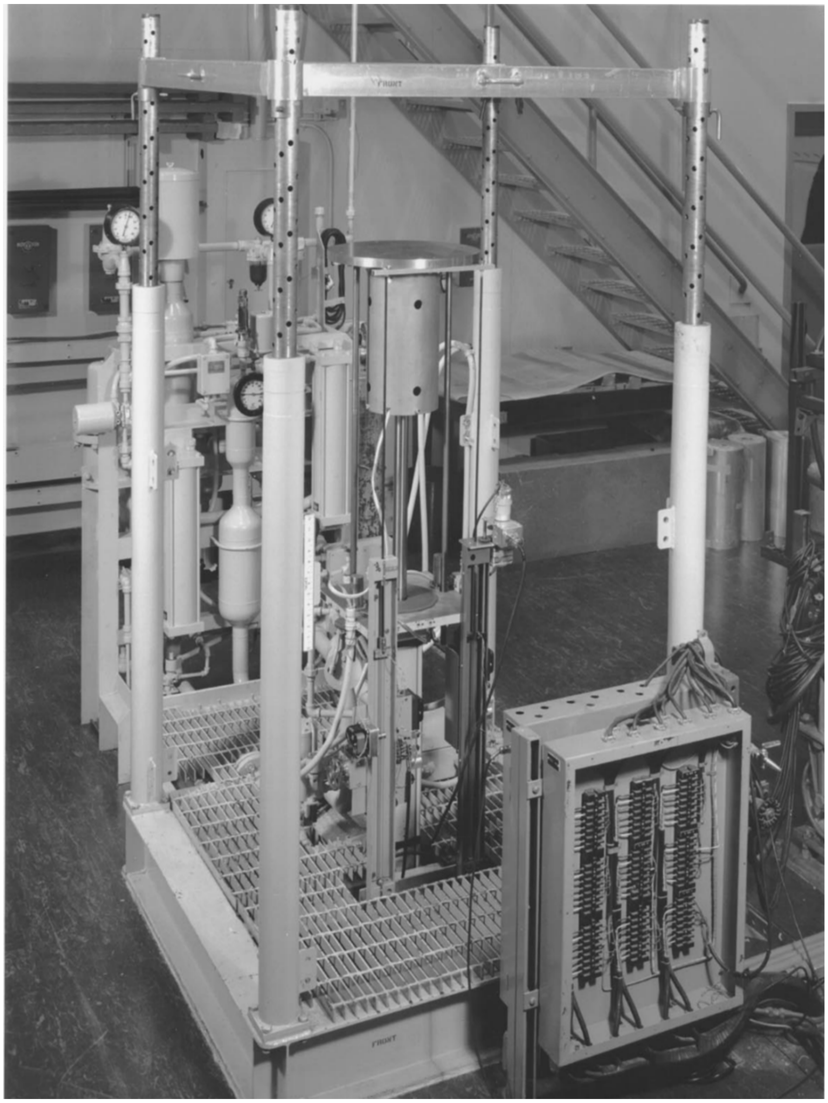


**Figure 2.1. Vertical assembly machine with the movable vertical lift table in the up position.** No lower support structures are shown in this photograph except for the vertical lift table; the upper support structure in this photograph was not used in these experiments.

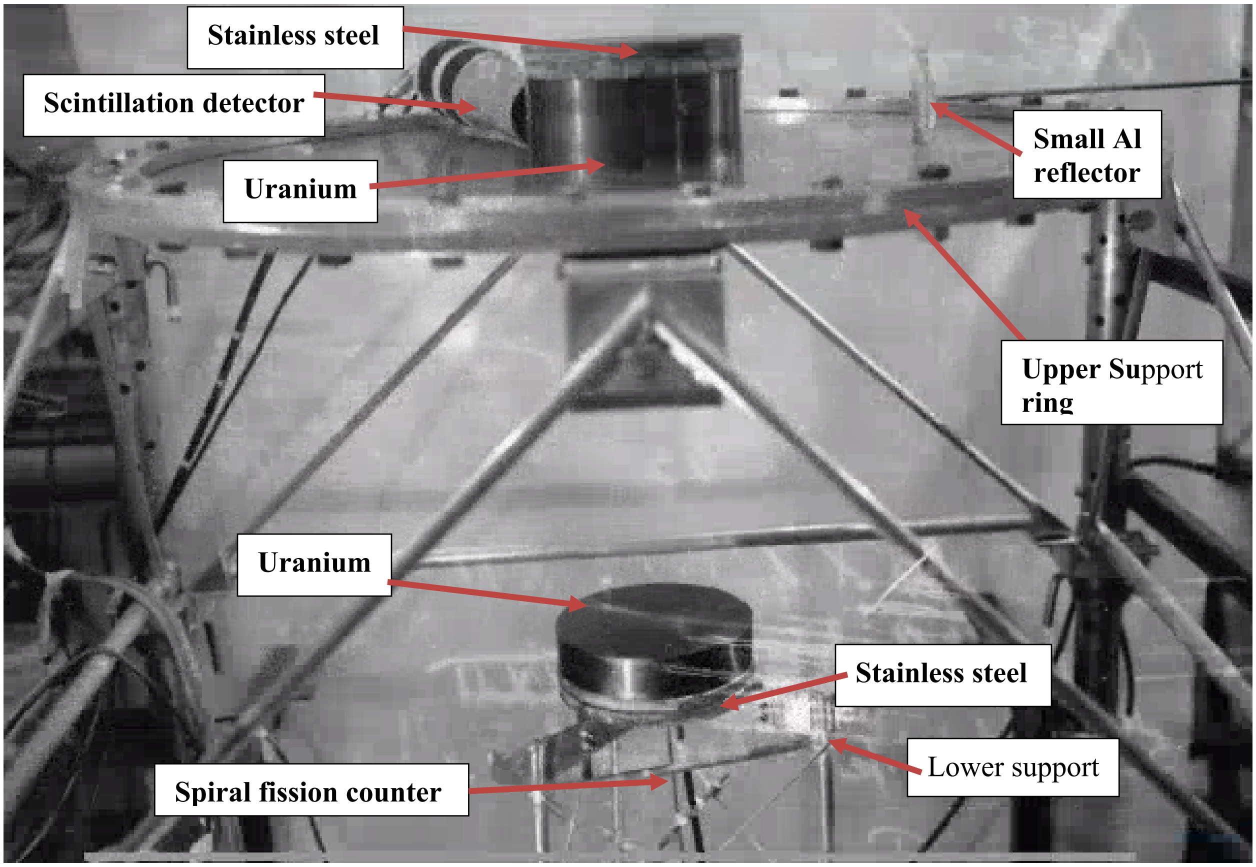


**Figure 2.2. The 7 in. diameter uranium metal cylinder with 1 in. thick top and bottom reflectors in the disassembled condition on the vertical** assembly machine at ORCEF. Scintillator adjacent to radial uranium surface on diaphragm and spiral fission counter adjacent to bottom reflector. The tube for the signal cable is pointed out in the figure, and the small fission counter itself adjacent to the steel reflector is not visible. A liquid scintillator in a 0.25 in. thick lead shield for prompt neutron decay measurements is on the diaphragm in the back on the left with the lead shield 0.5 in. from the radial surface of the uranium metal. A 2.875 × 1.875 × 0.25 in. aluminum reflector can be seen on the right that was used for fine reactivity adjustment during the Rossi-α measurement that were done usually with two detectors.

## 2.2.1 Alignment of each half

The upper and lower sections were aligned using the processes described below. Uncertainty in the radial alignment of the top uranium metal section with respect to the bottom uranium metal section was ±0.005 in.

### 2.2.1.1 Upper Section

To assemble the upper section, a uranium metal cylinder was added to the top diaphragm. A uranium metal cylinder was positioned on the sagging diaphragm and leveled with a high-precision level. This configuration ensured that the uranium cylinder was centered. The location of the material was continually adjusted with a precise high-quality level, first in one direction and then rotated 90° on the part. If the assembly was not exactly centered in the diaphragm, then it would not be precisely level because of the sag in the diaphragm as it was loaded. The remaining uranium metal cylinders were added to the top section. After this uranium metal cylinder was aligned with the upper uranium metal cylinder on the lower support stand, two precisely machined steel blocks (±0.0001 in.) were used to squeeze the material at the outer radial surface until the upper and lower sections were each aligned radially. An edge of the machined block was held at one outside radial location, and material was adjusted until minimal light was visible between the machined block and the uranium metal configuration. This process was repeated 90° from the position of the original adjustment, and then 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 differ only by the difference in the diameters of the uranium cylinders.

#### 2.2.1.2 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 stainless steel reflector with aluminum foil. The foil was placed between the edges of the support stand and the lowest reflector part so that the upper surface of the lower uranium section was level.

### 2.2.2 Lateral Alignment of the upper section with the lower section

Two identical fixtures (Figure 2.3) were used for lateral alignment between the upper section and the lower section. They were U-shaped and were machined out of 0.375 in. thick aluminum. The end pieces were carefully machined at the Y-12 shops to be perpendicular to the long direction of the fixture and coplanar with each other. When leveled properly on the diaphragm, the front face of the 4 × 4 × 0.5 in. end pieces were vertical and in the same plane to within ±0.001 in. This fixture was carefully machined and handled delicately when not in use so as not to damage it. In use, the lower side of the upper leg rested on the top surface of the clamping ring for the diaphragm. The fixture was perpendicular to the outer radial surface of the cylinder. As indicated in previous sections of this report one uranium metal cylinder was located on the diaphragm and one uranium cylinder was located on the lower reflector. The fixture was moved inward until it touched the uranium of the top section. The leveling screws were adjusted until the fixture was level. The second fixture was placed 90° apart from the first in a similar manner. Both fixtures were moved back slightly, and the lower section was raised until the uranium metal of the lower section was as high as the lower end piece of the fixture. Then, both fixtures were nearly adjusted properly. The fixtures were moved in until they touched uranium (either on the top or the lower section). When lack of contact was observed at either of the front-end faces of the fixture, the lower section was lowered to the full-out position, and the position of the uranium and reflector on the lower support stand was adjusted. The lower lift table was then raised, and the alignment was rechecked. The process was repeated several times as necessary. The rest of the uranium cylinders were added to the top section and the lateral alignment rechecked and adjusted appropriately. This was a long and tedious procedure that sometimes took up to 12 h or more; however, it was always performed, so the top and bottom sections were aligned within ±0.005 in. After alignment, the remaining materials were placed on the top and lower sections, as described in Sections 2.2.1.1 and 2.2.1.2. Whenever the bottom plate in an assembly differed from the previous measurement, these stacking and alignment procedures were repeated.

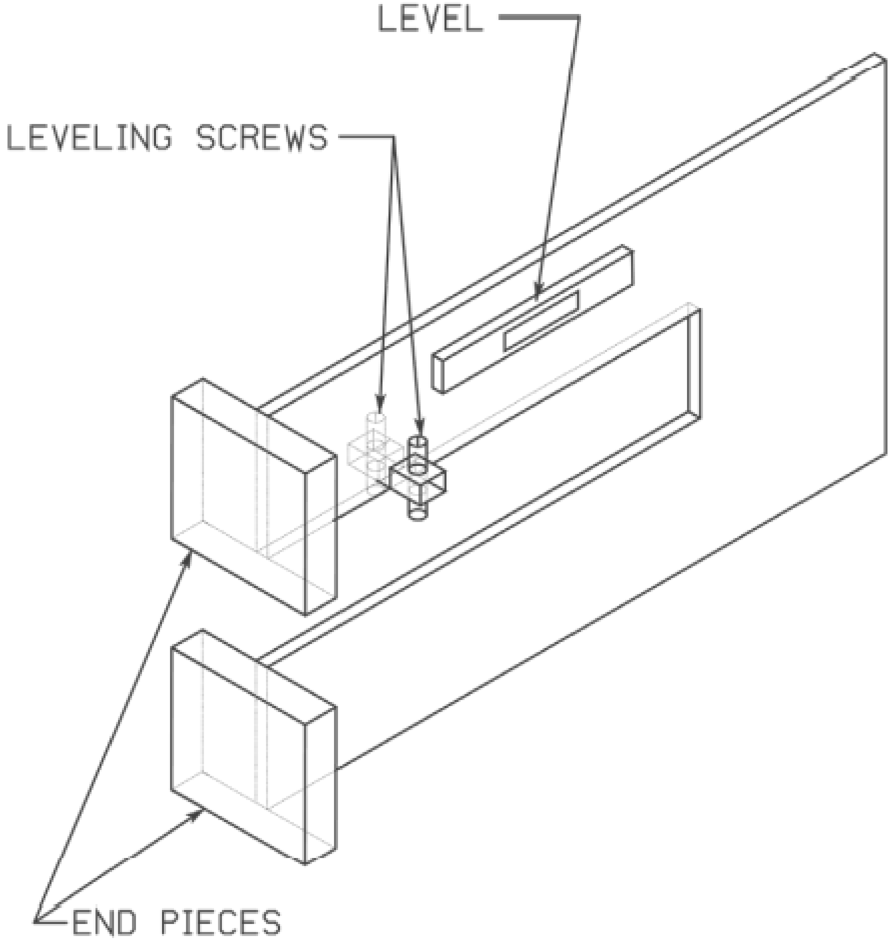


Figure 2.3. Sketch of the fixture for lateral alignment of upper and lower uranium metal cylinders.

The upper limit of the vertical lift motion was set so that it could hold the upper surface of the material on the lift at the position of the diaphragm with no load. As a result, upon completion of the assembly, the vertical lift also supported the material on the diaphragm because, with the load of the uranium metal, the diaphragm sagged about 0.15 in.

## 3. DESCRIPTION OF ASSEMBLIES

At the start of these measurements, the uranium metal parts had axial holes for fission density spatial distribution measurements for interacting uranium metal cylinders [3,7]. There were also a diametral hole in uranium metal cylinder 2732 and an additional vertical hole near the outside diameter in uranium metal part 2731. For measurements on or after January 20, 1965, uranium metal plugs became available and were used for plugging the holes. Thus, some experiments may have two delayed critical configurations: one with the holes empty and another with the hole filled with uranium plugs. The hole diameters were 0.375 in., and the uranium plug diameters were 0.365 in.

## 3.1 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 0.5 IN. THICK TOP AND BOTTOM REFLECTOR

This assembly was constructed on January 13, 1965, and is described on page 159 of ORCEF logbook E-22. The nominal height of the cylindrical uranium metal assembly was 4.5625 in. with a 5 × 5 in. uranium metal plate on top and 0.5 in. thick top and bottom reflectors outside the uranium. The reactor period was infinite and thus the $k_{eff}$ was 1.0000. All the cylindrical uranium metal parts had 0.375 in. diameter axial holes. Part 2732 also had a 3.25 in. long, 0.375 in. dimeter radial hole from the outside in with the center of the radial hole 0.3125 in. above the lower surface of the part. Part 2731 had a vertical hole 0.881 in. deep about 0.5 in. in from the radial surface. The axial hole in part 2731 was only 0.875 in. deep from the top. In this experiment, the holes in the uranium parts were empty.

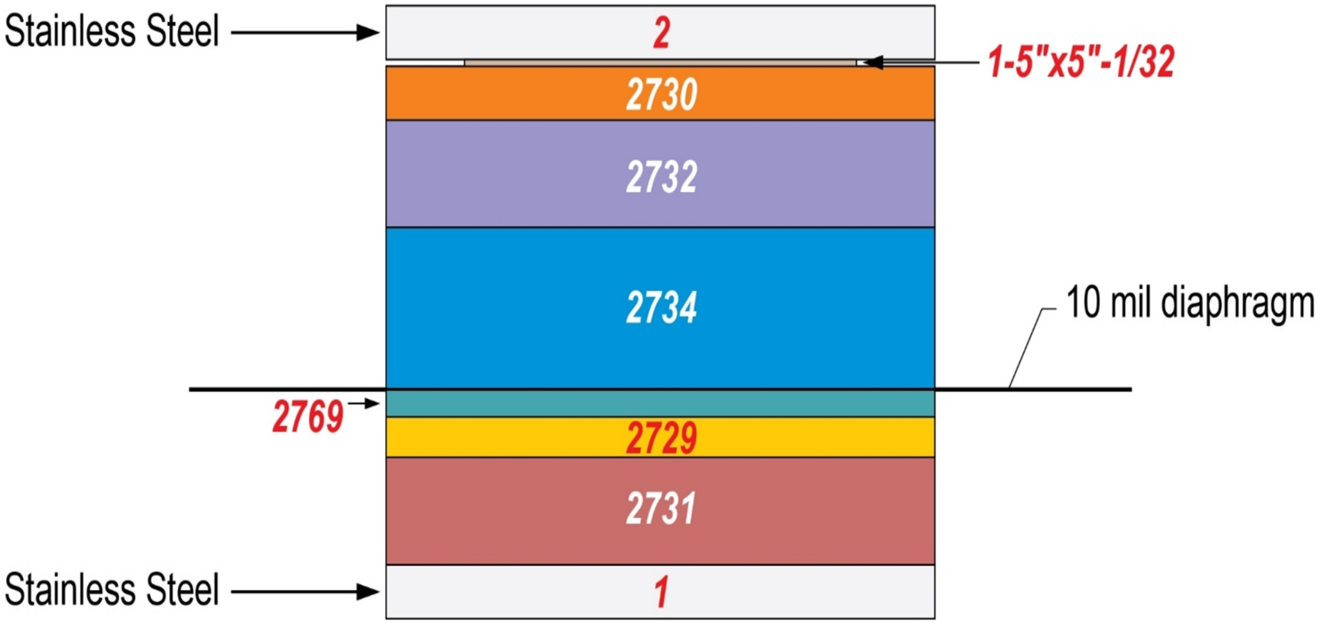


**Figure 3.1. Configuration of the uranium metal and steel material for the experiment with 0.5 in. thick top and bottom reflectors.** Measured thickness of the stainless steel was 0.507 in. on top and 0.505 in. on bottom; the 0.375 in. diameter holes in the uranium metal cylinders are not shown on the sketch.

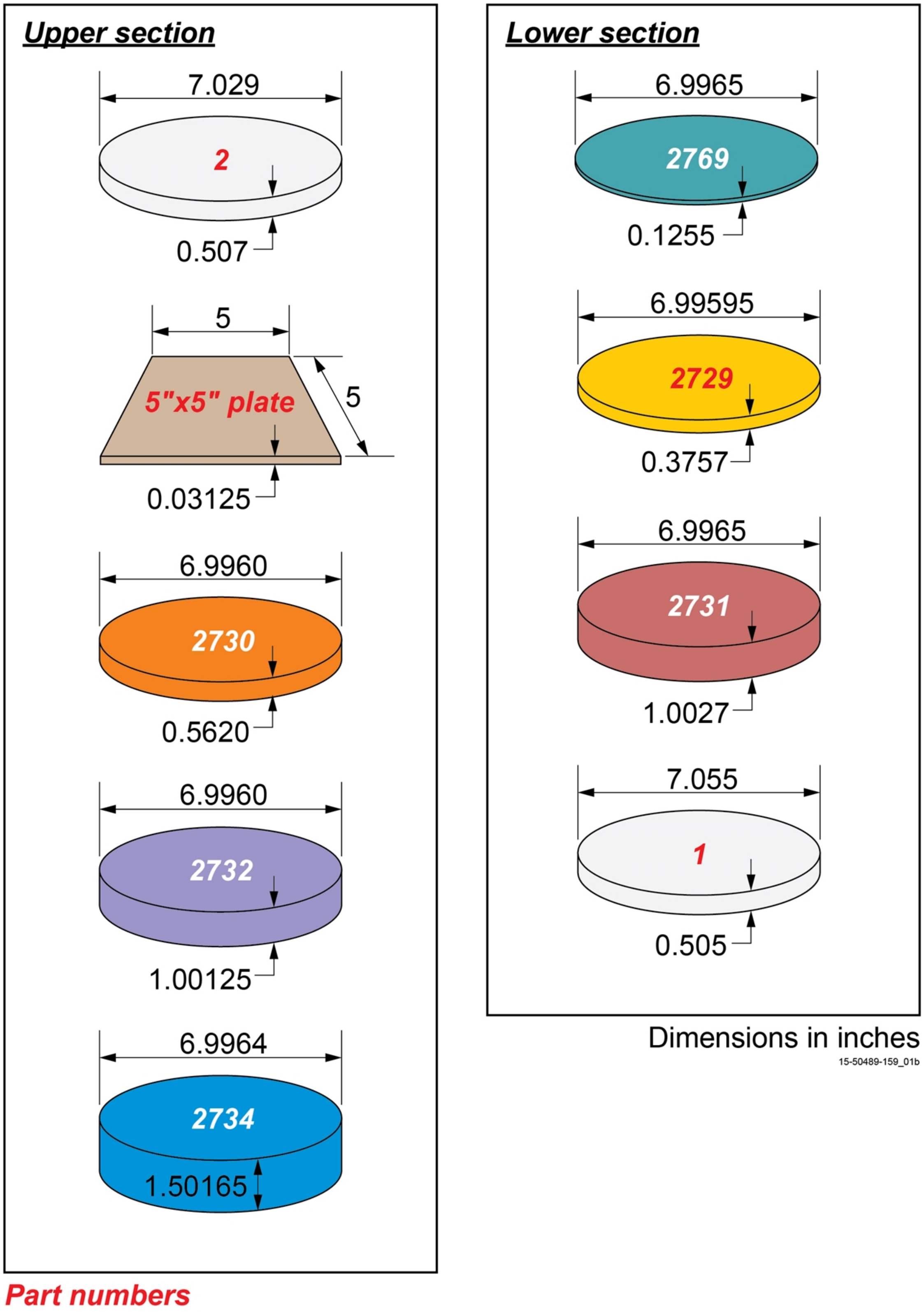


**Figure 3.2. Description of the uranium metal and steel parts for the experiment with 0.5 in. thick top and bottom reflectors.** Measured thickness of the stainless steel was 0.507 in. on top and 0.505 in. on bottom; the 0.375 in. diameter holes in the uranium metal cylinders are not shown

The sum of the thicknesses of cylindrical uranium metal parts in this assembly is 4.5688 in., and the total mass, including that of the 5 × 5 × 0.03125 in. plate, was 53,843 g. The uranium metal cylinders were precisely machined so that the gap between the stacked cylindrical pieces was essentially 0.000 in. This condition was verified in previous measurements with these same 7 in. diameter uranium metal cylinders [10]. However, the 5 × 5 in. uranium metal plate was not as flat as the cylindrical uranium metal parts. Measurements with the configuration of the system with 2 in. thick stainless steel on the top and bottom showed that with two plates between the stainless steel reflector and the cylindrical uranium metal parts, the measured distance between the steel and the cylindrical part was 0.069 in. for two plates. The thickness of the two plates was 0.0625 in. Thus, the air gap was 0.0065 in. for two plates. For the one plate of this experiment, it was assumed that the air gap for the one plate of this configuration was 0.00325 in.: half (0.0016 in.) above the plate between the steel and the uranium plate and half between the uranium plate and the cylindrical uranium metal part below the plate. This gap is probably not uniform because of the deformity of the flatness of the plate and probably varies radially slightly in the assembly.

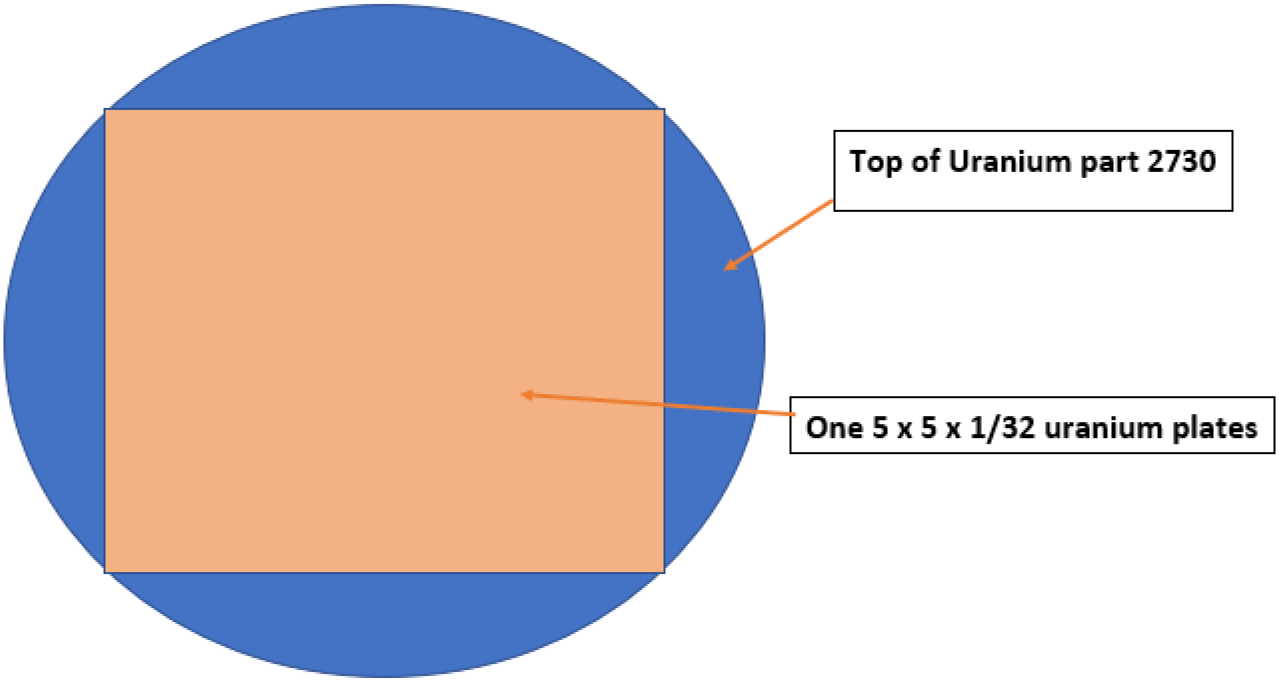


**Figure 3.3. Top view of the configuration of the top uranium parts for the uranium cylinder with 0.5 in. thick top and bottom reflectors.**

This assembly with 0.5 in. thick top and bottom reflectors was reassembled with the radial and axial holes filled with 0.365 in. diameter uranium metal plugs, as described on page 171 of ORCEF logbook E-22, Run V2, without the 5 × 5 × 0.03125 in. uranium metal plate on top. The holes were filled as full as possible with uranium metal. The uranium metal plugs had a variety of thicknesses (0.1, 0.125, and 0.25 in.) for fission density distributions, and larger lengths were used for plugging holes on some of the parts. Small voids were possible at the top of the vertical holes because the minimum plug height was 0.1 in. To calculate the mass of the uranium metal plugs, the uranium metal density was assumed to be 18.75 g/cm$^3$. This assumption results in a uranium metal mass of 32.15 g/in. for the plugs. Additional documentation of the plug characteristics may be available from Y-12's dimensional inspection reports and Nuclear Material Control and Accountability records dated just before January 20, 1965. The uranium axial hole plugs in the section below the diaphragm were 1.375 in. long, which resulted in a 0.0012 in. gap between the top of the plugs and the diaphragm. The 3.25 in. deep radial hole in part 2732 was filled with 3.25 in.

long plugs. The additional 0.881 in. deep hole near the outside surface in part 2731 was filled with a 0.875 in. long plug, a gap of 0.006 in. existed between the top of the plugs and the bottom of part 2729 above it. The 3.0649 in. axial hole in the uranium above the diaphragm was filled with a 3.00 in. long plug, which resulted in a 0.0649 in. gap between the top of the plugs and the top of part 2730. The system was supercritical. The reactivity was reduced by removing the 1.375 in. long uranium plugs from the axial hole in the uranium on the lower section. The total uranium mass of the system was 53,841 g, and the height of the uranium metal parts was 4.5688 in. This mass is almost identical to the mass of the system with empty holes in the uranium metal. The resulting reactor periods from two measurements were +18.67 and +20.75 s, corresponding to an average reactivity of +28.12 cents. Using an effective delayed neutron fraction value of 0.0066 yields a $k_{eff}$ of 1.00186.

The support structure's contribution to reactivity was evaluated by doubling the support structure: a support stand was added to the top, and an additional 0.010 in. thick stainless steel was placed between the upper and lower sections. The resulting reactivity change was −3.71 cents (run 2 compared with run 3). Adding the 0.010 in. thick stainless steel between the upper and lower sections to evaluate the reactivity reduction of the diaphragm (run 2 compared with run 4) reduced the reactivity 13.64 cents. This answer is not quite correct for the reactivity effect of the diaphragm because the change in reactivity from doubling the diaphragm thickness underestimates the decrease. Other measurements [16] support this observation; therefore, a better estimate must be obtained by calculating the ratio of the worth of the initial 0.010 in. to the worth of the added 0.010 in. of the diaphragm. The ratio can then be used with the measured −13.64 cents to obtain the reactivity value for the nominal thickness.

The effects of room return should be calculated using Monte Carlo simulations that 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. The 2 ft concrete thickness is adequate for the calculation because neutrons that reach 2 ft into the concrete have little chance of returning to the critical assembly.

The best calculated value for comparison with measurements may be obtained using the critical configuration with the support structure and the experimental cell (including air). This scheme eliminates uncertainties associated with corrections for surrounding materials. The 1 in. thick steel table of the vertical lift should also be included in this calculation. To get a statistically accurate result, the effects of the cell must be calculated with longer than usual Monte Carlo simulations. A calculation of room return alone must be used to estimate the calculation length required to estimate these small effects accurately. The length of time to obtain a good statistical estimate of the effect of room return should then be used for the calculation of the configuration with all surrounding materials.

## 3.2 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 1 IN. THICK TOP AND BOTTOM REFLECTOR

This assembly was constructed on January 14, 1965, and is described on page 161 of ORCEF logbook E-22, run I. At the time of this measurement, the axial holes and other holes in the 7 in. diameter uranium metal cylinders were empty. The uranium metal plugs were not available for filling the holes until January 20, 1965. The system was exactly at delayed critical, so the $k_{eff}$ value was 1.0000. This assembly contained 50,715 g of HEU metal, and the sum of the heights of the uranium cylindrical metal parts was 4.3166 in. The gaps between the uranium metal parts were essentially 0.000 in. with an uncertainty of −0.000 and +0.001 in. The configuration of the parts is given in Figure 3.4, and the parts are described in Figure 3.5.

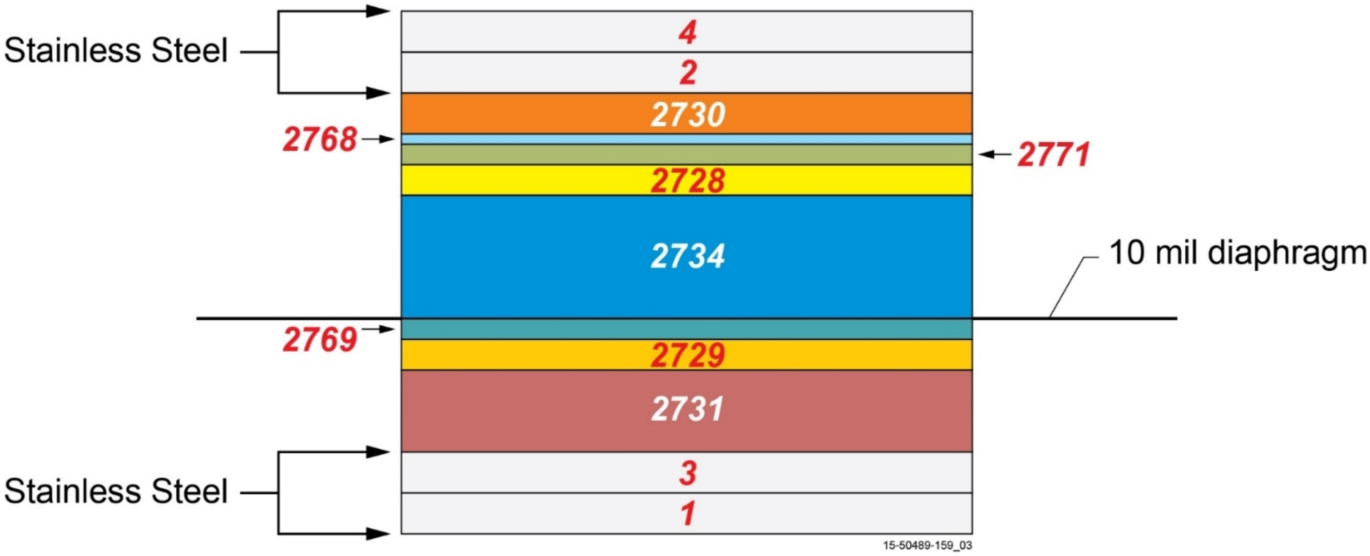


**Figure 3.4. Configuration of the uranium and steel material for the experiment with 1 in. thick top and bottom reflectors and unfilled holes in the uranium metal.** Measured thickness of the stainless steel on top was 1.026 in. and 1.0246 in. on bottom; 0.375 in. diameter holes in the uranium metal are not shown on the sketch.

The gap between the bottom and top steel reflector parts measured 0.0116 and 0.0140 in., respectively and the gap between the uranium and the steel measured 0.007 in.

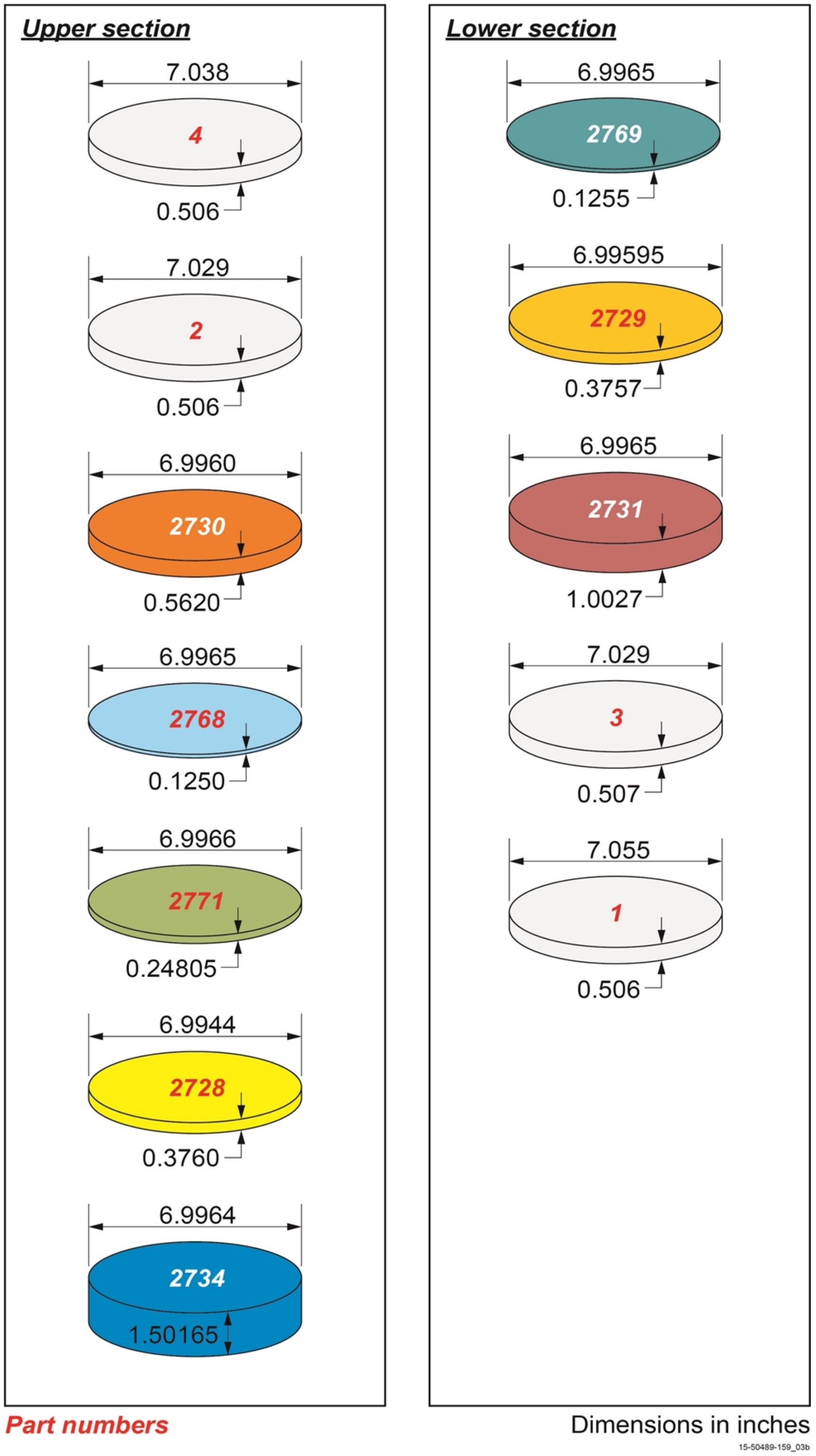


**Figure 3.5. Description of the uranium metal and steel parts for the experiment with 1 in. thick top and bottom reflectors and unfilled holes in the uranium metal.** Measured thickness of the stainless steel was 1.026 in. on top and 1.0246 in. on bottom.

On January 22, 1965, another configuration of the cylinder with 1 in. thick top and bottom reflectors was assembled. In this new configuration, the holes were filled with uranium metal inserts (page 168 of ORCEF logbook E-22, Run 3). In addition to the uranium metal cylinders there was a 5 × 5 × 0.03125 in. plate between the top of the upper uranium metal cylinder and the upper reflector. The reactivity was + 5.44 cents, and the corresponding $k_{eff}$ was 1.00036 using an effective delayed neutron fraction of 0.0066. The configuration of this assembly was a variation of that shown in Figure 3.4: parts on the diaphragm above part 2734 were replaced by parts 2732 and 2771 and a 5 × 5 × 0.03125 in. uranium plate, and all holes were filled. This configuration is shown in Figure 3.6, and the parts are described in Figure 3.7. The mass of uranium in the assembly was 50,388 g, including uranium metal plugs and the uranium metal plate, and the sum of the heights of the uranium metal cylinders was 4.2548 in. The gap between the uranium metal plate and the parts above and below it was assumed to be 0.0016 in.

**Figure 3.6. Configuration of the fissile material for the experiment with 1 in. thick top and bottom reflectors and filled holes in the uranium metal.** Measured thickness of the stainless steel was 1.026 in. on top and 1.0246 in. on bottom; 0.375 in. diameter holes in the uranium metal are not shown on the sketch.

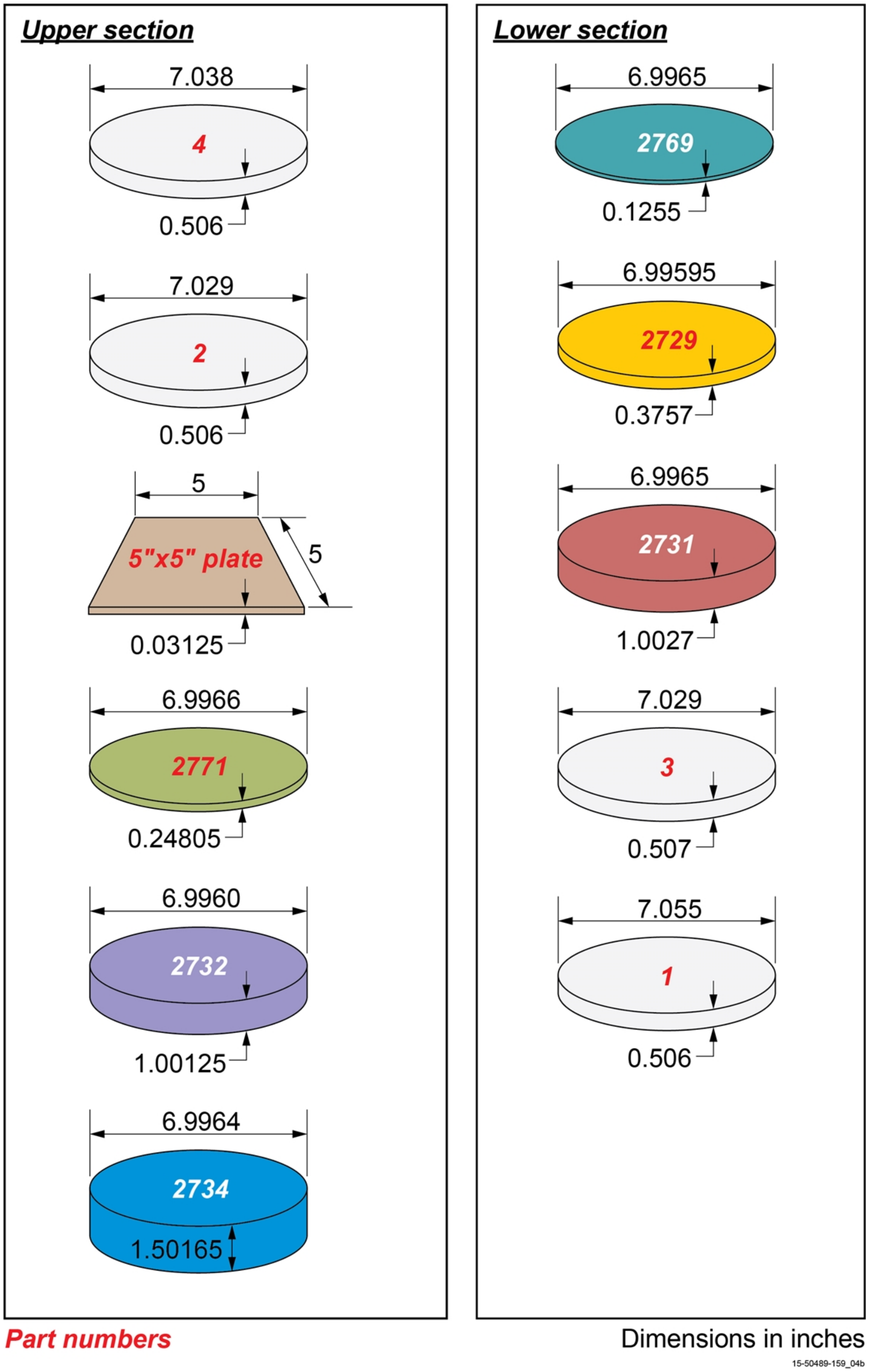


**Figure 3.7. Description of the uranium metal parts for the experiment with 1 in. thick top and bottom reflectors and filled holes in the uranium metal.** Measured thickness of the stainless steel was 1.026 in. on top and 1.0246 in. on bottom; the holes in the uranium metal are not shown.

The support structure was evaluated, and the total reactivity effect of the ring, diaphragm, and lower support stand was −10.6 cents. This value must be corrected for the underestimate of the worth of the stainless steel diaphragm [16].

The effects of room return should be calculated using Monte Carlo simulations that 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. The 2 ft thickness for the concrete is adequate for the calculation because neutrons that reach 2 ft into the concrete have little chance of returning to the critical assembly.

The best calculated value for comparison with measurements may be obtained using the critical configuration with the support structure and the experimental cell (including air). This scheme eliminates uncertainties associated with corrections for surrounding materials. The 1 in. thick steel table of the vertical lift should also be included in this calculation. To get a statistically accurate result, the effects of the cell must be calculated with longer than usual Monte Carlo simulations. A calculation of room return alone must be used to estimate the calculation length required to estimate these small effects accurately. The length of time to obtain a good statistical estimate of the effect of room return should then be used for the calculation of the configuration with all surrounding materials.

## 3.3 THE 7 IN. DIAMETER URANIUM METAL CYLINDER WITH 2 IN. THICK TOP AND BOTTOM REFLECTOR

This assembly was constructed on January 20, 1965, and is described on page 164 of ORCEF logbook E-22, run Q. This is the first assembly with the 0.375 in. diameter holes in the uranium parts 2731, 2732, and 2734 filled with 0.365 in. diameter uranium metal inserts. The configuration is shown in Figure 3.8, and the parts are described in Figure 3.9. The top square plate of the two at the top was rotated so that both plates had common sides. The reactivity of the assembly (run Q) was +1.85 cents, corresponding to a $k_{eff}$ of 1.00012 using an effective delayed neutron fraction of 0.0066.

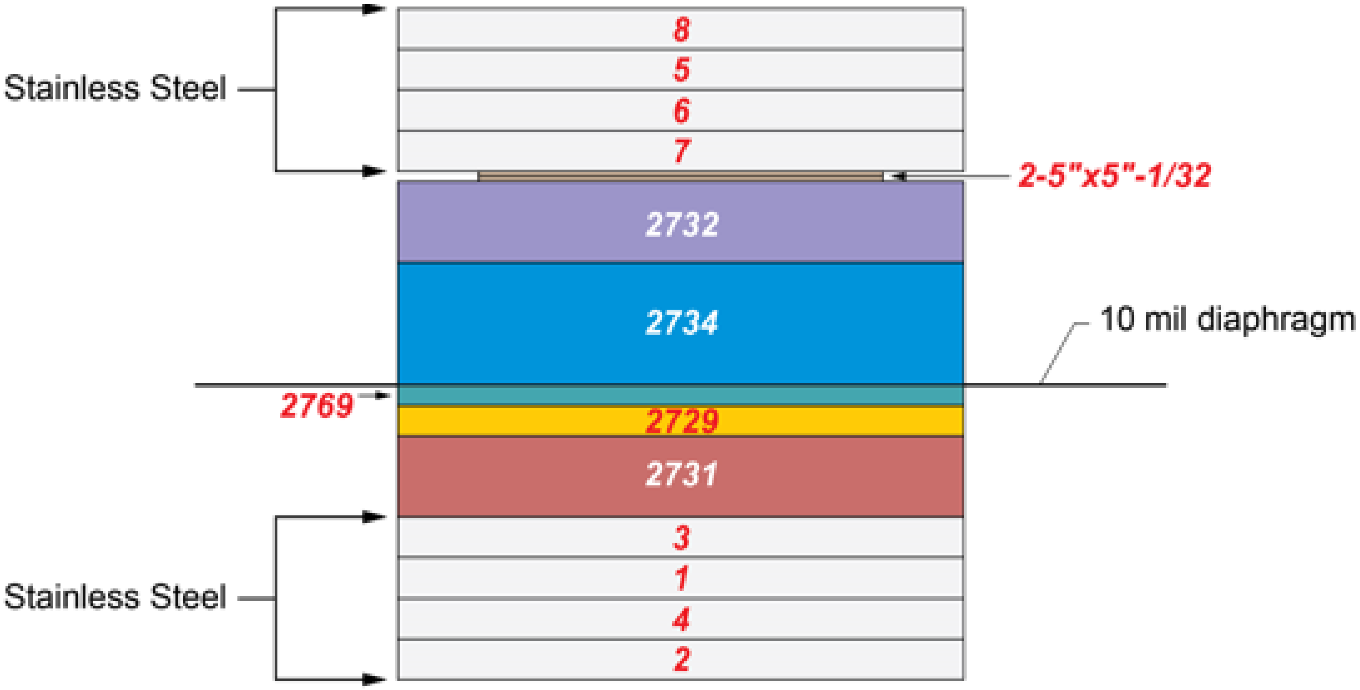


**Figure 3.8. Configuration of the fissile material for the experiment with 2 in. thick top and bottom reflectors.** Measured thickness of the stainless steel was 2.0705 in. on top and 2.0606 in. on bottom; 0.375 in. diameter holes in the uranium metal are not shown on the sketch.

The uranium axial hole plugs in the section below the diaphragm were 1.375 in. long, so there was gap of 0.0025 in. between the top of the plugs and the diaphragm. The additional 0.881 in. deep hole in part 2731 was filled with 0.875 in. long plugs and the there was a gap of 0.006 in. between the top of the plugs and the bottom of part 2729. The radial hole in part 2732 was completely filled with uranium plugs with total length of 3.25 in. The 2.5029 in. axial hole in the uranium above the diaphragm was filed with 2.500 in. long plugs and thus there was a gap of 0.0029 in. between the top of the plugs and the 5 in. square uranium metal plate. The total mass of uranium in the assembly including the uranium plugs was 47,711 grams and the height of the uranium metal cylinders was. 4.0068 in.

The measured thicknesses of the top and bottom reflectors were 2.0707 and 2.0606 in., respectively. The average thickness of each part was 0.506 in. and thus the total thickness of the steel in the top and bottom reflectors is 2.024 in. The total thickness of all three gaps was 0.0467 in. With steel adjacent to four gaps (three steel to steel and one steel to uranium), the gap between the steel and the uranium was assumed to be half of the gap between steel parts because the uranium is almost perfectly flat compared with the steel. This assumption implies that the thickness of each of the three gaps between steel for the top reflector is 0.016 in. and that for the bottom reflector was 0.013 in.

The measured distance between part 2732 and the stainless steel part 7 was 0.069 in. Thus, the space not occupied by the uranium metal plates (0.069 minus 0.625 in.) was 0.0065 in. between uranium part 2732 and steel part 7. The gap between the lower uranium plate and part 2732 and the upper uranium plate and reflector part 7 were both assumed to be 0.0016 in. The gap between the two uranium metal plates was assumed to be 0.0032 in. Previous measurements [10] for the 7 in. diameter uranium metal cylinders have shown that the assumption of no gap between the uranium metal cylinders of this diameter with an uncertainty of −0.000 and +0.001 in. is realistic

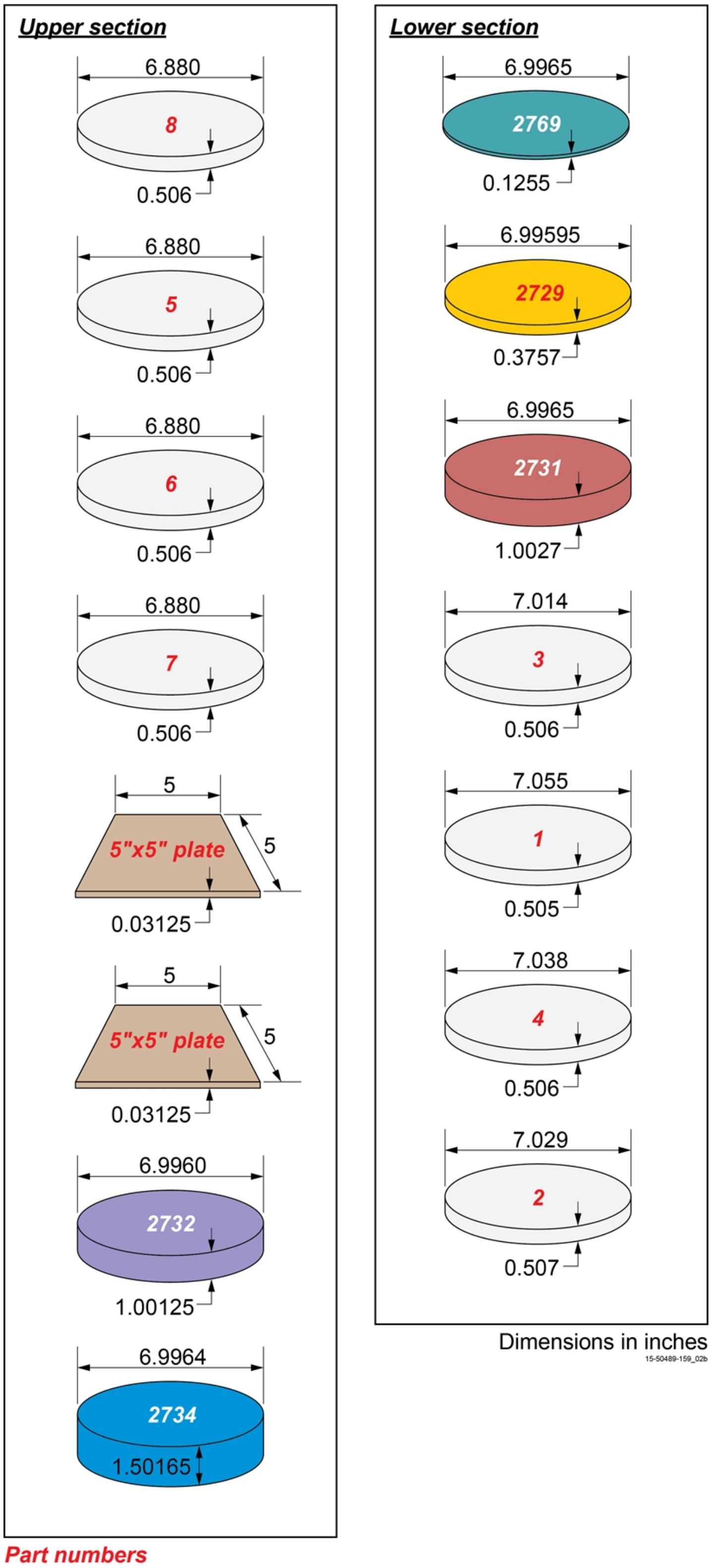


**Figure 3.9. Description of the uranium metal parts for the experiment with 2 in. thick top and bottom reflectors.** (Holes in the uranium metal parts not shown),

The effects of room return should be calculated using Monte Carlo simulations that 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. The 2 ft thickness for the concrete is adequate for the calculation because neutrons that reach 2 ft into the concrete have little chance of returning to the critical assembly.

The best calculated value for comparison with measurements may be obtained using the critical configuration with the support structure and the experimental cell (including air). This scheme eliminates uncertainties associated with corrections for surrounding materials. The 1 in. thick steel table of the vertical lift should also be included in this calculation. To get a statistically accurate result, the effects of the cell must be calculated with longer than usual Monte Carlo simulations. A calculation of room return alone must be used to estimate the calculation length required to estimate these small effects accurately. The length of time to obtain a good statistical estimate of the effect of room return should then be used for the calculation of the configuration with all surrounding materials.

## 4. DESCRIPTION OF MATERIAL

The uranium metal description and uncertainties have been given in previous documentation but are repeated here as appropriate [10, 17].

### 4.1 STAINLESS STEEL

The type 316 stainless steel used in the measurements as bottom and top reflectors on 7 in. diameter enriched uranium metal cylinders was obtained by a saw cut on an approximately 0.5 in. thick plate. Eight nominal 7 in. diameter reflector parts were fabricated. They were used to build 0.5, 1, and 2 in. thick top and bottom reflectors. The 0.5 in. reflectors used steel part 1 on the bottom and steel part 2 on the top. The 1 in. top and bottom reflectors used parts 1 and 2 on the bottom and parts 3 and 4 on the top. The 2 in. top and bottom reflectors used parts 2, 4, 1, and 3 on the bottom (part 3 was adjacent to the uranium metal) and parts 7, 5, 6, and 8 on the top (part 7 was adjacent to the uranium metal). The mass and dimensions of the reflector parts are given in Table 4.1.

**Table 4.1. Dimensions and masses of reflector parts**

| Reflector part number | Diameter (in.) | Thickness (in.) | Mass (g) | Density (g/cm$^3$) |
|---|---|---|---|---|
| 1 | 7.055 | 0.505 | 2,520 | 7.7898 |
| 2 | 7.028 | 0.507 | 2,520 | 7.8188 |
| 3 | 7.014 | 0.506[a] | 2,496 | 7.7906 |
| 4 | 7.038 | 0.506[a] | 2,517 | 7.8027 |
| 5 | 6.809 | 0.506[a] | 2,363[b] | 7.8263 |
| 6 | 6.869 | 0.506[a] | 2,405[b] | 7.8268 |
| 7 | 6.868 | 0.506[a] | 2,404[b] | 7.8259 |
| 8 | 6.948 | 0.506[a] | 2,460[b] | 7.8258 |

[a] Assumed to be 0.506, the average of that for stainless steel parts 1 and 2, because they were probably cut from the same steel plate.

[b] Sum of parts 5, 6, 7 and 8 from logbook was 9,632 g.

The mass given in the logbooks is not realistic because all eight parts were cut at the same time. The density was assumed to be the average of parts 1–4 with outside diameter of 7.034 and thickness of 0.506. The composition of stainless steel 316 is given in Table 4.2. The assumption is that the chromium and nickel wt % are midrange of 17% for chromium, 12% for nickel and 2.5% for molybdenum.

**Table 4.2. Composition of stainless steel 316**

| Element | wt % |
|---|---|
| Chromium | 16–18 |
| Nickel | 10–14 |
| Molybdenum | 2–3 |
| Carbon | 0.08 |
| Manganese | 2.00 |
| Phosphorus | 0.045 |
| Sulfur | 0.03 |
| Silicon | 0.75 |
| Nitrogen | 0.1 |
| Iron | balance |

## 4.1 URANIUM METAL

The cylindrical uranium metal parts for these experiments had 0.375 in. diameter axial holes, and any measurements after January 20, 1965, had uranium filler plugs in these holes. Other experiments for fission rate spatial distribution measurements in interacting uranium metal critical experiments used 0.365 in. diameter cylindrical uranium metal plugs of various lengths [10]. These plugs were used to fill axial and radial holes for measurements after January 20, 1965. Part 2732 had an additional radial hole 3.25 in. in from the outer radial surface and 0.375 in. above the bottom of the part that could be filled with a 3.25 in. long plug. Part 2731 had an additional axial hole (0.881 in. deep) 0.50 in. from the radial surface. Filling this hole with uranium metal plugs 0.875 in. thick resulted in a gap of 0.006 in. between part 2731 and the part above it. The axial hole in this part was only 0.875 in. deep. The exact location of these holes can be obtained from Y-12 Plant dimensional inspection reports dated around January 1965 for parts 2731 and 2732. The masses, dimensions and uranium isotopic composition of the major uranium metal parts .are listed in Table 4.3.

**Table 4.3. Mass, dimensions, and isotopics for uranium metal 7 in. diameter cylindrical parts**

| Part number | Measured[a] mass (g) | Measured height (in.) | Measured diameter (in.) | $^{235}$U (wt %) | $^{234}$U (wt %) | $^{236}$U (wt %) | $^{238}$U (wt %) |
|---|---|---|---|---|---|---|---|
| 2728 | 4,409 (4,435) | 0.3760 | 6.9944 | 93.17 | 0.97 | 0.24 | 5.66 |
| 2729 | 4,426 (4,480) | 0.3757 | 6.9964 | 93.15 | 0.98 | 0.26 | 5.64 |
| 2730 | 6,627[b] (6,646) | 0.5620 | 6.9960 | 93.14 | 0.9.7 | 0.25 | 5.64 |
| 2731 | 11,693 (11,841) | 1.0 027 | 6.9965 | 93.17 | 0.95 | 0.21 | 5.67 |
| 2732 | 11,674 (11,814) | 1.00125 | 6.9960 | 93.17 | 0.96 | 0.21 | 5.6 |
| 2734 | 17,693(17,742) | 1.50165 | 6.9964 | 93.18 | 0.95 | 0.24 | 5.63 |
| 2768 | 1,471 (1,481) | 0.1250 | 6.9967 | 93.14 | 0.92 | 0.26 | 5.68 |
| 2769 | 1,489 (1,495) | 0.1255 | 6.9965 | 93.15 | 0.97 | 0.25 | 5.63 |
| 2771 | 2,907 (2,916) | 0.24805 | 6.9966 | Not[c] available | Not available | Not available | Not available |
| 5 × 5 × 0.03125 i n. plate | 240 | 0.03125 | 5.000 in. square | 93.14 | 0.97 | 0.25 | 5.64 |

[a] Values in parentheses are the masses before the holes were drilled

[b] For part 2730, the weight after an axial hole was drilled is not given in the logbook. The reduction in mass was calculated using the volume of the hole and a uranium density of 18.75 g/cm$^3$.

[c] For part 2771, for uranium isotopics use the average of the preceding values in this table.

The mass for each uranium metal part was measured three times. The dimensions were measured at three different locations for each part. The uranium isotopics were measured by dividing a metal chip from the machining process into thirds and performing isotopic analysis on each third. In almost all cases, the different measurements agreed. The height and diameter were measured at three different locations on the parts to ±0.0001 in. and were the same at all locations. The average density of the cylindrical parts used in these experiments was 18.757 g/cm$^3$. Thus, the heights and diameters are known to ±0.00005 in. The isotopic enrichments for $^{234}$U, $^{235}$U, and $^{236}$U are measured to 0.01 wt % and thus are known to ±0.005 wt %. The uncertainties in the dimensions, uranium isotopics, and impurities are discussed in reference 17, and how these uncertainties affect previous critical experiments are discussed in reference 10.

The impurity content for the uranium were from these and uranium metal annuli fabricated at the same time and are given in Table 4.4 [18].

**Table 4.4. Measured average impurity content[a] of uranium metal cylinders for delayed critical experiments with two 7 in. diameter interacting cylinders**

| Element | Average parts per million by weight (ppm) | Range (ppm) |
|---|---|---|
| Silver | 8 | 3–25 |
| Bismuth | 164 | 81–311 |
| Carbon | 5 | 0–9 |
| Cobalt | 5 | 2–15 |
| Chromium | 7 | 4–12 |
| Copper | 25 | 10–40 |
| Magnesium | 3 | 2–3 |
| Manganese | 56 | 25–89 |
| Nitrogen | 30 | — |
| Sodium | 27 | 15–50 |
| Nickel | 100 | — |
| Oxygen | 20 | — |
| Antimony | 38 | 10–80 |
| Titanium | 1 | — |

[a] Measured via mass spectrographic analysis, except nitrogen and oxygen, which are assumed to be 30 and 20 ppm, respectively.

## 5. ADDITIONAL MEASUREMENTS

The prompt neutron decay constant was measured by the Rossi-α technique using two detectors: one to trigger a time analyzer and the other to count. The time distribution of detector counts in a spiral fission counter was measured with respect to a previous count in a 2.00 in. thick, 2 in. diameter Nuclear Enterprises NE-213 liquid scintillator in a 0.25 in. thick lead shield. The flat surface of liquid scintillator and lead shield were located 0.5 in. from the radial surface of the uranium on the diaphragm, and the spiral fission counter was located near the axis of the assembly adjacent to the bottom reflector. The 0.5 x 0.5 in. diameter spiral fission counter was provided by Hogterp of Los Alamos National Laboratory and is described in reference 19. The data from the measurement, both the counts as a function of time and the background-subtracted data, are plotted in Figure 5.1. The actual data are given in Appendix D. At this time a Rossi-α measurement was also performed for a delayed critical 7.0 in. diameter uranium metal cylinder without top and bottom reflectors. The data were fitted by linear least squares techniques to determine the prompt neutron decay constants; these results are given in Table 5.1 and Figure 5.1.

**Table 5.1 Prompt neutron decay constant of uranium metal cylinder with thin top and bottom steel reflectors**

| Stainless steel top and bottom reflector thicknesses (in.) | Stainless steel density (g/cm$^3$) | Prompt neutron decay constant (μs$^{-1}$) |
|---|---|---|
| 0 | 0 | 1.082 ± 0.0006 |
| 0.506 | 7.897 | 1.047 ± 0.010 |
| 1.026 | 7.722 | 1.015 ± 0.010 |
| 2.065 | 7.673 | 0.947 ± 0.007 |

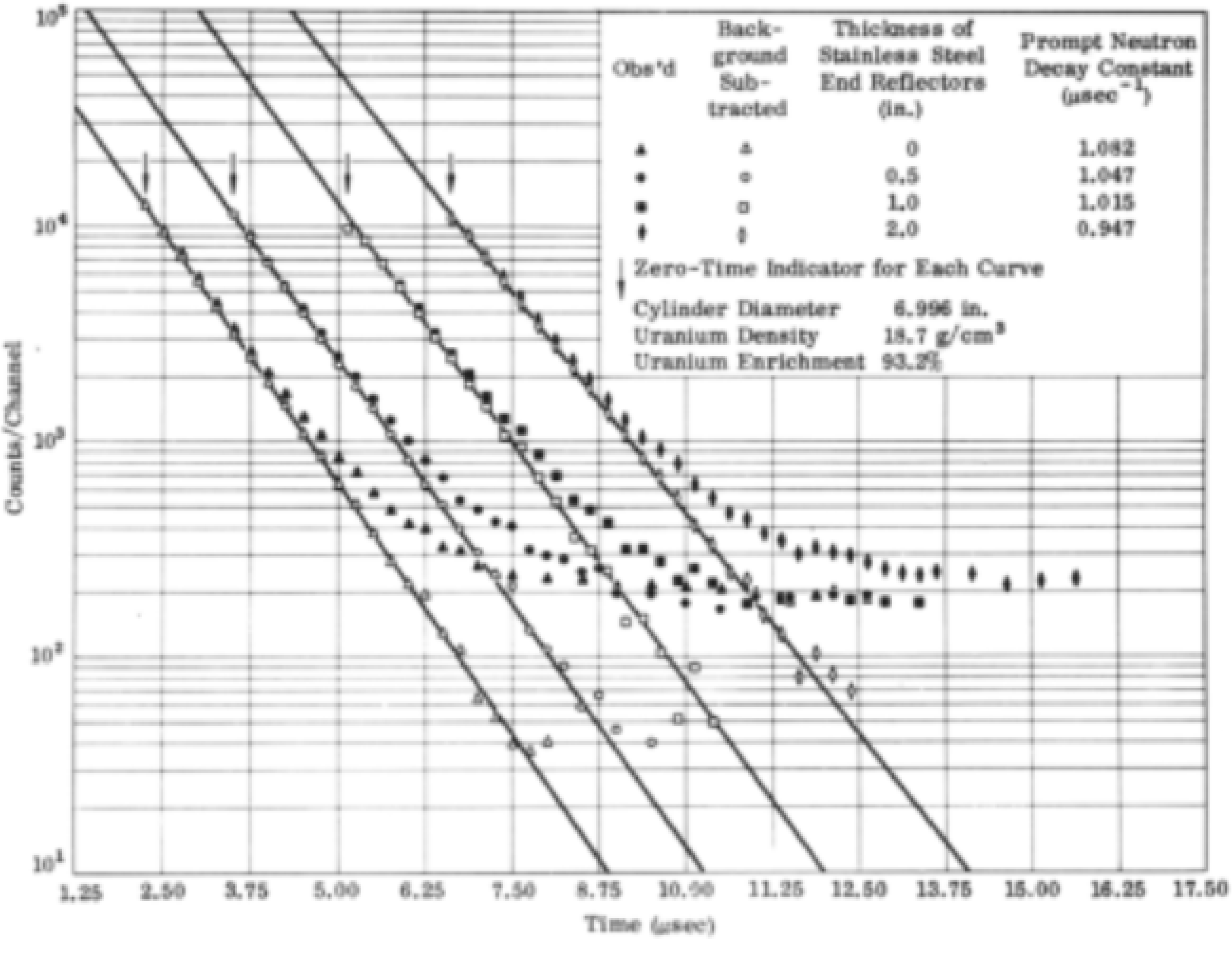


**Figure 5.1. Prompt neutron decay for delayed critical 7 in. diameter uranium metal cylinders**. Time zero of the decay is shifted to display multiple measurements on this figure and time zero for each measurement is indicated by a vertical arrow. The arrows point to the data point for the first time analyzer channel which begins at time zero for the decay.

## 6. CONCLUSIONS

Three 7 in. diameter HEU (93.17 wt % $^{235}$U) metal cylinders were assembled on the vertical assembly machine of the Oak Ridge Critical Experiments Facility (ORCEF with thin stainless steel reflectors (0.5, 1, and 2 in. thick) on the top and bottom. In addition to the critical experiments, the prompt neutron decay constant was measured via. the Rossi-α technique, and those results and the original data are also presented in this report. The uranium metal mass in these measurements varied between 47,714 and 53,843 g. The delayed critical configuration from the three experiments described are acceptable for use as criticality safety benchmark experiments for the International Criticality Safety Benchmark Evaluation Program (ICSBEP) once the uncertainty analysis is completed. Based on previous ICSBEP benchmarks with this enriched uranium metal at ORCEF, the uncertainty in $k_{eff}$ could be as low as ±0.0002. The prompt neutron time decay data could be the basis of an International Reactor Physics Evaluation Program benchmark.

## ACKNOWLEDGMENTS

The Y-12 Photography Department provided the photographs, and Daniel Campbell of Idaho National Laboratory provided the configuration sketches and those describing the uranium and stainless steel parts. The spiral fission counter and the time analyzer for the Rossi-α measurement were provided by Los Alamos National Laboratory. The publication of this report was supported by the Nuclear Criticality, Radiation Transport, and Safety Section of ORNL.

## REFERENCES

1. J. T. Mihalczo, *Brief Summary of Unreflected and Unmoderated Cylindrical Critical Experiments with Oralloy at Oak Ridge*, ORNL/TM-1999/302, Oak Ridge National Laboratory, Oak Ridge, Tennessee (November 1999).
2. J. T. Mihalczo, “Prompt-Neutron Decay in a Two-Component Enriched Uranium Metal Critical Assembly,” *Trans. Am. Nucl. Soc.* **6**, 60 (1963).
3. J. T. Mihalczo, *Prompt Neutron Decay in a Two-Component Enriched Uranium Metal Critical Assembly*, ORNL/TM-470, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1963).
4. J. T. Mihalczo, *Graphite and Polyethylene Reflected Uranium-Metal Cylinders and Annuli*, Y-DR- 81, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee (1972).
5. J. T. Mihalczo, “Prompt Neutron Lifetime in Critical Enriched-Uranium Metal Cylinders and Annuli,” *Nucl. Sci. Eng*. **20**, 60–65 (1964).
6. J. T. Mihalczo, “Monte Carlo Calculations of Two Core Delayed Critical Assemblies,” *Trans. Am. Nucl. Soc.* **11**, 603 (1968).
7. J. T. Mihalczo, “Prompt Neutron Time Behavior in Delayed Critical Coupled Uranium Metal Cylinders,” *Proceedings of the International Conference on Fast Critical Experiments and Their Analysis*, ANL-7320, 237–41 (October 1966).
8. J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, Delayed Critical ORNL Unreflected Uranium (93.20) Metal Sphere and the Pure Unreflected Uranium (93.80) Sphere Critical Mass, Ann. of Nucl. Energy **29**, 525 (2002).
9. J. T. Mihalczo, “Uranium (93.2) Metal Cylinders with Thin Stainless-Steel Reflectors,” *Nucl. Sci. Eng*., 25, 444 (1966).
10. Robert H. Elwood and John T. Mihalczo, *Uranium (93.2) Metal Cylinders (7-inch, 9-Inch, 11-inch, 13-inch, and 15-inch Diameter) and Two 11-inch-Diameter Interacting Uranium (93.2) Metal Cylinders*, HEU-MET-FAST-051, NSC/DOC/(95)03?II Volume II (2021).
11. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA No 7360 (December 2021).

12. John D. Orndoff, "Prompt Neutron Periods of Metal Critical Assemblies," *Nuc . Sci. Eng.*, **2**, p 450-460 (1957).

13. John T. Mihalczo, *Critical and Subcritical NEA Benchmark Possibilities for Measurements at ORCEF and Other US DOE Facilities*, ORNL/TM-2019/1188 (June 2019).

14. J. T. Mihalczo, *Superprompt Critical Behavior of an Unmoderated, Unreflected Uranium-Molybdenum Alloy Assembly*, ORNL/TM-230, Union Carbide Corp. Nuclear Division, Oak Ridge National Laboratory (1962). [OSTI #4805229]

15. A. D. Callihan, *A Safety Review of the Oak Ridge Critical Experiments Facility*, ORNL/TM-349, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1962).

16. John T. Mihalczo, *Uranium-Molybdenum Alloy Critical Experiment for the Health Physics Research Reactor*, ORNL/TM-2021/2234 (June 2022).

17. John T. Mihalczo, *Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF*, ORNL/TM-2012/32, Oak Ridge National Laboratory, Oak Ridge, Tennessee (September 2012). [OSTI #1052246]

18. John T. Mihalczo, *Two Delayed Critical 7-inch-Diameter Interaction Enriched (93.14) Uranium Metal Cylinders without Moderator and Reflector*, ORNL/TM-2019/1396 (November 2019) [OSTI 1606828]

19. J. T. Mihalczo, "Measurement of the Effective Delayed Neutron Fraction for an Unreflected Uranium Sphere," *Nucl. Sci. Eng.*, (1975).

# APPENDIX A. RECENT REPORTS DOCUMENTING PAST ORCEF UNDOCUMENTED EXPERIMENTS

The critical and subcritical experiments with insufficient documentation are described in Reference 12. The following reports are part of a program at Oak Ridge National Laboratory to document in detail the results of undocumented measurements, three of which were part of the 2021 cooperative Idaho National laboratory-Oak Ridge National Laboratory program.

1. John T. Mihalczo, “Delayed Critical and Subcritical Experiments with the HEU Metal 15-in.-diameter JEMIMA Plates” (in preparation)

2. John T. Mihalczo, *Uranium-Molybdenum Alloy Critical Experiment for the Health Physics Research Reactor*, ORNL/TM2021/2234 (July 2021)

3. John T. Mihalczo, *Critical and Californium Source-Driven Noise Analysis Subcritical Measurements with an Unreflected Cylindrical Tank of Mixed Uranium-Plutonium Nitrate Solution*, ORNL/TM-2021/1606 (July 021)

4. John T. Mihalczo, “Subcritical Measurements for a Changing Concentration Uranyl Nitrate Solution Tank by the Californium Source Driven Noise Analysis” (in publication process)

5. John T. Mihalczo, *Critical and Subcritical Californium Source Driven Noise Analysis Experiments with Fresh PWR Fuel Pins*, ORNL/TM-2020/1606 (December 2021)

6. John T. Mihalczo, *Subcritical Californium Source-Driven Noise Analysis Measurements with Unreflected Uranium (93.15) Hydride*, ORNL/TM-2021/1963 (June 2021)

7. John T. Mihalczo, *Data from Rossi-α and Pulsed Neutron Prompt neutron Time Decay Measurements at ORCEF*, Oak Ridge National Laboratory, ORNL/TM-2019/1455 (April 2019) [OSTI #1543205]

8. John T. Mihalczo, *Three Delayed Critical 15-inch-Diameter Interacting Enriched (93.14) Uranium Metal Cylinders without Moderator and Reflector*, ORNL/TM-2019/1456

9. John T. Mihalczo, *Two Delayed Critical 15-inch-Diameter Interaction Enriched (93.14) Uranium Metal Cylinders without Moderator and Reflector*, ORNL/TM-2019/1409 [OSTI #1661251]

10. John T. Mihalczo, *Two Delayed Critical 7-inch-Diameter Interaction Enriched (93.14) Uranium Metal Cylinders without Moderator and Reflector*, ORNL/TM-2019/1396 (November 2019) [OSTI 1606828]

11. John T. Mihalczo, *Reactor Physics Experiment Possibilities from Measurement at ORCEF and Other USDOE Facilities*, ORNL/TM-2019/384 (December 2019) [OSTI #1615820]

12. John T. Mihalczo, *Critical and Subcritical NEA Benchmark Possibilities for Measurements at ORCEF and Other US DOE Facilities*, ORNL/TM-2019/1188 (June 2019)

# APPENDIX B. EXPERIMENTS DOCUMENTED IN THE NUCLEAR ENERGY AGENCY INTERNATIONAL HANDBOOK OF EVALUATED CRITICALITY SAFETY BENCHMARK EXPERIMENTS

The following critical experiments performed by Oak Ridge National Laboratory at the Oak Ridge Critical Experiments Facility have been included in the Nuclear Energy Agency International Handbook of Evaluated Criticality Safety Benchmark Experiments.

| **Identifier** | **Experimenter** | **Title** |
|---|---|---|
| HEU-MET-FAST-007 | Mihalczo | Uranium Metal Slabs Moderated with polyethylene, Plexiglas and Teflon |
| HEU-MET-FAST-051 | Mihalczo | Uranium (93.2) Metal Cylinders (7-inch, 9- inch, 11-inch, 13-inch,15-Inch Diameter Cylinders and Two 11-Inch Diameter Interacting Uranium (93.2) Metal Cylinders |
| HEU-MET-FAST-059 | Mihalczo | Oralloy (93.15 235U) Metal Annuli With Beryllium Core |
| HEU-MET-FAST-061 | Mihalczo | Oralloy (93.2 235U) Metal Cylinder With Beryllium Top Reflector |
| HEU-MET-FAST-071 | Mihalczo | Uranium (93.14) Metal Annuli With One- And Two-Inch Graphite Reflectors |
| HEU-MET-FAST-074 | Mihalczo | Oralloy (93.2 235U) Bare Metal Annuli and Disks |
| HEU-MET-FAST-076 | Mihalczo | Uranium (93.14 235U) Metal Annuli and Cylinders with Thick Polyethylene Reflectors and/or Internal Polyethylene Moderator |
| HEU-MET-FAST-077 | Mihalczo | Experiments with HEU (93.14 wt. %) Metal Annuli with Internal Graphite Cylinder |
| HEU-MET-FAST-081 | Mihalczo | Grotesque: Complex Geometric Arrangement of Unreflected HEU (93.15) Metal |
| HEU-MET-FAST-083 | Mihalczo | Complex Geometry Bare Oralloy (93.15 235U) Metal Annuli Experiments |
| HEU-MET-FAST-096 | Mihalczo | Static Critical Experiments For The Sorgente Rapida (SORA) Reactor Mockup |
| HEU-MET-FAST-099 | Mihalczo | Fast Neutron Spectrum Potassium Worth for Space Power Reactor Design Validation (also known as ORCEF-SPACE-EXP-001) |
| HEU-MET-FAST-100 | Mihalczo | Orsphere: Critical, Bare, HEU (93.2)-Metal Sphere |
| SCCA-SPACE-EXP-001 | Mihalczo | Critical Configuration and Physics Measurements for Assemblies of U(93.15)O2 Fuel Rods |
| HEU-COMP-FAST-002 | Mihalczo | Critical Configuration and Physic Measurements for Graphite Reflected Assemblies of U(93.15)O2 Fuel Rods (1.506- CM Pitch) |
| HEU-COMP-FAST-004 | Mihalczo | Critical Configuration for Beryllium Reflected Assemblies of U(93.15)O2 Fuel Rods (1.506-CM Pitch and 7-Tube Clusters) |
| SCCA-FUND-EXP-001 | Mihalczo | Critical configurations and Physics Measurements for |

| | | |
|---|---|---|
| | | For Graphite Reflected Assemblies of U (93.15)O2 Fuel Rods (1.27-cm-pitch) |
| SUB-HEU-SOL-THERM-001 | Mihalczo | Unreflected high-enriched uranyl nitrate subcritical noise measurements |
| SUB-HEU-SOL-THERM-002 | Mihalczo | Subcritical Noise Measurements for Two Coaxial Cylindrical Tanks Containing 93.1 wt. % Uranyl Nitrate Solution |

# APPENDIX C. SUPPORT STRUCTURE

The support structure is described in this appendix. Figure C.1 represents the diaphragm and rings with its support structure. Figure C.2 represents the low-mass support structure. Both structures can be seen in Figure C.2. These support structures were used in many other critical experiments with enriched uranium metal at the Oak Ridge Critical Experiments Facility.

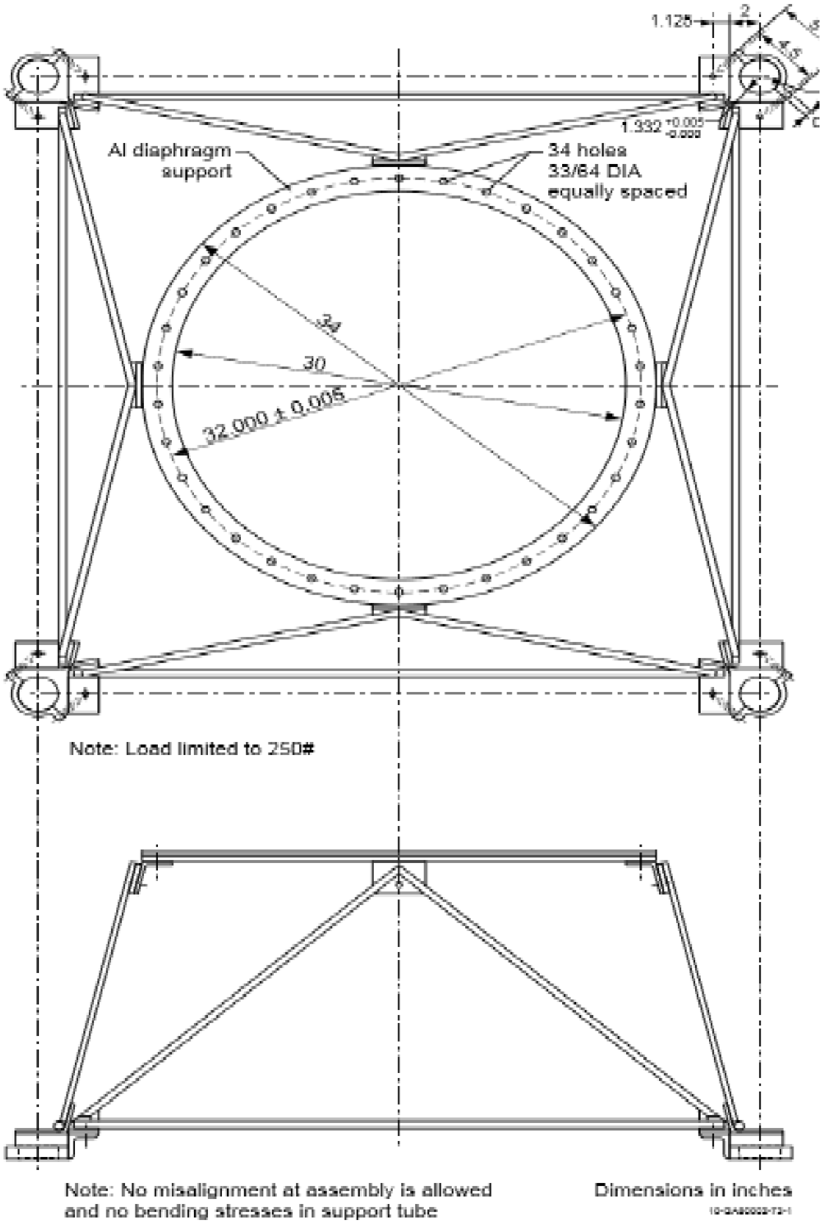


Figure C.1. Diaphragm support structure.

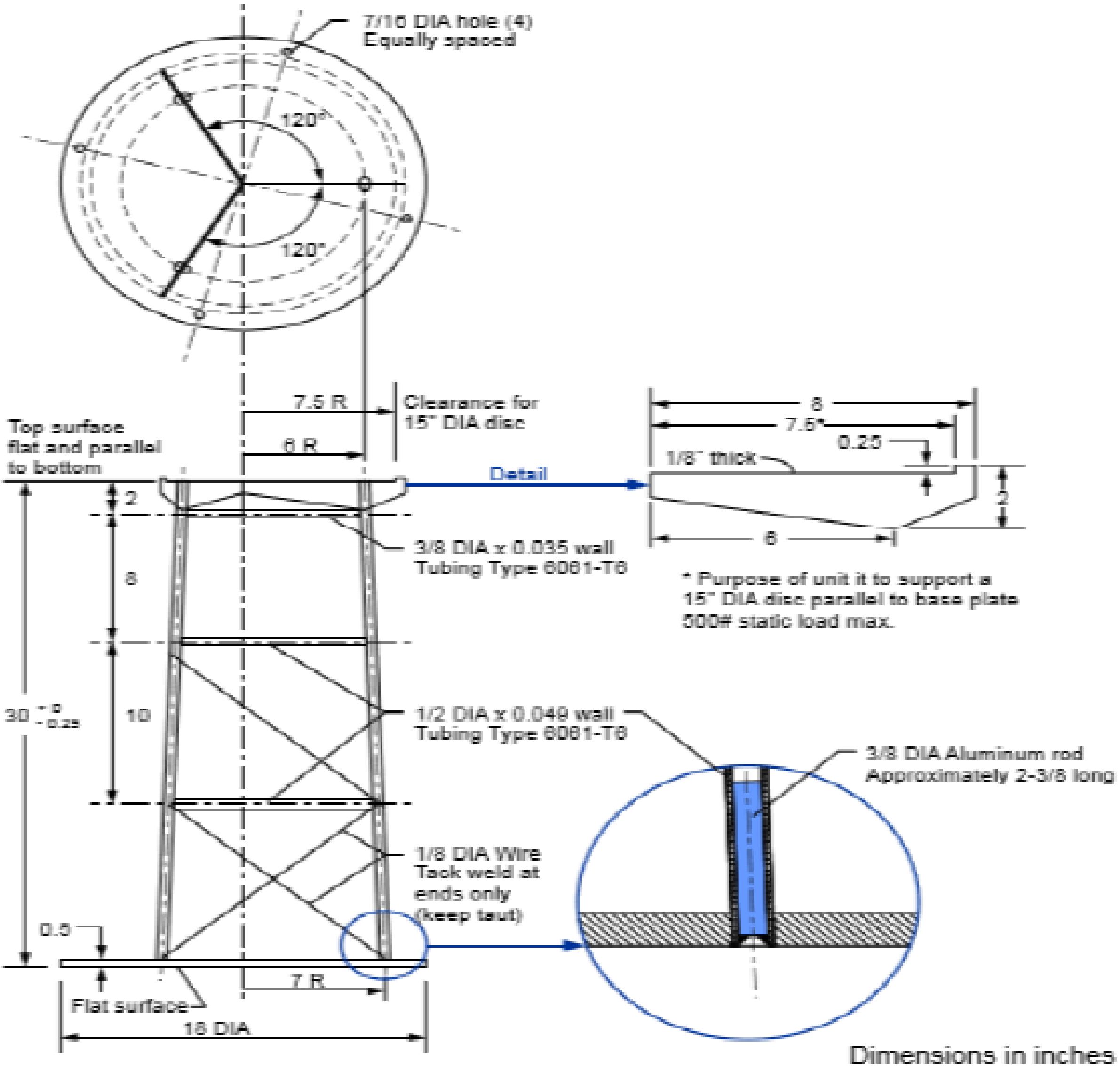
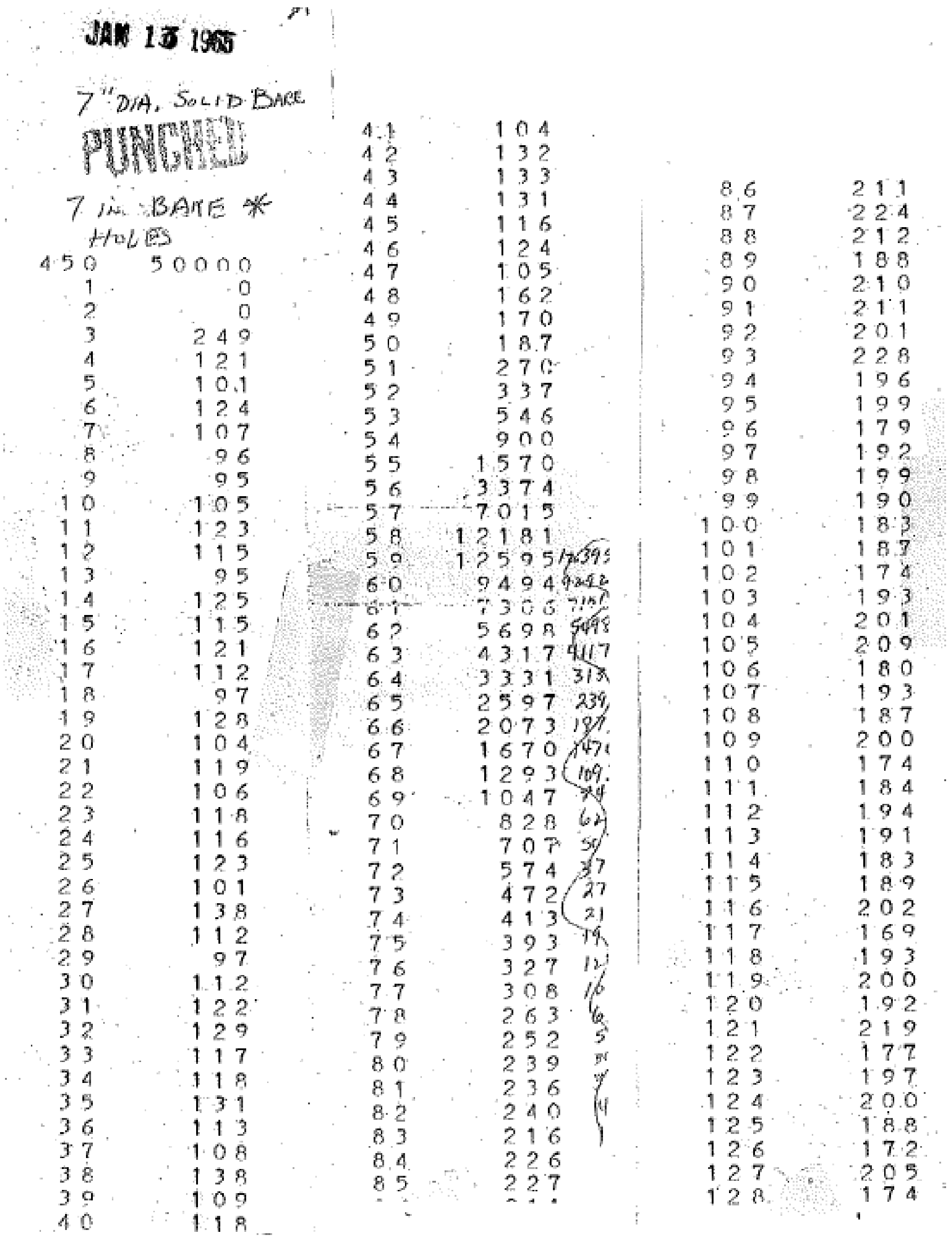


**Figure C.2. Details of the lower support structure.**

# APPENDIX D. ROSSI ALPHA DATE FOR THIN STAINLESS STEEL REFLECTED CRITICAL EXPERIMENTS

This appendix presents the data from the prompt neutron decay constant measurements by the two-detector Rossi-α technique. A Technical Measurement Corporation (TMC) time analyzer was used for the measurements. The two detectors used for the measurement were a 2.0 in. diameter, 2.0 in. thick Nuclear Enterprises NE-213 liquid scintillator in a 0.25 in. thick lead cup and a spiral fission counter underneath the lower section and at the center and adjacent to the center of the lower stainless steel reflector. The scintillator was located with the front face of the lead shield 0.5 in. from the upper uranium metal, as shown in Figure 2.2. The detections in the scintillator triggered the time analyzer, and the time distribution of the detections in the spiral fission counter was measured after the scintillator detection. The signal from the fission chamber was delayed (~15 µs) with respect to the signal from the scintillator to force the peak of the distribution to occur in later channels of the time analyzer. Measurements were also performed at this time for a uranium metal cylinder without top and bottom reflectors. A single measurement was made for the experiments with 0.5 and 1.0 in. reflectors, but two measurements were performed for the system with 2 in. thick reflectors. Images of the data from the original TMC analyzer in 1965 (recently discovered at Oak Ridge National Laboratory) are given in Tables D.1 through D.5 where real time zero for the decay is the beginning of channel 59, 59, 60, 58, and 58, respectively for Figure D.1 to D.5.  In these tables, the first column lists the time channel number, and the second column lists the data. Handwritten numbers in the data files are the background-subtracted data. The time width of the channels was 0.25 µs. The tables are copies of the original paper printout and have not been retyped (hence the table lower quality).



JAN 13 1965

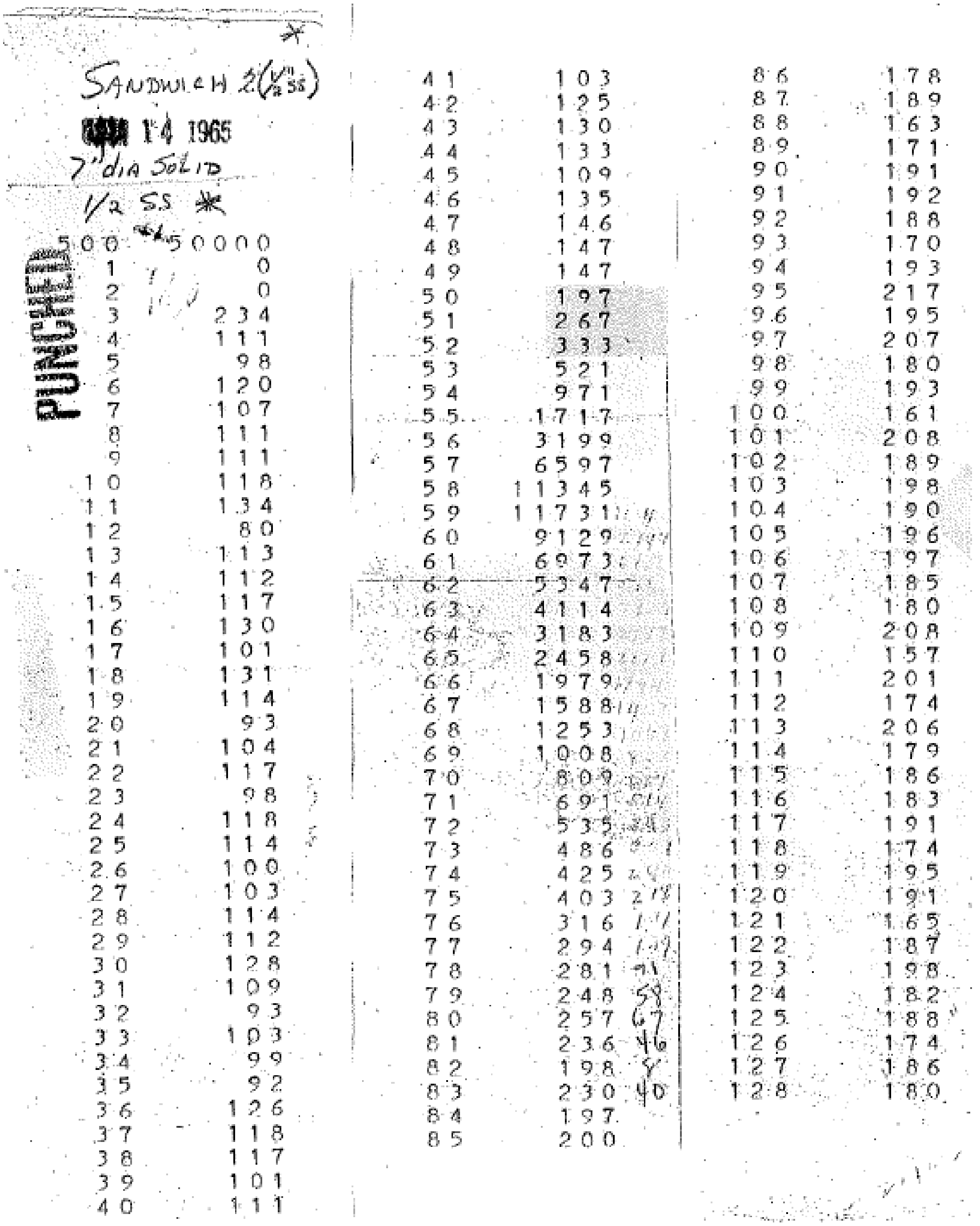
7" DIA. SOLID BARE

PUNCHED

7 in. BARE *
HOLES

| | | |
|---|---|---|
| 450 | 50000 | |
| 1 | 0 | |
| 2 | 0 | |
| 3 | 249 | |
| 4 | 121 | |
| 5 | 101 | |
| 6 | 124 | |
| 7 | 107 | |
| 8 | 96 | |
| 9 | 95 | |
| 10 | 105 | |
| 11 | 123 | |
| 12 | 115 | |
| 13 | 95 | |
| 14 | 125 | |
| 15 | 115 | |
| 16 | 121 | |
| 17 | 112 | |
| 18 | 97 | |
| 19 | 128 | |
| 20 | 104 | |
| 21 | 119 | |
| 22 | 106 | |
| 23 | 118 | |
| 24 | 116 | |
| 25 | 123 | |
| 26 | 101 | |
| 27 | 138 | |
| 28 | 112 | |
| 29 | 97 | |
| 30 | 112 | |
| 31 | 122 | |
| 32 | 129 | |
| 33 | 117 | |
| 34 | 118 | |
| 35 | 131 | |
| 36 | 113 | |
| 37 | 108 | |
| 38 | 138 | |
| 39 | 109 | |
| 40 | 118 | |
| 41 | 104 | |
| 42 | 132 | |
| 43 | 133 | |
| 44 | 131 | |
| 45 | 116 | |
| 46 | 124 | |
| 47 | 105 | |
| 48 | 162 | |
| 49 | 170 | |
| 50 | 187 | |
| 51 | 270 | |
| 52 | 337 | |
| 53 | 546 | |
| 54 | 900 | |
| 55 | 1570 | |
| 56 | 3374 | |
| 57 | 7015 | |
| 58 | 12181 | |
| 59 | 12595 | 12395 |
| 60 | 9494 | 9242 |
| 61 | 7306 | 7151 |
| 62 | 5698 | 5498 |
| 63 | 4317 | 4117 |
| 64 | 3331 | 313 |
| 65 | 2597 | 239 |
| 66 | 2073 | 187 |
| 67 | 1670 | 147 |
| 68 | 1293 | 109 |
| 69 | 1047 | 79 |
| 70 | 828 | 62 |
| 71 | 707 | 50 |
| 72 | 574 | 37 |
| 73 | 472 | 27 |
| 74 | 413 | 21 |
| 75 | 393 | 19 |
| 76 | 327 | 12 |
| 77 | 308 | 16 |
| 78 | 263 | 6 |
| 79 | 252 | 5 |
| 80 | 239 | [illegible] |
| 81 | 236 | [illegible] |
| 82 | 240 | 4 |
| 83 | 216 | |
| 84 | 226 | |
| 85 | 227 | |
| 86 | 211 | |
| 87 | 224 | |
| 88 | 212 | |
| 89 | 188 | |
| 90 | 210 | |
| 91 | 211 | |
| 92 | 201 | |
| 93 | 228 | |
| 94 | 196 | |
| 95 | 199 | |
| 96 | 179 | |
| 97 | 192 | |
| 98 | 199 | |
| 99 | 190 | |
| 100 | 183 | |
| 101 | 187 | |
| 102 | 174 | |
| 103 | 193 | |
| 104 | 201 | |
| 105 | 209 | |
| 106 | 180 | |
| 107 | 193 | |
| 108 | 187 | |
| 109 | 200 | |
| 110 | 174 | |
| 111 | 184 | |
| 112 | 194 | |
| 113 | 191 | |
| 114 | 183 | |
| 115 | 189 | |
| 116 | 202 | |
| 117 | 169 | |
| 118 | 193 | |
| 119 | 200 | |
| 120 | 192 | |
| 121 | 219 | |
| 122 | 177 | |
| 123 | 197 | |
| 124 | 200 | |
| 125 | 188 | |
| 126 | 172 | |
| 127 | 205 | |
| 128 | 174 | |

**Table D.1. Rossi alpha data for unreflected configuration.** Time zero for the measurement is the beginning of channel 59.



SANDWICH 2(1/2" SS)

[redacted] 1 4 1965

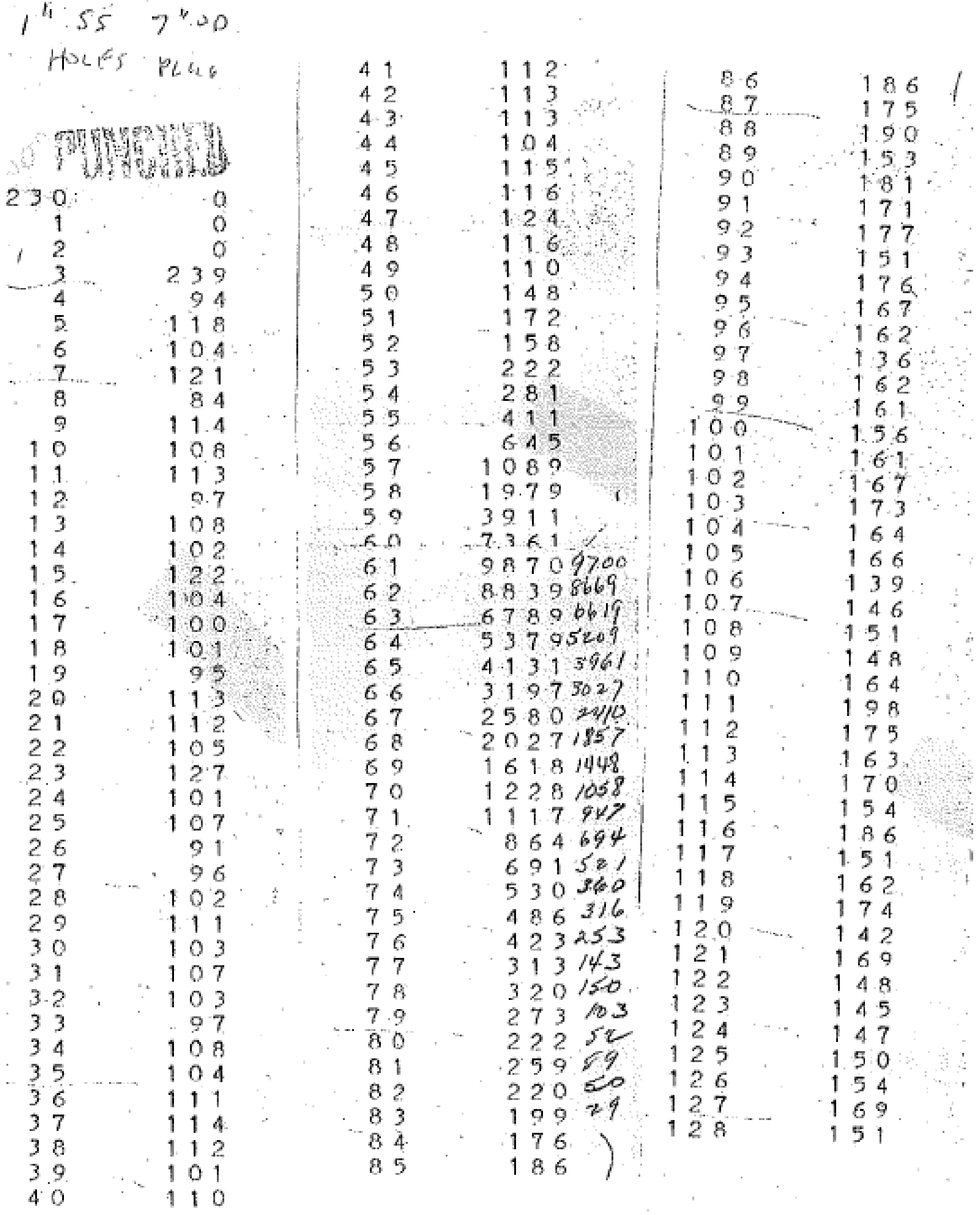
7" dia SOLID

1/2 SS *

PUNCHED

| | | | | | | |
|---|---|---|---|---|---|---|
| 500 | 50000 | 41 | 103 | | 86 | 178 |
| 1 | 0 | 42 | 125 | | 87 | 189 |
| 2 | 0 | 43 | 130 | | 88 | 163 |
| 3 | 234 | 44 | 133 | | 89 | 171 |
| 4 | 111 | 45 | 109 | | 90 | 191 |
| 5 | 98 | 46 | 135 | | 91 | 192 |
| 6 | 120 | 47 | 146 | | 92 | 188 |
| 7 | 107 | 48 | 147 | | 93 | 170 |
| 8 | 111 | 49 | 147 | | 94 | 193 |
| 9 | 111 | 50 | 197 | | 95 | 217 |
| 10 | 118 | 51 | 267 | | 96 | 195 |
| 11 | 134 | 52 | 333 | | 97 | 207 |
| 12 | 80 | 53 | 521 | | 98 | 180 |
| 13 | 113 | 54 | 971 | | 99 | 193 |
| 14 | 112 | 55 | 1717 | | 100 | 161 |
| 15 | 117 | 56 | 3199 | | 101 | 208 |
| 16 | 130 | 57 | 6597 | | 102 | 189 |
| 17 | 101 | 58 | 11345 | | 103 | 198 |
| 18 | 131 | 59 | 11731 | | 104 | 190 |
| 19 | 114 | 60 | 9129 | | 105 | 196 |
| 20 | 93 | 61 | 6973 | | 106 | 197 |
| 21 | 104 | 62 | 5347 | | 107 | 185 |
| 22 | 117 | 63 | 4114 | | 108 | 180 |
| 23 | 98 | 64 | 3183 | | 109 | 208 |
| 24 | 118 | 65 | 2458 | | 110 | 157 |
| 25 | 114 | 66 | 1979 | | 111 | 201 |
| 26 | 100 | 67 | 1588 | | 112 | 174 |
| 27 | 103 | 68 | 1253 | | 113 | 206 |
| 28 | 114 | 69 | 1008 | | 114 | 179 |
| 29 | 112 | 70 | 809 | | 115 | 186 |
| 30 | 128 | 71 | 691 | | 116 | 183 |
| 31 | 109 | 72 | 535 | | 117 | 191 |
| 32 | 93 | 73 | 486 | | 118 | 174 |
| 33 | 103 | 74 | 425 | | 119 | 195 |
| 34 | 99 | 75 | 403 | | 120 | 191 |
| 35 | 92 | 76 | 316 | | 121 | 165 |
| 36 | 126 | 77 | 294 | | 122 | 187 |
| 37 | 118 | 78 | 281 | | 123 | 198 |
| 38 | 117 | 79 | 248 | 58 | 124 | 182 |
| 39 | 101 | 80 | 257 | 67 | 125 | 188 |
| 40 | 111 | 81 | 236 | 46 | 126 | 174 |
| | | 82 | 198 | | 127 | 186 |
| | | 83 | 230 | 40 | 128 | 180 |
| | | 84 | 197 | | | |
| | | 85 | 200 | | | |

**Table D.2. Rossi alpha data for 0.5 in. thick reflected configuration.** Time zero for the measurement is the beginning of channel 59.



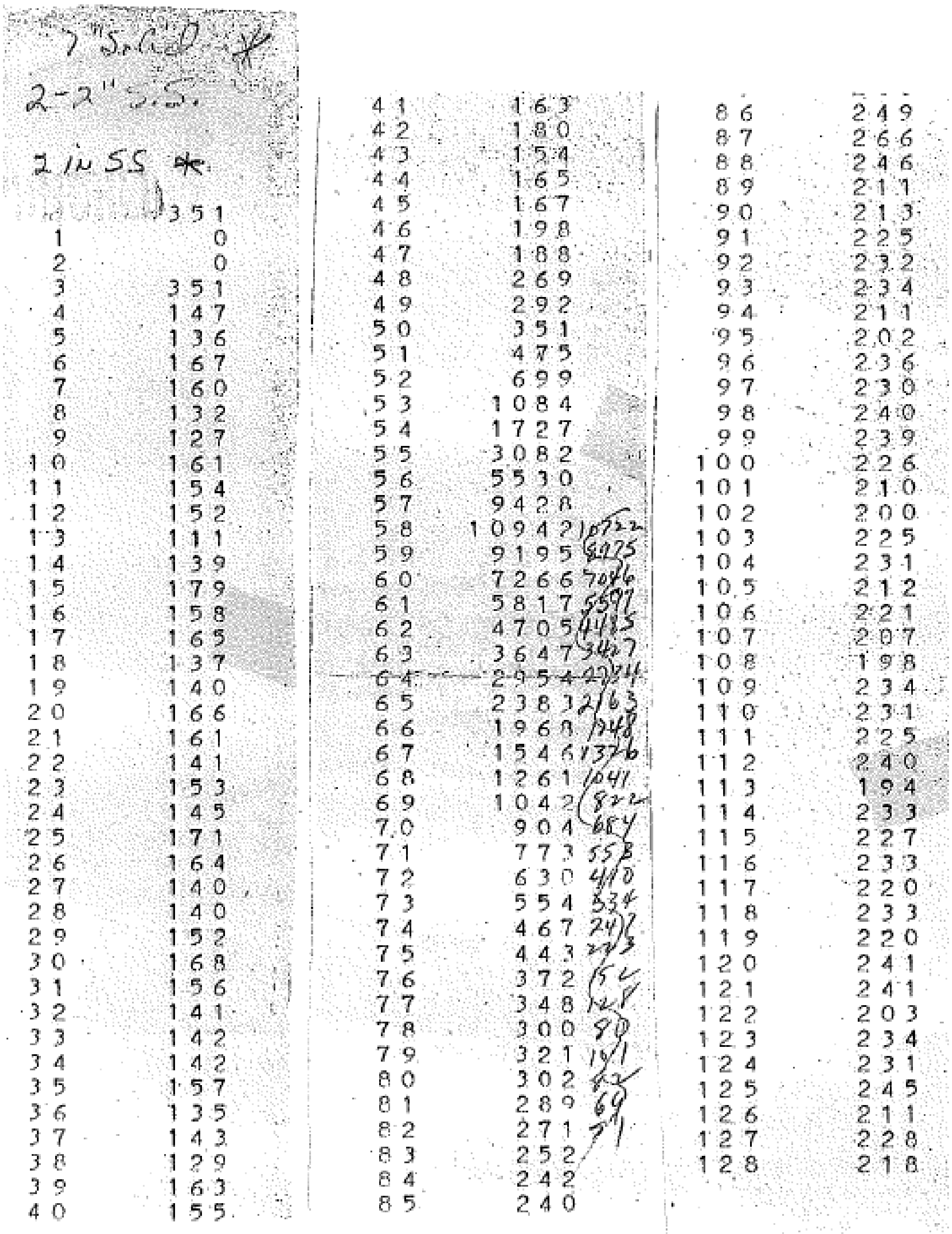
1" .55 7".00

HOLES PLUG

PUNCHED

| | | |
|---|---|---|
| 230 | 0 | |
| 1 | 0 | |
| 2 | 0 | |
| 3 | 239 | |
| 4 | 94 | |
| 5 | 118 | |
| 6 | 104 | |
| 7 | 121 | |
| 8 | 84 | |
| 9 | 114 | |
| 10 | 108 | |
| 11 | 113 | |
| 12 | 97 | |
| 13 | 108 | |
| 14 | 102 | |
| 15 | 122 | |
| 16 | 104 | |
| 17 | 100 | |
| 18 | 101 | |
| 19 | 95 | |
| 20 | 113 | |
| 21 | 112 | |
| 22 | 105 | |
| 23 | 127 | |
| 24 | 101 | |
| 25 | 107 | |
| 26 | 91 | |
| 27 | 96 | |
| 28 | 102 | |
| 29 | 111 | |
| 30 | 103 | |
| 31 | 107 | |
| 32 | 103 | |
| 33 | 97 | |
| 34 | 108 | |
| 35 | 104 | |
| 36 | 111 | |
| 37 | 114 | |
| 38 | 112 | |
| 39 | 101 | |
| 40 | 110 | |
| 41 | 112 | |
| 42 | 113 | |
| 43 | 113 | |
| 44 | 104 | |
| 45 | 115 | |
| 46 | 116 | |
| 47 | 124 | |
| 48 | 116 | |
| 49 | 110 | |
| 50 | 148 | |
| 51 | 172 | |
| 52 | 158 | |
| 53 | 222 | |
| 54 | 281 | |
| 55 | 411 | |
| 56 | 645 | |
| 57 | 1089 | |
| 58 | 1979 | |
| 59 | 3911 | |
| 60 | 7361 | |
| 61 | 9870 | 9700 |
| 62 | 8839 | 8669 |
| 63 | 6789 | 6619 |
| 64 | 5379 | 5209 |
| 65 | 4131 | 3961 |
| 66 | 3197 | 3027 |
| 67 | 2580 | 2410 |
| 68 | 2027 | 1857 |
| 69 | 1618 | 1448 |
| 70 | 1228 | 1058 |
| 71 | 1117 | 947 |
| 72 | 864 | 694 |
| 73 | 691 | 581 |
| 74 | 530 | 360 |
| 75 | 486 | 316 |
| 76 | 423 | 253 |
| 77 | 313 | 143 |
| 78 | 320 | 150 |
| 79 | 273 | 103 |
| 80 | 222 | 52 |
| 81 | 259 | 59 |
| 82 | 220 | 50 |
| 83 | 199 | 29 |
| 84 | 176 | |
| 85 | 186 | |
| 86 | 186 | |
| 87 | 175 | |
| 88 | 190 | |
| 89 | 153 | |
| 90 | 181 | |
| 91 | 171 | |
| 92 | 177 | |
| 93 | 151 | |
| 94 | 176 | |
| 95 | 167 | |
| 96 | 162 | |
| 97 | 136 | |
| 98 | 162 | |
| 99 | 161 | |
| 100 | 156 | |
| 101 | 161 | |
| 102 | 167 | |
| 103 | 173 | |
| 104 | 164 | |
| 105 | 166 | |
| 106 | 139 | |
| 107 | 146 | |
| 108 | 151 | |
| 109 | 148 | |
| 110 | 164 | |
| 111 | 198 | |
| 112 | 175 | |
| 113 | 163 | |
| 114 | 170 | |
| 115 | 154 | |
| 116 | 186 | |
| 117 | 151 | |
| 118 | 162 | |
| 119 | 174 | |
| 120 | 142 | |
| 121 | 169 | |
| 122 | 148 | |
| 123 | 145 | |
| 124 | 147 | |
| 125 | 150 | |
| 126 | 154 | |
| 127 | 169 | |
| 128 | 151 | |

**Table D.3. Rossi alpha data for 1 in. thick reflected configuration.** Time zero for the measurement is the beginning of channel 60.



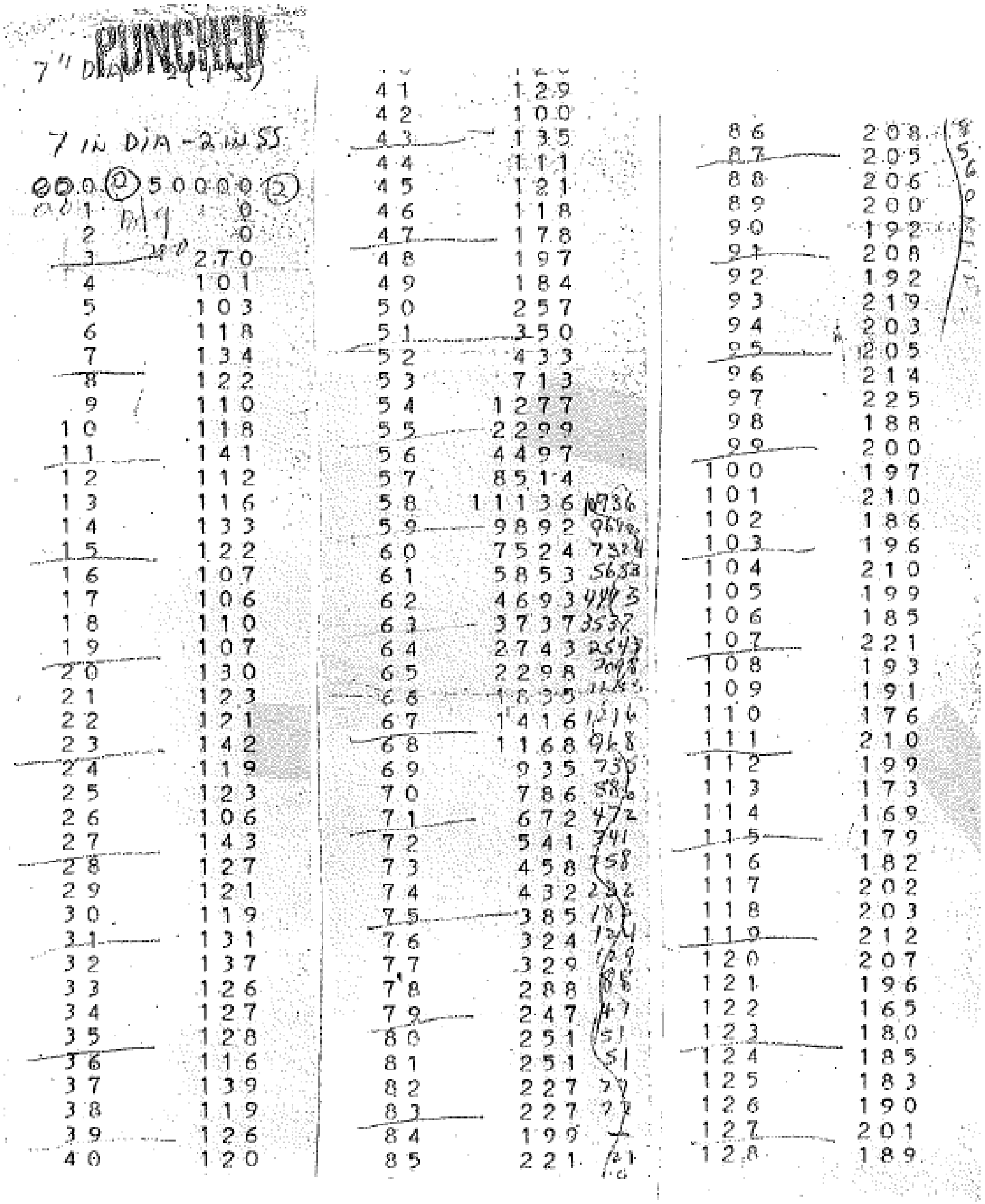
7" S.C.D. *

2-2" S.S.

2 in SS *

| | | |
|---|---|---|
| | 351 | |
| 1 | 0 | |
| 2 | 0 | |
| 3 | 351 | |
| 4 | 147 | |
| 5 | 136 | |
| 6 | 167 | |
| 7 | 160 | |
| 8 | 132 | |
| 9 | 127 | |
| 10 | 161 | |
| 11 | 154 | |
| 12 | 152 | |
| 13 | 111 | |
| 14 | 139 | |
| 15 | 179 | |
| 16 | 158 | |
| 17 | 165 | |
| 18 | 137 | |
| 19 | 140 | |
| 20 | 166 | |
| 21 | 161 | |
| 22 | 141 | |
| 23 | 153 | |
| 24 | 145 | |
| 25 | 171 | |
| 26 | 164 | |
| 27 | 140 | |
| 28 | 140 | |
| 29 | 152 | |
| 30 | 168 | |
| 31 | 156 | |
| 32 | 141 | |
| 33 | 142 | |
| 34 | 142 | |
| 35 | 157 | |
| 36 | 135 | |
| 37 | 143 | |
| 38 | 129 | |
| 39 | 163 | |
| 40 | 155 | |
| 41 | 163 | |
| 42 | 180 | |
| 43 | 154 | |
| 44 | 165 | |
| 45 | 167 | |
| 46 | 198 | |
| 47 | 188 | |
| 48 | 269 | |
| 49 | 292 | |
| 50 | 351 | |
| 51 | 475 | |
| 52 | 699 | |
| 53 | 1084 | |
| 54 | 1727 | |
| 55 | 3082 | |
| 56 | 5530 | |
| 57 | 9428 | |
| 58 | 10942 | 10722 |
| 59 | 9195 | 8975 |
| 60 | 7266 | 7046 |
| 61 | 5817 | 5597 |
| 62 | 4705 | 4485 |
| 63 | 3647 | 3427 |
| 64 | 2954 | 2734 |
| 65 | 2383 | 2163 |
| 66 | 1968 | 1748 |
| 67 | 1546 | 1326 |
| 68 | 1261 | 1041 |
| 69 | 1042 | 822 |
| 70 | 904 | 684 |
| 71 | 773 | 553 |
| 72 | 630 | 410 |
| 73 | 554 | 334 |
| 74 | 467 | 247 |
| 75 | 443 | 223 |
| 76 | 372 | 152 |
| 77 | 348 | 128 |
| 78 | 300 | 80 |
| 79 | 321 | 101 |
| 80 | 302 | 82 |
| 81 | 289 | 69 |
| 82 | 271 | 51 |
| 83 | 252 | |
| 84 | 242 | |
| 85 | 240 | |
| 86 | 249 | |
| 87 | 266 | |
| 88 | 246 | |
| 89 | 211 | |
| 90 | 213 | |
| 91 | 225 | |
| 92 | 232 | |
| 93 | 234 | |
| 94 | 211 | |
| 95 | 202 | |
| 96 | 236 | |
| 97 | 230 | |
| 98 | 240 | |
| 99 | 239 | |
| 100 | 226 | |
| 101 | 210 | |
| 102 | 200 | |
| 103 | 225 | |
| 104 | 231 | |
| 105 | 212 | |
| 106 | 221 | |
| 107 | 207 | |
| 108 | 198 | |
| 109 | 234 | |
| 110 | 231 | |
| 111 | 225 | |
| 112 | 240 | |
| 113 | 194 | |
| 114 | 233 | |
| 115 | 227 | |
| 116 | 233 | |
| 117 | 220 | |
| 118 | 233 | |
| 119 | 220 | |
| 120 | 241 | |
| 121 | 241 | |
| 122 | 203 | |
| 123 | 234 | |
| 124 | 231 | |
| 125 | 245 | |
| 126 | 211 | |
| 127 | 228 | |
| 128 | 218 | |

**Table D.4. Rossi alpha data for 2 in. thick reflected configuration.** Time zero for the measurement is the beginning of channel 58.



PUNCHED

7'' DIA 2 (1 SS)

7 IN DIA - 2 IN SS

00.0 ② 5 0 0 0 0 ②

|  |  |  |
|---|---|---|
| 1 | 0 |  |
| 2 | 0 |  |
| 3 | 270 |  |
| 4 | 101 |  |
| 5 | 103 |  |
| 6 | 118 |  |
| 7 | 134 |  |
| 8 | 122 |  |
| 9 | 110 |  |
| 10 | 118 |  |
| 11 | 141 |  |
| 12 | 112 |  |
| 13 | 116 |  |
| 14 | 133 |  |
| 15 | 122 |  |
| 16 | 107 |  |
| 17 | 106 |  |
| 18 | 110 |  |
| 19 | 107 |  |
| 20 | 130 |  |
| 21 | 123 |  |
| 22 | 121 |  |
| 23 | 142 |  |
| 24 | 119 |  |
| 25 | 123 |  |
| 26 | 106 |  |
| 27 | 143 |  |
| 28 | 127 |  |
| 29 | 121 |  |
| 30 | 119 |  |
| 31 | 131 |  |
| 32 | 137 |  |
| 33 | 126 |  |
| 34 | 127 |  |
| 35 | 128 |  |
| 36 | 116 |  |
| 37 | 139 |  |
| 38 | 119 |  |
| 39 | 126 |  |
| 40 | 120 |  |
| 41 | 129 |  |
| 42 | 100 |  |
| 43 | 135 |  |
| 44 | 111 |  |
| 45 | 121 |  |
| 46 | 118 |  |
| 47 | 178 |  |
| 48 | 197 |  |
| 49 | 184 |  |
| 50 | 257 |  |
| 51 | 350 |  |
| 52 | 433 |  |
| 53 | 713 |  |
| 54 | 1277 |  |
| 55 | 2299 |  |
| 56 | 4497 |  |
| 57 | 8514 |  |
| 58 | 11136 | 10936 |
| 59 | 9892 | 9692 |
| 60 | 7524 | 7324 |
| 61 | 5853 | 5653 |
| 62 | 4693 | 4493 |
| 63 | 3737 | 3537 |
| 64 | 2743 | 2543 |
| 65 | 2298 | 2098 |
| 66 | 1635 | [illegible] |
| 67 | 1416 | 1216 |
| 68 | 1168 | 968 |
| 69 | 935 | 735 |
| 70 | 786 | 586 |
| 71 | 672 | 472 |
| 72 | 541 | 341 |
| 73 | 458 | 258 |
| 74 | 432 | 232 |
| 75 | 385 | 185 |
| 76 | 324 | 124 |
| 77 | 329 | 129 |
| 78 | 288 | 88 |
| 79 | 247 | 47 |
| 80 | 251 | 51 |
| 81 | 251 | 51 |
| 82 | 227 | 27 |
| 83 | 227 | 27 |
| 84 | 199 | - |
| 85 | 221 | 21 |
| 86 | 208 |  |
| 87 | 205 |  |
| 88 | 206 |  |
| 89 | 200 |  |
| 90 | 192 |  |
| 91 | 208 |  |
| 92 | 192 |  |
| 93 | 219 |  |
| 94 | 203 |  |
| 95 | 205 |  |
| 96 | 214 |  |
| 97 | 225 |  |
| 98 | 188 |  |
| 99 | 200 |  |
| 100 | 197 |  |
| 101 | 210 |  |
| 102 | 186 |  |
| 103 | 196 |  |
| 104 | 210 |  |
| 105 | 199 |  |
| 106 | 185 |  |
| 107 | 221 |  |
| 108 | 193 |  |
| 109 | 191 |  |
| 110 | 176 |  |
| 111 | 210 |  |
| 112 | 199 |  |
| 113 | 173 |  |
| 114 | 169 |  |
| 115 | 179 |  |
| 116 | 182 |  |
| 117 | 202 |  |
| 118 | 203 |  |
| 119 | 212 |  |
| 120 | 207 |  |
| 121 | 196 |  |
| 122 | 165 |  |
| 123 | 180 |  |
| 124 | 185 |  |
| 125 | 183 |  |
| 126 | 190 |  |
| 127 | 201 |  |
| 128 | 189 |  |

**Table D.5. Repeated measurement Rossi alpha data for 2 in. thick reflected configuration.** Time zero for the measurement is the beginning of channel 58.