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Critical Experiments on Single-Unit Spherical Plutonium Geometries Reflected and Moderated by Oil

By
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LOCKHEED MARTIN

DISCLAIMER

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May 30, 1997

This paper is written under contract C96-175866 with the United States Department of Energy, administered by the Idaho National Engineering and Environmental Laboratory, although the work was performed at Rocky Flats, Colorado

DEDICATION

This paper is respectfully dedicated to the memory of the principal author of earlier reports of these results,

Dr. Douglas Clayton Hunt.

Tragically, Doug was killed in a mountain climbing accident several years ago. He fell more than a hundred feet while climbing one of Colorado's higher peaks. Poignantly, he died engaged in an activity he enjoyed immensely. Doug was quite knowledgeable in some areas of theoretical nuclear physics. In particular, he understood the theory of criticality; and he had a comfortable familiarity with the way neutrons interacted with matter.

Doug and this author were more than professional colleagues. He was a friend, an office mate, a car-pool partner, my bridge partner in a few duplicate bridge tournaments, and we shared an enthusiasm for mountain activities in Colorado's beautiful Rocky Mountains. Sadly, this last interest proved his demise.

This dedication ends with a humorous recollection stemming from our professional work together. Doug and I had jointly performed several hundred critical experiments spanning many programs. On many, some aspect of the outcome might have been in question. Whether or not criticality would be achieved upon full reflection was often such a question under the program discussed here. The following dialogue could frequently be heard:

one: "Do ya think this one'll be crit? I do! (or don't)"

two: "No, I don't (or do)!"

one: "Betcha a penny!"

The loser always paid his debt in full and the copper coin would be proudly taped to a wall above the winner's desk. Many were those, in later years, who inquired about the nearly equal strings of pennies taped near Doug Hunt's and Bob Rothe's desks!

ABSTRACT

Experimental critical configurations are reported for several dozen spherical and hemispherical single-unit assemblies of plutonium metal. Most were solid but many were hollow-centered, thick, shell-like geometries. All were constructed of nested plutonium (mostly ^{239}Pu) metal hemispherical shells. Three kinds of critical configurations are reported. Two required interpolation and/or extrapolation of data to obtain the critical mass because reflector conditions were essentially infinite. The first finds the plutonium essentially fully reflected by a hydrogen-rich oil; the second is essentially unreflected. The third kind reports the critical oil reflector height above a large plutonium metal assembly of accurately known mass (no interpolation required) when that mass was too great to permit full oil reflection.

Some configurations had thicknesses of mild steel just outside the plutonium metal, separating it from the oil. When used, the thickest of these was 50 mm. Steel laminations were used on both spherical and hemispherical assemblies; but hemispheres did not have steel against the plane face. Oil-reflected experiments were taken to or very close to delayed criticality; but those without oil were necessarily extrapolated to criticality for safety reasons. Still, extrapolations are believed to predict criticality quite accurately because of the strong linearity in the functional relationship between radius and reciprocal multiplication.

These experiments were performed at the Rocky Flats Critical Mass Laboratory in the late 1960s. They have not been published in a form suitable for benchmark-quality comparisons against state-of-the-art computational techniques until this paper. The age of the data and other factors lead to some difficulty in reconstructing aspects of the program and may, in turn, decrease confidence in certain details. Whenever this is true, the point is acknowledged.

The plutonium metal was alpha-phase ^{239}Pu containing 5.9 wt-% ^{240}Pu. All assemblies were formed by nesting 1.667-mm-thick (nominal) bare plutonium metal hemispherical shells, also called hemishells, until the desired configuration was achieved. Very small tolerance gaps machined into radial dimensions reduced the effective density a small amount in all cases. Steel components were also nested hemispherical shells; but these were nominally 3.333-mm thick. Oil was used as the reflector because of its chemical compatibility with plutonium metal.

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INTRODUCTION

This document is the fourth in a series of six peer-reviewed papers written under the International Criticality Safety Benchmark Evaluation Project. These six papers place into the public domain previously unpublished experimental data generated at the Rocky Flats, Colorado, Critical Mass Laboratory (CML). The benchmark evaluation project is administered for the Department of Energy by the Lockheed Idaho Technologies Company, Idaho National Engineering Laboratory (INEL). The previous three[1,2,3] papers were published between 1994 and 1996.

In this program, a series of critical mass measurements on alpha-phase plutonium metal were performed at the Rocky Flats Critical Mass Laboratory between May 31, 1967 and September 12, 1969. Most were essentially fully reflected by a hydrogen-rich oil in all directions. Several others were essentially unreflected. The remaining cases were fully oil-reflected in all directions except at the top. For these, critical oil reflector heights relative to the top of the metal configuration are reported.

Experiments included spherical, hemispherical, and "asymmetric spherical"[4] geometries. All were built of nesting hemispherical shells. Most were solid assemblies; but many were hollow centered, forming thick spherical or hemispherical shells. A steel region, up to 50-mm thick, sometimes was added outside the plutonium. Most of these plutonium or plutonium+steel configurations were placed into a tank and remotely flooded with a hydrogen-rich oil in an attempt to achieve criticality. However, critical configurations are also reported which correspond to essentially unreflected assemblies.

---

[1] Robert E. Rothe, "Experimental Critical Parameters of Plutonium Metal Cylinders Flooded with Water." September, 1994.

[2] Robert E. Rothe, "Experimental Critical Parameters of Enriched Uranium Solution in Annular Tank Geometries". April, 1996.

[3] Robert E. Rothe, "Critical Experiments on an Enriched Uranium Solution System Containing Periodically Distributed Strong Thermal Neutron Absorbers." September, 1996.

[4] Asymmetric spherical assemblies are those composed of two hemispheres of different diameter placed face to face with co-linear polar axes.

These experiments, like all critical experiments performed at Rocky Flats, were used to provide nuclear criticality safety data to ensure the continued safety of plant operations. Data from every program at that laboratory were always used in two ways in those early days of nuclear criticality safety. First, they were applied directly to plant operations if those operations were deemed suitably similar to the experiments. The degree of similarity required was often left to the discretion of the Criticality Safety Engineer. Secondly, they were used to compare experimental results with calculations from the state-of-the-art computational methods in vogue at the time; and, again, details of this comparison were often left to the discretion of the Safety Engineer. Computational methods, before the advent of Monte Carlo codes, required certain conditions of symmetry (spherical, infinite cylinders, or infinite planar slabs) exist. Because of that limitation, most of the experiments in the present program for which criticality occurred at less than full oil reflection were essentially ignored. They were not considered useful. In the 1990s, they probably form the more-valuable set for computational validation because plutonium masses and the critical oil height are well known. Fortunately, a good number of these unrecognized cases were discovered during research of archived records from this program. These cases may lack some confidence because these less-than-useful cases were not always documented sufficiently.

Usually, the geometry of experimental programs at Rocky Flats bore a strong physical resemblance to some plant operation. This Rocky Flats practice facilitated direct comparison; but it limited the scope of computer validations.

This study followed that practice. Although nuclear weapons were never of the dimensions used, they were moderately well approximated by the geometries studied. Steel in intimate contact with the fissile metal simulated holding fixtures used in forming processes. Oil immersion simulated some plant fabrication operations and also approximated fully reflected conditions. Fully reflected criticality data always yields a conservative approximation when issuing criticality safety operational limits. Water could have been used in place of oil; but that was known to be incompatible with the plutonium itself.

These experiments, even though quite old, should prove useful to modern Criticality Safety Engineers and to the International Criticality Benchmark Evaluation Project itself. Published criticality experiments on plutonium metal have been rare because of the cost and hazards associated with manufacturing and handling plutonium. Some experts[5] have recently expressed the opinion that any plutonium data - even with modest uncertainty - would be of considerable value to the nuclear criticality safety industry.

Furthermore, the unstable nature of plutonium metal also usually required the metal be encapsulated in some fashion after the 1970s; so these early experiments with unfettered plutonium metal are quite rare. Another advantage of this program is its geometrical simplicity. Spherical and hemispherical geometries fully reflected with a simple hydrogen-rich oil are quite easy to model on the computer. Finally, the resultant critical masses are about two to four times greater than single-unit masses commonly allowed at Rocky Flats; so they form a good validation of a limiting value of plutonium mass.

[5] Private communication with Thomas P. McLaughlin of Los Alamos National Laboratory during a meeting in April, 1997, concerning the archiving of old records from critical mass laboratories.

DATA QUALITY

The author of this paper was *not* the principal experimenter for this research; so he does not have the first-hand recollections about the program that such a person would have. Instead, the experimental study was designed, implemented, directed, and analyzed by Dr. Douglas C. Hunt. Sadly, Dr. Hunt died in a mountain climbing accident several years ago. This paper is an attempt to publish his data in sufficient detail that it can be used to benchmark calculational methods. Fortunately, this author did assist him as a second experimenter on almost all phases of the program at one time or another; so his memory *can* embellish existing records.

These phases included storage of the plutonium metal, their retrieval from storage for assembly, cleaning and other preparation of the fuel, assembly of many hemishells into one assembly, transfer of this into a small tank, moving this tank into another room, positioning it within a larger tank, remote addition of oil into both tanks to add reactivity, attaining criticality, and returning the plutonium metal to storage.

Dr. Hunt did publish three terse reports of this experiment. The first[6], published in November of 1968, was classified "Confidential" at the time because it contained information about then-sensitive geometries. The publication has recently been declassified. The second paper[7] was another internal report but was unclassified. The last[8] was a journal article, published in the open literature, immediately following the study and excluded classified results. All three brief articles reported only critical masses with very little detail about geometries and material compositions which produced those critical configurations. That level of detail seemed adequate in the early 1970s; but it is insufficient for present-day benchmark evaluations. This document is an attempt to fill in missing details necessary to upgrade Hunt's data to benchmark quality. The principle improvement is the addition of many new critical configurations. These are partially reflected hemispherical combinations of plutonium and mild steel where criticality was achieved at less than full oil-reflection above the metal assembly. These cases were of little value in 1970; but modern computer techniques can model them quite well. Another improvement is

[6] Douglas C. Hunt, "Plutonium Metal Critical Mass Measurements", **RFP-1216** (Confidential). Rocky Flats Plant, November 15, 1968. This report was declassified in April, 1997.

[7] D. C. Hunt and M. R. Boss, "Plutonium Metal Criticality Measurements", **RFP-1410** (unclassified), Transactions of the American Nuclear Society, **12 No.2** (1969).

[8] D. C. Hunt and M. R. Boss, "Plutonium Metal Criticality Measurements, Journal of Nuclear Energy, **25,** Pergamon Press 1971.

a detailed description of the geometry and composition of materials involved in the experiment. This is carried out as far as the thick concrete walls of the room which contained the experiments.

Fortunately, both this author and M. R. Boss, the co-author of two of the earlier publications, are still alive and can add useful information from memory. Furthermore, some log books, old records, and loose notes related to this study have been uncovered from this author's library of Rocky Flats' CML data. Dr. Hunt's sometimes terse notes are difficult to interpret, however. For example, he determined statistical uncertainties for the critical masses; but the source and exact meaning of these is not known.

In spite of this effort to improve Dr. Hunt's publications, some uncertainty still remains in this document. Materials often must be referred to by their common or commercial names because no specific analysis was performed; or, if performed, that analysis was not found. Even worse, a reference may have been made to an item fabricated of, say, "stainless steel" with no further detail as to which particular type (304, 304L, 316, etc.) was used. In such cases, the best that can be done is to recognize that most components manufactured at Rocky Flats were usually made from Type 304L or Type 316 stainless steel. Those performing benchmark calculations will have to evaluate the effect of both types and, if significant, increase the uncertainty of the critical parameter to account for that lost knowledge.

Another weakness of the original data is that materials beyond the immediate vicinity of the fissile material where seldom described. This is where the memories of the two surviving persons becomes important as they recall where and how measurements were made. Still, some uncertainty remains because exact distances between recalled objects were seldom recorded. At best, such specifications should be considered estimates rather than measurements.

A less serious flaw is the uncertain knowledge of specific masses and dimensions of individual plutonium hemishells. This is not so important as long as the important parameters - the mass and dimensions - of assembled *critical* configurations were preserved. Fortunately, they were. Still masses of individual components were measured on three occasions. These were not widely recorded because that data was classified "Confidential" at the time.

Some of these critical configurations were even compared against computer calculations of the day in Hunt's 1971 publication. He used then-current computational methods. Asymmetrically spherical geometries were converted into a supposedly equivalent sphere; and this was compared against DTF computer code results. Such results are questionable because the conversion is not rigorous and the experimental situation was never truly spherical. Hemispherical geometries were compared against a "modified" KENO computer code. KENO was in its infancy then and exactly how it was modified is not explained. Both techniques used the popular Hansen-Roach 16-group neutron cross section sets. Unfortunately, neither a sample set of these calculations nor any elaboration of calculational details is available. Still, the results of his calculations are recorded in an Appendix for whatever value they may offer.

DATA ARCHIVE

All records associated with this nuclear criticality safety experimental program performed at Rocky Flats in the late 1960s are now maintained at the Criticality Safety Information Resource Center at the Los Alamos National Laboratory. The particular building which houses them is called the Los Alamos National Laboratory's RECORDS CENTER and ARCHIVES. They are under the immediate control of the head archivist who may be contacted at:

Roger A. Meade, Archivist

Los Alamos National Laboratory
P.O. Box 1663
CIC-10, MS C322
Los Alamos, NM 87545
(505) 667-3809
(505) 667-9749 [fax]
rzxm@lanl.gov [e-mail]

The ultimate goal is to locate all records from all critical mass laboratories that have been closed down in past years at that center. Not all laboratories have transferred their materials there yet. Rocky Flats will complete its second and third transfers sometime during 1998.

To access any records associated with this plutonium study, request collection

A-96-051.

This yields a 13-page inventory of brief descriptions of line-by-line items from 30 year's of research at Rocky Flats. These, in turn, are somewhat arbitrarily divided into seventeen series. Each "Series" has a title and generally covers one experimental program at RFP; but this is not always the case. In particular, the present plutonium experiments, contained in Series 15, are mixed in with a uranium solution study referred to as "The Christmas Tree" experiment.

Each Series contains a number of "Boxes". These are the physical boxes that actually contain the archived data. Each box carries two identification numbers: the collection number and the box number within that collection. Finally, within each box, a few folders, numbered sequentially, contain the raw, archived data.

Specific records and raw data for this plutonium study may be located by providing the following information to the Archivist:

Collection Number: **A-96-051**

Box-Folder	Title			
36-1	Console Log #5,	10/27/67	-	12/31/69
36-8	3-3 Raw Data; Book I ...			. 3-3-1 to 3-3-40
36-9	3-3 Raw Data; Book II .			.. 3-3-81 to 3-3-??
36-10	3-1 Raw Data; Book II .			.. 3-1-72 to 3-1-??
42-4	Console Log #4,	2/1/67	-	10/27/67
42-5	3-1 Raw Data; Book I ..			.. 3-1-1 to 3-1-71
42-6	Hand Assembly Data			

These records are simple to access. This paper should help a user understand and interpret the sometimes terse notes, remarks, graphs, and penciled scribblings from three decades ago that will be encountered when viewing these archived records.

THEORY

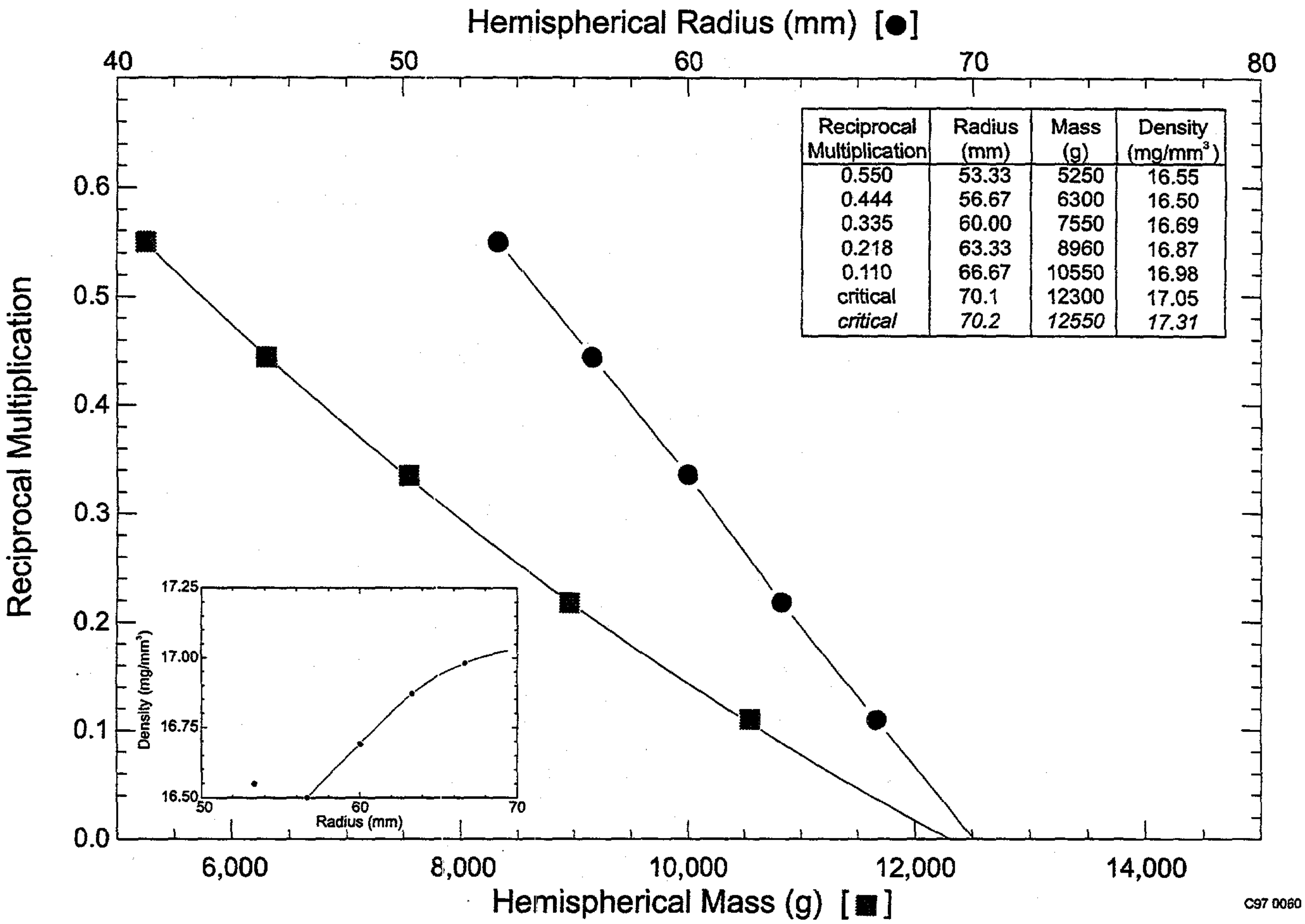
The *reciprocal multiplication* technique was selected for the safe approach to criticality on these experiments. Details of this method have been described in the first three papers under this contract and will not be repeated again. Two different methods of adding reactivity were used in this program. (1) Air-assembly of plutonium from a planar array of hemishells into the desired geometry employed the increase in radial thickness, proportional to the number of parts, as the reactivity increment. (2) Later, the introduction of oil used the height of that reflector oil as the reactivity addition parameter. Both methods of adding reactivity were never used at the same time.

Unreflected Cases

The *manual* construction, in air, of each hemisphere was done by adding shells, one at a time, to the outside of a subcritical hemisphere, producing a slightly larger hemisphere. If a thick hemispherical shell was desired, the smaller, inner hemishells were simply left in storage. If a sphere or asymmetric sphere was wanted, the above construction was repeated, building a second hemisphere on top of the first. Reciprocal multiplication curves were generated for each construction to assure safety; and these had a multiplication limit of ten (10). This safety limit was imposed upon the construction because human beings were present and could be injured or killed if criticality were attained.

Figure 1 illustrates the last five data points for such a curve generated during the construction of one typical assembly. The same reciprocal multiplication data is graphed against two parameters of the growing hemisphere: mass (bottom axis) and radius (top). The radial dependence tends to be very close to linear, although the mass-dependent curve exhibits only minimal curvature. In this example, a plutonium hemisphere was being built; but each stage had a constant 33.3-mm-thick steel hemispherical shell outside it. The multiplication increased, as expected, with each addition until its allowed operational limit (10) was approached. The inset to the upper right contains both graphed and derived data (density).

All critical parameters for assemblies **not** reflected by oil were obtained by extrapolating such curves to criticality. That condition corresponds to a multiplication of infinity or a reciprocal multiplication of zero. The strong linearity evident for the radial dependence curve suggests that its extrapolation is, in fact, quite certain.



Reciprocal Multiplication	Radius (mm)	Mass (g)	Density (mg/mm³)
0.550	53.33	5250	16.55
0.444	56.67	6300	16.50
0.335	60.00	7550	16.69
0.218	63.33	8960	16.87
0.110	66.67	10550	16.98
critical	70.1	12300	17.05
critical	*70.2*	*12550*	*17.31*

Figure 1. Critical parameters for unreflected plutonium assemblies were determined by the extrapolation of reciprocal multiplication data from a number of subcritical assemblies. The strong linearity of the radial dependence lends confidence to extrapolated critical values even though extrapolations are long. Two extrapolated critical results are given in the upper right inset. One, obtained from an extrapolation of radius, is shown in italics; the other ordinary font. The lower inset shows that even the density of assemblies varied smoothly with one exception (53.33 mm).

The mass data, however, shows some curvature; and its extrapolation would be a little less certain. Usually, both curves were used to predict the "best" critical assembly parameters. Fortunately, another valuable test of extrapolated data is possible. The density of nested assemblies would be expected to be constant or to vary only slowly with other parameters. The inset to the lower left shows the densities for the same five subcritical assemblies; and an extrapolation of that data to the extrapolated critical radius yields an expected density of the critical hemisphere. This density and that critical radius can be combined to predict the critical mass of the hemisphere. Fortunately, that mass agrees well with a reasonable extrapolation of the mass data.

The strong linearity between assembly radius and reciprocal multiplication is demonstrated for two other cases in Fig. 2, although one is more linear than the other. The greater the linearity over the last several data points, the greater the confidence in the extrapolated critical radius. The abscissa in the figure is the number of plutonium hemishells; but this is clearly proportional to the radial thickness. These two curves were selected at random and truly represent the common pattern.

Oil Reflected Cases

The reflection of any assembly with oil reflector was done by adding oil in incremental heights noting the increase in multiplication caused by each increment. This was continued, using the reciprocal multiplication curve to ensure safety, until one of two situations resulted. Either criticality was attained at some height less than full oil reflection or the plutonium was essentially fully reflected by oil in all directions and still remained subcritical.

The first increments of oil reflected neutrons from below the assembly. Later ones returned neutrons on the side. Finally, oil above the assembly reflected the top. The ideal case, of course, could never happen. That would be a plutonium assembly that just happened to be precisely critical (k = 1.0000) exactly when the oil thickness had become effectively infinite in all directions. The probability of this using shells of discrete mass was negligibly small

Instead, criticality of fully oil-reflected cases was derived from a small number of experiments each of which proved to be subcritical upon full reflection. The varied fissile masses of each of these was too small to attain criticality even with full reflection. For such an assembly, however, the reciprocal multiplication curve

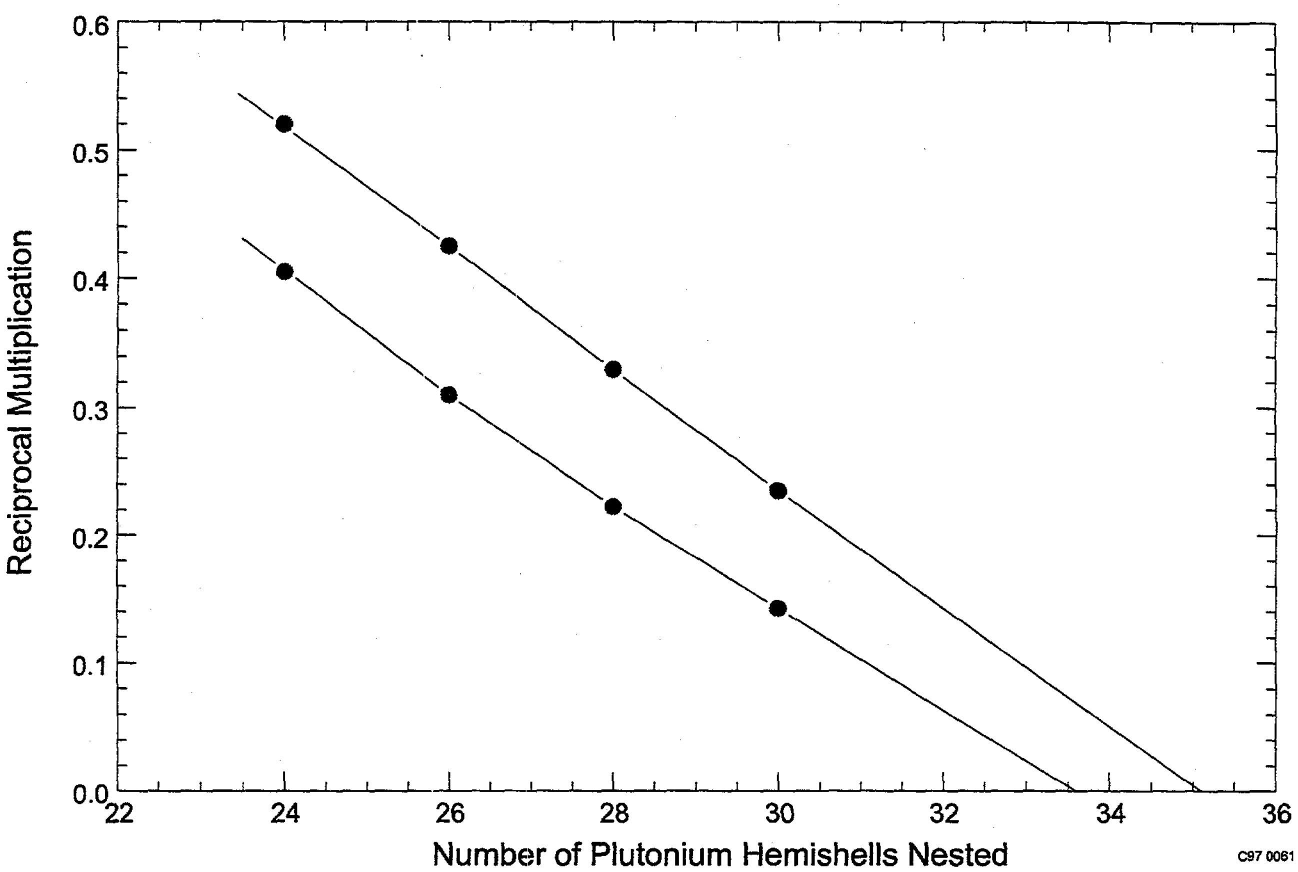


Figure 2. Radial dependence (proportional to the number of hemishells) was always more linear than the same data graphed against mass.

would level off and cease to increase at some oil height regardless of further additions. This was called the *asymptotic reciprocal multiplication*. The closer the fissile mass was to the ideal condition, the closer to zero would be that asymptotic value. Figure 3 illustrates this two-stage procedure for determining the critical mass. Four plutonium units of increasing mass (4370 g through 5721 g) produce asymptotic reciprocal multiplications for each (0.080 through 0.006). When these asymptotes are graphed against the corresponding masses, as in the inset to the figure, the critical mass of the "ideal" configuration can be determined (7752 g).

In many cases, this critical mass prediction was upper bounded by one additional experiment. The next-larger plutonium assembly in the sequence was assembled and reflected by oil. When that attained criticality at less than full reflection, an upper bound to the critical mass was established. In the figure, the arrow along the horizontal axis indicates the common center of all these assemblies.

The curves of Fig. 3 are, unfortunately, fictional; they do not represent actual experiments. This is necessary because no actual data so clearly presented the procedure. The set does, however, illustrate very well the procedure used to obtain critical parameters.

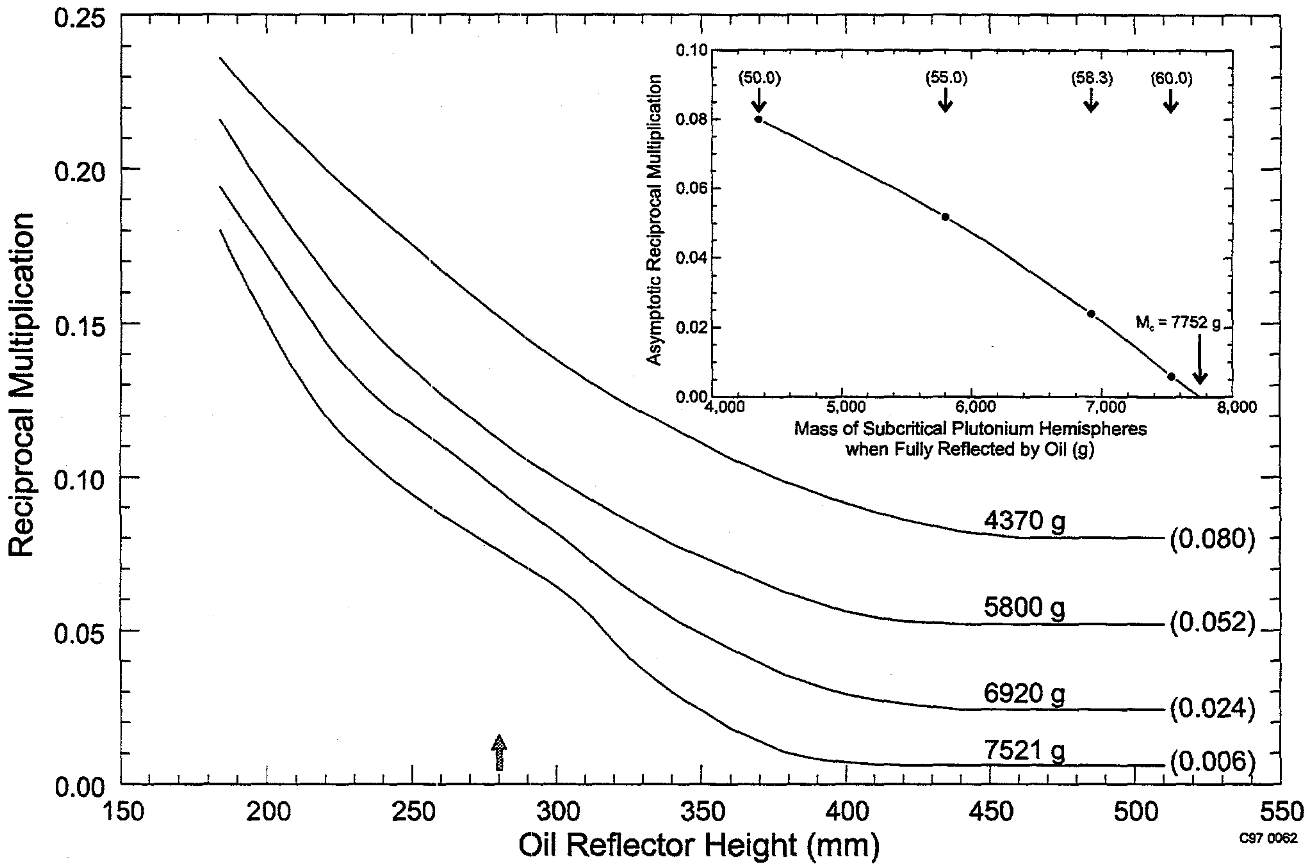


Figure 3. Four subcritical assemblies of increasing mass, all centered at the shaded arrow, produced ever-smaller *asymptotic reciprocal multiplications* (parentheses) as the critical mass was approached. These parameters were then graphed against one another (inset) to predict the critical mass of a still-larger assembly (7752 g). The radius of each of the four is shown in parentheses in the inset. In many cases, critical configurations were also bounded by a larger assembly for which criticality occurred with less than full reflection.

PROCEDURE

Downdraft Room

Plutonium hemishells were stored in commercial pressure cookers on shelves inside a walk-in all-stainless-steel room. The atmosphere inside the room and within the pressure cookers was ordinary air; so the metal was exposed to that environment during its lifetime. Several shelves at different levels lined the back and one side wall of the walk-in room. Another wall contained the access doorway. This consisted of a stainless steel door lined with a rubber seal. When the door was closed and latched, a leak-tight seal prevented contamination spread outside the room. The remaining wall contained only an opening into an adjoining glovebox. That opening was in the center of the wall and about waist high. It was large enough to pass through one hemishell at a time held in the hands. The opening was normally closed by a pneumatically operated sliding plastic door that could be opened by a foot treadle. The last feature of this room was a "downdraft table". Sides to this "table" formed a waist high rectangular plenum standing vertically. The table top was a heavy-gauge wire screen suitably strong to support the weight of a loaded pressure cooker. A strong ventilation exhaust duct was coupled to the plenum close to the floor. This exhaust caused a flow of air from the room, through the wire mesh, down the plenum, and out the exhaust duct. This downdraft table was located right under the access opening into the glovebox. Figure 4 shows this Downdraft Room.

Before an experiment, the plutonium hemishells needed that day were determined. Then, three persons entered the downdraft room to obtain them. Two removed the metal from their pressure cookers. The third was a safety person who monitored activities for contamination control.

A clean piece of paper was placed on the center of the wire mesh table top. The bottom surface was instantly contaminated; but the top remained clean. A pressure cooker was moved from the shelf and placed on the paper. This kept the exterior of the pressure cooker uncontaminated. The lid was slowly removed by one worker and raised out of the way. It was held over the table so loose contamination would be swept down into the table. The other worker reached into the cooker with his gloved hands and lifted the hemishell. Holding the raised part, he opened the passage into the glovebox using the foot treadle. The plutonium component was passed into the glovebox and set upon its floor. The lid was returned to the pressure cooker; and the still-uncontaminated container was returned to the storage shelf. This process was repeated until all the needed plutonium hemishells were in place of the glovebox floor.

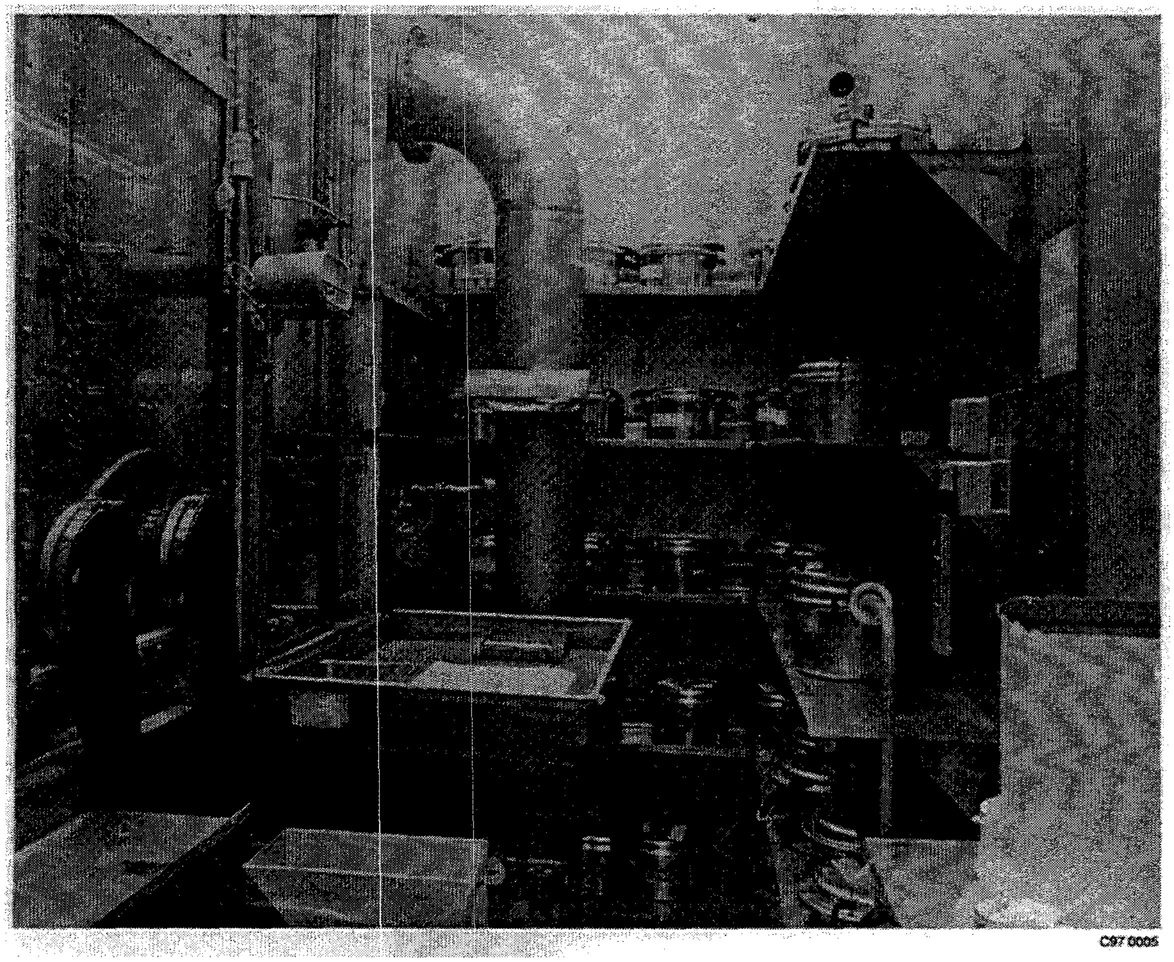


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Figure 4. Plutonium metal was stored in commercial pressure cookers. Hemishells were removed over a Downdraft Table (lower center) and passed into an adjoining glovebox through a clear plastic door (left, above table).

When mild steel hemishells were also required for the day's experiment, these parts were also introduced into the glovebox. This author does not recall whether these parts were handled the same way as plutonium or if they were introduced to the glovebox a different way. The end result, however, is that the required number of steel parts shared the glovebox floor with fissile metal.

The Glovebox

The glovebox was long and narrow. People working on opposite sides could easily touch the same part. A planar array of any number and configuration of un-nested plutonium hemishells had previously been approved by criticality safety personnel; so the initial condition for the day's experiment was known to be critically safe.

Each experiment began with an inspection of the hemishells. Parts that appeared too oily from the last experiment had excess oil absorbed into paper wipes. Somewhat dry parts received an additional coating of lithium grease. Occasionally, a part suffered from some exposure to air leading to small regions of surface oxidation. These areas were cleaned by abrading loose material from the part. After cleaning, additional grease was always applied. Sometimes - but not always - hemishells were reweighed. The required number of hemishells, spread across the floor, were then ready for assembly.

Plutonium metal contains an intrinsic neutron source. That source strength is in proportion to the ^{240}Pu content. Those neutrons produced the background count rate for the reciprocal multiplication approach toward criticality as the individual hemishells were assembled. Two boron trifluoride proportional counters were positioned under the floor of the glovebox to detect the increasing flux of neutrons. Output signals from the detectors fed directly to instruments nearby. Both experimenters had both visual and audible readout of the instantaneous neutron flux. Thus, a safe approach toward criticality was assured as these several plutonium metal hemishells were nested together.

All critical parameters presented in the RESULTS section for assemblies *without* oil reflection were obtained in this fashion. This is true for both spherical and hemispherical assemblies. The maximum system multiplication allowed by operational safety limits was ten (10); so an extrapolation of these data to criticality was necessary to obtain critical data. Extrapolations of reciprocal multiplication data against the radius of the plutonium hemisphere proved to be remarkably linear, as discussed previously. Great confidence is placed in the continued linearity of the curve throughout its extrapolation distance.

When regions of steel of constant thickness were outside a growing plutonium assembly, the smallest steel hemishell would be removed to make room for added plutonium; and the next-larger steel would be added to the outside to retain that constant thickness. Steel shells came in increments twice as large as plutonium; so two plutonium shells had to be added at a time in these cases. This restricted the plutonium mass increments available to the program.

Hemispherical assemblies were built using a single reciprocal multiplication curve; that fact is certain. Spherical assemblies *probably* needed two, although this detail is not recalled for certain. The first hemisphere would have been built using one curve. Then, a second was *probably* generated as the second was assembled. This would have been necessary because the intrinsic shape of one curve is expected to differ from the other. The safety limit of ten was *probably* preserved by starting the second curve at the same reciprocal multiplication existing at the completion of the first. Procedures contained in this paragraph are conjecture based on sound scientific method.

All these procedures produced two results. First, critical parameters of plutonium metal assemblies, with and without steel laminations, had been determined. These useful data are contained in the RESULTS section of this paper. Second, an assembly had been built that could now be placed into another container for the remote introduction of oil. This would later provide additional criticality data.

The glovebox described above had a small L-shaped wing off one corner. Its floor stood about 2½ meters above the room's floor and a little less than a meter above the floor of the rest of the glovebox. This square wing had a large-diameter (about 0.6 m) port cut into its floor. This opening was covered with a flexible plastic bag to prevent contamination spread. This bag was left over from the previous experimental operation.

Loading the Experimental Tank

The inner experimental tank, described in detail later, was wheeled into the room. It, also, had a flexible plastic bag covering its top opening. The tank was positioned directly below the opening in the glovebox wing;

and a fresh flexible plastic bag was installed coupling the tank to the glovebox. The two old bags covering tank and port were removed and discarded as contaminated waste. This action connected the tank to the glovebox with access from one to the other. The outside of the new bag was uncontaminated.

The completed fissile assembly, was then raised from the glovebox floor, translated to the wing, and lowered into the smaller experimental tank. A hand-operated winch on a short length of monorail was used for this operation. With the assembly secured in position, the experimental tank was rotated several times, twisting the flexible plastic bag coupling the two. The portable cart used to transport this inner experimental tank was equipped with a rotatable platform to enable this step. The twist was continued until the plastic bag was tightly wound. The center of the twisted region was bound even tighter with vinyl tape forming a nearly solid region. This was cut through using a knife. The blade of the knife became slightly contaminated and was used only for these "bag cuts". The two severed and exposed surfaces of the cut bag were also slightly contaminated; and these were covered over with a fresh patch of plastic tape. These bags became the old bags to be discarded during the next day's experiment.

This operation left the plutonium assembly securely fastened in position within the inner experimental tank; and its top now had a new plastic bag to prevent contamination spread. The port in the floor of the glovebox wing also had a new bag; and the glovebox was empty of plutonium and steel hemishells. The Downdraft Room had its full compliment of pressure cookers on the shelves; but some of them were now empty.

The Experiment

The Downdraft Room and its associated glovebox were located in a room a short distance from the Assembly Room. All critical experiments were to be conducted in this Assembly Room; so the loaded inner experimental tank was wheeled into the Assembly Room and positioned close to the larger outer experimental tank.

The Assembly Room had a ceiling-mounted travelling crane. This crane could reach all floor locations of the Assembly Room except very close to each wall; and the lifting capacity of the crane far exceeded anything associated with this program. That crane was used to raise the loaded inner tank, translate it into position directly above the empty, larger, outer tank, and then lower it inside the outer.

This procedure produced one tank, loaded with plutonium metal in the desired configuration, roughly centered within a larger tank. Each tank had its own supply of reflector oil. Oil associated with the inner tank was always plutonium contaminated; but that contained in the outer tank's reservoir remained uncontaminated. In fact all features of the outer tank remained uncontaminated by these procedures.

Two tanks were used, instead of one ample-sized tank, to reduce the volume of plutonium-contaminated oil. The inner tank was not nearly large enough to provide "effectively infinite" reflection; but the outer tank provided that additional reflection. When both tanks were ultimately full of oil, any fissile load would have at least 0.2 m of reflection; and this thickness is generally accepted as "essentially infinite".

At this point, the Assembly Room would be abandoned, locked, sealed, and environmentally isolated from the rest of the world. This was done for safety. The assumption was that the worst credible accident might occur during each experiment; and the experiment should be conducted in such a manner as to mitigate consequences. These consequences were three fold. (1) an overpressure shock wave could accompany any unplanned nuclear criticality excursion. The thick concrete walls and sturdy doors of the Assembly Room were more than adequate to contain such an overpressure. (2) An instantaneous and intense burst of radiation would also result. Thick walls and the geometry of access passageways would prevent any such radiation from streaming out of the Assembly Room. Finally, (3) a large inventory of highly radioactive fission byproducts would be instantly created. These fission fragments would be fully contained by the walls of the room, the rubber seals on the doors, and the fact that all ventilation leading from the Assembly Room had been shut down before the experiment.

Reactivity could now be added safely to the fissile assembly. This was accomplished by simultaneously pumping reflector oil from both reservoirs into both tanks. One caution might go unnoticed. The inner tank, including its small reservoir of oil, was completely contained within the outer tank. Thus, whenever oil was pumped within the inner system, air space was created within that reservoir. That space existed above the remaining oil.

Certain details of this procedure are not recalled some three decades after the program; but this author *thinks* both tanks were filled simultaneously. The reason for this belief is that sequential filling would have required reciprocal multiplication curves for each; and the generation of two curves is not recalled. However, the method of ensuring equal oil heights in both tanks is also not recalled.

Ultimately, one of two conditions would have existed following these procedures. One, the fissile assembly would be subcritical upon full reflection and a certain asymptotic reciprocal multiplication noted. Second, criticality would occur at some oil height less than full reflection. In the 1960s, these upper limit boundary cases were considered not very useful. They were not amenable to the computational methods of the day which required certain symmetry considerations. In recent decades, these would be the most worthwhile data points because modern computer techniques have the ability to compare directly with whatever geometry existed at the precise moment of criticality. Because of this, considerable effort was expended by this author to reconstruct any such cases.

When the experiment was finished, all oil was returned to reservoirs. Contaminated oil remained in the smaller; and uncontaminated oil flowed back to its reservoir. The assembly procedure was followed in reverse order. The inner tank was removed from the outer tank. It was, of course, coated with oil which was wiped as dry as reasonable. The inner tank was moved back to the metal storage room and reconnected to the glovebox using a fresh, new bag. The fissile load was removed from the tank and returned to the floor of the glovebox. It, too, was wiped clean of excess oil before being disassembled into a planar array of hemishells. These hemishells were returned to storage by the reverse of the procedure described above.

These experiments were time consuming and tedious. A great deal of care was required to prevent contamination releases. Typically, only two or three experiments could be performed per week. Existing records reveal that at least 167 experiments were conducted during the 28 months of this experimental program. Not all of these critical approach experiments resulted in useful data.

PLUTONIUM METAL

All fissile assemblies were composed of alpha-phase plutonium metal. The isotopic composition is given in Table I; and the metal contained only about 0.07 weight-percent other metallic impurities. All constructions were generally "sphere like" consisting of true spheres, thick spherical shells, hemispheres, thick hemispherical shells, and asymmetric spheres. Asymmetric spheres were built from two hemispheres of different diameter placed face to face with axes co-linear. Figure 5 illustrates this construction for an assembly also having a steel lamination.

Hemispherical geometries were built by nesting thin hemishells onto a small solid hemisphere. To begin, this hemisphere would be nested inside the smallest hemishell. Next, both would be slipped inside the next-larger hemishell. Then, that would be placed inside a larger fourth and this process repeated until the desired hemisphere was built. Such construction resulted in a solid hemisphere of discreet mass and radius dictated by the properties of the plutonium components available. The density of this assembly - somewhat less than the bulk metal density - was also determined by the total mass of all the parts and the outside radius of the largest.

Plutonium components were machined at Rocky Flats in the late 1960s. A few additional shells were probably machined at a later date. This is not absolutely certain; but all records point to that being a correct assumption. Shells were nominally 1-2/3 millimeter thick; but the need to assemble and disassemble required tolerance gaps machined into both radii. The size of these gaps is uncertain; but the density of finished

Table I. Isotopic Composites of Alpha-Phase Plutonium Metal

Plutonium Isotope	Weight Percent
238	0.01
239	93.58
240	5.90
241	0.49
242	0.02

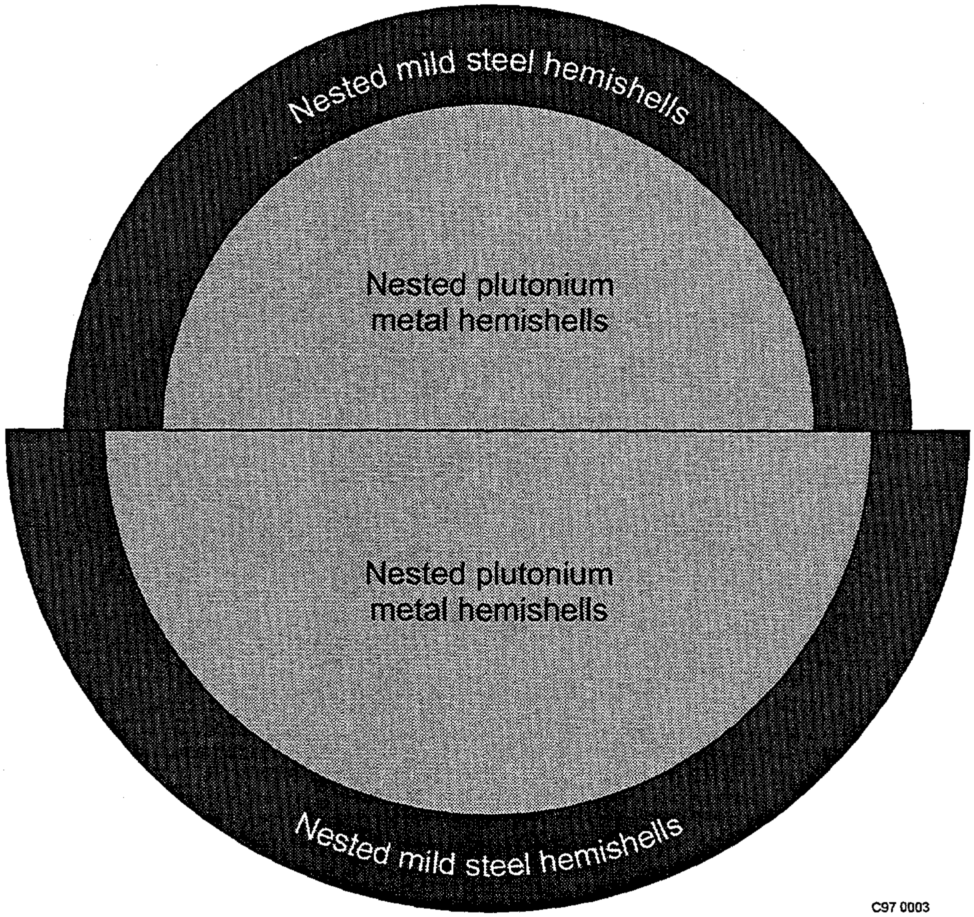

Figure 5. Experimental "asymmetric spheres" were actually two hemispheres placed face to face and coaxial with one another. Whenever steel covered one hemisphere, the same thickness covered the other. All four regions were composed of nested hemishells; therefore, each suffered a slight reduction in density due to necessary radial tolerances.

assemblies *was* always known; so specific in radial dimensions are not important. Tolerance gaps were not great; but they *did* decrease density below pure metal density. The average thickness of a machined hemishell was about 3.28 mm. The solid hemisphere at the center was 40 mm in diameter.

Although no photographs of the *plutonium* metal exist, Fig. 6 shows a nearly identical set of *enriched uranium* hemishells. Three important differences between the two sets were: (1) plutonium components were half as thick as uranium, (2) they appeared more silver in color than black, and (3) their mass did not always remain constant over the duration of this study.

Each plutonium shell had a metal density of 19.74 mg/mm^3 according to the 1971 journal article. An earlier report (1968) claimed a density of 19.52 mg/mm^3. The discrepancy is not important because the bulk density is never required to express experimental results. Furthermore, since it appears that sets of hemishells were machined at different times, both may be reasonably accurate.

The important density is the assembly density, reduced from whatever bulk density existed because of the tolerance gaps. This assembly density was always the sum of the masses of all components divided by the volume of the fissile assembly. This density for spherical and asymmetric spherical assemblies ranged between 16.36 and 18.72 mg/mm^3. For hemispheres, the range was 16.19 and 18.32 mg/mm^3. The reason for this surprisingly wide variation in density is probably related to changes in the mass of individual components over time, discussed next.

Plutonium is now known to be relatively unstable when exposed to air, especially moist air. Plutonium chemistry was not so well known in the 1960s. Moisture attacks the surface causing the formation of some plutonium compound (an oxide and/or hydride). This author recalls occasions when hemishells were "cleaned" as part of the assembly process. This entailed wiping grease and oil from the surface; but it also involved abrading away any regions of loose compound with an abrasive cloth. This difficult and unpleasant chore was discussed recently with M. L. Boss[9], Hunt's co-author; and he recalled these cleanings sometimes reduced the weight of a part by "a few grams each". Several shells are believed to have actually gained or lost from a few to several grams over their 28 month's use. This variation in mass of each component could account for the variation in assembly densities.

[9] Private Communication, March, 1997.

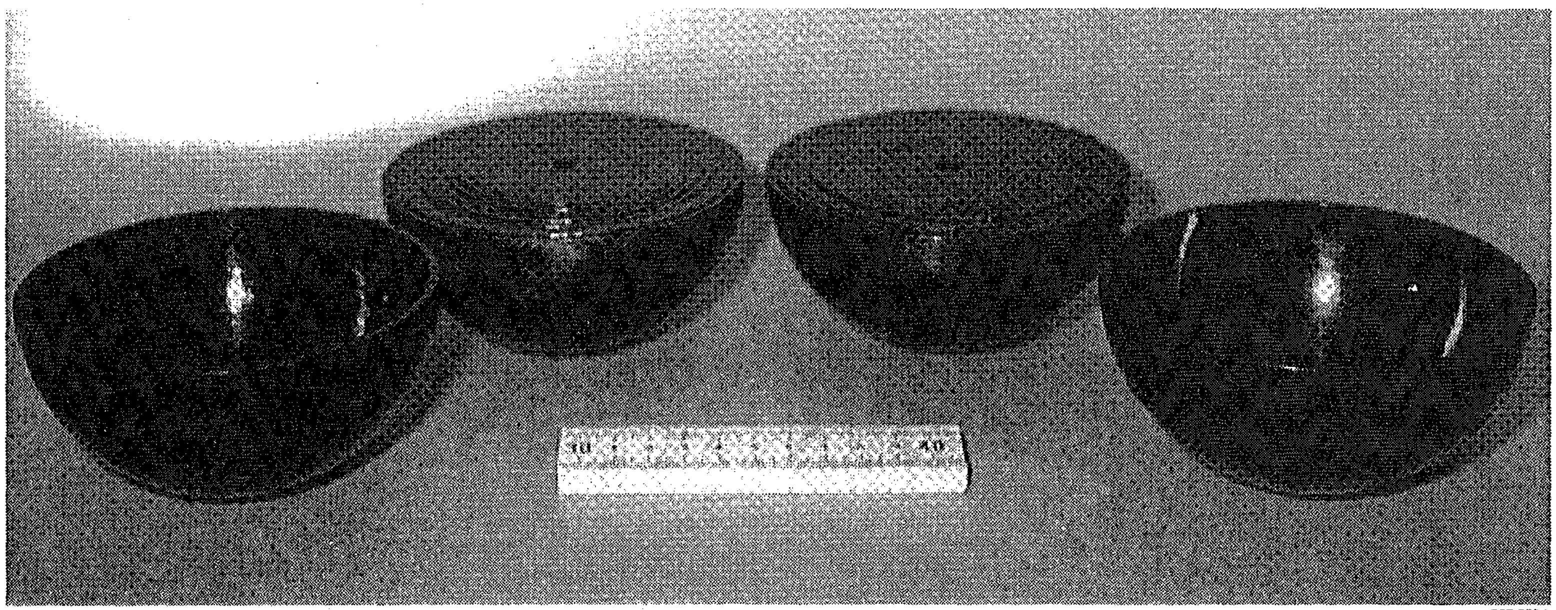

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Figure 6. Both plutonium metal and mild steel components were machined hemispherical shells. This photograph, from another program, shows neither but does illustrate the shape. Plutonium hemishells were 1.67 mm thick, half that shown here, and were silver in color. Mild steel components were the thickness shown (3.33 mm). The center set of nested components was intentionally aligned poorly to highlight nesting.

Even though an unambiguous table of *precise* masses and radial dimensions of each and every part is impossible to compose, that data is, fortunately, *not* required to yield useful criticality benchmark validation information. The measured total mass and outermost radius of assemblies at or near criticality is quite adequate for this purpose; and, fortunately, that data *is* available. Still, such a table would be very desirable and provide a sense of completeness to this paper, so three avenues were explored to generate that information.

First, these parameters for at least certain combinations of nested components can be determined from available data near criticality. D. C. Hunt had often recorded the *actual* mass and density of two specific assemblies which bounded that condition: (1) the largest assembly that proved to be subcritical at full reflection and (2) the smallest assembly that proved critical at some height less than full reflection. Using these data, a calculation of the radius of certain actually assembled hemispheres is possible. That radius is the cube root of the following:

$$\frac{\text{(known mass of the hemisphere)}}{(2\pi/3)\text{(its known density)}}$$

When that calculated radius proves to be very close to the nominal outside radius of one of the hemishells, considerable confidence can be placed in the assumption that that actual mass corresponds to a hemisphere of that radius. Hemispherical parameters presented in Table II were obtained in this fashion. Masses, especially, are believed to be quite accurate. Subtracting successive entries gives the mass of individual hemishells or sets of two adjacent shells.

A similar procedure may be applied to asymmetric spheres; but these results are less certain. Here, the critical mass of an asymmetric sphere, the difference in mass between the top and bottom hemispheres, and the density of the overall assembly is used as described in the footnote[10]. One such calculation suggests that, for the larger hemisphere:

$M = 4721$ g $\qquad R = 49.90$ mm (nominally, 50.0 mm).

[10]The mass of the larger hemisphere is one-half the sum of the critical mass and the difference mass. When this mass is converted to a radius by the simple arithmetic of the preceding paragraph, that radius will be very close to the nominal outside radius of one of the plutonium hemishells. Having determined parameters of the larger hemisphere, the remaining mass of any asymmetric sphere must belong to the smaller hemisphere. If the calculation of *this radius* by the same arithmetic also yields a radius very close to the nominal radius of a hemishell, then confidence exists that the properties of both hemispheres of an asymmetric sphere have been correctly determined.

Table II. Derived Radius (bold font) of a Few Specific Hemishells from Hemispheres of Known Mass

Number of Hemishells in Hemisphere	Mass of Next Hemishell or {Next Two} (g)	Known Mass of Hemisphere (g)	Density[a] of that Hemisphere (mg/mm^3)	**Derived Outer Radius of Hemishell (mm)**	Nominal Radius of that Hemishell (mm)
21		5237	*16.7*	**53.1**	53.3
22	{1061}				55.0
23		6298	*16.7*	**56.5**	56.7
24	{1237}				58.3
25		7535	16.86	**60.0**	60.0
26	703	8238	16.86	**61.78**	61.7
27	724	8962	16.86	**63.31**	63.3
28	{1607}				63.3
29		10569	17.3	**66.3**	66.7
30	{1766}				68.3
31		12335	17.38	**69.72**	70.0

a. Two densities in italics are estimated values.

Then, when two smaller hemispheres (the bounding cases described above) were built on top of this at different times, those were:

M = 2459 g   R = 40.15 mm (nominally, 40.0 mm) and

M = 3039 g   R = 43.09 mm (nominally, 43.3 mm),

again, calculated by the method in the footnote.

A similar calculation for another case produced the following three hemispheres (the larger and two bounding ones):

M = 4555 g   R = 50.09 mm (nominally, 50.0 mm),

M = 1806 g   R = 36.79 mm (nominally, 36.7 mm), and

M = 2237 g   R = 39.52 mm (nominally, 40.0 mm).

The questionable nature of these determinations for asymmetric spheres is illustrated by different masses obtained for supposedly the same hemisphere. The 50-mm hemisphere was estimated at both 4721 and 4555 g; and the 40-mm one, at 2459 and 2237 g by this method. Indeed, agreement was poor.

The second avenue of tabulating individual component masses comes from a Table in the 1968 confidential report repeated here as Table III. Two facts emerge from a careful examination of this table.

(1) The footnote confirms what has already been alluded to. These shells were unstable in air; and their mass varied with time.

(2) This set was insufficient to allow the construction of spheres. Any solid hemisphere or thick-walled hemispherical shell could have been constructed up to a nominal outside radius of 103.3 mm; but components necessary to build a second hemisphere did not exist. The first shells for which two of the same nominal size existed had an inside radius of 50 mm. In fact, spherical *shells* could only be constructed in three ranges for which the inside and outside radii in millimeters are: 50 to 63.3, 70 to 80, and 90 to 100.

Fortunately, this incomplete set was adequate to allow the determination of the critical masses of two thick spherical shells (IR = 50 and 70 mm) and a large number of hemispherical configurations. Note that this report was published early in the experimental program, before all experiments had been completed.

The third avenue for constructing a probably-accurate table of discrete masses of individual hemishells was found in April, 1997, among the archives of this program at LANL. It is a single page of unlabeled columns of numbers; and considerable detective work is required to interpret it properly. The page contains three sets of three typed columns, clearly composed some time before two additional, hand-written columns were added to each set.

Although columns are not labeled, typed entries are identical to Table III, copied without change[11] from the 1968 confidential report. This lends great confidence to the fact that those unlabeled typed columns represent: the part number for each and every hemishell, its inner radius, and its mass prior to 1968. The typed mass columns even have the date "December, 1967" hand written above them, strengthening that belief.

The first hand-written column, just to the right of the 1968 mass, contains another mass measurement dated "December, 1968". These one-year-later masses are sometimes unchanged; but others show significant deterioration with significant loss of mass. A couple of cases actually reveal a gain of a gram or two. The second hand-written column, just to the left of typed entries, is dated "September, 1969"; and these numbers, too, show some large mass changes as well as some unchanged values. A very significant variation over 21 months is noted for some parts.

Parts *could* gain weight by two means: (1) If some portion of the surface had oxidized, that region of the shell would gain weight by about 13% (the ratio of PuO_2 to Pu) and (2) If residual grease and/or oil had not been completely removed (difficult in a glovebox), that foreign material would add weight.

The format of this often-copied[12] page is consistent with human thought processes. If a parameter were to be re-measured a year after its typed value, one might well write the new number in the blank space to the right. Several months later, another measurement might well be written to the left of the original if no more blank space existed to the right. The interpretation of this very valuable page is believed correct.

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[11] Except for the inside radius columns which this author changed to millimeters.

[12] This page is at least the fourth copy of some original. That is known because of page edge markings on the copy. Photocopiers of the 1960s left grip marks at the top of the page and reduced the size of the image a few percent.

Table III. Properties of Plutonium Hemishells as of December, 1967

Part No.	Inner Radius (mm)	Mass (grams)	Part No.	Inner Radius (mm)	Mass (grams)
901	0	302.4	853	63.4	790.4
801	20.1	77.5	855	65.1	824.4
803	21.8	91.3	857	66.8	869.2
805	23.5	105.6	859	68.4	909.9
807	25.1	121.9	860	70.1	968.0
809	26.8	134.5	861	70.1	966.0
811	28.4	158.3	862	71.7	966.3
813	30.2	174.6	863	71.7	1002.6
815	31.8	192.1	864	73.4	1051
817	33.4.	213.9	865	73.4	1025
819	35.0	240.3	866	75.2	1087
821	36.8	256.5	867	75.0	1116
823	3.83	283.9	868	76.8	1132
825	40.0	312.1	869	76.9	1111
827	41.8	339.0	870	78.5	1223
829	43.3	361.3	871	78.5	1185
831	45.1	390.0	873	80.2	1238
833	46.7	429.3	875	81.8	1312
835	48.3	464.5	877	83.5	1348
836	50.1	486.0	879	85.1	1400
837	50.1	485.5	881	86.8	1490
838	51.7	522.2	883	88.5	1501
839	51.8	524.2	884	90.1	1561
840	53.5	554.3	885	90.1	1600
841	53.4	559.6	886	91.7	1640
842	55.1	589.2	887	91.7	1639
843	55.1	587.7	888	93.8	1594
844	56.7	629.3	889	93.4	1722
845	56.7	621.6	890	95.1	1737
846	58.5	660.7	891	95.1	1758
847	58.4	670.6	892	96.8	1792
848	60.1	702.9	893	96.8	1775
849	60.1	712.2	894	98.4	1845
850	61.8	742.3	895	98.4	1855
851	61.8	739.3	896	100.2	1922

NOTE: Due to part deterioration with time, the masses represent an average over the first year of the program. About a 1-percent mass uncertainty should thus be associated with masses tabulated in the Results section.

Ten additional entries have been hand written below the three sets of columns. These tend to confirm the recollection that additional hemishells were machined some time months after the original set had been made. Exactly when these were made and put into service is not specified. These part numbers include: 802, 804, 806, 808, 810, and 812. Clearly, these are nominally identical counterparts to the odd numbered parts 801 to 811. Another part number (#76902) appears to be a second hemisphere with a nominal outside radius of 20 mm. Its mass is similar to part number 901, a little over 300 g. The radius listed seems to be an outside radius rather than an inside; but this it thought to be simply an error. With these seven new hemishells, a solid sphere could have been constructed with a radius of 30 mm.

The remaining three of the ten new parts are not at all recalled from memory; but their existence (or some other parts) would have been necessary to construct some of the assemblies reported in the RESULTS section. One of these (#901-801-11) appears to be a 30-mm-diameter hemisphere; and its mass is consistent with that assumption. The part number also fits the theory; read it as an abbreviation of parts #901, #801, #803, ... #811. The other two (#81323 and #82535) appear to be thick-walled hemispherical shells with inner and outer radii of 30 to 40 and 40 to 50 mm, respectively. Again, their masses are consistent with that assumption. With all these new parts, any sphere of plutonium metal could have been formed up to a diameter of 80 mm. Hemispheres up to 103.3 mm outside radius were always possible.

This valuable page contains *even more* useful information. Check marks alongside twelve of the December, 1968, weights indicate the intention to obtain replacement hemishells. These twelve had experienced the greatest deterioration over the preceding year. Whether or not these parts were ever replaced is not known. One part (#843) did appear to have been replaced. In addition, two of the larger parts (#877 and #879) bare the comment "cracked"; and part #883 (IR = 88.5 mm) is described as "10 pieces"; it probably had broken into that many pieces like a broken vase.

This recently discovered page may be so important to the evaluator who wants to know the properties of individual hemishells that it is reproduced photographically as Fig. 7. The reader will understand the difficulty in interpreting it unambiguously.

Table IV contains the same information but shuffled into chronological order horizontally and to ever-larger shells vertically. Ordinary font represents 1968's original set of hemishells, italics represent the ten new

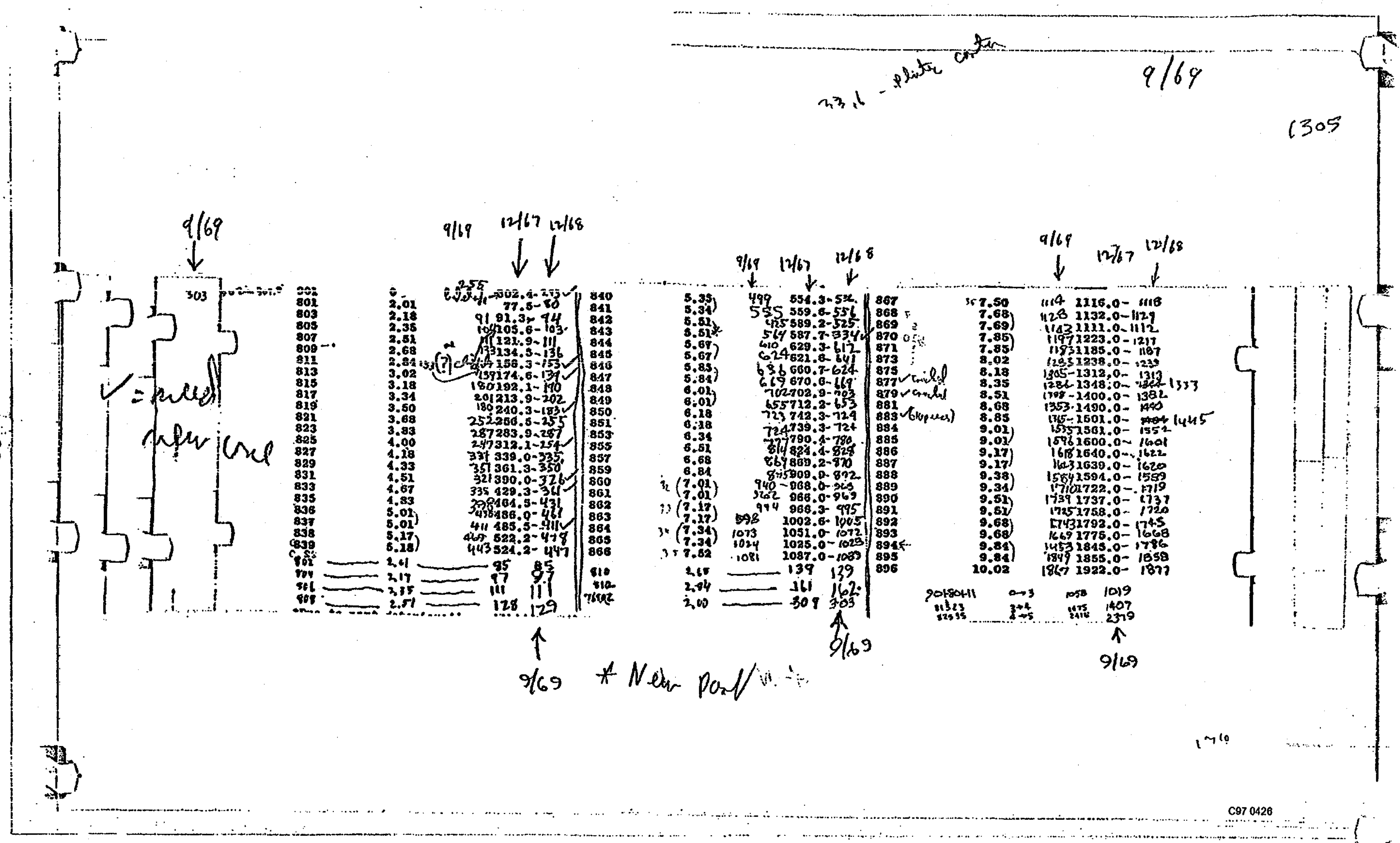

Figure 7. This often-copied page, discovered in April, 1997, was used to determine masses of the original set and ten later (new) plutonium metal components. Three weighings were recorded over 21 months spanning three years; and these show significant losses for some parts. This figure demonstrates the difficulty in determining meaning of unlabeled information.

Table IV. Masses of Both Original and Added Plutonium Hemishells
Over the Full Duration of the Experimental Program

Part Number[a]	IR [OR] (mm)	Theoretical Mass[b] (g)	Dec. 1967 Mass (g)	Dec 1968 Mass[c] (g)	Sept. 1969 Mass (g)
901	0 to [20]	303	302.4[d]	283	255
902	*0 to [20]*	303		[*307.9*]	*303*
901-801-11	*0 to [30]*	1024		[*1058*]	*1019*
801	20.1	82	77.5	80	
802	*20.1*	82		[*85*]	*85*
803	21.8	96	91.3	94	91
804	*21.7*	96		[*97*]	*97*
805	23.5	111	105.6	103	104
806	*23.5*	111		[*111*]	*111*
807	25.1	127	121.9	111	111
808	*25.1*	127		[*128*]	*129*
809	26.8	143	134.5	136	133
810	*26.8*	143		[*139*]	*139*
811	28.4	161	158.3	153	153
812	*28.4*	161		[*161*]	*162*
81323	*30 to [40]*	1403		[*1475*]	*1407*
813	30.2	180	174.6	136	133
815	31.8	200	192.1	190	180
817	33.4	221	213.9	202	201
819	35.0	243	240.3	183	180
821	36.8	267	256.5	255	252
823	38.3	291	283.9	287	287
82535	*40 to [50]*	*2312*		[*2416*]	*2379*
825	40.0	316	312.1	254	247
827	41.8	342	339.0	335	331
829	43.3	370	361.3	350	351
831	45.1	398	390.0	326	321
833	46.7	427	429.3	361	335
835	48.3	458	464.5	431	398
836	50.1	490	486.0	461	435
837	50.1	490	485.5	411	411
838	51.6	522	522.2	478	469
839	51.8	522	524.2	447	443
840	53.5	556	554.3	536	499
841	53.4	556	559.6	556	555
842	55.1	591	589.2	525	
843	55.1	591	587.7	334[g]	564
844	56.7	627	629.3	612	610
845	56.7	627	621.6	641	624
846	58.5	664	660.7	624	636

Table IV (Continued)

Part Number[a]	IR (or) (mm)	Theoretical Mass[b] (g)	Dec. 1967 Mass (g)	Dec 1968 Mass[c] (g)	Sept. 1969 Mass (g)
847	58.4	664	670.6	669	669
848	60.1	701	702.9	703	702
849	60.1	701	712.2	653	655
850	61.8	740	742.3	729	.723
851	61.8	740	739.3	724	724
853	63.4	780	790.4	780	777
855	65.1	822	824.4	828	814
857	66.8	864	869.2	870	869
859	68.4	907	909.9	872	875
860	70.1	951	968.0	965	940
861	70.1	951	966.0	969	962
862	71.7	996	966.3	995	994
863	71.7	996	1002.6	1005	993
864	73.4	1043	1051	1072	1073
865	73.4	1043	1025	1028	1024
866	75.2	1090	1087	1089	1081
867	75.0	1090	1116	1118	1114
868	76.8	1138	1132	1129	1128
869	76.9	1138	1111	1112	1143
970	78.5	1188	1223	1217	1197
871	78.5	1188	1185	1187	1183
873	80.2	1239	1238	1239	1233
875	81.3	1290	1312	1313	1305
877	83.5	1343	1348	1333	1286[e]
879	85.1	1396	1400	1382	1388[e]
881	86.8	1451	1490	1440	1353
883	88.5	1507	1501	1445	1365[f]
884	90.1	1564	1561	1552	1555
885	90.1	1564	1600	1601	1596
886	91.7	1622	1640	1622	1618
887	91.7	1622	1639	1620	1623
888	93.3	1681	1594	1589	1584
889	93.4	1681	1722	1719	1710
890	95.1	1741	1737	1737	1739
891	95.1	1741	1753	1720	1725
892	96.8	1802	1792	1745	1743
893	96.8	1802	1775	1668	1669
894	98.4	1864	1845	1768	1453
895	98.4	1864	1855	1858	1849
896	100.2	1927	1922	1877	1867

Table IV (Continued)

a. All entries in italics correspond to hemishells added some unknown time after the original set was machined

b. See text for assumptions

c. Square brackets correspond to those 10 new components added some time after the December 1967 weighing

d. Figure 7 describes this part with the words: "bad shape"

e. Figure 7 describes this part with the words: "cracked"

f. Figure 7 describes this part with the words: "10 pieces"

g. This badly decomposed hemishell appears to have been replaced with a new one of the same nomimal size parts introduced some unknown time later. An occasional number that proved hard to read in the hand-written columns is given in a smaller font. One new calculated mass is also presented; it is the theoretical mass of a ten-sixth-mm-thick hemishell reduced to an (arbitrary) density of 18.1 mg/mm^3 (to account for tolerance gaps). A survey of this table reveals that, indeed, a few of these hemishells suffered severe degradation over their life span!

Each component had a 6.85-mm-diameter hole drilled in its polar location. A metal tie bolt later passed through these holes to hold the assembly together and fasten it to its mounting fixture. The tie bolt was aluminum for hemispherical assemblies and steel for asymmetric sphere assemblies.

Mild steel hemishells components, when they were used, were always placed just outside their associated plutonium metal hemispheres. Thus, a completed metal assembly might be just plutonium metal or it might consist of plutonium metal with a contiguous layer of carbon steel. This is illustrated in one of the figures. Steel regions as thick as 50 mm were used. No steel parts were used in conjunction with experiments reported in the 1968 confidential document.

The steel was SAE 1018 carbon steel as designated by the American Iron and Steel Institute (AISI). The elemental composition is presented in Table V, although these are handbook[13] values because any laboratory analyses of the specific material has been lost. The density of the steel hemishells was 7.62 mg/mm^3.

Table V. Elemental Composition of Carbon Steel Hemishells,
Sometimes Laminated Outside Plutonium Hemispheres

Element	Weight-%
carbon	0.15 to 0.2
magnesium	0.6 to 0.9
phosphorus	0.04 max
sulfur	0.05
manganese	1.0 max
iron	remainder

[13] Chemical Engineering Handbook, 5th Edition, Perry and Chilton, editors.

Steel hemishells were machined at Rocky Flats to a nominal radial thickness of ten-thirds millimeter - twice the thickness of plutonium hemishells. These steel components were intended to be perfectly compatible with both the enriched uranium and every *second* plutonium component machined during the late 1960s. This author believes that no steel component ever contacted both plutonium and enriched uranium at different times in its life; but this is not certain. One consequence of this thickness was that changes in steel-laminated plutonium assemblies were constrained to add **two** plutonium parts at a time.

Each component, either plutonium or mild steel, was coated with a thin layer of a lithium-silicon grease. This minimized binding between nested parts; but it also aided in retarding surface oxidation and controlling contamination. The grease had a density of 0.972 mg/mm^3; and its elemental composition is given in Table VI. The grease is assumed to occupy completely the interstitial tolerance gaps of a finished assembly and, therefore, to exclude any reflector oil from those gaps.

A few months prior to machining these plutonium hemishells, a very similar set of enriched uranium metal hemishells, shown in one of the figures, had been built. The uranium was twice as thick as the plutonium; so every other plutonium component had nominally the same outside radius as a uranium part. Both had the same sized pole holes, used for mounting. Both had four additional holes drilled into their body at 90° intervals. Often, considerable effort was required to separate shells. These quite small holes were a distance away from the equatorial plane and were designed to be used to pry apart any two nested shells that became stuck to one another. In three decades, they were never needed.

Table VI. Elemental Composition of Grease Used Between Nested Metal Components

Element	Weight-%
hydrogen	8.9
lithium	0.6
carbon	47
oxygen	17.2
silicon	26.1
impurities	0.2

The plutonium components were stored in commercial pressure cookers between experimental use. The ambient atmosphere in the containers, in the room containing the downdraft table, and in the glovebox where they were nested together was ordinary air. That air was not even dehumidified. This was an acceptable practice in the 1960s even though plutonium metal has since been constrained to inert (oxygen-free) environments at Rocky Flats. In light of later experiences, these were questionable practices. The plutonium parts probably lasted as long as they did because of the coating of grease and the residual oil remaining after experiments.

The precise meaning of plutonium masses presented in tables associated with the Results section is not certain beyond question. Two possibilities exist. One would be that individual masses from the *last time* a part was weighed (December, 1967; December, 1968; or September, 1969) were simply added together to yield the mass of an assembled hemisphere. If so, some tabled masses could be in error due to part deterioration between weighings. The second possibility would be that each load was weighed before being positioned into the inner tank. The former seemed more likely until a visit to the facility in May, 1997. Then, this author rediscovered a compartment, not previously remembered, built into the glovebox. He recalled that this contained a precision balance with a hydraulic seal to allow the balance to remain outside the glovebox but weigh objects inside. This observation suggests that *probably* assembly masses were measured much more frequently than previously thought. Still, a survey of later tables casts a cloud over this opinion. Precisely the same configuration reassembled, say, many days after an earlier construction often lists the same weight to within four-place accuracy. The balance was not good enough to yield that precision. One explanation might be that reconstructed loads that close in time were not measured anew. This small question is not considered resolved.

REFLECTOR OIL

The reflector oil was a commercial, clear, pale liquid manufactured by Texaco Lubricants Company[14] as their Texaco #522 oil. The same oil is still sold as product #00522 Canopus 19. It is a dry, pure hydrocarbon fluid with a density of 0.889 mg/mm^3. It was essentially free of any additives; the oil contains only about 0.2 wt% total impurities (elements other than hydrogen and carbon). Although its elemental composition was never measured at Rocky Flats, the carbon-to-hydrogen mass ratio claimed by the manufacturer was 6.8. Its hydrogen number density is 0.0699 x 10^{21} atoms/(mm)^3; and that for carbon, 0.0386 x 10^{21} atoms/(mm)^3. The [C]/[H] number density ratio is, therefore, 0.552. The viscosity is recalled to be similar to a 20- or 30-weight automotive lubricant. Present manufacturing specifications claim a viscosity in the range of 18.9 to 22 cSt at 40° C.

Oil was chosen instead of water as the neutron reflector because water was known to be very incompatible chemically with metallic plutonium. Parts would have decomposed quickly if immersed in water; that was clearly recognized even in those early years. This oil is also neutronically quite similar to water, being a pure hydrocarbon relatively free of additives. Upon closer inspection, the oil may even be a slightly better moderator than water. Water would have had an 2:1 hydrogen-to-oxygen atomic ratio, compared to the nominal 1.8:1 hydrogen-to-carbon ratio for oil. Hydrogen is, of course, the most important moderator and is only "diluted" by neutronically unimportant oxygen in water. The dilution by carbon in the oil is smaller; so a greater number of hydrogen atoms per unit volume is expected. Furthermore, the diluent in oil (carbon) is a better neutron moderator than oxygen. Thus, oil is claimed to be probably a better moderator than water.

The actual organic compound claimed for Texaco #522 oil is not known these three decades later. The above assertion that oil may have been a superior moderator compared to water was based on the assumption that the hydrocarbon monomer looked something like:

$$CH_{1.76}$$

This assumption yields a carbon-to-hydrogen mass ratio of 6.8:1. No other information on the oil was available.

[14] Texaco Lubricants Company, A Division of Texaco Refining and Marketing Inc., P.O. Box 4427, Houston, TX 77210-4427.

The same oil was used in both inner and outer tanks. The only reason for two reflector regions instead of one was to reduce the volume of plutonium-contaminated oil. The oil was quite compatible with both the fissile metal and the lithium grease. In fact, although it was treated as contaminated oil, no truly high levels of contamination are recalled. This may be in error considering the large amounts of plutonium compound generated; but that information is no longer available. No noteworthy physical changes to the oil were observed over the life of this program. Oil pools dripped from assemblies onto the floor of the glovebox resembled the bulk oil in every respect. Neither color or clarity seemed to be affected; and the viscosity seemed unchanged. A small amount of oil seepage between hemishells was a common problem and observed during disassembly. Oil-coated parts were difficult to manipulate through heavy rubber gloves.

The chemistry and metallurgy of plutonium metal was not as well understood in the 1960s as it has become since. This experimental program would probably never be approved currently because of the "hostile" (to the plutonium) environments encountered. The only concern at Rocky Flats in the 1960s was whether the air in contact with metal should be dehumidified or not. No one questioned the use of bare plutonium metal in air! Many contended that the oil, itself, could be a sufficient barrier against moist air. The actual longevity of these thin, machined, plutonium shells - in light of present-day knowledge - is actually somewhat surprising.

EQUIPMENT

The experimental apparatus may be considered a "tank within a tank". The smaller inner tank was not large enough to provide essentially infinite oil reflection on all sides of the experimental assembley; but it did limit the volume of contaminated oil. The larger outer tank provided that needed additional reflection but kept that oil free of plutonium contamination. Each tank actually consisted of three parts: an oil storage reservoir, a pumping system, and a cylindrical container. The introduction of oil added reactivity in the approach toward criticality.

Outer System

The reservoir for the larger system was almost a rectangular parallelepiped. It was 1.88-m long by 0.66-m wide. The top surface was level; but the bottom was sloped for drainage. One end was 0.381-m high, the other, 0.356 m. The capacity of the reservoir was about 430 liters. It was constructed of 4.76-mm-thick Type 6061-T6 aluminum plate except for the top; it was thicker (12.7 mm) to support the weight of a person. The reservoir was externally braced at the thick end with aluminum angle stock about 25 mm on a side. Similar bracing was found at one-third and two-thirds the length; but the shallower end had no such stiffener. The reservoir was elevated above the floor by aluminum angle stock at both ends. The thicker end had a 51 mm by 51 mm angle (9.5 mm thick); the other was 76 mm by 51 mm angle, also 9.5 mm thick. This difference matched the sloped bottom. The top surface was fitted with two rectangular access plates; and a submersible pump would later be placed at the deeper end. Two nominally 25-mm-diameter threaded pipes welded into the top surface would later be connected to the SCRAM lines; and a coupling welded into this top was used to connect the pump to the distribution manifold.

The bottom of the associated experimental tank was centered 0.3 m above the top surface of the reservoir and also centered along its length and width. An aluminum channel framework outside the experimental tank provided this support. The fact that some reflector oil remained inside the reservoir when criticality was attained must be recognized because that oil provided additional bottom reflection to the assembly under study. The higher the critical height proved to be, the less significant this problem became because the reservoir contained less oil and it was further away.

The oil distribution system connecting tank and reservoir was constructed mostly of copper tubing and brass valves. The pump used to move the oil was an inexpensive submersible one resting on the bottom of the reservoir. Control valves were actuated by electric solenoids. The pump operated continuously during an experiment; but oil did not move unless one or more of three valves were opened. These valves allowed oil to flow at different rates. The fastest was that attained with the chosen pump and a single copper line. Two lesser rates were accomplished by placing cupped metal diaphragms into the two parallel lines. These diaphragms had small holes of different sizes drilled in them; and different flow rates resulted simply from the increased impedance. This simple expedient worked very well. A fourth flow rate resulted from both solenoid valves on the two diaphragmed lines opening at the same time. Both SCRAM valves were screwed directly to the bottom of the tank. This assured that any experiment could accurately be described as having no oil columns projecting below the bottom surface of a tank. Steel pipe (not copper tubing) connected these valves to the reservoir.

Reflector heights were indicated outside the tank by a simple U-tube sight gauge. This 12.7-mm-diameter clear plastic tube from a fitting at the bottom of the tank was clamped vertically to the tank. Oil heights were read remotely from an adjacent calibrated linear scale by a closed circuit television camera. The camera was mounted on a vertical shaft and could move up and down with the oil level. This eliminated inaccuracies due to parallax resulting from a fixed-height camera merely rotating vertically.

The outer experimental tank was a right circular cylindrical shell 711 mm in outside diameter[15]. The shell was formed by rolling 6.4-mm-thick Type 6061-T651 aluminum plate and welding that along the vertical side seam. The tank stood 1.31-m tall (inside) over its top stiffening ring welded to the rolled plate. It had a flat bottom but was open at the top. The radial width of the stiffening ring was 25 mm; and its inside diameter was 673 mm. The ring was 32 mm high but heavily chamfered at both top edges and the bottom inside edge. This chamfer facilitated movement of hardware into and out of the tank.

The bottom had the same thickness and composition as the rolled side. Both SCRAM connections were welded there as pipe couplings diametrically opposed from one another but near the outside of the tank. The fill connection coupling was 90° between and also welded near the outer edge. The only other hole in the bottom was

[15] Reference 1 reports a (inside) diameter of 686 mm; but even adding twice the 6.4-mm wall thickness suggests an outside diameter of 699 mm, slightly smaller than the quoted value (711 mm). The larger is believed more reliable because it has been obtained by direct measurement; the smaller is a nominal value.

a welded coupling for the reflector height measurement. It, too, was near the outer edge but rotated 15° from the SCRAM valves.

Three ports were welded to the side 0.43 m above the bottom. These were *originally* intended to receive (after loading the metal) radiation detectors projecting radially inside the tank; but this design was never used. The presence of detectors would have excluded oil which would have altered the moderation of the assembly under study. Still, the three ports, on 120° centers, formed small "pockets" of oil outside the smooth boundary of the right circular cylinder. Each pocket was a cylinder about 64 mm in diameter projecting 38 mm from the side.

Most features described above are clearly evident in Figs. 8 and 9. In the first, part of the reservoir is hidden by the perforated table in the foreground. The never used detector tubes rest on that table; and one of the resultant "pockets" can be seen just above the one to the right. Seven radiation detectors can be found in their alternative locations, four below the tank and three strapped to the side. The sight gauge is to the left of tank center. The second of these figures permits a view from above into the outer tank. This is the region that would later receive the inner tank. In this much later photograph (1974), the tank has been wrapped in a thermal insulation blanket in anticipation of another experimental program. The insulated piping and hardware to the right of the tank and reservoir were not part of this program.

Inner System

The entire inner system was essentially axially symmetric. Its reservoir was cylindrical except for a small section cut away to support the pump. Inside dimensions were 0.57-m in diameter by 0.25-m high. Top and bottom were 9.5-mm thick; but the cylindrical wall was only 3.18-mm thick. The capacity of this reservoir was *about* 56 liters, allowing for the 18% (approximately) of the reservoir truncated to make room for the pump. It was constructed of Type 6061-T6 aluminum plate.

The bottom of the associated experimental tank was centered 0.3 m above the top surface of the reservoir and coaxial with it. The interconnecting piping between the two held them apart. This separation was probably adequate to always provide essentially infinite reflection to the bottom of an assembly; but the fact that some air

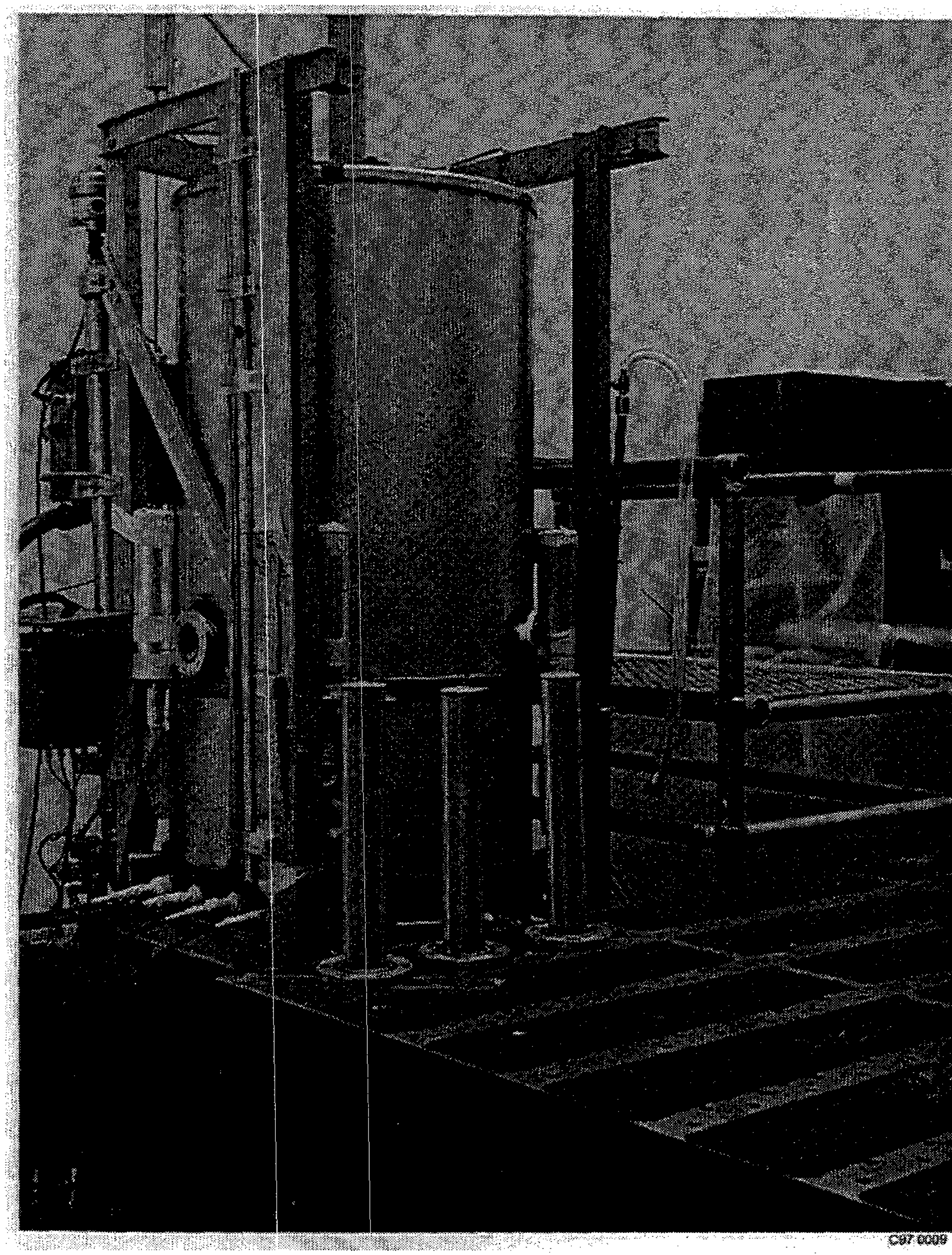

Figure 8. The outer tank (side view) stands above its own reservoir, hidden by a heavy steel table in the foreground. Three re-entrant tubes, intended to hold radiation detectors, rest on the table but were never used. The sight gauge tube used to measure oil reflector height can be seen to the left alongside a pair of wooden meter sticks.

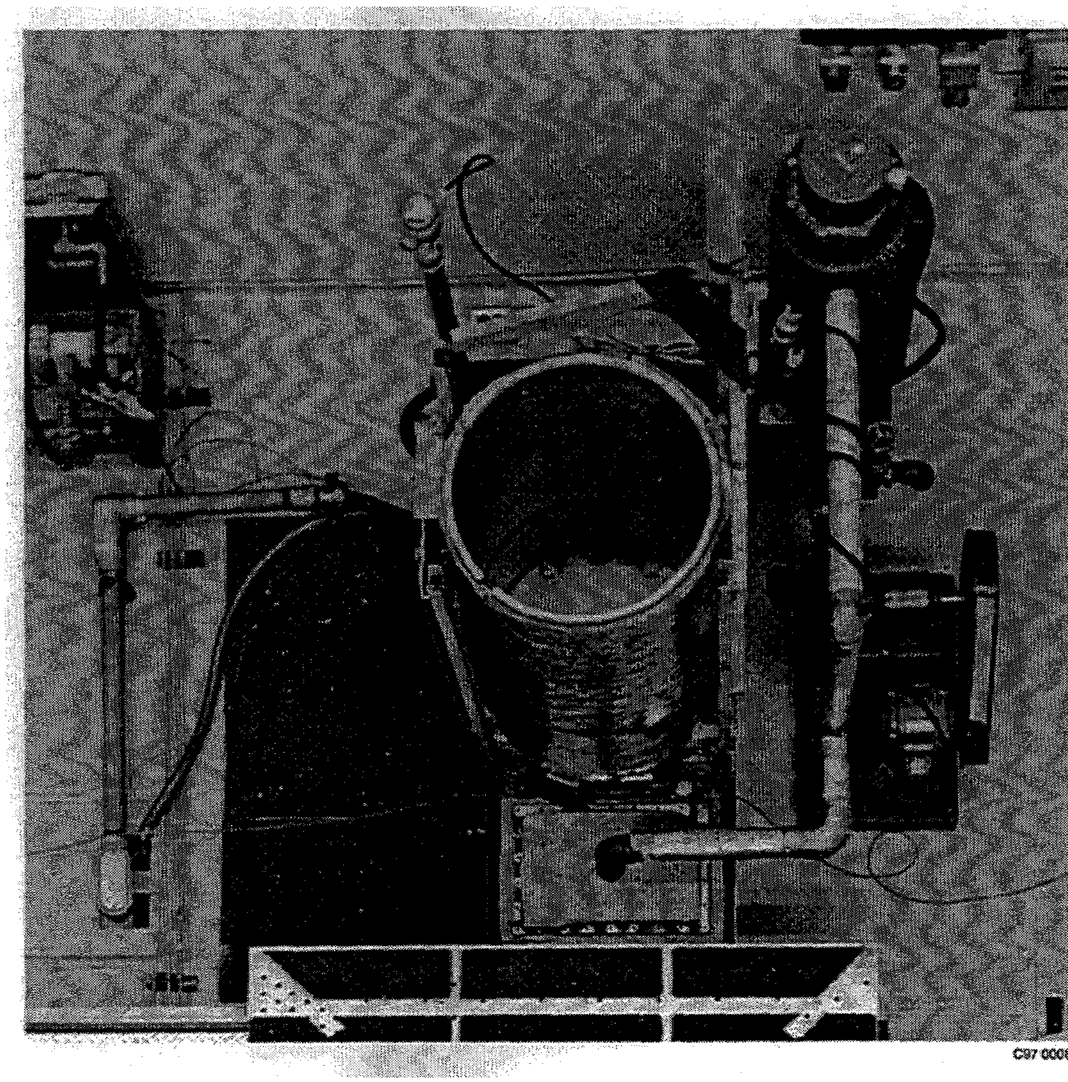

Figure 9. The 711-mm-diameter outer container received the inner container shown in Fig. 11. Only a portion of the long rectangular reservoir holding a large volume of uncontaminated reflector oil is visible at the bottom of the photograph. Equipment to the right in this much later photograph was not a part of this program and was not present during this study.

space remained inside the reservoir when criticality was attained might be useful in a detailed calculation. That air reduced neutron reflection due to oil in the reservoir. The greatly simplified sketch of Fig. 10 (not to scale) illustrates this probably insignificant caution.

The oil distribution system connecting tank and reservoir was constructed mostly of galvanized pipe and brass valves. The pump used to move the oil was an inexpensive submersible one resting on a ledge by the reservoir. Control valves were actuated by electric solenoids. The pump operated continuously during an experiment; but oil did not move unless one or more of three valves were opened. Three different rates were available on this system just as on the larger. Both SCRAM valves were screwed directly to the bottom of the tank. This assured that any experiment could accurately be described as having no oil columns projecting below the bottom surface of a tank.

Reflector heights within the inner system were transmitted outside the outer tank for readout via a capacitance probe. The probe projected down a vertical clear plastic tube adjacent to but a short distance from the inner tank itself. This tube was connected to the tank near its top and bottom but had a tee-connection at the top to receive the probe. As oil filled the plastic tube, the capacitance between the probe and its surroundings changed. This changing capacitance was read out in terms of changing oil height. This probe could be calibrated by filling the inner tank with oil apart from the larger tank and without fissile material. During such calibration, both the electronic readout and the visual height in the clear plastic could be compared to produce that calibration.

The inner experimental tank, like the outer, was also a right circular cylindrical shell; but it was only 364 mm in outside diameter (Reference 1 reports this diameter as 368 mm). The shell was formed by rolling 3.2-mm-thick Type 6061-T651 aluminum plate and welding that along the vertical side seam. The tank stood 0.73-m tall (inside) over its top stiffening ring welded to the rolled plate. It had a flat bottom but was open at the top. The bottom was 9.5-mm thick but had the same composition as the rolled side.

The stiffening ring at the top differed markedly from the larger tank. It was 12.7-mm thick and also Type 6061-T6 aluminum. Its inside radius equalled that of the inner tank; but the outside radius was several millimeters larger than the stiffening ring atop the larger tank. This design allowed the inner tank to "hang" from the top flange of the outer tank.

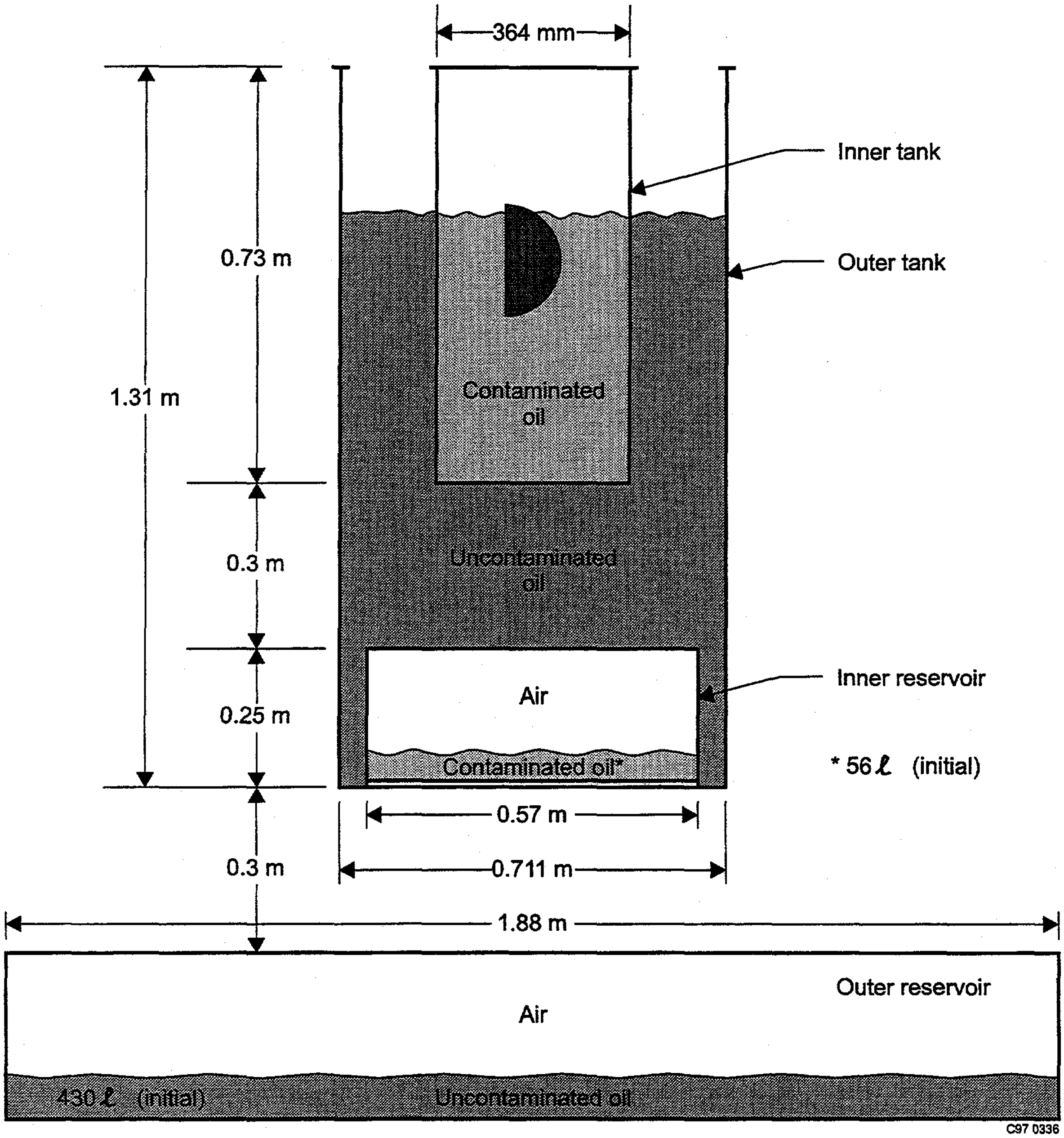

Figure 10. The relative locations of the inner and outer tanks and their associated reservoirs are shown in this drawing. All solid lines represent metal; and regions of air (unshaded) and both contaminated and uncontaminated oil (2 degrees of shading) are shown. An arbitrary oil height relative to an arbitrary fissile hemisphere is illustrated.

Finally, a 12.7-mm-thick by 457-mm-diameter Type 6061-T6 aluminum disk covered the top opening in the inner tank. It was gasketed and bolted in place to contain contamination. The mounting fixture for supporting the actually fissile metal assembly load hung from this disk.

Most features described above are clearly evident in the photograph of Fig. 11 and the drawing of Fig. 12. The first is shown at the loading station just below the wing of the glovebox. The flexible plastic bag can be seen at the top of the figure. The capacitance probe's tube is to the right and the pump can be seen on its indentation in the reservoir. The drawing details the relationship between inner and outer tanks when ready for an experiment. The mounting fixture for a hemispherical geometry is shown.

Fissile Material Mounts

These mounting fixtures were used to hold the fissile metal rigidly in its assembled shape in its intended location within the inner tank. Although they differed greatly in design, both mounts were made of Type 6061-T6 aluminum. The one for asymmetrical spherical assemblies rested on the floor of the inner tank. That for hemispherical geometries was suspended from the lid of the tank.

The *asymmetric sphere mounting fixture* consisted of two circular aluminum plates separated from one another, four lengths of threaded rod stock, and lengths of aluminum tubes which slipped over the rods. The plates were about 360 mm[16] in diameter with a concentric hole about 108 mm in diameter. The aluminum appears to be 12.7 mm thick. Eight holes were drilled on an (about) 300 mm bolt circle; and, during use, every other hole had one of the threaded rods pass through it. The rods appear to be 610 mm long and were almost certainly made of stainless steel. They were either 9.5 mm (probably) or 6.4 mm (possibly) in diameter. Stainless steel wing nuts top and bottom clamped the mounting fixture rigidly. Length of aluminum tubing spaced the two plates the desired distance apart; and they also held the bottom plate the desired distance above the floor of the inner tank. More tubes above the upper plate allowed the wing nuts to clamp the whole fixture tightly.

[16] Dimensions of this mount and its components were never recorded. Values quoted here are inferred from photographs and the author's recollection. Some uncertainty may exist although stock of common thicknesses or diameters were always used.

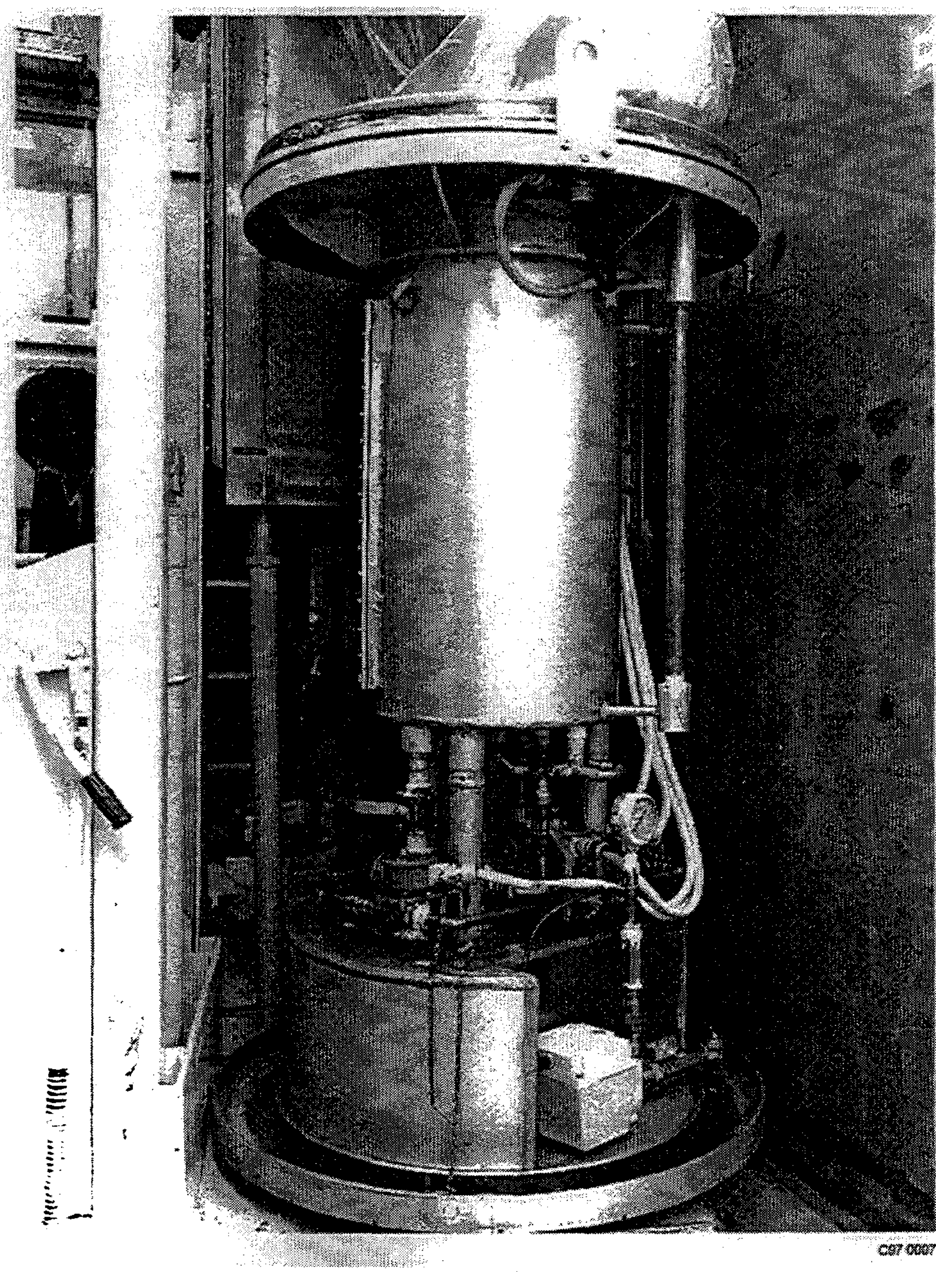

Figure 11. The inner container housed oil in contact with plutonium. The reservoir and associated plumbing is shown near the bottom of the photograph. The cylindrical region above it received the assembled experimental configuration; and, after sealing the plastic bag shown at the very top of the photograph, the whole container was moved to the Assembly Room for the experiment.

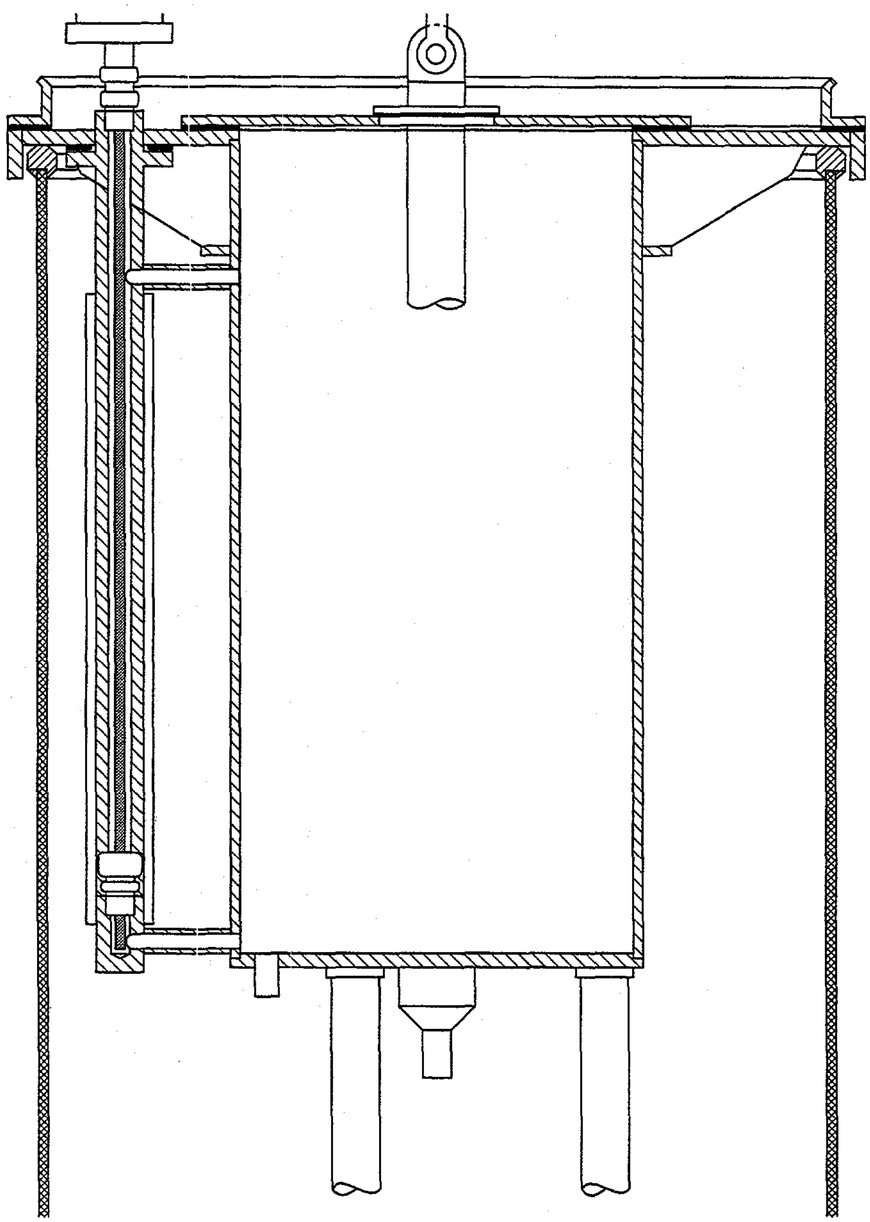

Figure 12. This cross sectional drawing of the smaller, inner tank shows the fill line connection for contaminated oil to the left along the bottom. One of two SCRAM lines is shown in the center; and part of two legs are shown. The wavy line break in the bar suspended from the lid connects to the wavy line in the left part of Fig. 14.

A 12.7-mm-thick aluminum cross (x) had an eye bolt welded to its center. This cross also slid over the threaded rods and was clamped by the wing nuts. It was used to lift the loaded fixture for positioning within the inner tank. The bottom portion of the photograph of Fig. 13 illustrate all these features of the asymmetric sphere mounting fixture.

The diameter of the bottom hemisphere of the fissile load (plutonium only or plutonium and steel) determined how far below the lower plate that hemisphere might project. This fact plus the length of the lowest aluminum tubes plus the number of threads exposed below the wing nuts determined the distance between the bottom of this hemisphere and the bottom of the inner tank. This was always adjusted to be about 200 mm or more.

One recorded entry in a log book of experiments stated that the equatorial plane of one specific asymmetric sphere was 230 mm above the bottom of the inner tank. This configuration had a 40-mm radius of the bottom hemisphere; so the bottom was well reflected. This equatorial plane dimension was certainly not constant from one experiment to another; but it never varied much.

Some experiments (but not all) recorded the distance between that equatorial plane and the top surface of the bottom plate of the asymmetric sphere mount. That information has been omitted from this document because the elevation of that plate varied a little and the distance was not recorded consistently. The parameter is considered of little value.

The upper portion of Fig. 13 is a photograph of the *mounting fixture used for hemispherical assemblies*. The drawing of Fig. 14 shows greater detail of this complicated fixture. Hemispheres were supported such that the normal to their equatorial plane was horizontal. That is, the hemisphere's plane was vertical. This configuration was selected to prevent a dramatic and sudden change in reactivity (Dr/Dh) as reflector oil passed this plane if it were horizontal.

A side view of this mount had the shape of an inverted "L" as shown to the left in Fig. 14. This had a pivotable bar with a centered clamping screw also shown to the left of that figure. Actually, three pivotable bars were fabricated and two of these are shown in phantom lines. Close examination of Fig. 13 shows that the middle of these is the size in the photograph.

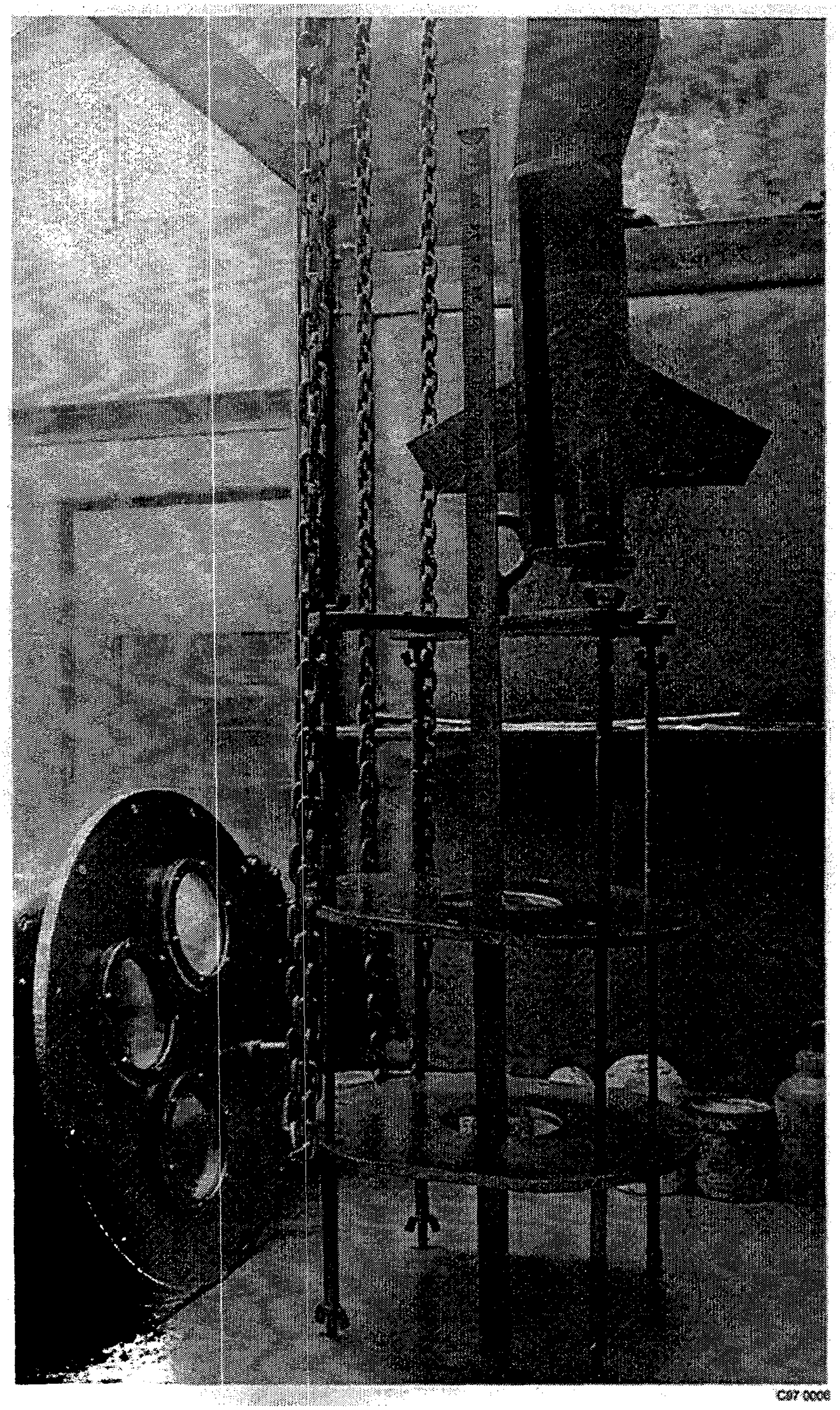

Figure 13. The mount for spherical loads is shown in the lower portion of the photograph resting on the glovebox floor. That for hemispherical assemblies is shown near the top. In use, hemispheres hung from the top lid of the inner tank.

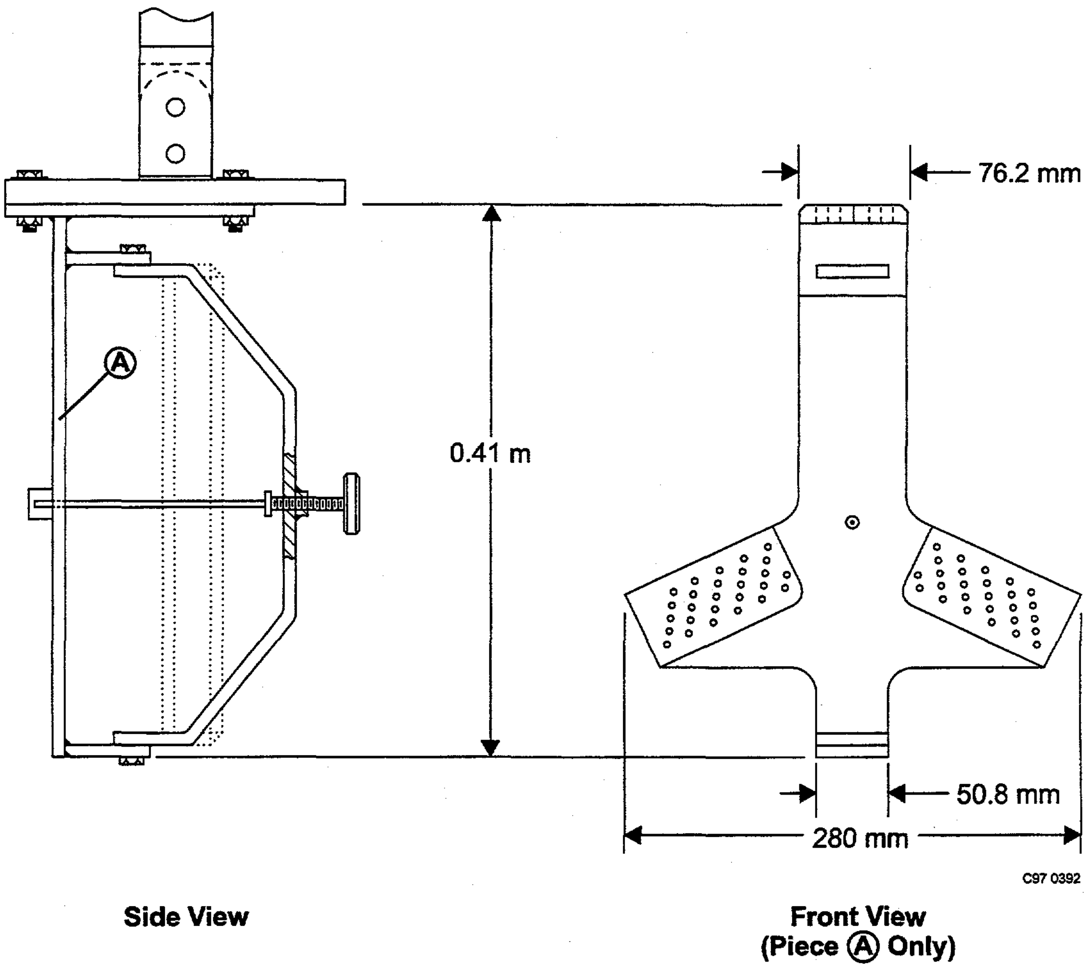

Figure 14. The fixture for supporting hemispherical assemblies was complicated. Three "yokes" were used to accommodate various sized hemispheres; but only one at a time was used. the other two are shown in phantom. This scale drawing shows two views of the fixture.

The top of the inverted "L" was bolted to a lifting bracket, in turn, bolted to a bar suspended from the top of the tank. The right hand side of Fig. 14 shows only the shape of the machined plate (part "A") against which the equatorial plane of the hemispheres rested. This plate was 9.5-mm-thick aluminum. A total of 54 holes were drilled in its wings for steel pins to help stabilize the fissile load.

ENVIRONMENT

Oil-reflected experiments were performed within Room 101, called the Assembly Room, at the Rocky Flats Plant's Critical Mass Laboratory. Most of the 1700 critical and critical approach experiments performed at Rocky Flats between 1964 and its closure in 1989 were carried out in that room. It is a large concrete room containing only a few items large enough and/or close enough to the plutonium to provide any additional reflection.

Unreflected experiments were performed in Room 103, a short distance from the Assembly Room. These data were garnered during the manual assembly of asymmetric spherical or hemispherical fissile loads eventually transferred into the inner tank. Room 103 was principally a storage room for enriched uranyl nitrate solution also used in critical experiments. The solution storage tanks were in a depressed pit covering about half the room. The Downdraft Room, its associated glovebox, and the loading station shared the upper level of the room with a small analytical laboratory.

The following two sections describe the Assembly Room and the Solution Storage Room in detail. They also describe nearby equipment which may be large enough to contribute some reflection. Both rooms contained other smaller pieces of equipment; but these are considered too small and too far away to be worth describing: portable tool boxes and normal clutter.

Assembly Room

The interior measured 11.28 m in the east/west direction by 10.67 m in the other. It was 9.75 m high. Concrete walls and ceiling were formed in one, continuous, monolithic (seamless) pour in 1964. The north wall was 1.52-m thick; but the other three were only 1.22 m. The north wall was thicker because people occupied rooms to the north; and the small additional shielding would further protect them from radiation during experiments. The thick ceiling varied between 0.61-m and 0.71-m thick. The floor was poured later and was 0.15-m thick but rested directly upon compacted earth. Figure 15 shows the layout of the room with the approximate center of the experimental tank located by the rosette.

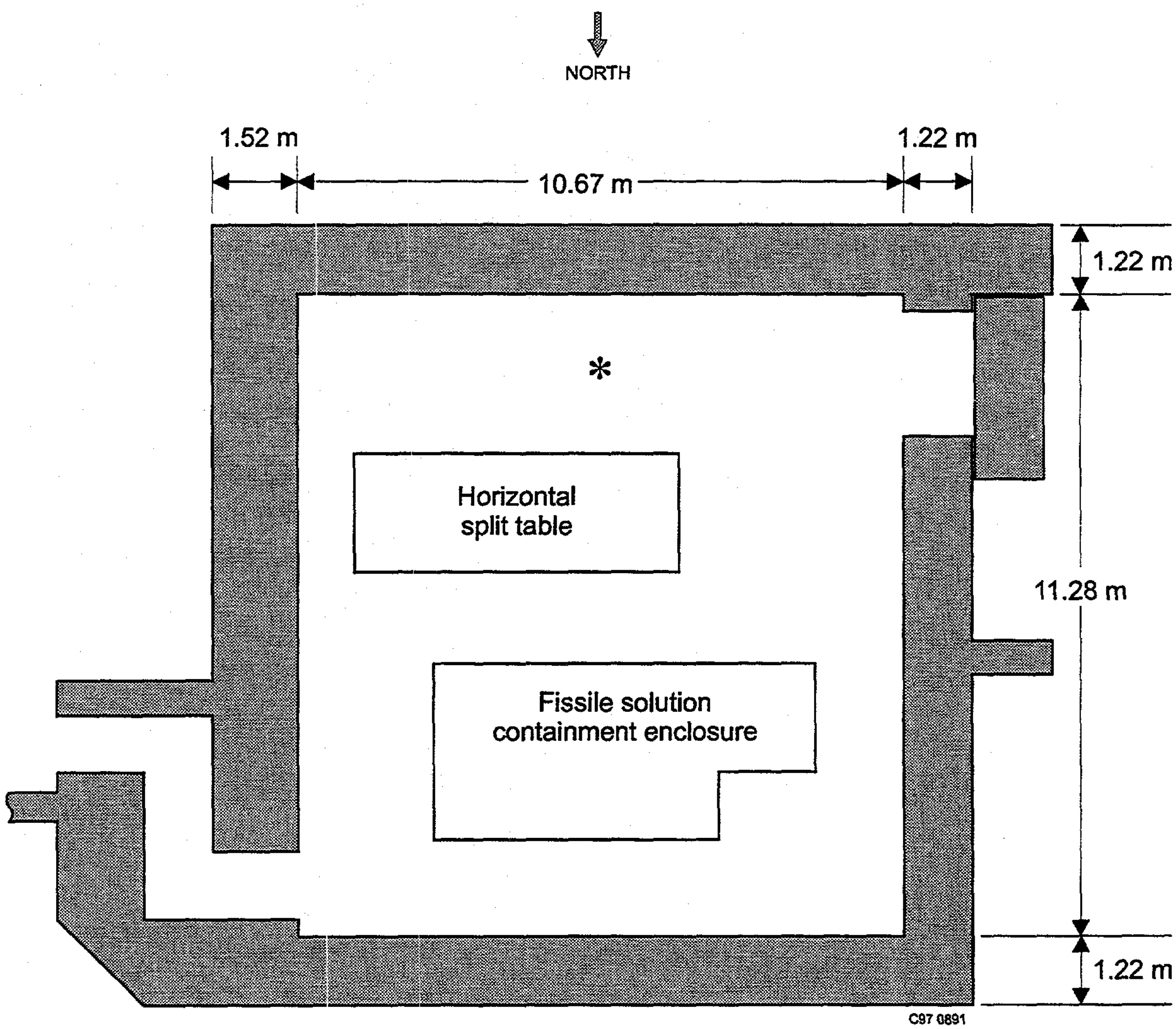

Figure 15. A schematic drawing of the Assembly Room shows the approximate location of the center of the experimental tank at the rosette.

Two layers of crossed steel rebar strengthened the concrete. One layer was about 80 mm in from the outer surface; the other, the same distance out from the inner. Horizontal rebars were #8 size on 0.3-m centers. Vertical bars were #6 size on the same centers. Approximately 7,000 kg of steel strengthens the concrete.

Specifications for the concrete poured in 1964 were quite common for industrial applications. Type I Portland cement was called for using 307 kg/m³. The maximum water content in the fresh mix was 30 kg/m³; and the water had to be pure. Allowed aggregate sizes ranged from 6 to 18 mm; and this rock had to be low in amorphous siliceous materials.

In later years, the room had been painted a number of times. These were not just cosmetic; instead, paintings were aimed at improving the leak-tight integrity of the room. Whether or not the walls had been painted a first time before these experiments is not recalled.

Two doorways penetrated this room. One in the north wall at the west end was a 1.07-m-wide by 2.44-m-tall passage way used for personnel access. Small experimental components were introduced here too. The passage way extended the full thickness of the north wall plus 1.07 m (2.59-m total) before making a 90° turn east. The wall backing the first passage way was also very thick. A similar turn back north after a 1.52-m-long hallway completed a Z-shaped labyrinth. The purpose of this labyrinth was to prevent radiation streaming out of the room in the event of a nuclear criticality accident. It might pass through the closed steel door; but it would not make the two right angle turns to propagate down the hallway.

The second opening was diagonally across the room. It was in the south wall but at the east side. This was an equipment door way connecting directly to the out-of-doors. The opening was larger to accommodate movement of larger and heavier components: 2.44-m square. This equipment opening was backed by a sliding concrete shield door. This massive shield was 1.07-m thick. Its 3.05-m-wide by 2.78-m-high size effectively would stop any radiation streaming south out of the room.

Both door openings were closed off during experiments. Strong blast doors with a rubber seal between them and the room served this purpose. One such door existed at the personnel passage way; and two were used at the heavy equipment opening. Each door was 1.22-m wide by 2.59-m high and 0.10-m thick, although the fairly thick door was constructed as a honeycomb to reduce its weight. All three blast doors were made of steel;

and each can be modeled as two 6.4-mm-thick plates on either face separated by 25 linear meters of honeycomb material (steel) 6.4-mm thick by 90-mm wide. Each door weighed about 425 kg.

Figures 8 and 9 both show the larger, outer experimental tank in locations relative to the east wall of the Assembly Room and the heavy weight table. This table was called the Horizontal Split Table and was later used for many experiments. A sharp-eyed reader will notice a difference in the relative placement of tank and table in the two photographs, taken many years apart. Figure 8 shows the correct location of the tank for these oil-reflected experiments. Figure 9 would be more accurate if the tank and reservoir were more to the left (closer to the inner edge of the Split Table).

The actual location of the outer tank relative to the east wall of the Assembly Room was never measured for this program; but a reasonable estimate of its location is possible from memory. The center of the tank was *about* 5 to 6 m from the south wall and about 1.3 m from the east.

The closest large item was the Horizontal Split Table. Another large feature of this room was a walk-in, stainless steel containment enclosure. Most fissile solution experiments were performed there between 1967 and 1987. The purpose of this room was to control contamination upon the inevitable small leaks expected when handling fissile solutions. Third, an air handling deck existed several meters away. This structure supported the room's heating and cooling equipment. The final component described is the heavy equipment travelling crane built into the room for general us. This crane was used in this program to load the smaller inner tank containing the fissile assembly into the larger outer tank.

No materials in this section were chemically analyzed for their specific elemental composition. Therefore, materials are described rather generally with the code validator required to use typical compositions.

The Horizontal Split Table was situated within the east portion of the Assembly Room. Its overall dimensions were about 5.4 m long by 2.2 m wide; and it rose about 0.7 m above the floor. Although the table had a complicated geometry of honeycombed steel webbing and structural steel channel, a conservative approximation to its steel content would be a 25-mm-thick vertical rectangular cylinder measuring 5.4 m by 2.2 m on the outside supporting <u>two</u> horizontal and co-planar table tops. Each top would be 1.9-m-long by 2.2-m-wide and 50 mm thick. One would be located at each end of the rectangle. The long dimension of this table was parallel to the east wall and the long dimension of the containment enclosure and about 1.9 m east of it. The northeast corner of the Split Table was 2.44 m west of the east wall and 1.09 m south of the north wall. This very heavy table was never moved during the life of the laboratory.

The fissile solution containment enclosure was on the west side of the room. Generally, it was about centered north/south and also about centered in the west half of the room. The room was constructed mostly of stainless steel (1.6 mm thick); but it had an estimated 30% of its surface covered with 13-mm-thick plastic windows. The room was 5 m north/south by 3 m and stood 6 m tall. The nearest wall to the experimental tanks was approximately 5 m away.

The air handling deck existed in the southwest corner of the room. This all-steel structure was 4.8 m east/west by 2.4 m and stood 4.5 m above the floor. It was constructed of about 30 m of nominally 0.2-m-sized channel iron. The room's travelling crane was a typical heavy-duty (5-ton) industrial crane built into the room a short distance below its ceiling. Its massive steel travel I-beams ran east/west with a bridge for orthogonal movement. No record was kept of where the bridge nor the crane's winch was situated at the time of the experiments.

Solution Storage Room

This room was oddly shaped being roughly 11.5 m north/south by 7.6 m; but the area involving plutonium (the Downdraft Room and glovebox) were located in a rectangular portion about 6 m square. The Downdraft Room was adjacent to the 0.4-m-thick concrete east wall of this area; and the glovebox projected into the center of the room. Any plutonium assembly in the glovebox would have been at least 1.5 m to 1.8 m from the thick (0.4 m) north concrete wall, the thick (0.2 m) west concrete wall, and the fissile solution storage tanks to the south.

The floor of the glovebox stood well above the concrete floor of the room. The glovebox, itself, was made of 1.6-mm-thick stainless steel with many 13-mm-thick plastic windows on the sides. Windows covered about 75% of the side surface.

The nine stainless steel storage tanks housed 560 kg of enriched uranium as uranyl nitrate solution. These nine tanks were all Raschig ring filled; so no reactivity would be added to any plutonium assembly occurring in the glovebox. The closest two tanks contained only 250 liters of solution each.

A small analytical laboratory area existed west of the glovebox against the west wall of the room. No fissile material or significant reflectors would have been in or near that laboratory area.

RESULTS

Results from this experimental program fall into a number of categories. This stems from the fact that data was garnered from many sources which, themselves, span a great many years. It also results from the variety of procedures used to obtain the data and the number of parameters needed to define each experiment.

Furthermore, two *kinds* of critical determinations are offered. One is the *extrapolation* of critical parameters from a set of subcritical experiments. These predict criticality for effectively fully oil-reflected systems. The other reports the critical reflector height for a fixed metal geometry of *known* mass. Here, that mass was too great to permit full reflection and criticality occurred sooner.

Finally, experimental critical parameters also vary markedly in uncertainty. One reason for this is the instability of the metal with its attendant degradation in mass. Other reasons include the long duration of the actual program, the number of decades elapsed since the study was done, and the fact that this author was not the lead experimenter.

Categories

Two categories stem from the publication history of these results. Many have been published in earlier papers; but a number of others have only recently come to light. Previously published data include a once-classified internal report (declassified in 1997) issued early in the program, an unclassified internal report released toward the end of the study, and a journal article published months after the program ended. The last two were, of course, limited to unclassified results.

None of the three can stand alone. They lack sufficient detail about apparatus and environment to validate modern computer codes. Furthermore, little information is given about how uncertainties were determined.

Recently-discovered results would not have been published earlier, even if recognized at the time, because they were thought to be of little value in the 1960s. They were viewed as "stepping stones" toward a more important objective:

the critical mass of a fully reflected plutonium assembly.

They were discounted then because criticality occurred at some oil height less than full reflection; and fledgling computer codes of the 1960s could not calculate such systems. Those of the 1990s, however, can easily model these; so the new findings prove quite valuable. Sadly, uncertainties *may* be somewhat increased *because* those experiments were not considered important.

Another way to categorize experiments involves geometry. Spheres, asymmetric spheres, thick-walled spherical shells, hemispheres, and thick-walled hemispherical shells were all studied at one time or another during this program. Still, another category arises from reflector conditions. The objective was critical parameters for fully oil-reflected assemblies; but their construction permitted the determination of critical parameters for unreflected geometries as well as those reflected by a pair of human hands. Finally, one more category emerges. Some plutonium assemblies were sheathed with a region of mild steel. This metal separated the plutonium from the hydrogen-rich oil reflector. Thus, experiments may also be characterized by the absence or presence of mild steel; when present, the thickness of this steel region was important.

Summary of Program Parameters

Critical parameter:
- extrapolated plutonium mass for infinite reflection
- reflector height of a known plutonium mass

Geometry:
- sphere
- thick spherical shell
- asymmetric sphere (unequal hemispheres)
- hemisphere
- hemispherical shell

Reflector:
- effectively infinite oil reflection
- critical upon partial reflection
- essentially unreflected
- reflected only by a pair of human hands

Steel:
- none
- thickness of steel region

1968 Results

Table VII is essentially copied from the once-classified report issued early in the experimental program. Most configurations are hemispherical in nature; only two spherical shells are reported because of limitations on plutonium shells available. Much of the data pertains to thick-walled shells (spherical or hemispherical). These were not published in the later journal article because of the then-classified nature of non-solid geometries.

Entries in this table have been modified in three respects. Uncertainties have been eliminated; they are discussed later (and the basis for those presented in the 1968 report are not well understood). Units have been converted to those now in vogue. Finally, all "corrections" to the data have been omitted because the basis behind them is also not well understood. They are considered unreliable. Still, all omitted data are preserved in the Appendix which contains all three 30-year-old reports.

Six entries in Table VII are included with considerable trepidation. They are those labeled "half reflected". The meaning of a "half-reflected hemisphere" is not clearly understood. One conjecture suggests that these corresponded to hemispheres for which criticality would have occurred with oil height at the exact polar axis; but this definition is not at all certain.

This author does not even recall performing any experiments to produce such data. These results clearly stem from Fig. 17 of the 1968 report; but how they were determined is not at all known. One possibility is that the same reciprocal multiplication curves used to extrapolate fully-reflected cases were also used to extrapolate "half-reflected" results. Extrapolating *asymptotic* reciprocal multiplications yielded the former; but an extrapolation of the reciprocal multiplication values that existed when the plutonium was exactly half reflected for each of the same curves might be thought to yield the latter critical mass. This is pure conjecture; but it is supported by observing that all six half-reflected results have a counterpart in the fully reflected portion of the table. Even the densities are identical suggesting that these were exactly the same assemblies. Critical masses for half-reflected cases should be much less certain because the longer extrapolation.

Attempting to "milk" additional information, such as the critical mass of half-reflected configurations, from such a set of parametric curves seems likely to succeed. This is so because all aspects of experiments - both

Table VII. Experimental Results Obtained from the 1968 Report

Reflection Conditions	Inner Radius (mm)	Properties of Critical Assemblies		
		Avg. Pu Density (mg/mm^3)	Outer Radius (mm)	Critical Pu Mass (kg)
Hemispherical Geometry				
Full Oil	0	18.15	57.5	7.25[b]
	20	18.14	59.2	7.57
	30	18.15	62.6	8.26
	40	18.22	67.5	9.30
	50	18.21	74.2	10.82[b]
	60	18.23	80.8	11.94
	75	18.30	92.5	14.17
Half Oil (a)	0	18.15	63.7	9.8
	30	18.15	67.4	10.61
	40	18.22	74.0	13.02[b]
	50	18.24	81.1	15.50
	60	18.23	87.8	17.50[b]
	75	18.30	99.4	21.30
Essentially Unreflected	0	18.15	73.3	14.97
	20	18.14	74.5	15.41
	30	18.15	76.6	16.06[b]
	40	18.22	82.5	18.99
	50	18.24	90.0	23.07[b]
	75	18.30	107.5	31.44
Pair of Human Hands	0	18.15	69.7	12.87
	20	18.14	71.5	13.58[b]
	30	18.15	74.0	14.38
	40	18.22	80.2	17.24[b]
	50	18.24	88.6	21.79
Spherical Geometry				
Full Oil	50	18.13	65.8	12.10[b]
	70	18.18	82.7	16.82

a. See text for discussion of the questionable nature of these results.
b. Nine cases were spot checked to compare consistency between columns; see text for discussion.

tanks, the oil, assembly mounts, the environment, etc. - were so similar from one subcritical load to the next. The only parameter changed was the plutonium itself. Successive curves would, therefore, be expected to be quite similar.

The last three columns of Table VII are not perfectly consistent with one another, although differences are very small. A spot check of nine entries where the listed density and radii were used to calculate a mass to be compared with the listed critical mass yielded five cases where the two agreed to within 0.01%! The worst disagreement was only 0.57%. This slight disagreement is attributed to uncertainties in rounding off listed values and/or to the use of nominal inside diameters instead of actual values. Furthermore, volumes calculated ignored the pole hole passing through plutonium geometries.

One final observation about the 1968 data is that no steel regions were involved. The reason for this is not recalled. Perhaps they had not yet been machined.

Post-Experiment Published Results

The unclassified internal report and the later journal article were both released after the experimental program was completed. Both contain much the same data. Indeed, the journal article data is simply a repetition of the other for *all* 20 asymmetric sphere cases! Unfortunately, most hemispherical results differ between the two. Only the steel-free, fully oil reflected, hemispherical data agree. Even then, the later article contains one additional data point. Four unreflected hemispherical results are significantly smaller in the earlier report, although both sets are quite massive (much in excess of 10 kg!). The two are consistent, however, in that both show a similar decrease in critical mass as the steel thickness outside the fissile metal increases.

When differences exist, results published in the journal are assumed better, based on two observations. The journal article is later and less likely to contain errors. Secondly, an internal report is usually not subject to the same level of peer review as a publication in the open literature. Still, for completeness, both sets are presented in the following tables; however, those from the suspect report are downplayed by showing them in a grey-backed font.

Masses presented in these tables contain probably one more significant figure than is reasonable. The unrealistic precision is retained to maintain consistency with earlier publications.

Table VIII presents results from both papers for fully oil reflected asymmetric spheres. The last two columns present the bounding cases on either side of criticality; they are the masses of actually constructed plutonium assemblies. The smaller was the largest assembly that proved to be subcritical upon full reflection. The larger was the next larger asymmetric sphere which proved critical before full reflection could be attained. The closer the critical mass is to either bounding case, the more nearly does that asymmetric sphere, itself, represent a critical configuration.

The third column contains purely calculated radii. The two entries give the outer radius of the two hemispheres which form the asymmetric sphere. Both were calculated from data in the 2nd, 4th, and 5th columns. In 7 out of 8 cases, the larger hemisphere's radius is very close to an integral number of ten-sixths-millimeter plutonium shells: 50 or 53.3 mm.

The assumption is that either of those two hemispheres was built once and remained constant as the mass of the other hemisphere grew until the critical configuration could be extrapolated. Consequently, the extrapolated radius would be that of the *second* hemisphere and would fall somewhere between adjacent shells.

Each steel thickness has two entries (lines) instead of one because two hemispheres (50 and 53.3 mm) were used as the starting point. Recall that steel-laminated assemblies were constrained to adding **two** plutonium shells per increment.

Table IX presents results from both papers for essentially unreflected asymmetric spheres. The last column represents the lower bounding case to criticality; clearly, there can be no upper bound to a manually assembled configuration for safety reasons. That lower bound is the largest still-subcritical assembly built.

The third column again contains purely calculated information: both outer radii of the two hemispheres which comprise the asymmetric sphere. Both entries in that column were calculated from data in the 2nd, 4th,

Table VIII. Experimental Results for Oil-Reflected Asymmetric Spheres Obtained from Both Post-Experiment Reports

Steel Thickness (mm)	Properties of Critical Assemblies					Bounding Assemblies	
	Avg. Pu Density (mg/mm^3)	Outer Radii[a] (mm)		Mass Difference[b] (kg)	Critical Pu Mass (kg)	Largest Subcritical (kg)	Critical at Less than Full reflection (kg)
0	17.31	49.5	39.8	2.112	6.667	6.361	6.792
0	18.56	50.3	34.2	3.371	6.494	6.452	6.654
10	17.30	52.4	40.3	2.836	7.576	6.978	7.917
10	17.97	50.0	39.7	2.342	7.039	6.722	7.264
30	17.32	53.7	40.6	3.172	8.044	8.044	
30	18.14	49.9	40.6	2.182	7.260	7.180	7.760
50	17.31	53.7	40.7	3.169	8.043	7.469	8.049
50	18.16	49.9	41.1	2.070	7.373	7.153	

a. These are calculated radii. The larger is half the sum of the critical mass and the mass difference converted to a radius assuming the listed density . The smaller is half the difference between the same two masses converted to a radius in the same way.

b. Difference in mass between the top and bottom hemispheres forming the asymmetric sphere.

Table IX. Experimental Results for Essentially Unreflected Asymmetric Spheres Obtained from Both Post-Experiment Reports

Steel Thickness (mm)	Properties of Critical Assemblies: Avg. Pu Density (mg/mm^3)	Outer Radii[a] (mm)		Mass Difference[b] (kg)	Critical Pu Mass (kg)	Largest Subcritical Assembly (kg)
0	17.43	71.1	30.4	12.086	14.128	11.029
0	17.41	69.2	40.2	9.713	14.455	12.380
0	17.17	61.9	50.1	4.002	13.064	11.347
10	16.36	71.1	30.4	11.377	13.294	11.729
10	17.22	64.1	40.1	7.162	11.842	10.162
10	17.48	54.1	50.1	1.190	10.401	9.337
30	17.06	65.3	30.6	8.929	10.973	8.728
30	16.81	59.8	40.3	5.226	9.836	8.969
30	17.95	50.2	46.6	0.932	8.559	7.906
50	16.84	63.1	30.5	7.866	9.876	8.713
50	17.61	55.9	40.1	4.040	8.811	7.884
50	18.72	42.6	49.7	1.766	7.849	7.299

a. These are calculated radii. The larger is half the sum of the critical mass and the mass difference converted to a radius assuming the listed density . The smaller is half the difference between the same two masses converted to a radius in the same way.
b. Difference in mass between the top and bottom hemispheres forming the asymmetric sphere.

and 5th columns. In all cases, the smaller[17] hemisphere's radius is very close to an integral number of ten-sixths-millimeter-thick plutonium shells: 30, 40, and 50 mm or 30, 40, and 46.6 mm.

In all these cases, the assumption is that one of these fixed-radius hemispheres was built and remained constant as the mass of the *other* hemisphere was increased until the critical configuration could be extrapolated. That is, the extrapolated radius would be that of the *other* hemisphere.

Each steel thickness has three entries (lines) instead of one because three fixed hemispheres were used as the starting point. A study of the three asymmetric spheres for each steel thickness shows that all change from a high asymmetry toward a much more nearly symmetric sphere. The ratio of radii for the worst case is 2.34, the most symmetric, 1.08. The critical mass tends to decrease as assemblies become

[17] The last case in the table is an exception.

more nearly spherical; but this is as expected. The steel-free case proves to be an exception for some reason.

Table X presents results from both papers for fully oil reflected hemispheres. Again, the last two columns represent the bounding cases on either side of criticality; they are the masses of actually constructed assemblies. The smaller was the largest assembly that proved subcritical upon full reflection. The larger was the next larger hemisphere which proved to be critical before full reflection could be attained. The closer the critical mass is to either bounding case, the more nearly does that hemisphere, itself, represent a critical configuration.

The middle case in the table was not included in the earlier unclassified report. The reason for this is not known. The density of the 7.752 kg assembly was reported differently in the earlier report, probably through an editorial error.

Table XI also presents results from both papers for fully oil reflected hemispheres; but the outside of the plutonium is covered by steel shells of various thickness. The plane face of the hemisphere had no steel but did contact the mounting bracket. Critical masses in the last column are suspect. They differ markedly from those published later in the journal article except for the first steel-free case (see Fig. 16 for comparison). No explanation is offered for this. Suspect results are included in grey-backed font.

Table X. Experimental Results for Oil-Reflected Hemispheres
Obtained from Both Post-Experiment Reports

Properties of Critical Assemblies			Bounding Assemblies	
Avg. Pu Density (mg/mm^3)	Outer Radius (mm)	Critical Pu Mass (kg)	Largest Subcritical (kg)	Critical at Less Than Full Reflection (kg)
16.68[a]	60.5	7.752	7.535	8.238
17.84	57.2	6.985[b]	6.801	7.430
18.32	55.9	6.687	6.424	6.949

a. The unclassified internal report lists this as 16.88; but the lower density appears twice elsewhere at the listed value.
b. This case was not included in the unclassified internal report.

Table XI. Experimental Results for Oil-Reflected Hemispheres Covered with Steel Shells of Various Thickness Obtained from Both Post-Experiment Reports

Steel Thickness (mm)	Properties of Critical Assemblies[a]			
	Avg. Pu Density (mg/mm^3)	Outer Radius (mm)	Critical Pu Mass (kg)	Critical Pu Mass[b] (kg)
0		60.0	7.637	7.637
3.3		60.4	7.808	7.717
6.7		61.2	8.113	7.860
10.0		61.4	8.166	7.885
13.3		61.6	8.242	7.921
16.7		61.6	8.262	7.930
20.0		61.6	8.269	7.934
23.3		61.8	8.317	7.956
26.7		61.8	8.323	7.961
30.0		61.9	8.365	7.979
33.3		61.9	8.355	7.974
36.7		61.8	8.333	7.964
40.0		61.8	8.319	7.957
43.3		61.7	8.310	7.953
46.7		61.7	8.291	7.944

a. All critical assemblies were bounded by an 8.962 kg hemisphere which attained criticality at less than full reflection for all cases.

b. The earlier unclassified report differed significantly from the journal article results.

The upper bound for all cases in Table XI was 8.962 kg. That hemisphere always attained criticality before full reflection was achieved. For the 1971 journal article only, critical oil heights relative to the top of the plutonium hemisphere were reported and are repeated in Table XII[18]. The table also contains another column of the same parameter. This reflects another examination of the same raw data by this author in 1997. Small differences are noted.

This later review revealed that a few replacement and repeated experiments were performed. These are summarized in Table XIII. Most "base cases" used a "new" 308 g, 20-mm-diameter part at

[18] An interesting observation is that the maximum in two different functional relationships against steel thickness both occur at about 30 mm thickness. One of these is "the critical oil reflector height relative to the top of an 8.962 kg hemisphere". The other is "the critical mass of smaller hemispheres subject to full oil reflection". No arguments are offered to explain this possible coincidence; and both maxima are really quite broad.

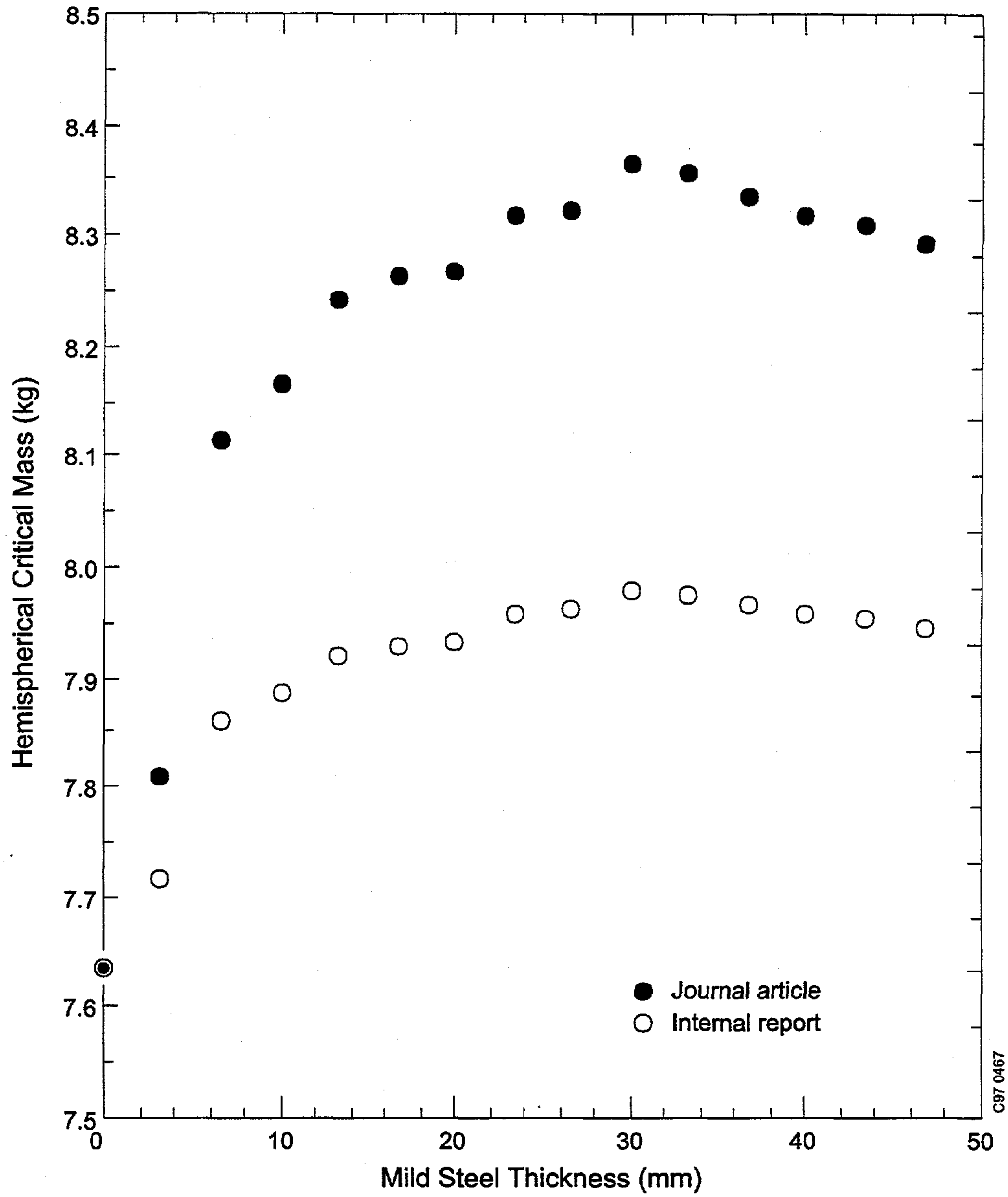

Figure 16. The variation in critical mass of an oil-reflected hemisphere with the thickness of mild steel shells contacting the plutonium differed in two reports of the same data. Journal article results are considered more reliable.

Table XII. Experimental Critical Heights for the Upper Bound Hemisphere (8.962 kg) of Table XI Obtained from the Post-Experiment Journal Article

Nominal Steel Thickness (mm)	Critical Height Above Top of Plutonium[a]	
	1971 article (mm)	1997[b] (mm)
0	-11.2 ± 0.2	-11.7
3.33	-10.5 ± 0.5	-10.9
6.67	-6.4 ± 1.1	-6.3
10.0	-3.9 ± 1.1	-3.2
13.3	1.5 ± 1.4	0.9
16.7	3.7 ± 1.2	3.1
20.0	4.5 ± 1.1	4.7[c]
23.3	11.2 ± 1.2	11.7
26.7	11.8 ± 1.3	11.8
30.0	18.2 ± 1.2	18.4
33.3	17.0 ± 1.2	14.9
36.7	13.2 ± 1.1	13.0
40.0	11.1 ± 1.2	10.8
43.3	9.6 ± 1.2	9.6
46.7	6.7 ± 1.2	6.7

a. Negative numbers indicate that the tip of the plutonium extended above the surface of the oil.
b. A re-evaluation of the raw data by the present author.
c. A different measure of this parameters yielded 3.9 mm, which is better is not known.

the center of the nested hemisphere. The 1967 original core piece had deteriorated[19] to 287 g. The "old" was substituted for the "new" in some experiments. Furthermore, other experiments were repeats of previously assembled configurations, sometimes many days later.

Table XIV presents results from both papers for essentially unreflected hemispheres. The last column, again, represents the lower bounding case to criticality: the largest still-subcritical assembly built. Clearly, there can be no upper bound for safety reasons. Critical parameters in two columns are suspect. Both density and critical mass differ markedly from those published later in the journal article.

[19] Elsewhere, this one part is reported as decomposing to a mass of 278 g. Whether this is an accidental transposition of numbers or the part actually continued to decay to the lower mass is not known. The part *is* known to have degraded to a mass of only 255 g as shown in Fig. 7.

Table XIII. Experimental Critical Height for Repeated and Replacement Experiments of Table XII.

Nominal Steel Thickness (mm)	Total Pu Mass (kg)	Critical Oil Height Above Pu - 1997 - (mm)	Nature of Changes to Nominal 63.3 Hemisphere
	8.962	6.7	base case
46.7	8.931	15.9	308g center replaced by 287g 4 days later
	8.962	7.1	base case reassembled 5 days later
	8.962	11.7	base case
23.3	8.931	21.0	308g center replaced by 287 g 7 days later
	8.962	9.8	base case reassembled 8 days later
	8.962	-3.2	base case
10.0	8.962	-4.3	base case assembled 16 days earlier
	8.962	-7.6	base case
6.7	8.962	-5.0	repeat 4 days later
	8.962	-11.7	base case
0.0	8.931	-11.4	308g center replaced by 287g same day

No explanation is offered for this discrepancy. Still, suspect results are included in grey-backed font. The discrepancy is <u>not</u> explained by assuming proportionality between density and critical mass. Again, the functional dependence on steel thickness appears to be about the same.

Tables VII through XIV and Fig. 16 complete an updated analysis of previously published experimental results. Adequate information should now allow computational validation.

Recently Uncovered Data

A number of experiments *not* included in previously published papers were discovered while searching archived data for other purposes. This discovery took place in April of 1997. These results were not considered useful in the late 1960s; but now they are. They pertain to systems for which criticality occurred at some oil height less than full reflection. Usually, but not always, these cases are the same as the upper bound configurations presented in Tables VIII and X.

Table XIV. Experimental Results for Essentially Unreflected Hemispheres Obtained from Both Post-Experiment Reports

Steel Thickness (mm)	Properties of Critical Assemblies					Largest Subcritical Assembly (kg)
	Avg. Pu Density (mg/mm^3)	Outer Radius (mm)	Critical Pu Mass (kg)	Critical Pu Mass[a] (kg)	Avg. Pu Density[a] (mg/mm^3)	
0	17.38	77.0	16.650	14.500	16.90	12.355
10.0	17.31	72.5	13.800	12.800	16.20	10.569
33.3	17.29	70.2	12.550	11.250	16.19	10.569
46.7	17.28	70.1	12.420	11.040	17.00	8.962

a. The earlier unclassified report differed significantly from the journal article results..

These new results are obtained from an interpolation between two reflector oil heights in almost all cases. These heights differed by only a very few millimeters. One was the slightly super critical height; the other, slightly subcritical. A comforting observation is that the interpolated critical height was always the same as a linear extrapolation of the reciprocal multiplication curve such as the one illustrated in Fig. 17. This figure also serves to highlight another important parameter: *the critical oil height above the top of the plutonium configuration*.

Some detective work was necessary to glean these results. After all, almost 30 years had elapsed! A detailed and simultaneous examination of reciprocal multiplication curves *and* the day's logged entries pertaining to the same experiment allowed identification of sufficient parameters to specify critical configuration uniquely in many cases.

The major defect was inadequate documentation. Recorded entries had been terse, often symbolic, sometimes camouflaged to avoid classification issues, and frequently devoid of dimensions. When the latter happened, a similar entry at a similar stage of another experiment - but this time labeled - allowed the assumption that the meaning had been correctly inferred. Plutonium masses were classified; but a few numbers written on a page were not. This author's memory completes the connection.

Even with correct identification, results may still be a little less certain than those elsewhere because only *nominal* radial dimensions were written down. A careful analysist might choose to *estimate better* radii. For example, a nominal inner radius of later tables might be increased a little to account for tolerance gaps and oxidation; and their nominal outer radii may be decreased a small amount for the same reasons. Indeed, densities calculated in these tables employed that assumption (0.1 mm). Plutonium masses, on the other hand, had been measured and may be considered as accurate as those measurements. Sometimes, masses of both top and bottom halves of asymmetric spheres were recorded.

Considerable effort has been expended in this paper to distinguish between information *actually recorded* in the 1960s from that *inferred*, *derived*, or *calculated* in 1997. The former are presented by ordinary font in the following tables; the latter, in italics. This fact is not footnoted on each table.

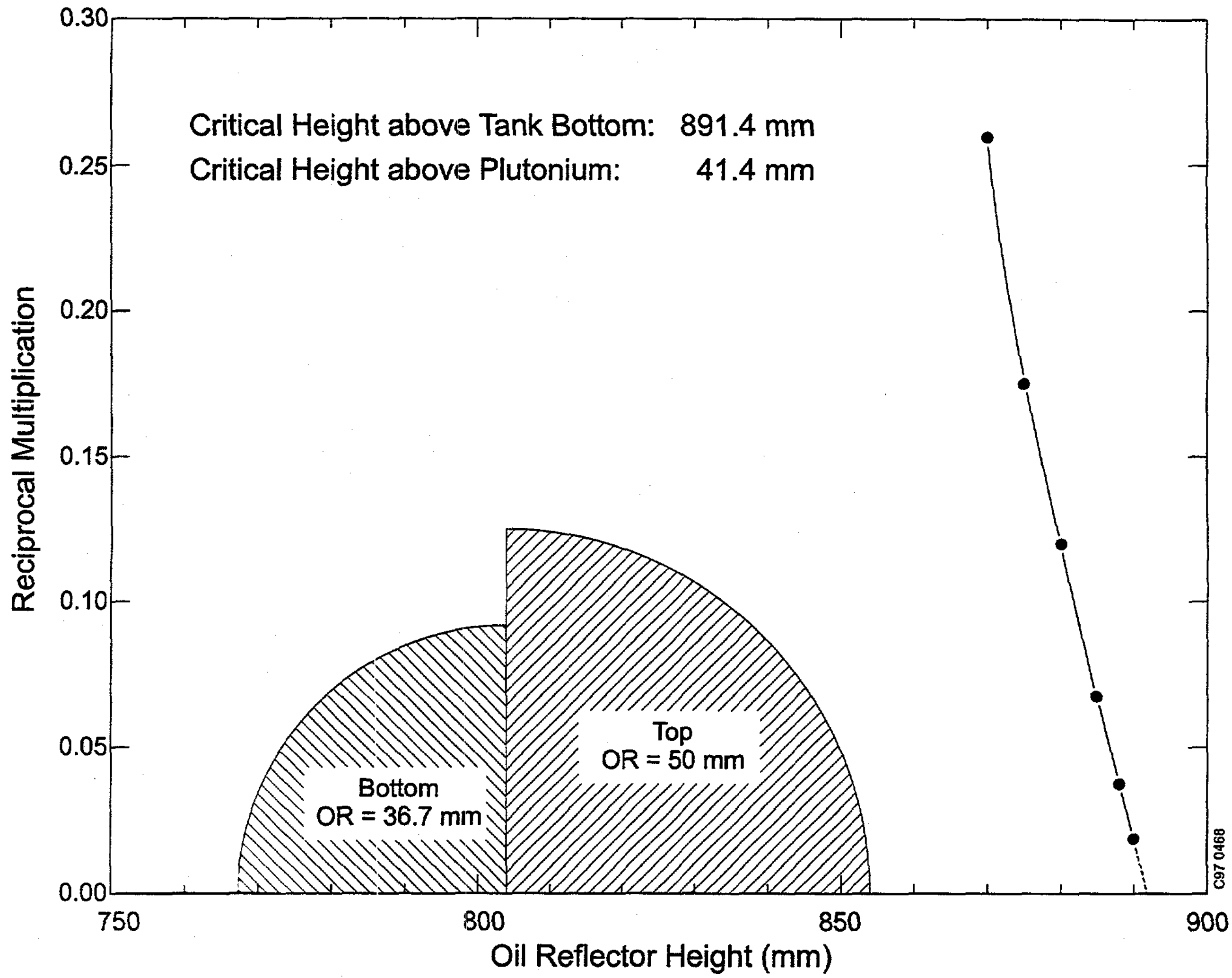

Figure 17. Critical heights extrapolated from essentially linear reciprocal multiplication data points almost always agreed perfectly with those interpolated between oil heights corresponding to slightly super critical and slightly subcritical situations.

Table XV presents the newly-found critical oil heights for ten asymmetric spheres. These are expressed both in terms of the height relative to the bottom of the tank bottom and as the height relative to the *top of the plutonium*. Two assemblies reported in Table XV had been selected in 1969 to evaluate the effect of small changes in an otherwise identical configuration. One asymmetric sphere had a 50-mm-radius hemisphere atop a 35-mm one. The other consisted of 50 mm and 40 mm hemispheres. The first entry for each is considered the "base case" and is merely copied from Table XV. Each next case had the small, 30-mm, central, solid hemisphere traded between halves of the sphere. A significant change is noted in the first section but a much smaller effect in the second. This inconsistency is not understood[20]. The third entry in each section had the 308 g critical height increased about 27 mm; the other became subcritical! The last entry in the table was an attempt to estimate the effect of the mount needed to support the load. The top plate (only) of the "spherical mount" was central hemisphere replaced by a 278 g one[21]. The effect of this mass decrease was dramatic in both cases. One omitted to allow oil to replace the metal. Such an experiment might not be allowed in later years for safety reasons fearing the stability of the load. The critical height decreased as expected; and the change was a quite significant 4.5 mm.

Ten additional new cases for thick-walled asymmetrically spherical shells are reported in Table XVII. Half of these had an inside radius of 40 mm; the other half, a quite large 70 mm. Records do not indicate whether oil was admitted into the interior or not. The evaluator will have to determine this by calculating both possibilities; the difference is expected to be so great that the ambiguity should be cleared up by those

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[20] The log book documents that the larger hemisphere was composed of "3 parts forming a 50 mm radius". This implies those parts were: 30-mm hemisphere + 10-mm-thick shell (30 to 40 mm) + 10-mm-thick shell (40 to 50 mm). It also states that the smaller contained "10 parts forming a 35 mm radius". This implies: 20-mm hemisphere + 9 thin hemishells. The same log book records three experiments later that the experiment is "the same as (the first) with the 30-mm centers reversed". This does not seem possible.

[21] This is clearly a 20-mm-radius hemisphere and suggests that at least one half of the final assembly did have a central core that size. This compounds the confusion of the previous footnote.

Table XV. Experimental Critical Heights for Upper Bound Asymmetric Spheres Obtained from 1997 Data Search

Larger Hemispheres		Smaller Hemisphere					Critical Oil Height	
Pu Mass (kg)	Nominal Outer Radius (mm)	Pu Mass (kg)	Nominal Outer Radius (mm)	Total Pu Mass (kg)	Avg. Pu Density (mg/mm^3)	Nominal Steel Thickness (mm)	in tank (mm)	above Pu (mm)
4.949	50	2.285	40	7.234	*18.39*	0	863	9
4.949	50	1.998	38.3	6.947	*18.43*	0	874.1	20.1
4.949	50	*1.743*	36.7	6.692	*18.44*	0	891.4	41.4
4.949	50	*1.560*	35	6.509	*18.64*	0	919.3	65.3
4.342	50	2.533	40	6.875	*17.48*	0	908.2	42.2
4.371	50	*2.504*	40	*6.875*	*17.48*	0	907.6[c]	41.6
4.371	50		40	*6.875*	*17.48*	0	903.7[c]	35.7
4.949	50	*2.285*	40	7.234	*18.39*	10[a]	913.6	26.6
5.281	53.3	2.533	40	7.814	*17.48*	10	910.7	20.7
5.281	53.3	*2.533*	40	7.814	*17.43*	50[b]	931.5	66.5

a. Same as 1st entry in table except for steel
b. Same as previous entry in table except for steel thickness
c. Also contained in Table XVI

Table XVI. Experimental Results for Repeated Configuration with Minor changes to Otherwise Similar Plutonium Assemblies

Common Configuration	Specific Change (footnote)	Pu Mass (kg)	Critical Oil Height in tank (mm)	Critical Oil Height above Pu (mm)
50-mm hemisphere atop 35-mm one	a	6509	919.3	65.3
	b	*6509*	970.5	114.5
	c	*6478.5*	Subcritical	
50-mm hemisphere atop 40-mm one	a	6875	908.2	42.2
	b	*6875*[e]	907.6	41.6
	c	*6875*	935.1	67.1
	d	*6875*[e]	903.7	35.7

a. Initial case
b. 30-mm central hemispheres exchanged
c. 308 g central hemisphere replaced by 277.5g one
d. Top plate of spherical mounting bracket not used
e. Also contained in Table XV

calculations. If the center contained oil, it is no clear how it was admitted. If not, it is equally unclear how it was excluded - seepage could have caused a criticality accident!

plutonium are included. The last three configurations present yet another ambiguity. They contained mild steel *inside* the hollow plutonium hemisphere; but records do not unambiguously reveal the thickness. It may have been either solid steel (70 mm radius!) or 10-mm thick. The thinner is suggested by an otherwise unexplained "1.0" (centimeters?) written near the terse description of the configuration. Again, hopefully, calculations should resolve this dilemma. The last entry contained the same uncertainty; but the outer region of steel (30 mm thick) is certain.

The critical oil height above (or below) the top of the plutonium was usually determined from the reciprocal multiplication curves. A mark on the graph paper noted the top of each assembly; and a second corresponded to the equatorial plane. Reciprocal multiplication curves for the last two entries in Table XVII could not be found. Lacking those, a confident determination of the critical height above the top is not possible.

Table XVII. Experimental Critical Heights for Upper Bound, Thick-Walled, Asymmetric Spherical Shells Obtained from 1997 Data Search

Nominal Inner Radius (mm)	Larger Hemisphere Nominal Outer Radius (mm)	Larger Hemisphere Avg. Pu Density (mg/mm^3)	Smaller Hemisphere Nominal Outer Radius (mm)	Smaller Hemisphere Avg. Pu Density (mg/mm^3)	Total Pu Mass (kg)	Avg. Pu Density (mg/mm^3)	Nominal Steel Thickness (mm)	Critical Oil Heights in tank (mm)	Critical Oil Heights above Pu (mm)
40	66.7	a	63.3	a	15.430	*17.59*	30	854.55	69.45
	70	a	60	a	15.745	*17.59*	30	784.45	104.55
	70	a	56.7	a	14.435	*17.50*	30	881.7	0.3
	60	a	58.3	a	10.349	*17.45*	0	939.7	-40.7
	61.7	a	61.7	a	12.374	*17.45*	0	933.5	-27.5
70	85	18.04	80	18.38	16.757	18.17	0	897.8	-2.8
	88.3	18.00	80	18.38	19.562	18.13	0	958.3	-50.3
	88.3	18.00	80	18.38	19.562	18.13	0[b]	933.2	-26.2
	93.3	17.94	80	18.38	24.150	18.06	0[b]	793.5	a
	93.3	17.94	76.7	18.45	21.804	18.04	30[b]	875	a

a. Data not available

b. Some steel inside thick-walled shell; see text

Fortunately, it may be estimated because each experiment in a series was built so similarly. A survey of the previous seven experiments showed that equators only varied between 815 mm and 839 mm above the tank's bottom; and the preceding two (also IR=70mm) averaged 827.5 mm. Assuming 827.5 mm and adding the radius of the top hemisphere located the top of the plutonium at approximately 908 and 904 mm, respectively, for these last two cases. The seventh column of Table XVII gives the *critical* height relative to the tank's bottom. A simple subtraction gives an estimate of the critical height "above" the plutonium: - 114 mm and - 29 mm, respectively. These last two entries in Table XVII have a greater uncertainty because of these assumptions.

Table XVIII presents the newly-found critical oil heights for twelve hemispheres. All are expressed both in terms of the critical height in the tank relative to its bottom and relative to the *top of the plutonium*. They fall into three groups. The first varied the inside radius of the thick-walled hemispherical shell between zero and 75 mm; and they occurred within a few months of the first general weighing of parts. The second contains two miscellaneous cases and took place the same month as the second weighing. The last three occurred close to the end of the whole program, about 5 months before the last weighing.

Assembly masses in Table XVIII require some discussion. Masses for the first set of seven were determined differently than for the remainder of the table. Even though only masses of *individual* parts were classified in 1967, the sum of those forming a given hemisphere were not recorded. Parts built into one were listed by part number. These are the same identifiers found in the first column of Table III. This assumption is considered justifiable because all seven experiments took place within five months of the December, 1967, weighing. The rest of the masses were recorded in log books and probably were the result of direct measurement as discussed elsewhere.

Radial dimensions are, again, nominal. Analysists should consider modifying them to account for tolerance gaps and part deterioration. Densities were calculated assuming a 0.1 mm adjustment to each radius. These suggestions were discussed earlier, too.

One unexplained dilemma exists in the table. The first entries in each of the first two sets are everywhere similar except that the second is larger and heavier than the first by two shells. Inexplicably, the critical height above the top is only less than a millimeter lower for the heavier case! The first entry of the third set is also similar in all respects except in overall size (smaller); but its critical height is substantially greater as expected.

Table XVIII. Experimental Critical Heights for Upper Bound Hemispheres and Thick-Walled Hemispherical Shells Obtained from 1997 Data Search

Nominal Inner Radiums (mm)	Nominal Outer Radius (mm)	Avg. Pu Density (mg/mm^3)	Total Pu Mass[a] (kg)	Nominal Steel Thickness (mm)	Critical Oil Height	
					in tank (mm)	above Pu (mm)
0	58.3	18.37[b]	7.430		893.8	3.8
20	60.0	*17.98*	7.788		894.8	4.8[b]
30	63.3	*16.18*	7.628		873	-21.0
40	63.3	*18.25*	7.183	0	876	-20.0
50	75.0	*18.33*	11.302		874	-27.5
60	81.7	*18.35*	12.540		887.7	-31.9
75	93.3	*18.55*	14.999		920	6.0
0	61.7	*16.83*	8.238	0	875	3.0
0	63.3	*16.95*	8.962	10	862	-4.0
0	56.7	18.22[b]	6.949		898.1	37.4
40[c]	68.3	*17.81*	9.426	0	910.1	37.8
40	70.0	*17.75*	10.298		898.8	24.8

a. First 7 masses are obtained by summing weights from Table III.
b. These 2 densities were recorded in 1960s and not calculated in 1997; the height had also been recorded and not derived in 1997 by extrapolation.
c. This assembly was shimmed away from the face of the hemispherical mounting plate a small amount. This procedure is also discussed in Table XIX.

Both densities of the middle set are quite low. This may be associated with part deterioration. The last three, again, have greater densities; but this may be associated with the use of replacement parts and/or finally using larger shells which had not seen much use previously.

One assembly in Table XVIII, the 56.7-mm-radius hemisphere with no steel, had been selected in 1969 to evaluate the effect of small changes in an otherwise identical configuration. These results appear in Table XIX The first entry is considered the "base case" and is merely copied from Table XVIII. Next, the same plutonium hemisphere was merely shimmed away from the plane face in the mount. A larger yoke was used. This admitted oil closer to that face; and the critical height was expected to decrease. It did significantly. The amount of this "shimming" was not specified for this experiment; however, footnote "c" to Table XVIII listed that shim as 50 mm. It may have been the same in this case, too.

All of these newly-discovered critical configurations are subject to the same caution. Most are probably quite adequate for validation purposes even though nominal dimensions were used. Still, the analysist is forewarned that any one of them (or even a few) might contain some error in interpretation which would render that configuration useless for code evaluations. One example already acknowledged is the thickness of the innermost steel for the last three entries in Table XVII.

Table XIX. Experimental Results for Reassembled Configurations with Minor Changes to Otherwise Similar Plutonium Hemispherical Assemblies

Common Configuration	Specific Change (footnote)	Pu Mass (kg)	Critical Oil Height in tank (mm)	Critical Oil Height above Pu (mm)
56.7-mm hemisphere	a	6.949	898.1	37.4
	b	6.949	883.1	22.4
	c	6.920	894.6	33.9

a. Initial case
b. Exactly the same load as the "base case" except it was shimmed some unspecified amount from the hemisphere mount
c. 30-mm central hemisphere (1058g) replaced by composite of 20-mm one plus six thin shells (1029g)

UNCERTAINTIES

This is a very old experimental program - certainly, one of the first at the Rocky Flats Critical Mass Laboratory. Parameters were not always recorded as completely as computational needs of the 1990s would desire. Plutonium metal chemistry was not as well understood then as in later years; so the fissile metal, itself, deteriorated over months. Finally, the classified nature of the plutonium itself fostered a tendency to terse documentation and sometimes unlabled parameters, requiring significant detective work to glean necessary data.

Still, these experiments are extremely important to the nuclear criticality safety industry today. Their principal value lies in the major dearth of experimental data involving plutonium in any form. A second value stems from the hydrogenous composition of the oil reflector. It resembled water very closely; and there simply does not exist a wealth of data for water-reflected plutonium metal. Thirdly, the geometry of simple spheres, hemispheres, and hollow shells of the same shape is easy to model computationally. Finally, large masses, equal to or somewhat larger than encountered in the plant, permit conservative assessments of criticality safety questions spanning a wide range of plant applications.

All this is to justify thorough evaluation of these experiments against modern computer codes in spite of sometimes larger experimental uncertainties than might exist in later studies. Some errors in interpreting some experiments - especially those recently uncovered - may produce nonsense results upon computational validation. The evaluator is warned of this possibility. These errors are solely the responsibility of this author and stem from his imperfect recollection of all events. In spite of this, the majority of experiments are believed to have been successfully correctly described and parameters defined through considerable research. They form the essential value of this document.

The first issue is the mass of each plutonium assembly. Each individual part was weighed on three occasions: December, 1967; December, 1968; and September, 1969. All experiments took place between June, 1967, and September, 1969. Even though parts changed through oxidation, the weighing program should provide good estimates of the weights used at any given time. Some of the more-damaged parts were replaced with new ones; so parts close to their intended mass were almost always available. Specific masses for a great many experiments were specifically recorded somewhere; and the existence of a certified balance for weighing items has recently been verified. This suggests that assembly masses were the result of direct measurement, not merely the summation of months-old data from some general weighing program. Unfortunately, this important detail is not recalled with sufficient confidence to declare it with certainty. Dr. Hunt, in his once-classified internal report (1968), admonished his readers to consider each plutonium assembly mass to have an uncertainty of about $\pm$ 1 %. This author generally concurs with that opinion, although he might increase the uncertainty a little. Assembly masses in the vicinity of six to nine kilograms may be uncertain to about $\pm$ 100 g.

Other than these masses, the number of significant figures published are a strong indication of the suggested uncertainty ascribed to a parameter. The last digit may be a little uncertain. For example, the outside diameter of the outer tank was stated to be 711 mm. That means that the tank was sufficiently round to be within 710 and 712 mm and yet not so precisely determined that its diameter could be quoted to tenths of a millimeter. Plutonium masses are an exception to this practice. They are given with the same number of significant figures published in previous reports. All three are appended to this document for completeness. This adds confidence to the association between results here and in the much-earlier publications.

Critical heights are another major parameter that warrant detailed discussion. Often, they were ignored in the 1960s because computational methods of the time could not accommodate them. Usually, however, they were still recorded on graphs of the reciprocal multiplication and/or in record books of the program. Almost all critical heights were the result[22] of an interpolation between two closely spaced oil heights corresponding to slightly super critical and slightly subcritical situations. That implies that criticality was confidently bounded by these two heights, little different from one another. That would tend to lend great confidence in these measurements; but the reader is reminded that every "height" was actually composed of two heights. One, in the outer and much larger tank, was read directly by closed-circuit television; but the smaller volume of oil was determined by a capacitance probe. This process did not permit direct visual confirmation of the oil height in the smaller tank and lessens confidence that both were exactly the same. In fact, one note found in one log book reported a difference of a "couple of millimeters" on one occasion. If this every were actually the case, the wavy lines of Fig. 10 indicating the tops of the oil in the two tanks would be different by that millimeter or two. Still, every effort was made to keep these two tanks at the same height all the time.

[22] Only a few critical heights were the result of an extrapolation of reciprocal multiplication data; and even then, the extrapolations are really quite unambiguous.

Factors affecting the uncertainty of these results have been discussed throughout this report whenever prudent. This author's opinion is that these experiments are not quite on a precision par with later studies performed at Rocky Flats; but they still are extremely valuable and almost as precise in almost all cases. A few are expected for which agreement will be extremely poor.

A PROBLEM

These experiments were performed between May of 1967 and September of 1969. A total of 86 more-or-less spherical assemblies and 81 hemispherical ones were studied. Furthermore, during this 28-month interval, the Rocky Flats CML was entering the arena of experiments involving enriched uranium solutions and continuing its experiments with enriched uranium metal hemispherical shells. It was a busy and productive time for this relatively new CML.

Time after time, these plutonium shells were nested, immersed in oil, and then disassembled for return to storage. In between bursts of activity, they would set idle, giving preference to other programs, awaiting the resumption of plutonium experiments. This mode of operation seemed as though it could continue forever. How wrong that observation was!

One day, probably in the fall of 1969, Dr. Hunt and this author set out to do another simple (?) plutonium experiment. The plan called for a prescribed set of plutonium hemishells. One by one, these parts were removed from their storage pressure cookers and passed into the glovebox. Each one had the bright, silvery surface with which we had become familiar. The shiny gleam on the surface assured the metal was protected from air and water by a coating of oil or grease. The operation was proceeding as it had many other times in the previous two years or more.

The next pressure cooker was removed from the shelf. It was set on a piece of clean paper on the downdraft table's screen. The two experimenters positioned themselves to perform again the oft-repeated task. The safety monitor stood ready to scan hands and clothing for contamination. The lid was twisted off and raised only enough for an initial survey of the pressure cooker joint. When the lid was handed from one experimenter to the other to be laid temporarily out of the way, all three persons gazed in amazement at the sight before them.

The pressure cooker did not contain the expected shiny, silver, heavy hemispherical shell. Instead, a surprising mound of olive-drab green loose, fluffy powder rested on the floor of the pressure cooker! The plutonium metal hemishell had completely decomposed into a mound of some form of plutonium hydride and/or sub-oxide! Somehow, water or moist air must have penetrated the protective barrier of oil and grease generating the mound of unspecified plutonium compound.

Whatever compound it was, it spelled the sudden end of the experimental program involving nested plutonium metal hemishells. The lid was carefully returned to the pressure cooker such as to not disturb the pile of fluffy powder. Other unaffected parts were returned to storage, too. Three "unsettled" men explained their findings to management who were quick to take action.

Within days or weeks, the entire set of plutonium hemishells were returned to the plutonium production stream at Rocky Flats. This experience taught this author a lot about the unstable nature of bare plutonium metal. I suspect Rocky Flats learned a lot, too.

ACKNOWLEDGMENTS

This paper is written under the auspices of the *International Criticality Safety Benchmark Evaluation Project*, funded by the United States Department of Energy. The project is administered by J. Blair Briggs of Lockheed Idaho Technologies Company. This author is grateful to Mr. Briggs for the opportunity to publish these data in the peer-reviewed literature before the author's full retirement. This is the fourth of six papers presenting previously unpublished or inadequately documented results from criticality experiments performed at the Rocky Flats Critical Mass Laboratory. These six documents will mark a satisfying closure to this author's long career in the arena of critical experiments.

Special recognition is due Mr. Merlyn R. Boss, of Denver, Colorado. He has retired from other activities at Rocky Flats; but, in the late-1960s, he was a co-worker at the laboratory. He was Dr. Hunts principal assistant on this program; and he co-authored two of the three documents published some three decades ago. Mr. Boss has agreed to be one of the reviewers. This peer-review will prove invaluable because the author's recollection of events will be filtered through the memory of another involved experimenter.

As always, the patient and capable efforts of Christine White and Peggy Shiffer are gratefully recognized. They prepared the figures and tables, respectively. This task was made more difficult because of the circumstances. They worked in Idaho; the author, in Colorado. Iterative improvements were accomplished through mail services.

APPENDIX

Three previously published documents related to this program are contained here. These are included for completeness. Neither any one of them nor any combination can stand alone to provide adequate documentation suitable for computer evaluations of the 1990s.

The first is a once-classified document that was declassified in April of 1997 specifically for this paper. It was published only as a Rocky Flats internal plant report as RFP-1216. The second was the written text of a verbal paper presented to the American Nuclear Society. The text of RFP 1410 was published in the *Transactions of the American Nuclear Society*, **Vol 12**, No. 2 (1969). The last was a journal article published in 1971 in the *Journal of Nuclear Energy* (Pergamon Press).

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RFP-1410

4. Plutonium Metal Criticality Measurements, *D. C. Hunt, M. R. Boss (Dow-Colo)*

The results of a series of critical mass measurements on alpha plutonium metal (^{238}Pu = 0.01 wt%; ^{239}Pu = 93.58 wt%; ^{240}Pu = 5.90 wt%; ^{241}Pu = 0.49 wt%; ^{242}Pu = 0.02 wt%) assemblies reflected by mild steel (SAE 1018) and/or oil (Texaco No. 522) are reported. The experimental apparatus[1] consists of two aluminum tank-reservoir combinations. The assemblies are secured by aluminum mounting fixtures in the smaller of these tanks. This tank is then transported to the test cell where it is placed inside the larger tank. Both tanks are independently and identically plumbed to allow three different liquid filling speeds.

The plutonium assemblies are either spheres or hemispheres built up from nested subassemblies. Spherical assemblies are measured because of the relative

TABLE I

Experimental Critical Masses*

Geometry	Average Fuel Density (g/cm³)	Steel Reflector Thickness (cm)	Oil Reflected[a]	Mass Difference[b] (grams)	Critical Mass (grams)
Hemisphere	16.88	0	Yes	---	7 752 ± 100
	18.32				6 687 ± 170
Asymmetric Sphere	17.31	0	Yes	2 112 ± 114	6 667 ± 192
	18.56			3 371 ± 64	6 494 ± 180
	17.30	1		2 836 ± 112	7 576 ± 135
	17.97			2 342 ± 129	7 039 ± 101
	17.32	3		3 172 ± 10	8 044 ± 202
	18.14			2 182 ± 28	7 260 ± 57
	17.31	5		3 169 ± 2	8 043 ± 212
	18.16			2 070 ± 95	7 370 ± 88
Hemisphere	16.86	0	Yes	---	7 637 ± 100
		0.33			7 717 ± 137
		0.67			7 860 ± 152
		1.0			7 885 ± 156
		1.33			7 921 ± 157
		1.67			7 930 ± 158
		2.0			7 934 ± 158
		2.33			7 956 ± 158
		2.67			7 961 ± 158
		3.0			7 979 ± 158
		3.33			7 974 ± 158
		3.67			7 964 ± 159
		4.0			7 957 ± 159
		4.33			7 953 ± 159
		4.67			7 944 ± 159
Asymmetric Sphere	17.43	0	No	12 086 ± 251	14 128 ± 220
	17.41			9 713 ± 250	14 455 ± 272
	17.17			4 002 ± 92	13 064 ± 135
	16.36	1		11 377 ± 249	13 294 ± 216
	17.22			7 162 ± 203	11 842 ± 109
	17.48			1 190 ± 89	10 401 ± 112
	17.06	3		8 929 ± 139	10 973 ± 215
	16.81			5 226 ± 46	9 836 ± 153
	17.95			932 ± 55	8 559 ± 140
	16.84	5		7 866 ± 102	9 876 ± 188
	17.61			4 040 ± 101	8 811 ± 148
	18.72			1 766 ± 94	7 849 ± 90
Hemisphere	16.90	0	No	---	14 500 ± 300
	16.20	1			12 800 ± 200
	16.19	3.33			11 250 ± 150
	17.06	4.67			11 040 ± 150

*No correction for interstitial grease loading, mounting fixtures, or tie bolts is included in the critical masses reported in this table.

[a]The difference in mass between the two halves of the critical asymmetric spherical assembly.

[b]Effectively infinite (~ 30 cm) oil reflection is present for all oil-reflected assemblies.

TABLE II

Comparison of Experimental and Calculated Perfect Sphere Critical Masses

Oil Reflected	Average Fuel Density[a] (g/cm^3)	Steel Thickness (cm)	Observed Critical Mass[b] (grams)	Computed Critical Mass (grams)	Scaled Critical Mass[c] (grams)
Yes	18.37 ± 0.05	0	6 123 ± 200	5 924	5 474
	21.80 ± 0.1	1	4 813 ± 400	4 985	5 662
	19.94 ± 0.1	3	5 838 ± 300	6 025	5 942
	19.74 ± 0.1	5	6 210 ± 350	5 971	6 210
No	17.35 ± 0.25	0	12 709 ± 590	12 954	9 825
	17.71 ± 0.36	1	9 996 ± 330	10 381	8 121
	17.85 ± 0.26	3	8 271 ± 260	8 326	7 043
	18.46 ± 0.21	5	7 356 ± 360	7 260	6 555

[a]Deduced from plots of mass difference (see Table I) vs average fuel density.

[b]Deduced from plots of mass difference (see Table I) vs critical mass. Corrected for effect of mounts and interstitial grease and oil loading.

[c]Scaled from observed critical masses to a density of 19.74 g/cm^3 using computed scaling exponents.

ease with which their critical masses may be calculated. Hemispherical geometries are measured since they are easily assembled, and offer greater measurement precision. The steel assemblies are also constructed from nested subassemblies and have an average density of 7.62 g/cm^3. When steel is present in the reflector region, it is always in contact with the plutonium assembly. The oil used in the reflector region has been found to be compatible with metallic plutonium and also has a C:H ratio (0.56) which is close to the O:H ratio of water (0.5).

A total of 41 critical masses are identified. These critical masses are shown in Table I. In Table II, the "perfect sphere" critical masses, deduced from the Table I values, are compared with S_4 DTF[2] calculations made using Hansen-Roach[3] 16-group cross sections.

The critical masses reported here are of interest since, owing to handling difficulties, only a limited number of plutonium-metal critical mass measurements have been reported.[4-8] Specific conclusions include: the critical masses of steel-oil reflected assemblies are increased, relative to oil-only reflection; the curve of critical mass variation with steel thickness, for steel-oil reflection of hemispherical assemblies, shows structure which is similar to that found in previous enriched-uranium metal measurements on spherical assemblies.[9] The structure observed consists of a pair of inflection points at steel thicknesses of 2 and $2\frac{2}{3}$ cm together with a maximum at ~ 3 cm. This structure has been shown to a be associated with the scattering resonances of ^{56}Fe in the energy range[9] 20 to 100 keV.

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RFP-1216

November 15, 1968

PLUTONIUM METAL CRITICAL MASS MEASUREMENTS

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PLUTONIUM METAL CRITICAL MASS MEASUREMENTS

Douglas C. Hunt

Abstract. Reported are the measured critical masses and dimensions of several hemispherical and spherical plutonium-metal shell assemblies. The inner radius of the assemblies is varied from 0 centimeters (cm) (solid assembly) to 7.5 cm. The assemblies were measured with no reflector, with a pair of hands as a reflector, and with an oil reflector. The critical parameters of similar assemblies of alpha-phase and delta-phase metal are deduced from the experimental results.

The measured values are compared with the results of Monte Carlo, multigroup transport, and collision probability calculations.

INTRODUCTION AND SUMMARY

The measured critical masses and dimensions of several hemispherical and spherical plutonium-metal shell assemblies are reported. The inner radius of the assemblies is varied from 0 centimeters (cm) (solid assembly) to 7.5 cm. The assemblies were measured with no reflector, with a pair of hands as a reflector, and with an oil reflector. The critical parameters of similar assemblies of alpha-phase and delta-phase metal are deduced from the experimental results.

The measured values are compared with the calculational results and the calculational techniques are described. The three calculational methods used were:

1. Monte Carlo (the Ø5R Computer Code),

2. Multigroup Transport (the DTF Computer Code), and

3. Collision probability.

The latter method is based on zero-order solutions to an integral form of the Boltzmann transport equation.[1]

[1]K. M. Case, F. deHoffmann, and G. Placzek. *Introduction to the Theory of Neutron Diffusion. Volume I, Chapter II. Page 17.* Los Alamos Scientific Laboratory, Los Alamos, New Mexico. 1953.

EXPERIMENTAL EQUIPMENT AND COMPONENTS

Reflectors and Fissile Components:

The experimental fissile assemblies are spherical and hemispherical shapes built up from a series of subassemblies. The subassemblies are all 0.167 ±0.005-cm thick hemishells with the exception of a single 2-cm radius hemisphere. The subassembly properties are given in Table I. The plutonium of which the subassemblies are composed is alpha-phase metal containing approximately 0.07-percent impurities with an isotopic plutonium-240 (^{240}Pu) content of about 5.9 weight percent (wt %). The average crystal density is 19.52 grams per cubic centimeter (g/cm^3) and a typical assembly density is 18.20 g/cm^3.

Three reflectors were used in the experiments:

1. Texaco No. 522 oil.

2. A pair of hands.

3. Air.

The No. 522 oil had a hydrogen number density of 0.0699×10^{24} cm^{-3} and a carbon density of 0.0386×10^{24} cm^{-3} giving a carbon to hydrogen number density ratio of 0.552. The oil contains about 0.2-wt % impurities.

The assemblies also contain a lithium-silicon grease which partially fills the interstitial gaps between subassemblies. The grease typically occupies about 5 percent of the assembly volume. The grease composition, by wt % is 8.9 percent hydrogen, 17.2 percent oxygen, 47.0 percent carbon, 0.6 percent lithium, 26.1 percent silicon, and 0.2 percent impurities. The grease density is 0.972 g/cm^3.

Experimental Apparatus:

The fissile components are contained in a sealed tank-reservoir combination designated as the *inner system*.

The *inner system* acts as a portable vessel which restricts the spread of plutonium contamination when

TABLE I. Properties of Plutonium Hemishells.

Part No.	Inner Radius (centimeters)	Mass (grams)	Part No.	Inner Radius (centimeters)	Mass (grams)
901	0	302.4	853	6.34	790.4
801	2.01	77.5	855	6.51	824.4
803	2.18	91.3	857	6.68	869.2
805	2.35	105.6	859	6.84	909.9
807	2.51	121.9	860	7.01	968.0
809	2.68	134.5	861	7.01	966.0
811	2.84	158.3	862	7.17	966.3
813	3.02	174.6	863	7.17	1002.6
815	3.18	192.1	864	7.34	1051.0
817	3.34	213.9	865	7.34	1025.0
819	3.50	240.3	866	7.52	1087.0
821	3.68	256.5	867	7.50	1116.0
823	3.83	283.9	868	7.68	1132.0
825	4.00	312.1	869	7.69	1111.0
827	4.18	339.0	870	7.85	1223.0
829	4.33	361.3	871	7.85	1185.0
831	4.51	390.0	873	8.02	1238.0
833	4.67	429.3	875	8.18	1312.0
835	4.83	464.5	877	8.35	1348.0
836	5.01	486.0	879	8.51	1400.0
837	5.01	485.5	881	8.68	1490.0
838	5.17	522.2	883	8.85	1501.0
839	5.18	524.2	884	9.01	1561.0
840	5.35	554.3	885	9.01	1600.0
841	5.34	559.6	886	9.17	1640.0
842	5.51	589.2	887	9.17	1639.0
843	5.51	587.7	888	9.38	1594.0
844	5.67	629.3	889	9.34	1722.0
845	5.67	621.6	890	9.51	1737.0
846	5.85	660.7	891	9.51	1758.0
847	5.84	670.6	892	9.68	1792.0
848	6.01	702.9	893	9.68	1775.0
849	6.01	712.2	894	9.84	1845.0
850	6.18	742.3	895	9.84	1855.0
851	6.18	739.3	896	10.02	1922.0

NOTE: Due to part deterioration with time, the masses represent an average over the period of time during which the experiments were done. About a 1-percent mass uncertainty should thus be associated with the figures in the table.

the fissile assemblies are moved between the plutonium handling area and the experimental area. The system consists of a small tank (36.8 cm in diameter and 74.6 cm high) in which the fissile material is mounted; a reservoir for the experimental liquid; and the necessary valves, piping, and vents. Two side views of the inner system are shown in Figures 1 and 2. A view of the tank interior appears in Figure 3. The liquid level in the inner system tank is monitored by a capacitance probe. The tank and reservoir are vented to the facility *hot-area* exhaust system.

To ensure full reflection of the assemblies during an experiment, the inner system is placed in a larger tank called the *outer system*. Except for size, the outer system is similar to the inner system with these exceptions:

1. The outer system is vented to the atmosphere directly.

2. The liquid level in the outer system is read from a level gauge.

3. There is an orificed drain line on the outer tank.

The outer system is shown in Figure 4. The controls for the inner and outer systems are the same. Both systems have two independent drain lines and valves, and a single filling line with valve-orifice combinations which allow three pumping speeds. The orifices of both systems are sized so that each system drains faster than it can fill for all liquid levels which could measurably contribute to the reactivity of an assembly. This permits the drain lines to act as the two required independent system *scrams*.

Monitoring and Detection Instrumentation:

The following monitoring devices are standard for any reflected plutonium critical measurement:

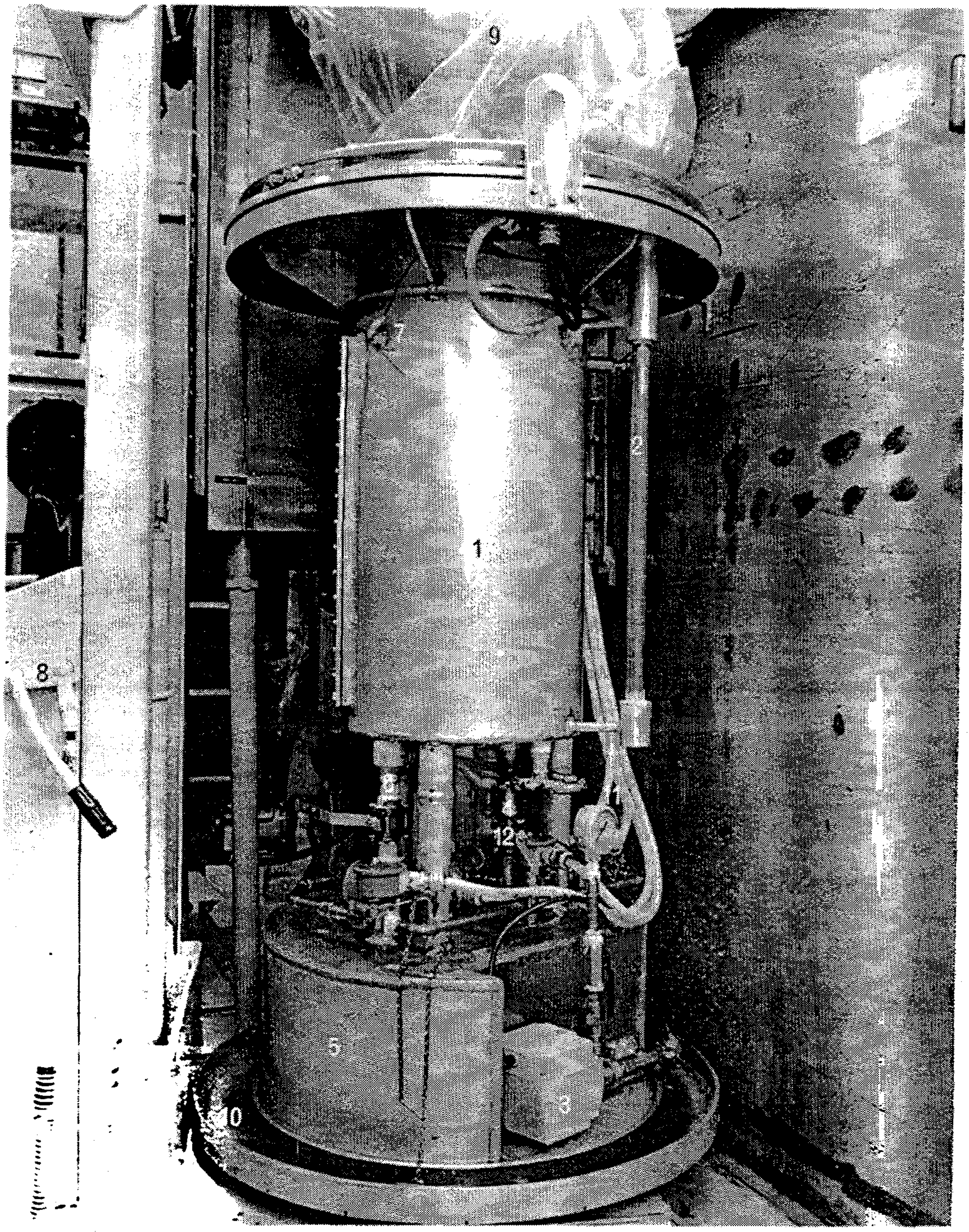
1. A level gauge, viewed by closed-circuit television, which gives the liquid level in the outer system. A capacitance-probe readout is also available (see Figure 4, Items 8 and 9).

2. A capacitance-probe readout for the inner system which is read at the control console (Figures 1 and 3).

3. Four boron-trifluoride (BF_3) proportional counters. These counters supply the digital data used to plot the subcritical reciprocal multiplication curves. During an experiment, three of these counters are in the counter ports (see Figure 4, Items 3 and 5), while the other counter remains under the outer system tank.

4. One gamma meter, supplied by a gamma-sensitive ionization chamber. This meter serves as a secondary monitoring instrument and as a *scram* sensor.

5. A period- and power-level meter. This meter senses the current from an ionization chamber mounted on the side of the outer system tank. It serves as a secondary monitoring device and as a differentiating instrument which supplies a

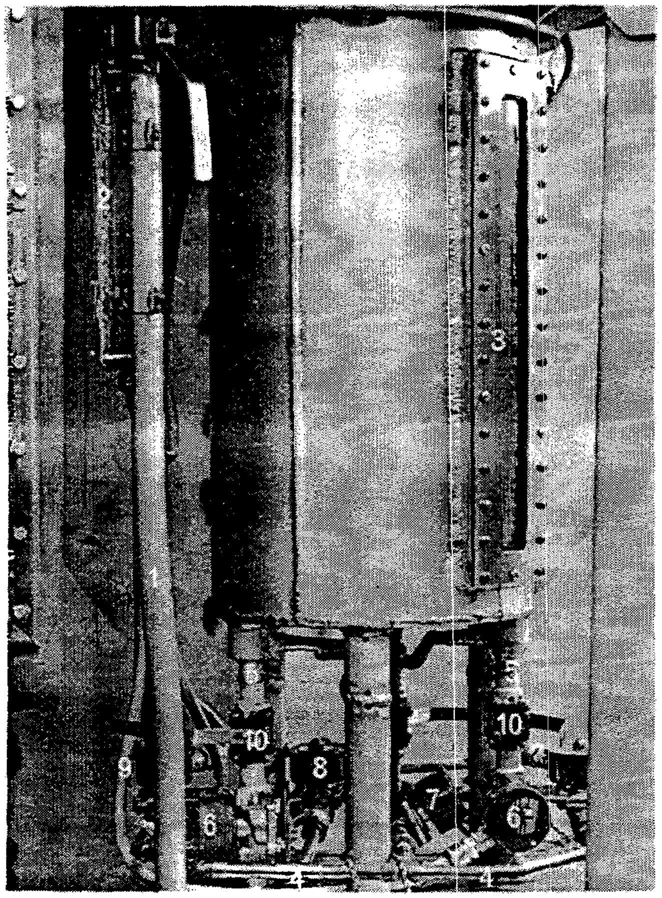


Legend

12753-10

1. Tank.
2. Capacitance probe tube.
3. Pump.
4. Fill line.
5. Reservoir.
6. Dump line.
7. Thermocouple lead.
8. Platform lift truck.
9. Plastic sleeve connection to glove-box loading port.
10. Drip pan.
11. Fill-line pressure gauge.
12. Manual valve for fill line.

FIGURE 1. First View of Experimental Vessel.



Legend

1. Vent line.
2. Junction box.
3. Sight port.
4. Fill manifold.
5. Drain lines.
6. Solenoid valve for drain lines.
7. Solenoid valve for fast-speed filling.
8. Solenoid valve for medium-speed filling.
9. Solenoid valve for slow-speed filling.
10. Manual valves for drain lines.

FIGURE 2. Second View of Experimental Vessel.

readout of the system period. It also acts as a scram initiator when a present current level is exceeded.

6. Two thermal neutron-ionization chambers (Figure 4, Item 6). The current from these chambers is read out on linear-scale picoammeters. These meters are primary monitoring devices which may be used to construct inverse multiplication curves, but are most useful in observing the behavior of near critical systems. They also act as scram initiators.

The readings from the picoammeters, the gamma meter, the power level-period meter, and one of the count-rate meters (associated with the proportional counter output) are displayed on strip charts. Reading trends and transient responses of instruments are thus easily seen and a permanent data record is maintained.

The proportional-counter output may also be used in connection with inverse multiplication meters.[2] These meters invert the count-rate data and multiply them by a preset background-count rate. In practice, most of the inverse multiplication curves were plotted from the inverse multiplication meter readings.

Safety Devices:

As noted earlier, the scram-activating devices present during any experiment are the picoammeters (100 percent of full scale reading), the power level-period meter [10^{-7} amperes (amp) and 10 seconds (sec)], and the gamma meter (10^{-10} amp). The valves given here are the readings on the associated meters which cause a scram condition. The gamma meter and the picoammeters also have high level trips, at 10^{-9} amp and 150 percent of full scale reading respectively, which activate a building alarm. In addition, a manual-scram-activating button is available at the control console.

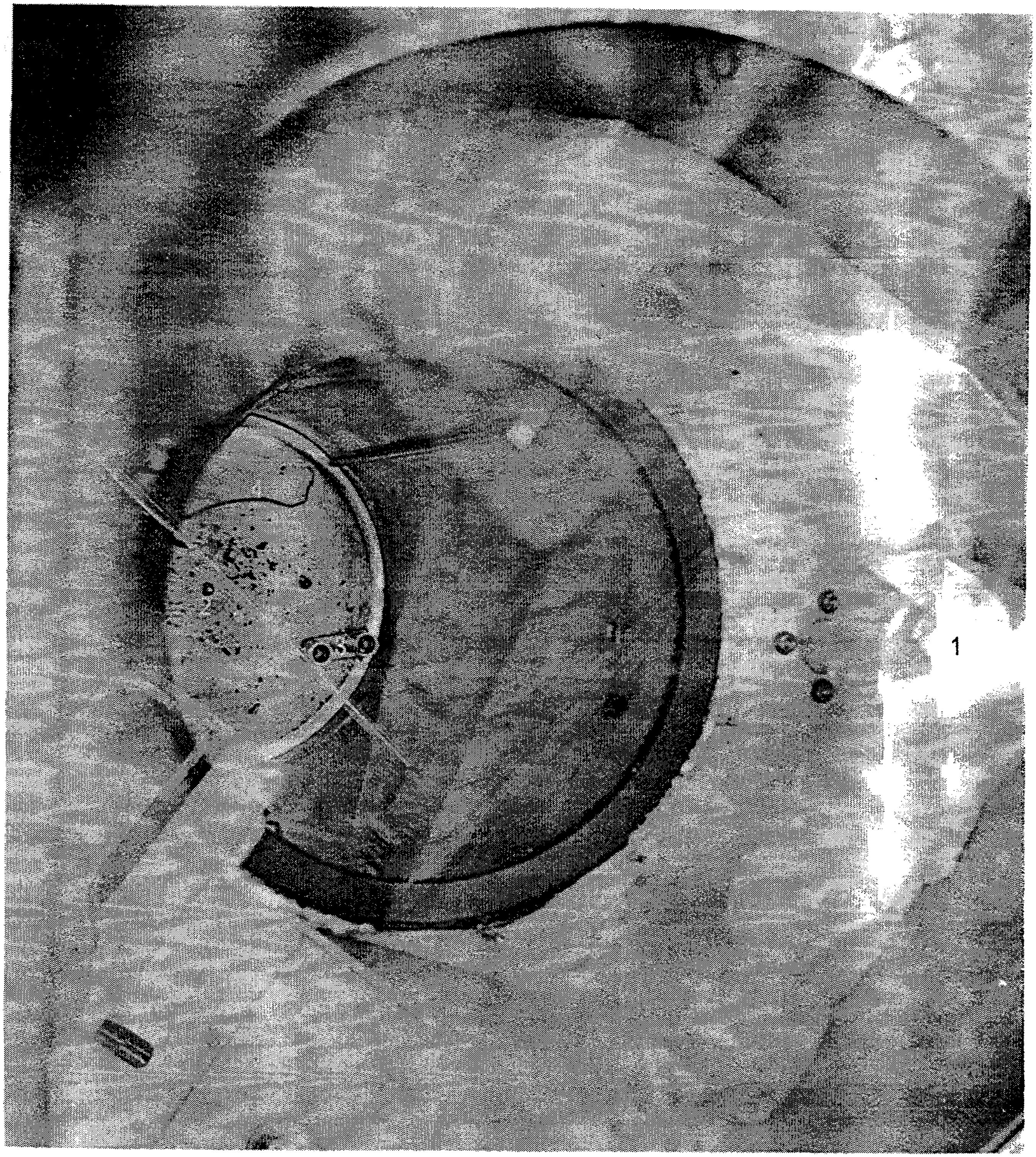
The scram removes all power from the test equipment, and also acts to open the drain valves and close the fill valves.

EXPERIMENTAL PROCEDURES

Hand-Assembly Measurements:

Hand-assembly measurements are begun by removing the component parts for an assembly from their storage containers over a down-draft table (Figure 5). All the needed parts are put into the glove box (via the guillotine door) and are moved to the hand-assembly area (Figure 6). The parts there are arranged in a plane array which is approximately symmetric with respect to the hand-assembly proportional counters (Figure 6). A background count is

[2] *Research and Development Quarterly Progress Report, August, September, and October 1966. Nuclear Safety.* RFP-851. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. November 21, 1966. Page 9. (Classified)



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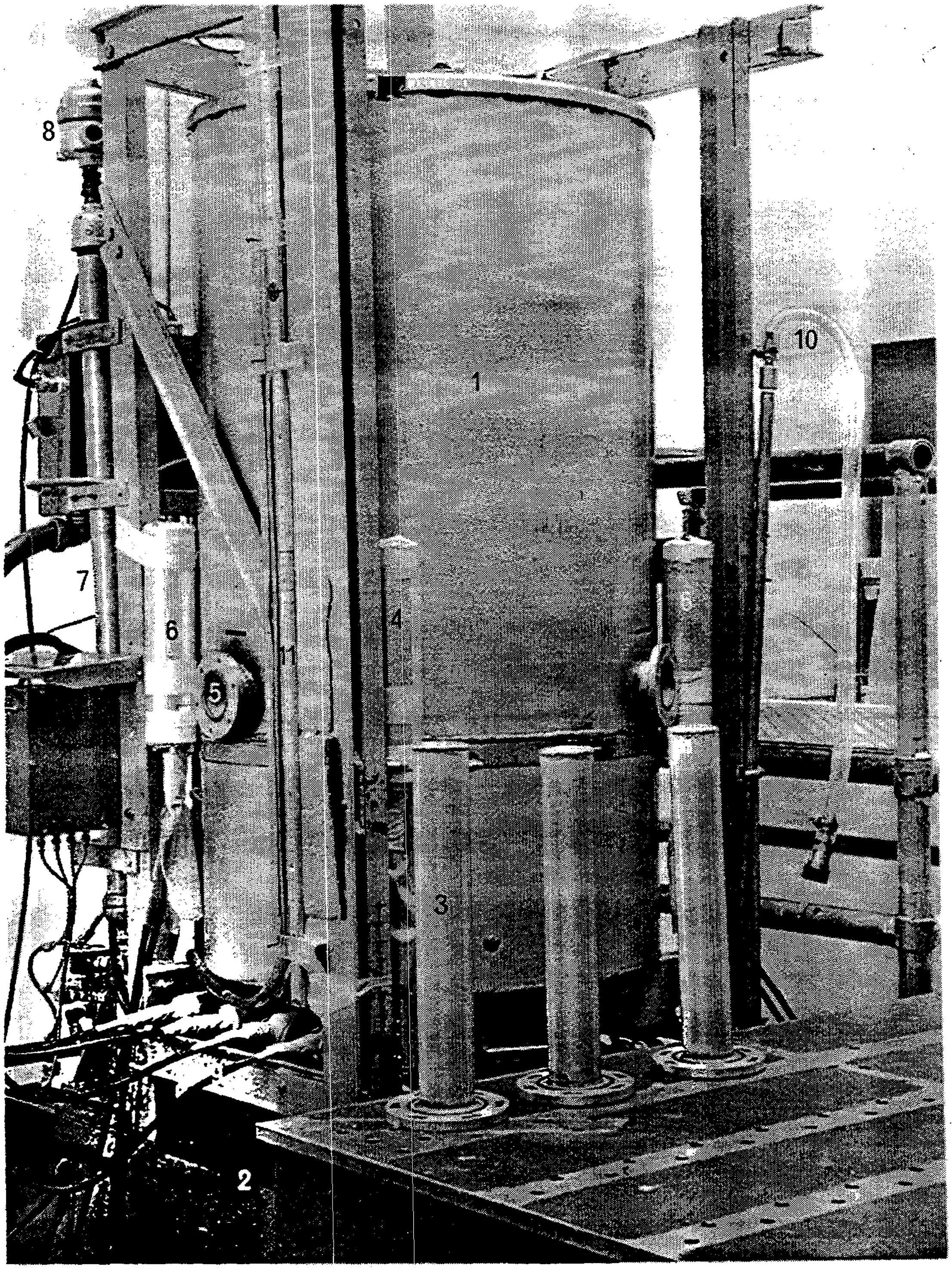
Legend

1. Capacitance probe-sensing head.
2. Tank bottom.
3. Fill line.
4. Thermocouple lead.

FIGURE 3. Interior View of Experimental Vessel.



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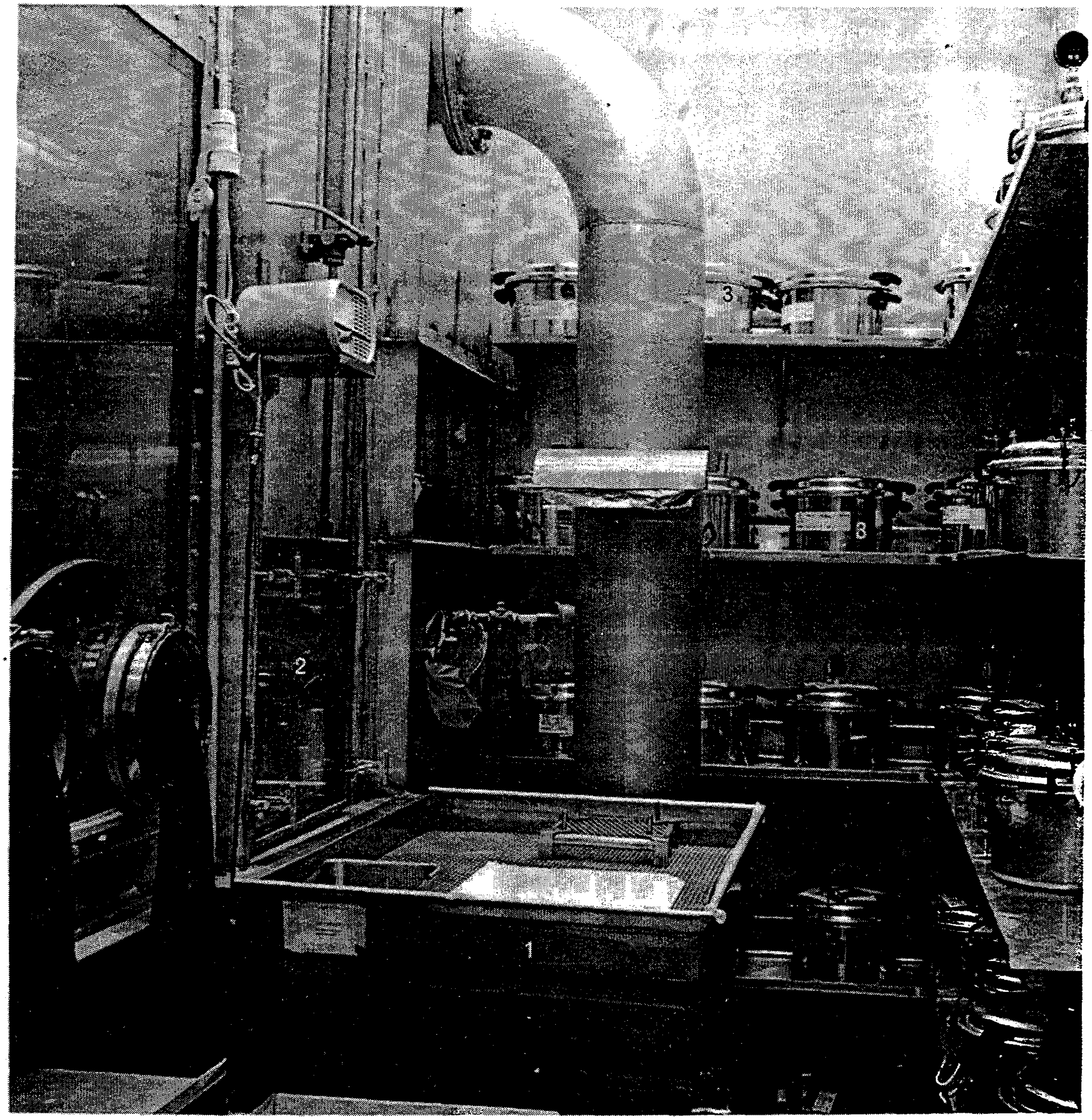
Legend

1. Tank.
2. Reservoir and drip pan.
3. Counter-port tubes.
4. Period power-level ionization chamber.
5. Counter port.
6. Picoammeter ionization chamber.
7. Capacitance probe tube.
8. Capacitance probe-sensing head.
9. Boron-trifluoride proportional counters in prerun position.
10. Vent line to hot exhaust.
11. Level gauge.

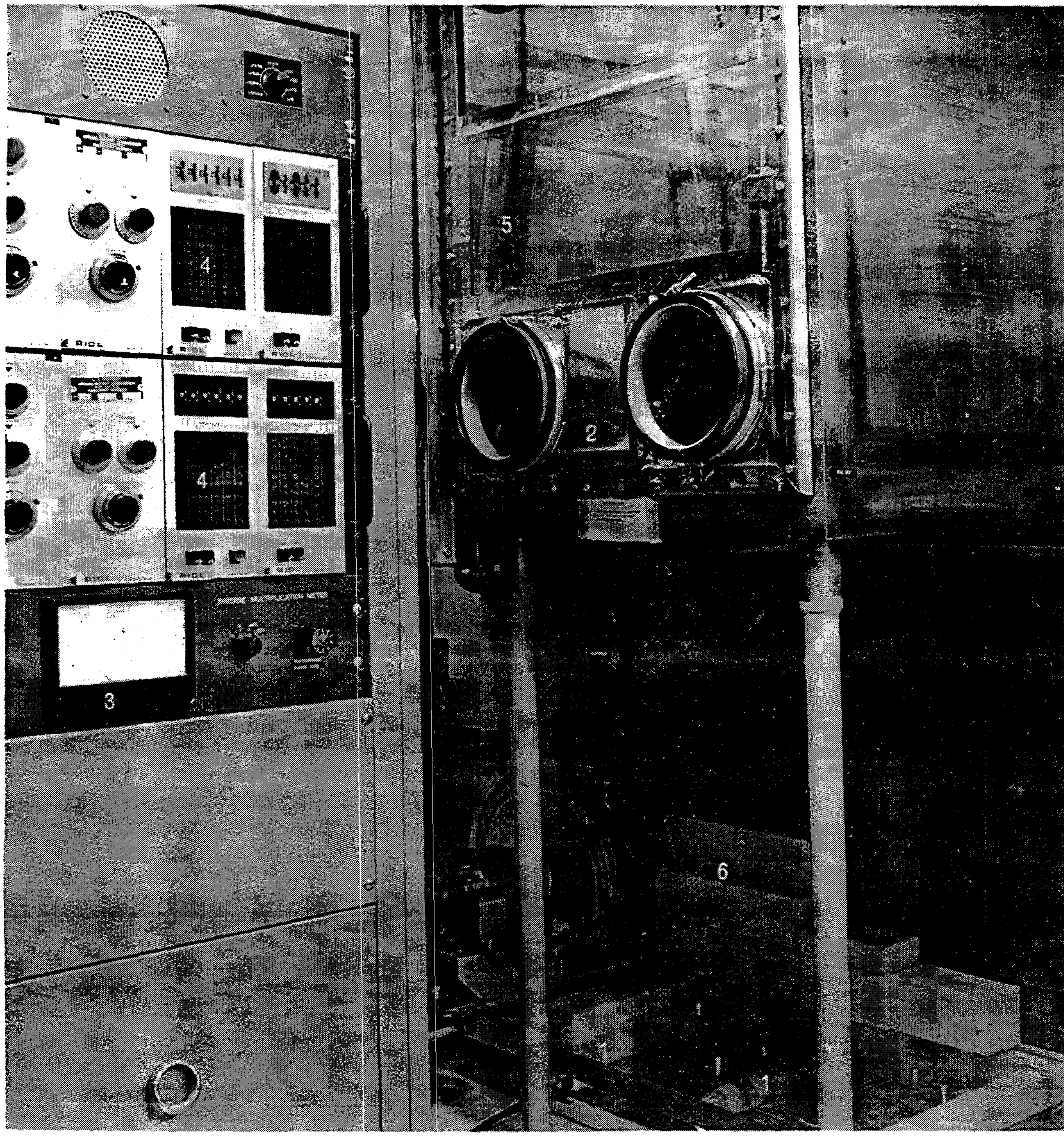
FIGURE 4. Outer System Experimental Vessel.



Legend

1. Down-draft table.
2. Guillotine door to glove box.
3. Part storage containers on storage shelves.

FIGURE 5. Plutonium Handling and Storage Room.



12753-12

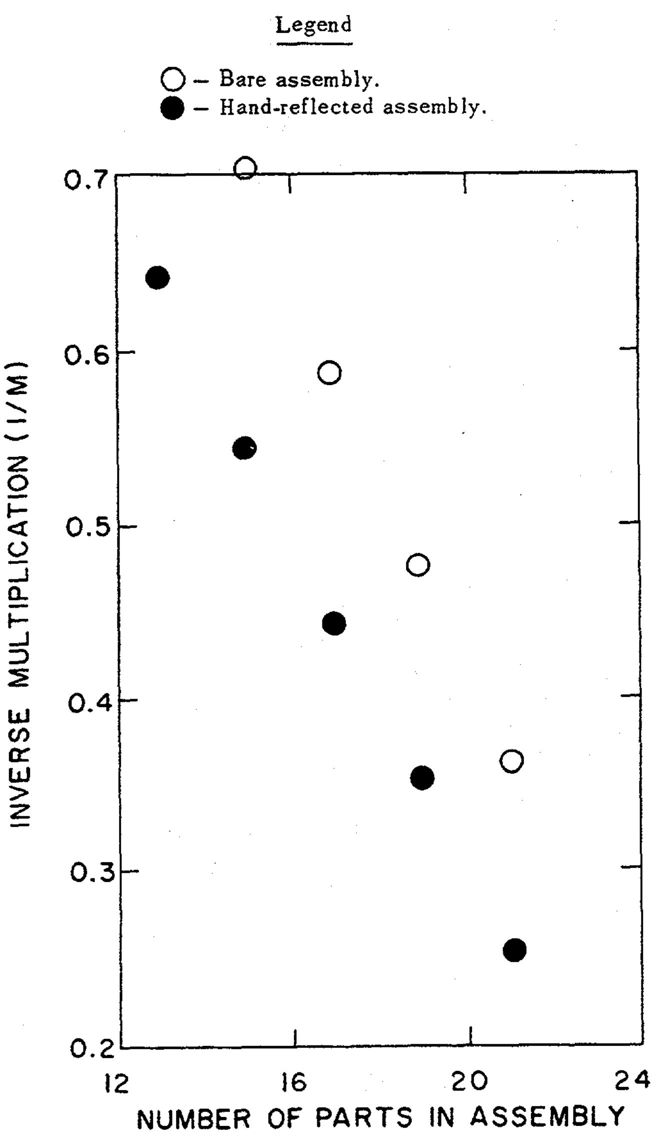
Legend

1. Boron-trifluoride counters under two-inch plastic slab.
2. Hand-assembly area (inside glove box).
3. Inverse multiplication meter.
4. Digital readout from boron-trifluoride counters.
5. Plutonium handling glove box.
6. Boron-loaded polyethylene bricks for shielding boron-trifluoride counters.

FIGURE 6. Plutonium Hand-Assembly Area.

taken for this geometry. A partial assembly is made with the unassembled parts remaining in their *background-count* geometry. Counts are taken for this assembly both with and without the reflection of the experimenter's hands. The ratio of the background count to the partial-assembly count then gives a point on a curve of inverse multiplication versus number of parts in the partial assembly. Iteration of this procedure forms a curve whose extrapolation to zero inverse multiplication gives the critical properties of the assembly. In Figure 7, a typical hand-assembly inverse multiplication plot is shown.

FIGURE 7. Hand-Assembly Inverse Multiplication Plot.



Oil-Reflected Measurements:

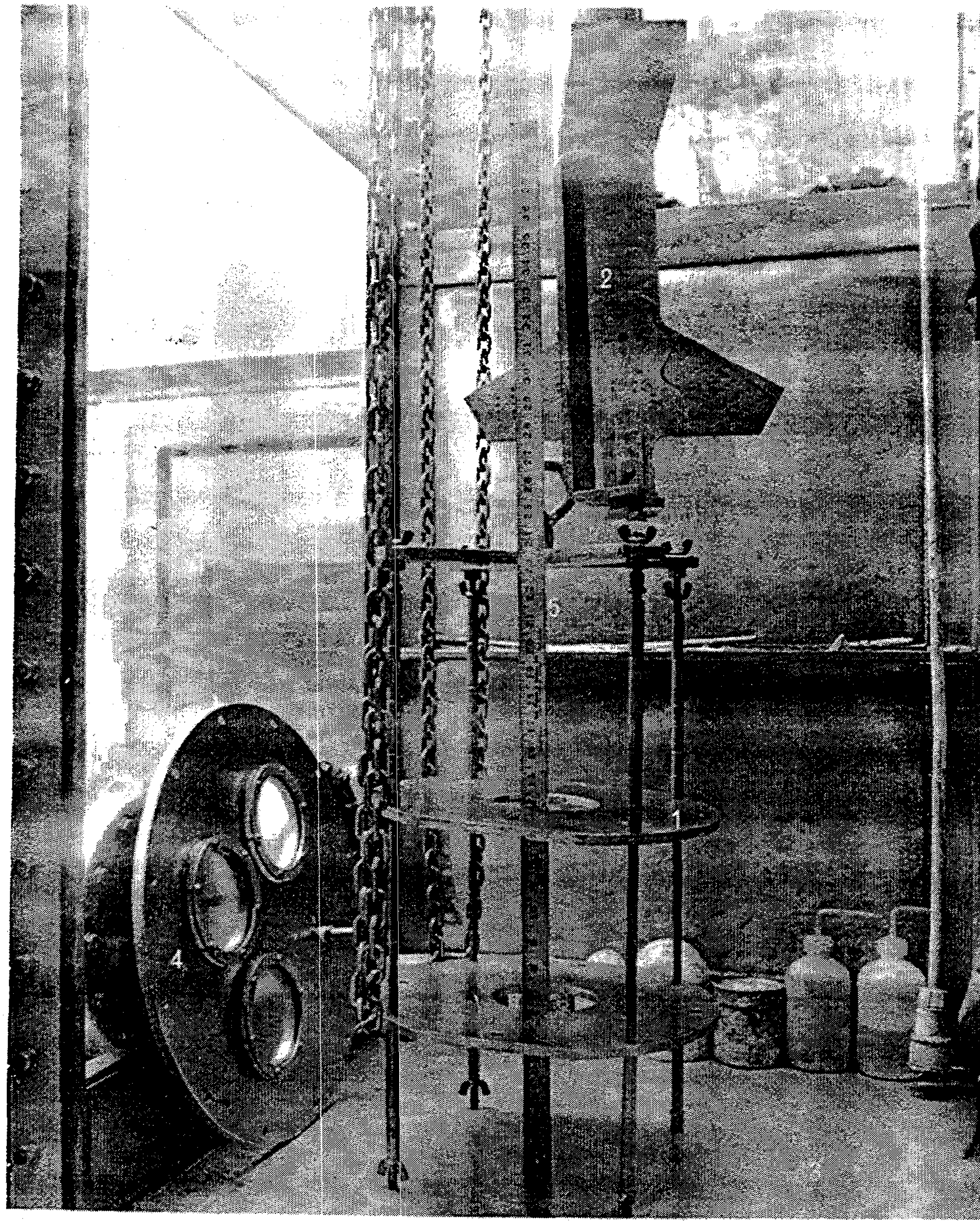
The completed assembly is mounted in an aluminum-holding fixture and placed in the inner system tank. The tank loading is done while the inner system is connected to the glove-box loading station as shown in Figure 1. The holding fixtures for spherical and hemispherical assemblies are shown in Figure 8. The hemispherical assemblies are always mounted with the plane face vertical. This ensures a uniform addition of reactivity as reflector liquid is added and allows meaningful measurements on partially reflected assemblies.

Once loaded and sealed, the inner system is moved to the assembly area and placed in the outer system. Liquid reflector is then added remotely from the facility control room. A background count is taken when the count-rate meter strip-chart trace shows a monotonic upward trend. This usually occurs when reflector liquid just touches the bottom of the assembly. Additional counts are taken when either the reflector liquid is at a level of experimental interest or the count rate has increased a certain factor over the rate at the start of the addition. After each addition, an inverse multiplication, with respect to the observed background, is either computed or read from the inverse multiplication meters. In this manner, a plot of reciprocal multiplication versus reflector liquid height is obtained. A typical curve for a critical measurement is given in Figure 9.

When the indicated system multiplication exceeds about 50, and it seems probable from the inverse multiplication curve shape that criticality will be achieved, no further counts are taken. As reactivity is added beyond this point, the strip-chart traces of the picoammeters and the power-level period meter are carefully monitored. If a sustained rise in these traces can be observed after a reactivity addition, the system is assumed to be supercritical. A positive period for the system is obtained and then small amounts of reactivity are subtracted until the assembly becomes subcritical. A negative period is read and the experiment is then scrammed.

The usual loading sequence for oil-reflected critical mass determinations is:

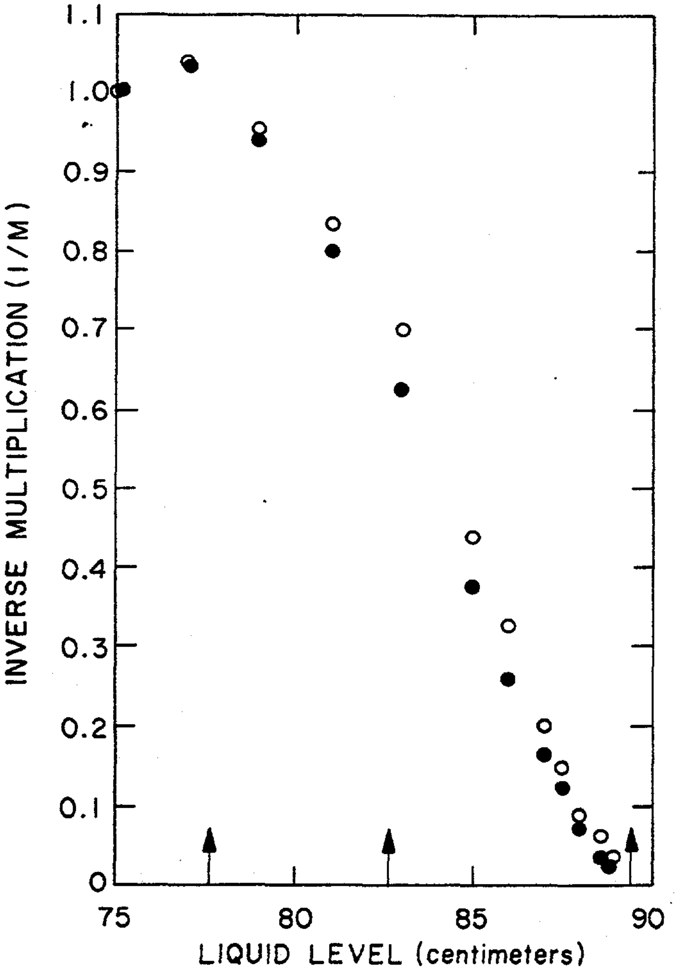
1. Assemble a load which is thought to be slightly subcritical, when fully reflected.



Legend

1. Mount for spherical assemblies.
2. Mount for hemispherical assemblies.
3. Hand-assembly area.
4. Lid for inner system.
5. Meter stick showing inch scale.

FIGURE 8. Plutonium Assembly Holding Fixtures.



Legend

Inverse Multiplication Meters

○ – Meter No. 1
● – Meter No. 2

NOTE: Arrows on x axis indicate bottom center and top of assembly.

FIGURE 9. Typical Inverse Multiplication Plot for a Reflected Critical Assembly.

2. Determine the multiplication of this load.
3. If it is subcritical, add a component; but if it is supercritical, subtract a component for the second assembly.
4. Find the multiplication of the second assembly.
5. If the second assembly becomes critical and the first does not, or vice-versa; the critical properties are assumed to be determined.
6. If the second assembly and the first assembly are both critical, components are removed until Condition 5 is achieved.
7. If both the first and second assembly are subcritical, this information is used to find the just-critical assembly, and this assembly is then tested.

The critical properties of partially reflected assemblies may be obtained by noting the inverse multiplication, at the partial reflection of interest, for each system used in the determination of a fully reflected critical mass. An inverse multiplication versus the number of parts plot is then made (as in the hand-assembly measurements) and the extrapolation to zero reciprocal multiplication used to find the critical system properties.

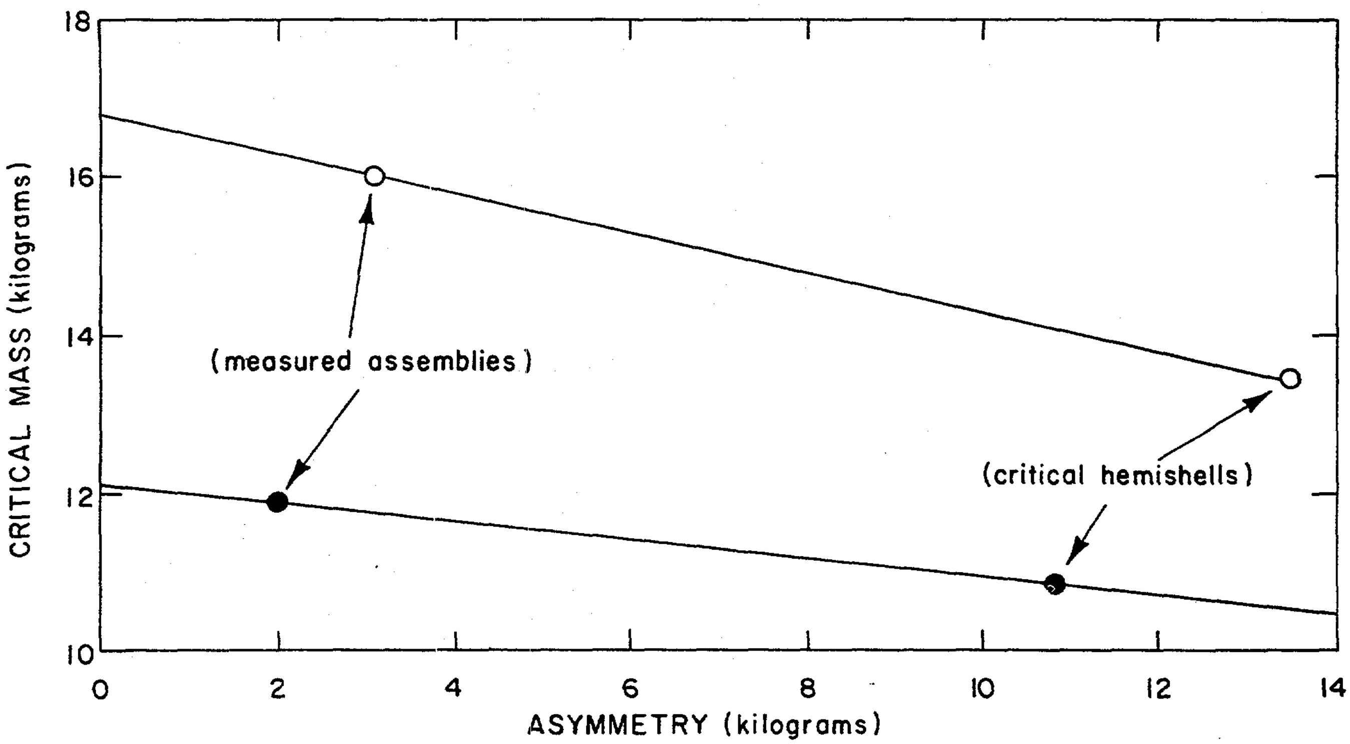
DATA ANALYSIS

Measurement Corrections:

ASYMMETRY OF SPHERICAL ASSEMBLIES – The critical properties of spherical assemblies were determined using asymmetric loads. Thus, the top half of the critical assembly has the same inner radius as the bottom half, but a different outer radius.

The critical mass of a symmetric assembly is obtained by plotting the mass difference between the top and bottom halves of two asymmetric critical assemblies versus the assembly critical mass (Figure 10). The line drawn through these two points is extrapolated to zero mass difference and this number is given as the *measured* spherical critical mass.

GREASE LOADING – The component hemishells of an assembly are coated with a lithium-silicon grease which fills the gaps between adjacent parts. This precludes uncontrolled leakage of reflector liquid into the assembly during an experiment. A series of Multigroup-Transport critical mass calculations were performed on spherical assemblies with and without full grease loading. The results of these calculations appear in Figure 11. The independent variable in Figure 11 is the critical assembly mean chord length, $\bar{l}$, which is defined as four times the assembly volume-to-surface area ratio. At equal $\bar{l}$ values, spherical and hemispherical assemblies are assumed to have equal correction factors. The curve labeled



Legend

○ – Inner radius, 7 centimeters.
● – Inner radius, 5 centimeters.

FIGURE 10. Effect of Asymmetry on Spherical Shell Critical Masses.

Reflected Assemblies gives the percentage critical mass change due to grease loading for fully reflected assemblies. The curve labeled *Bare Assemblies* gives the fractional $\bar{l}$ change due to grease for unreflected systems, but also includes a correction for glove-box reflection (discussed in the next section). The *reflected* curve shows that both positive and negative grease-loading corrections can occur for reflected assemblies. The negative corrections occur for nearly solid systems where the neutron-energy spectrum is such that the poisoning effect of the lithium in the grease amounts to less than the moderating effect of the hydrogen.

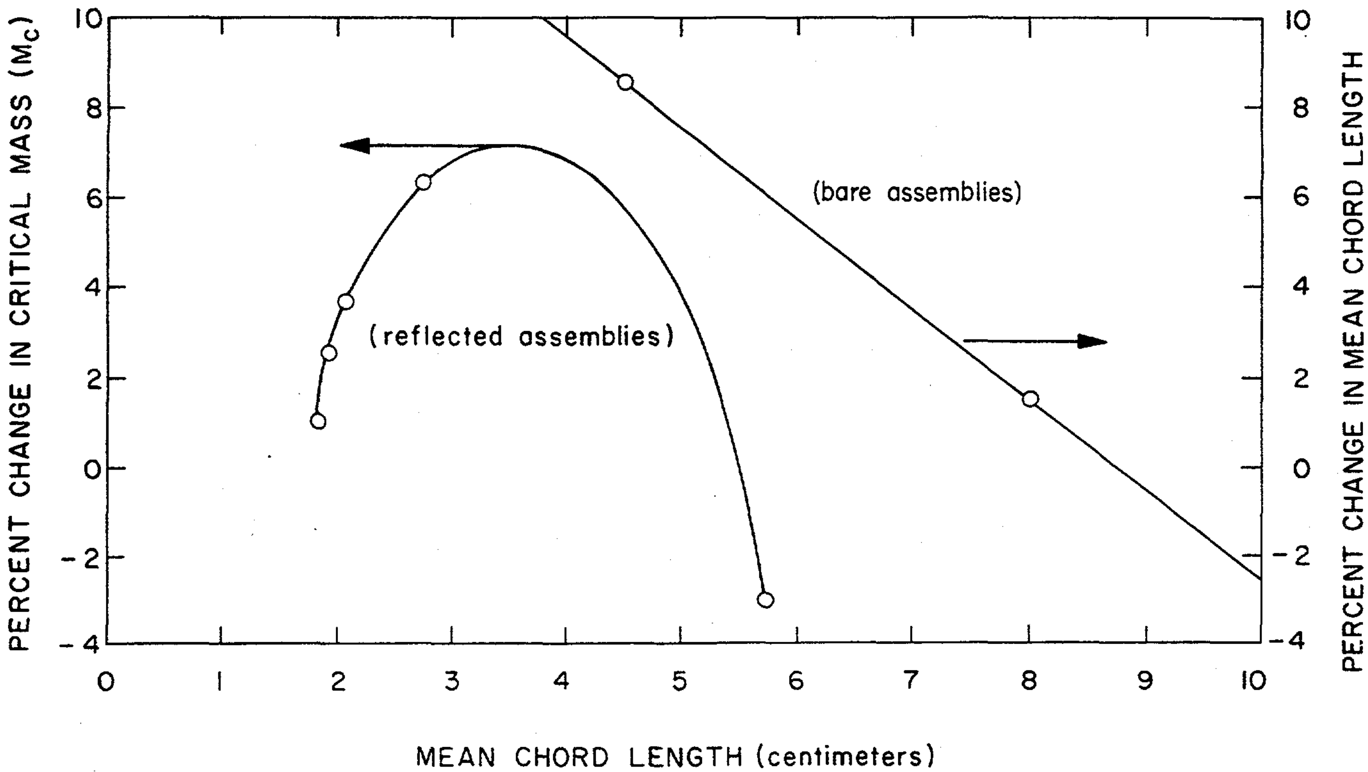
GLOVE-BOX REFLECTION – For hand-assembly measurements, a correction is needed for the ¼-inch thick, stainless steel walls of the glove box. This correction is included in the calculations shown in Figure 11 by surrounding the assemblies with a 0.15-inch thick layer of iron. The glove-box reflection and grease-loading effects are estimated to be of about the same magnitude.

The correction factors computed for bare assemblies are used to correct the measured values for hand-reflected assemblies. Similarly the correction factors for fully reflected assemblies are assumed to apply to half-reflected[3] assemblies.

Error Estimation:

The errors associated with the measured values are all quoted at a confidence level of one standard deviation. For subcritical measurements, the error estimates are based solely on the length and difficulty of the critical parameter extrapolation. For critical measurements, the mass and outer radius of the supercritical and subcritical assemblies must bracket the critical mass and outer radius. The estimated errors are found by taking 66 percent of the above ranges on mass and outer radii.

[3]Half-reflected assemblies are those for which the reflector liquid covers the bottom half of the assembly surface area.



Legend

○ – Computed points. Arrows show the ordinate associated with each curve.

$$\text{Percent Change in Critical Mass } (M_c) = \frac{M_c \text{ (grease)} - M_c \text{ (no grease)}}{M_c \text{ (no grease)}}$$

FIGURE 11. Effect of Grease Loading on Critical Masses.

RESULTS

The experimentally determined critical masses and dimensions, together with their associated errors, are given in Table II. The average assembly densities are found using the measured masses and dimensions of the hemishells given in Table I, Page 2. The last two columns of Table II give the critical masses and dimensions corrected for grease loading and glove-box reflection. The same error is associated with the corrected values as that given for the measured values. The corrected results are plotted versus inner shell radius in Figures 12 through 17. The values of masses and dimensions for large inner radii are obtained by extrapolation of the observed critical radial thicknesses to the computed infinite slab critical thicknesses.

In Figure 12, the critical masses of reflected hemispherical assemblies are shown. Along with the experimental results, critical-mass plots are given for plutonium assembly densities of 15.49 g/cm³ (delta-phase Pu) and 19.49 g/cm³ (alpha-phase Pu). These latter two plots are obtained from the experimental critical masses by a scaling procedure discussed in the next section. Figure 13 gives the experimental masses for reflected spherical shell assemblies, while mass plots for bare and half-reflected hemispherical shells appear in Figure 14. Figures 15 and 16 give critical-radial thickness

TABLE II. Properties of Critical Assemblies.

Reflection	Geometry	Inner Radius (centimeters)	Average Assembly Plutonium Density (grams per cubic centimeter)	Measured Outer Critical Radius (centimeters)	Measured Critical Mass (kilograms)	Mass Correction for Grease and/or Ambient Reflection (kilograms)	Corrected Outer Critical Radius (centimeters)	Corrected Critical Mass (kilograms)
Full	Hemispherical	0	18.15	5.75 ±0.03	7.25 ±0.10	−0.26	5.68 ±0.03	6.99 ±0.10
		2	18.14	5.92 ±0.06	7.57 ±0.23	−0.33	5.84 ±0.06	7.24 ±0.23
		3	18.15	6.26 ±0.06	8.26 ±0.25	−0.42	6.16 ±0.06	7.84 ±0.25
		4	18.22	6.75 ±0.06	9.30 ±0.30	−0.56	6.65 ±0.06	8.74 ±0.30
		5	18.21	7.42 ±0.06	10.82 ±0.33	−0.63	7.33 ±0.06	10.19 ±0.33
		6	18.23	8.08 ±0.06	11.94 ±0.39	−0.72	8.00 ±0.06	11.22 ±0.39
		7.5	18.30	9.25 ±0.06	14.17 ±0.56	−0.87	9.19 ±0.06	13.30 ±0.56
Half	Hemispherical	0	18.15	6.37 ±0.108	9.8 ±0.5	+0.11	6.39 ±0.108	9.91 ±0.5
		3	18.15	6.74 ±0.197	10.61 ±1.0	−0.18	6.70 ±0.197	10.43 ±1.0
		4	18.22	7.40 ±0.154	13.02 ±1.0	−0.24	7.37 ±0.154	12.78 ±1.0
		5	18.24	8.11 ±0.133	15.50 ±1.0	−0.33	8.07 ±0.133	15.17 ±1.0
		6	18.23	8.78 ±0.113	17.50 ±1.0	−0.45	8.74 ±0.113	17.05 ±1.0
		7.5	18.30	9.94 ±0.132	21.30 ±1.5	−0.61	9.89 ±0.132	20.69 ±1.5
None	Hemispherical	0	18.15	7.33 ±0.13	14.97 ±0.75	+2.25	7.68 ±0.13	17.22 ±0.75
		2	18.14	7.45 ±0.097	15.41 ±0.60	+2.32	7.80 ±0.097	17.73 ±0.60
		3	18.15	7.66 ±0.093	16.06 ±0.65	+2.45	8.01 ±0.093	18.51 ±0.65
		4	18.22	8.25 ±0.091	18.99 ±0.70	+2.67	8.58 ±0.091	21.66 ±0.70
		5	18.24	9.00 ±0.078	23.07 ±0.70	+2.88	9.30 ±0.078	25.95 ±0.70
		7.5	18.30	10.75 ±0.092	31.44 ±1.2	+3.54	11.04 ±0.092	34.98 ±1.2
Pair of Hands	Hemispherical	0	18.15	6.97 ±0.11	12.87 ±0.60	+1.93	7.30 ±0.11	14.80 ±0.60
		2	18.14	7.15 ±0.088	13.58 ±0.50	+2.05	7.49 ±0.088	15.63 ±0.50
		3	18.15	7.40 ±0.079	14.38 ±0.50	+2.19	7.74 ±0.079	16.57 ±0.50
		4	18.22	8.02 ±0.069	17.24 ±0.50	+2.43	8.34 ±0.069	19.67 ±0.50
		5	18.24	8.86 ±0.058	21.79 ±0.50	+2.72	9.16 ±0.058	24.51 ±0.50
Full	Spherical	5	18.13	6.58 ±0.041	12.10 ±0.40	−0.64	6.51 ±0.041	11.46 ±0.40
		7	18.18	8.27 ±0.042	16.82 ±0.65	−0.53	8.24 ±0.042	16.29 ±0.65

values for hemispherical and spherical assemblies, respectively. Figure 17 shows the critical masses for hemispherical assemblies plotted versus the fraction of the assembly surface which is fully reflected.

CALCULATIONAL METHODS

Monte Carlo Code:

The Rocky Flats modification of the Ø5R Computer Code[4] was used to compute the critical mass of the reflected hemisphere. The Ø5R Program is a neutron-tracking code which has the usual geometric flexibility, common to most Monte Carlo treatments. In addition, the Ø5R tracks neutrons according to importance weighting and has the option of extremely fine neutron-energy resolution. In the Ø5R calculations which were performed, the neutron-energy range of interest is divided into 1600 energy groups.

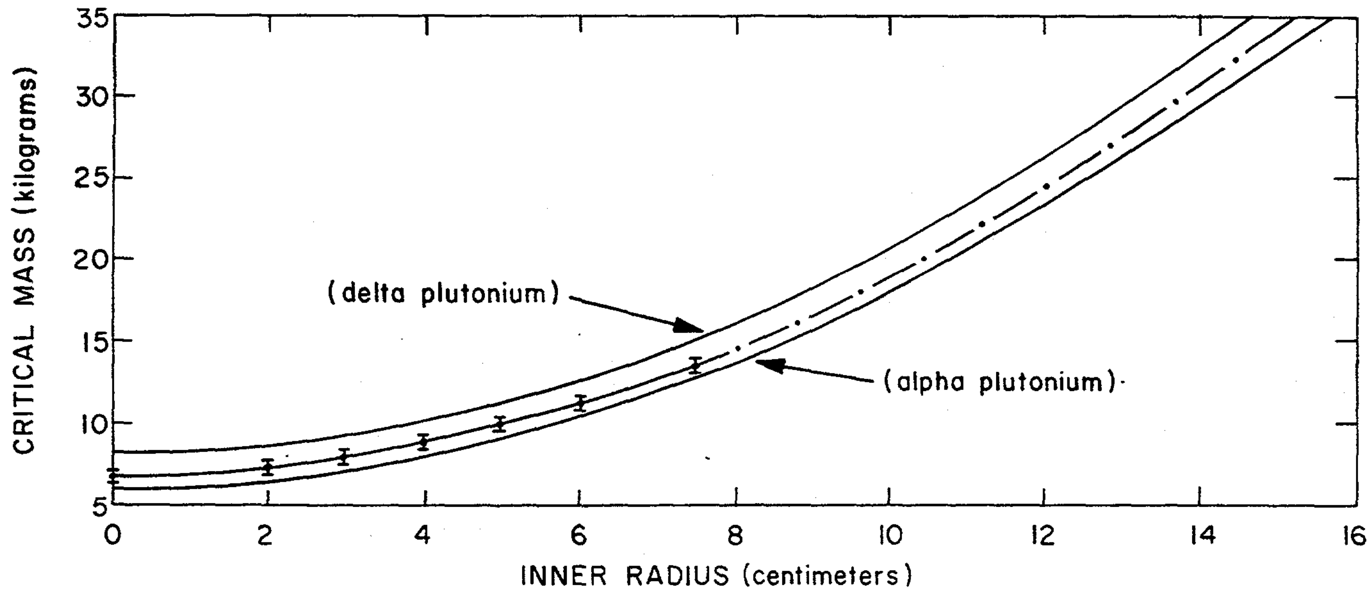
Multigroup Transport Theory:

The Rocky Flats version of the Computer Code DTF[5] is used for all one-dimensional[6] criticality calculations. The DTF Code is a difference equation solution of the Boltzmann transport equation for

[4] D. C. Irving, R. M. Free Stone, Jr., and F. B. K. Kam. *Ø5R, A General Purpose Monte Carlo Neutron Transport Code.* ORNL-3622. Union Carbide Corporation, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 1965.

[5] B. G. Carlson, W. J. Worlton, Walter Gruber, and Martin Shapiro. *DTF Users Manual.* UNC Physics-Mathematics 3321. United Nuclear Corporation, White Plains, New York. Volume I, November 1963; Volume II, May 1964.

[6] One dimensional systems are defined as three dimensional geometries, which may be specified by a single coordinate.



Legend

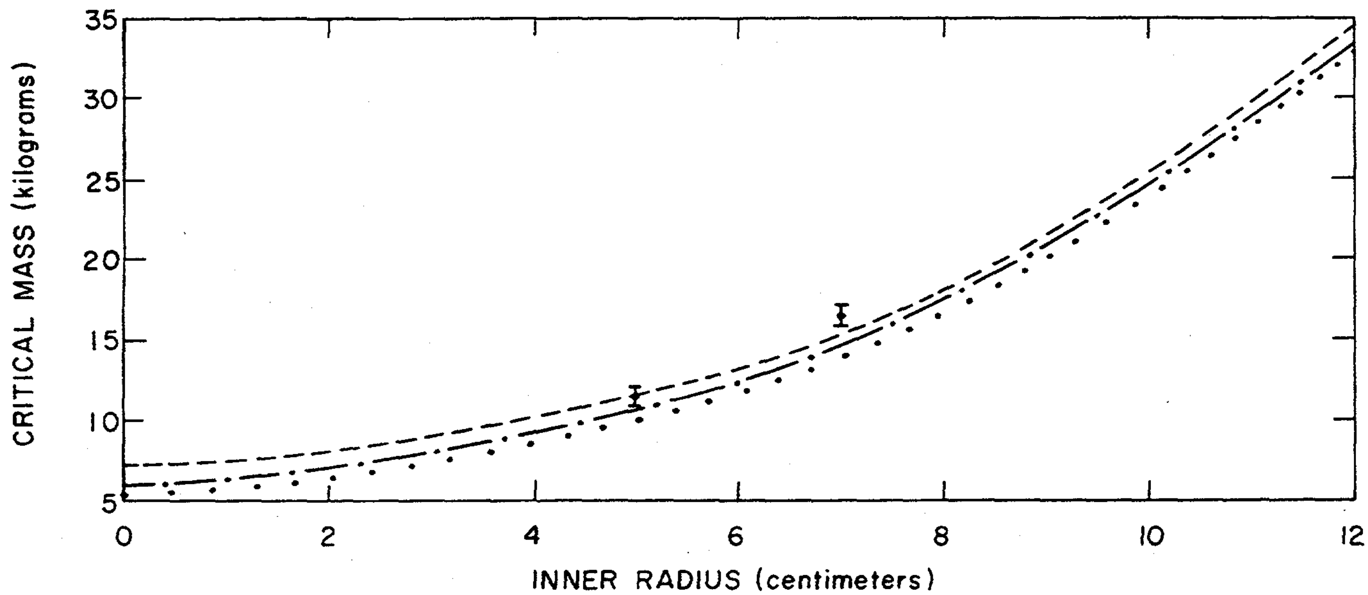
- I – Experimental points with error bars (corrected for grease loading).
- —·— – Obtained from Figure 15, $\bar{\rho}$ (rho) = 18.20 grams per cubic centimeter.
- ——— – Scaled from experimental curve:
  - Alpha plutonium, ρ = 19.49 grams per cubic centimeter.
  - Delta plutonium, ρ = 15.49 grams per cubic centimeter.

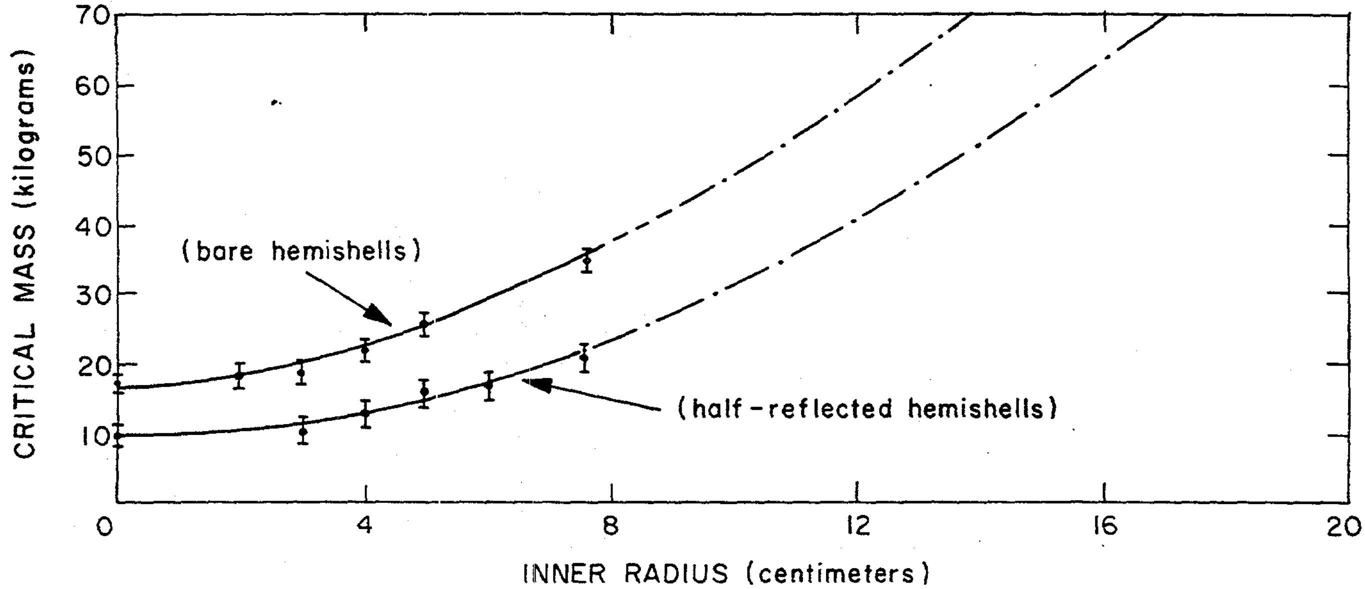
FIGURE 12. Critical Masses of Reflected Plutonium Hemishells.

FIGURE 13. Critical Masses of Reflected Plutonium Spherical Shells.

Legend

- I – Experimental values with error bars (corrected for grease loading).
- ······· – Alpha plutonium, ρ(rho) = 19.49 grams per cubic centimeter (computed).
- – – – – Delta plutonium, ρ = 15.78 grams per cubic centimeter (computed).
- —·— – Average assembly density, ρ = 18.14 grams per cubic centimeter (computed).





Legend

– – – – Estimated extrapolation.

—·— – Obtained from Figure 15, where $\bar{\rho}$ = 18.20 grams per cubic centimeter.

Ī – Experimental masses with error bars (corrected for grease loading and for ambient reflection).

FIGURE 14. Critical Masses of Partially Reflected Plutonium Hemishells.

FIGURE 15. Dimensions of Critical Plutonium Hemishells.

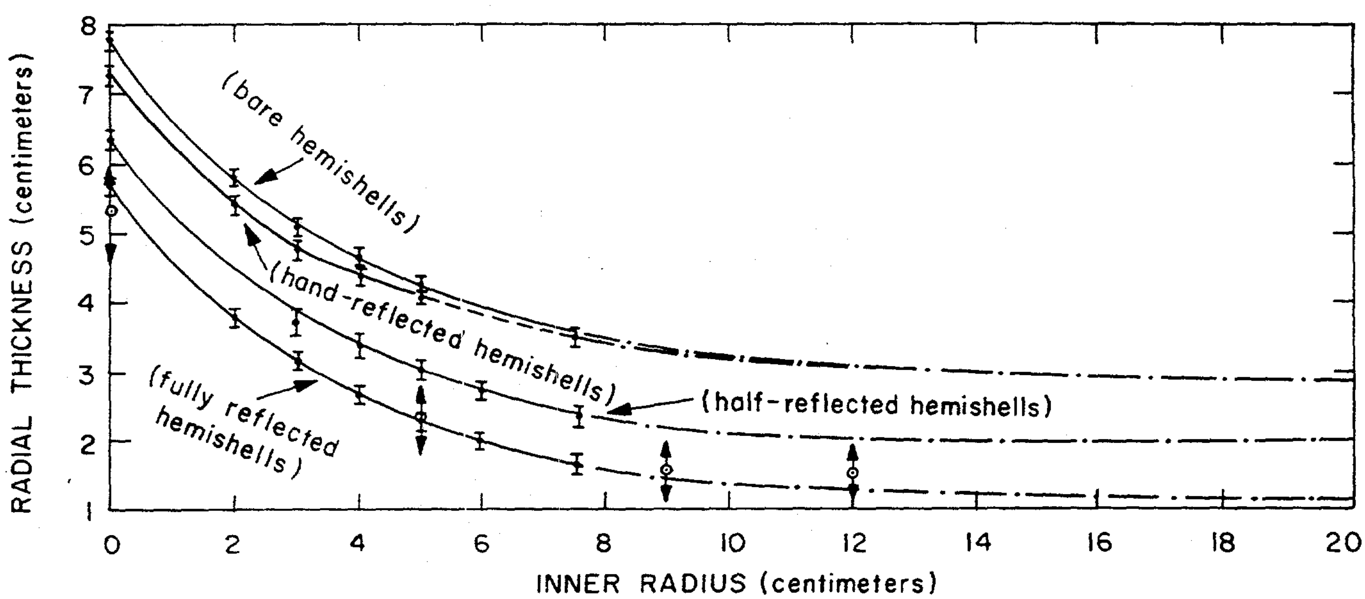
Legend

– Collision-Probability Method with limit bars.

– Experimental thicknesses with error bars (corrected for grease loading and for ambient reflection).

—·— – Extrapolation to slab critical thickness.

– – – – Estimated extrapolation.



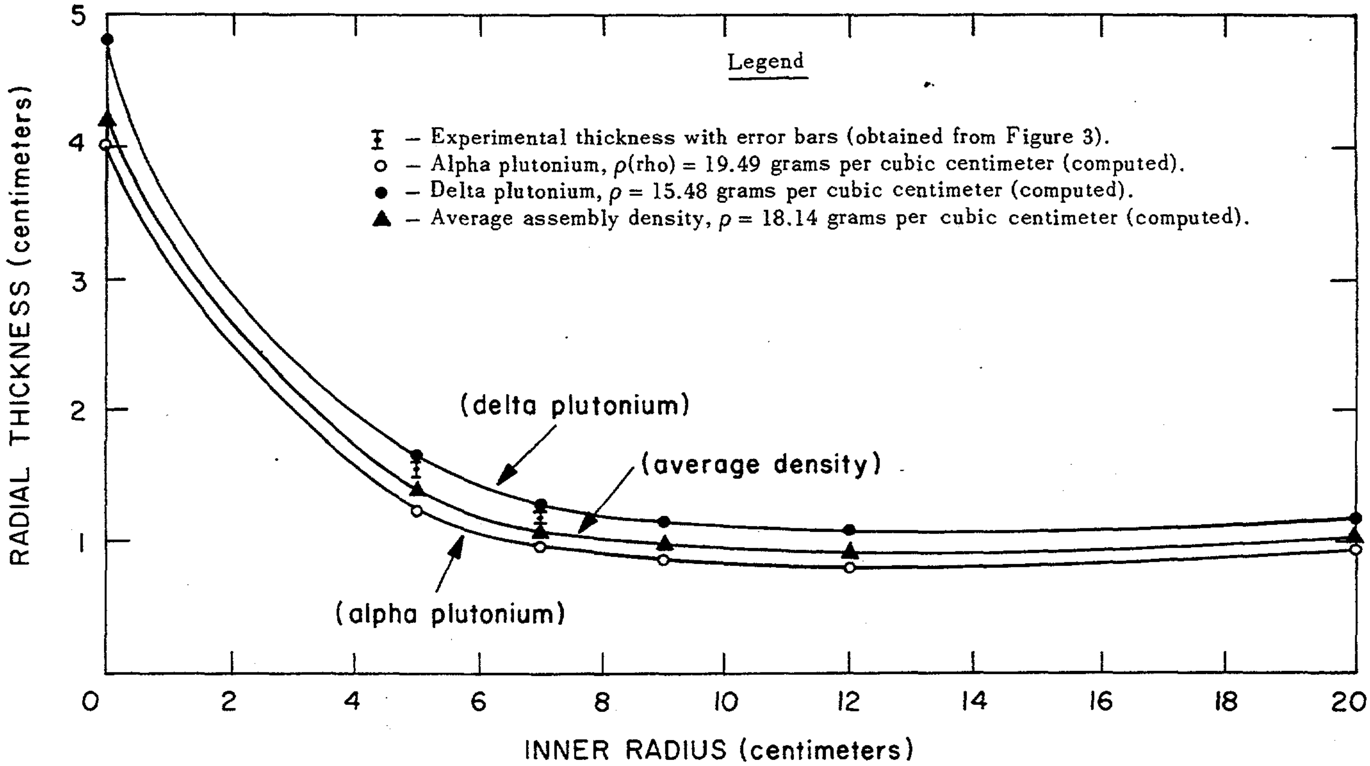
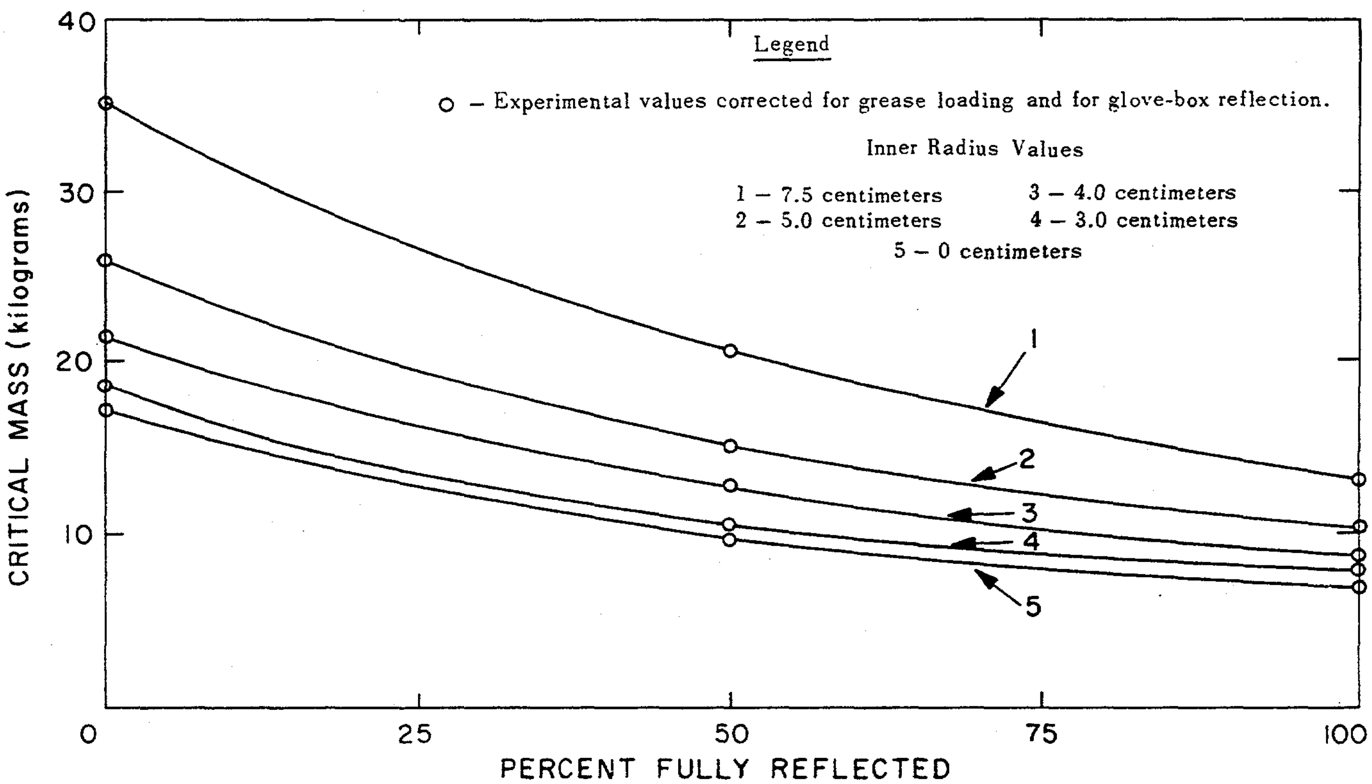


FIGURE 16. Dimensions of Critical Plutonium Full Shells.

FIGURE 17. Effect of Reflector on Hemishell Critical Masses.



neutrons, using the discrete ordinate S_n approximation.[7] In all the DTF calculations, four angular groups and sixteen energy groups are assumed. The spatial-flux variation is typically represented by ten spatial intervals per material region. The cross sections used in the calculations were those developed by Hansen and Roach.[8] The precision on the multiplication factor specified for all calculations is 10^{-4}. This physically implies for plutonium assemblies a reactivity uncertainty of about 4.4 *cents* in the calculation of the critical condition.

The critical masses and dimensions of oil-filled and oil-reflected plutonium spherical shells, computed with DTF, appear in Figures 13 and 16, respectively. Three densities are assumed in the calculations for the Pu metal: 19.49 g/cm³ (alpha-phase Pu), 18.14 g/cm³ (typical experimental assembly density), and 15.78 g/cm³ (delta-phase Pu). The changes in critical mass, for geometries which are identical except for the density difference, are used to obtain density exponents. These exponents are defined by Equation 1:

$$m = -\left(\frac{\rho_f}{M_c}\right)\left(\frac{dM_c}{d\rho_f}\right) \qquad (1)$$

ρ_f – fissile material density

M_c – critical mass

m – A plot of m, as defined by Equation 1, is given in Figure 18.

The independent variable in Figure 18 is the *mean chord length* of the fissile assembly.

Collision-Probability Method:

REFLECTED SYSTEMS – A method based on first-flight collision probabilities was used to compute the critical properties of fully reflected hemispherical-shell assemblies. The primary formula follows as Equation 2:

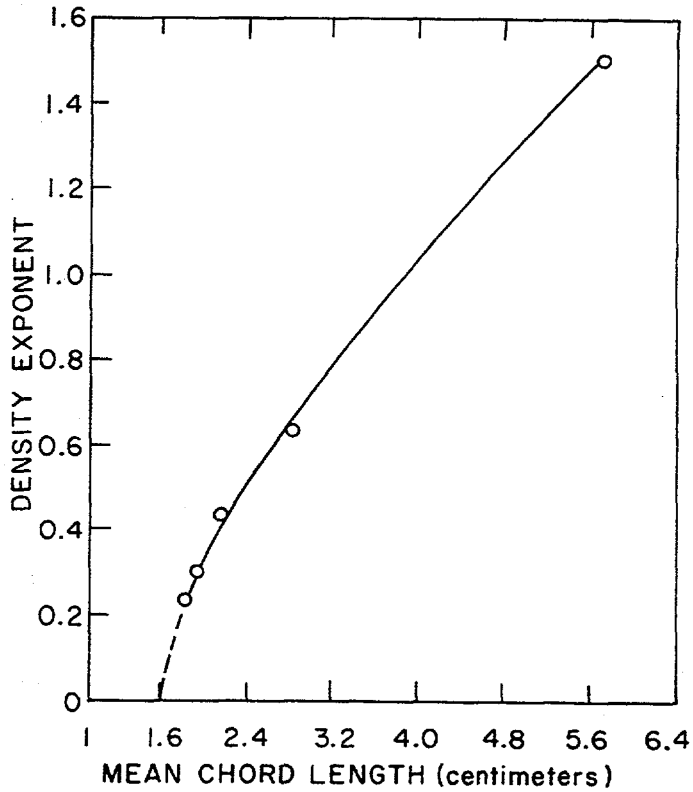


FIGURE 18. Exponents Used in Density-Scaling Calculations.

$$k_{eff} = \overline{K_m}\ \overline{P_c\ c} + [1 - (\overline{K_m}\,\overline{P_c})]\,\bar{\eta}\,\bar{\beta} \qquad (2)$$

k_{eff} – multiplication factor

P_c – first-flight collision probability for neutrons

c – number of secondary neutrons produced in a collision

η – number of fission neutrons produced per absorbed reflected neutron

β – albedo of the fissile material with respect to the oil reflector

K_m – correction factor to account for multiple neutron scattering

[7] M. Clark, Jr., and K. F. Hansen. *Numerical Methods of Reactor Analysis*. Chapter V. Academic Press, New York and London, England. 1964.

[8] G. E. Hansen and W. H. Roach. *Six and Sixteen Group Cross Sections for Fast and Intermediate Critical Assemblies*. LAMS-2543. University of California, Los Alamos Scientific Laboratory. Los Alamos, New Mexico. December 1960.

The bars in Equation 2 imply an average over the neutron-energy spectrum. Thus:

$$\overline{P_c} = \sum_{j=1}^{j_m} P_{c,j}\ \phi_{r,j} \tag{3}$$

$$\overline{P_c\ c} = \sum_{j=1}^{j_m} P_{c,j}\ c_j\ \phi_{r,j} \tag{4}$$

$$\overline{\eta} = \sum_{j_m+1}^{16} \eta_j\ \phi_{r,j} \tag{5}$$

$$\overline{\beta} = \sum_{j=1}^{j_m} J_j \Big/ \sum_{j_m+1}^{16} J_j \tag{6}$$

The j subscripts refer to neutron-energy groups. The value j_m refers to the lowest energy group for which neutron production exceeds neutron loss within the fissile assembly (excluding transport losses or gains). The $\phi_{r,j}$ (phi) notation is defined in terms of the neutron-scalar group fluxes ϕ_j by:

$$\phi_{r,j} = \frac{\phi_j}{\Sigma_j\ \phi_j} \tag{7}$$

The J_j in Equation 6 refers to the total neutron currents at the reflector-fissile material interface. The values of J_j are only readily available for one-dimensional geometries.

For more complex geometries, such as the hemispherical shells, $\overline{\beta}$ is found from Equation 8, where β (slab) is the albedo of an infinite slab of assembly material, A_F is the total assembly surface area, and A_R is the area of a *reflectivity surface*.

$$\overline{\beta} = \frac{\bar{\beta}\ (\text{slab})\ A_F}{A_R} \tag{8}$$

The reflectivity surface neutronically replaces the assembly reflector. It is defined as being an inwardly directed shell source of neutrons with appropriate geometry and dimensions. The current from the surface is assumed to be proportional to the cosine of the angle between the direction of neutron emission and the inward-directed surface normal. The cosine distribution is assumed since the emitted neutrons from the assembly must have approximately a cosine distribution. The area ratio in Equation 8 represents the fractional solid angle subtended by the assembly, with respect to a cosine-emitting and inwardly directed source located outside the assembly. For spherical assemblies, a concentric spherical reflectivity surface can be shown to satisfy Equation 8, and hence would be a suitable reflectivity-source geometry. For hemispherical shell assemblies, only limiting shapes can be specified for the reflectivity surfaces and these shapes are used together with Equation 8 to compute limiting $\overline{\beta}$ values. The models for reflector-surface calculation are given in Appendix A, Page 23. The procedure for obtaining critical-system properties using Equation 2 is given in Appendix B, Page 27.

UNREFLECTED SYSTEMS – The critical size of the bare hemisphere was computed using a modification of Equation 2. In the modified method, multiple scattering effects are fully accounted for and no attempt is made to correct for spatial-flux nonuniformity.[9]

COMPARISON BETWEEN CALCULATIONS AND EXPERIMENT

The comparison of the corrected experimental critical masses and dimensions with computed values is given in Table III and Figures 13 through 16. The differences between experiment and theory for the three calculational methods are discussed.

Collision-Probability Calculations:

In Figure 15, the results of the Collision-Probability Method calculations for reflected hemishell assemblies are shown. The calculations were done for inner-shell radii of 0, 5, 9, and 12 centimeters (cm). It is seen that the predicted critical thicknesses show less variation with inner radius than do the observed thicknesses. This trend is due primarily

[9] D. C. Hunt. "Collision-Probability Criticality Calculations." (Unpublished Report in Process.) 1968.

TABLE III. Comparison of Theory and Experiment.

Reflection	Geometry	Inner Radius (centimeters)	Corrected Outer Radius (centimeters)	Computed Outer Radius (centimeters)	Percent Difference	Corrected Critical Mass (kilograms)	Computed Critical Mass (kilograms)	Percent Difference	Computational Method
Full	Hemispherical	0	5.68	5.38	−5.3	6.99	5.92	−15.3	Collision Probability
Full	Hemispherical	5	7.33	7.34	+0.14	10.19	10.25	+ 0.58	Collision Probability
Full	Hemispherical	0	5.68	5.80	+2.1	6.99	7.41	+ 6.0	Monte Carlo
None	Hemispherical	0	7.68	7.84	+2.04	17.22	18.32	+ 6.37	Collision Probability
Full	Spherical	5	6.51	6.40	−1.72	11.46	10.35	−10.72	Multigroup Transport
Full	Spherical	7	8.24	8.11	−1.60	16.29	14.32	−13.76	Multigroup Transport

to the linear dependence on mean chord length assumed for the collision-probability parameters used in the calculations (see Figure 19). In the limit of large inner radii, the predicted critical thickness must approach the computed (by DTF) critical thickness. This limit occurs since the multiple-scattering correction factor K_m is normalized to give $k_{eff} = 1$ for the infinite slab. The smaller variation of the predicted critical thicknesses causes the experimental curve and the computed values to coincide at an inner radius of 4.5 cm (Figure 15). Thus, close agreement with the experiment is obtained with the 5-cm radius point.

The Collision-Probability Method calculation for the bare hemisphere did not involve any normalization techniques, but did assume (as Equation 2 also assumes) a uniform spatial neutron distribution throughout the assembly. This forces too many neutrons to be near the assembly surface, overestimating the neutron-leakage probability. The method hence somewhat overpredicts the critical mass.

Monte Carlo Method:

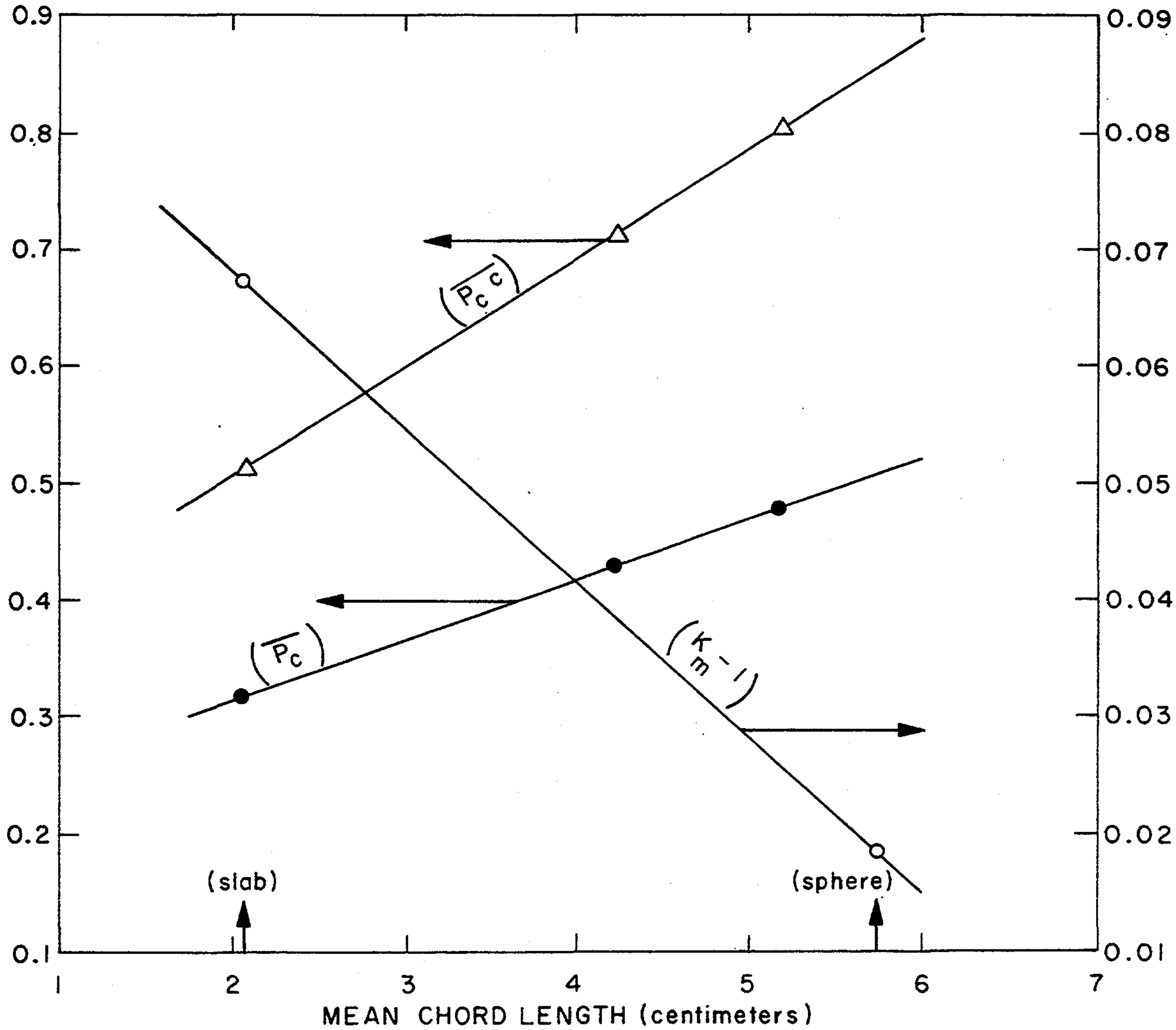
One critical system (the reflected hemisphere) was computed using the 05R Code. In these calculations, 10 batches of neutrons, each containing 200 neutrons, were processed. The standard deviation of the computed multiplication factors was 0.017. Due to the high level of accuracy and precision associated with this method. much of the theory-experiment discrepancy (6 percent on the critical mass) is attributed to experimental uncertainty.

Multigroup Transport Method:

The critical masses and dimensions of two critical assemblies were compared with the results of DTF transport calculations. The geometries considered were fully reflected spherical-shell assemblies, having inner radii of 5 and 7 cm. The comparative results, given in Table III, show that the Transport Method significantly underestimates the critical properties of these systems. The explanation for most of the difference is thought to be associated with the computed values. The calculations had several deficiencies. First, the spatial mesh in the reflector is too coarse; and secondly the plutonium cross sections used in the resonance region are not sufficiently energy self-shielded. These two effects have been investigated by Coonfield and Hunt.[10,11] The authors conclude that in reflected metal-uranium assemblies (similar to the spherical plutonium shells considered in this report), the agreement between calculations and experimental results can be greatly improved by proper handling of these two factors. In addition, the inclusion of higher-order anisotropy in the transference function expansion and of more angular groups in the representation of the directional flux would increase the accuracy of the calculations.

[10] D. C. Coonfield and D. C. Hunt. *The Effect of Spatial Resolution on Critical Mass Calculations*. RFP-1133. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. May 31, 1968.

[11] D. C. Coonfield and D. C. Hunt. "Energy Self-Shielding in Reflected Metal Critical System." (Unpublished Report in Process.) 1968.



Legend

O – Computed points. Arrows show ordinates associated with each curve.

FIGURE 19. Parameters Used in Collision-Probability Calculations.

DISCUSSION AND CONCLUSIONS

Collision-Probability Method:

REFLECTED ASSEMBLIES – Collision-probability calculations on reflected assemblies are not self-contained since they rely on the results of transport calculations for evaluating constants. They are useful however in estimating the critical properties of reflected systems (such as cylindrical or cuboidal shells), which cannot be directly evaluated by the usually available transport methods. The critical properties of such systems may be found with Monte Carlo methods but such calculations are expensive and time-consuming, whereas transport computations are relatively simple to perform. Also, collision-probability calculations, using the maximum reflectivity surface model (see Appendix A) are useful from a nuclear safety standpoint as they provide conservative critical parameter estimates.

UNREFLECTED ASSEMBLIES – Collision-Probability calculations on bare assemblies[12] are completely self-contained. The method is however limited to assemblies whose mean chord length is less than about two-transport mean free paths and in which the scattering probability is much less than one. These restrictions arise from the uniform neutron-density approximation and cause the method to slightly overestimate critical dimensions.

Spherical Assembly Measurements:

The critical masses of the two spherical shell assemblies which were measured are important as they permit normalization of transport-theory calculations to experimental results. The hemishell-assembly measurements are not useful for this purpose as the DTF Transport Theory Code handles only one-dimensional assemblies. As previously mentioned, most of the observed difference between the DTF results and the measured values is thought to be due to spatial mesh and energy self-shielding problems in the calculations.

Density Scaling Results:

The critical mass values for alpha- and delta-phase reflected plutonium hemishell assemblies are given in Figure 12. These values were obtained from the scaling procedure mentioned earlier using the density-exponent values from Figure 18. The interesting feature of Figure 12 is that the scaling procedure gives critical mass differences, with density variation, which are almost independent of the assembly inner radius. Thus, each delta-plutonium assembly is about 1.35 kilograms (kg) heavier than the same inner-radius experimental assembly while each alpha-plutonium assembly is about 0.5 kg lighter.

Critical Mass versus Percent of Full Reflection:

The curves of Figure 17 (Nos. 1 through 5) showing the variation of critical mass with the fraction of the assembly surface which is fully reflected, deserve some comment. These curves are all concave upward, indicating that the initial fraction of the surface which is infinitely reflected is more important than later fractions. This effect is due to the coupling, via reflected neutrons, between the bare and reflected fractions of the assembly. Thus the reflected neutrons cause the *fast neutron* (neutron energies greater than 1-kiloelectron volt) flux peaks to be shifted toward the reflected fraction of the assembly volume. This causes a decreased leakage of fast neutrons from the unreflected surface and a resultant increase in fission-neutron production in the unreflected volume.

Hand-Reflected Assemblies:

Hand-reflection data are important in evaluating criticality problems where manipulation of fissile assemblies is necessary. It is seen from Table II, Page 14, that a pair of hands may decrease the bare critical mass by as much as 14 percent (hemisphere) or as little as 4 percent (5-cm, inner radius hemishell). From Figure 17 the equivalence may be obtained between the percent of infinite assembly reflection and the effect of a pair of hands. For the hemisphere, a pair of hands is worth 12.5 percent full reflection, while for the 5-cm, inner radius hemishell it is worth 5.3 percent.

Curve Fits to Observed Data:

The observed critical-assembly radial thickness, Δr, (see Figure 15) may be represented by the empirical relation in Equation 9, where r_i is the assembly inner radius and A, B, and C are constants:

$$\Delta r = A + B\, e^{cr_i} \qquad (9)$$

The constant A is the critical thickness of the infinite slab while B is the radius of the critical hemisphere minus the infinite slab thickness. The values of C for unreflected, half-reflected, and fully reflected hemishells are $-0.209\ cm^{-1}$, $-0.278\ cm^{-1}$, and $-0.278\ cm^{-1}$, respectively. The constant C plays the role of a macroscopic removal cross section; i.e., it represents the probability of neutrons emitted from the concave surface of the hemishell *not* returning to the hemishell.

[12] D. C. Hunt. *Op. cit.*

APPENDIX A. Calculation of Reflector Surface Areas.

Minimum Reflectivity:

The generating curves for the reflector surfaces are sketched as (a), (b), and (c) in Figure 1-A. The formulas for computing the reflector surface areas follow:

$$A = 2\pi (r_o + \Delta r_{out})^2 + \pi (r_o + \Delta r_{out}) [h^2 + (r_o + \Delta r_{out})^2]^{1/2}; \quad r_i = 0 \qquad \text{(A-1)}$$

$$A = 2\pi (r_3^2 + r_1^2) + \pi (r_3 + r_2) [h'^2 + (r_3 - r_2)^2]^{1/2}; \quad \Delta r_{in} < r_i \qquad \text{(A-2)}$$

$$r_1 = r_i - \Delta r_{in}$$

$$r_3 = r_o + \Delta r_{out}$$

$$r_2 = (r_3 + r_1) / 2$$

$$h' = h (\Delta r_{out} + \Delta r_{in} + \delta_r) / 2r_3, \text{ and}$$

$$A = 2\pi r_3^2 + \pi (r_3 + r_2) [h'^2 + (r_3 - r_2)^2]^{1/2}; \quad \Delta r_{in} \geq r_i \qquad \text{(A-3)}$$

$$r_3 = r_o + \Delta r_{out} \qquad h'' = h' - r_1$$

$$r_2 = r_3 r_i / 2 \Delta r_{in}$$

$$r_1 = \Delta r_{in} - r_i$$

$$h' = h (1 - r_2 / r_3)$$

The symbols used in Equations A-1, A-2, and A-3 are noted in Figures 1-A (a), (b), and (c).

Maximum Reflectivity:

The generating curves for the maximum reflectivity surfaces are shown in Figures 2-A (a), (b), and (c). The corresponding reflector surface area formulas are:

$$A = 2\pi (r_o + \Delta r_{out})^2 (1 - \sin \theta_o) + 2\pi r_o Z_o + \pi r_o (r_o^2 + h^2)^{1/2} \qquad \text{(A-4)}$$

$$r_i = 0$$

$$\cos \theta_o = r_o / (r_o + \Delta r_{out})$$

$$Z_o = \Delta r_{out} (1 + 2r_o / \Delta r_{out})^{1/2}$$

$$A = 2\pi (r_o + \Delta r_{out})^2 (1 - \sin \theta_o) + 2\pi r_i^2 + 2\pi r_o Z_o + \pi (r_o + r_2) [h'^2 + (r_o - r_2)^2]^{1/2} + \pi (r_2 + r_1) [h'^2 + (r_2 - r_1)^2]^{1/2} \qquad \text{(A-5)}$$

$$\Delta r_{in} < r_i$$

$$r_2 = (r_1 + r_o) / 2$$

$$r_1 = r_i - \Delta r_{in}$$

$$h' = (r_o - r_1) h / 2r_o$$

Z_o and $\cos \theta_o$ as in (A-4), and

$$A = 2\pi (r_o + \Delta r_{out})^2 (1 - \sin \theta_o) + 2\pi r_o Z_o + \pi (r_o + r_2) [h'^2 + (r_o - r_2)^2]^{1/2} + \pi r_2 (h''^2 + r_2^2)^{1/2}; \quad \Delta r_{in} \geq r_i \qquad \text{(A-6)}$$

$$r_2 = r_o r_i / 2 \Delta r_{in}$$

$$r_1 = \Delta r_{in} - r_i$$

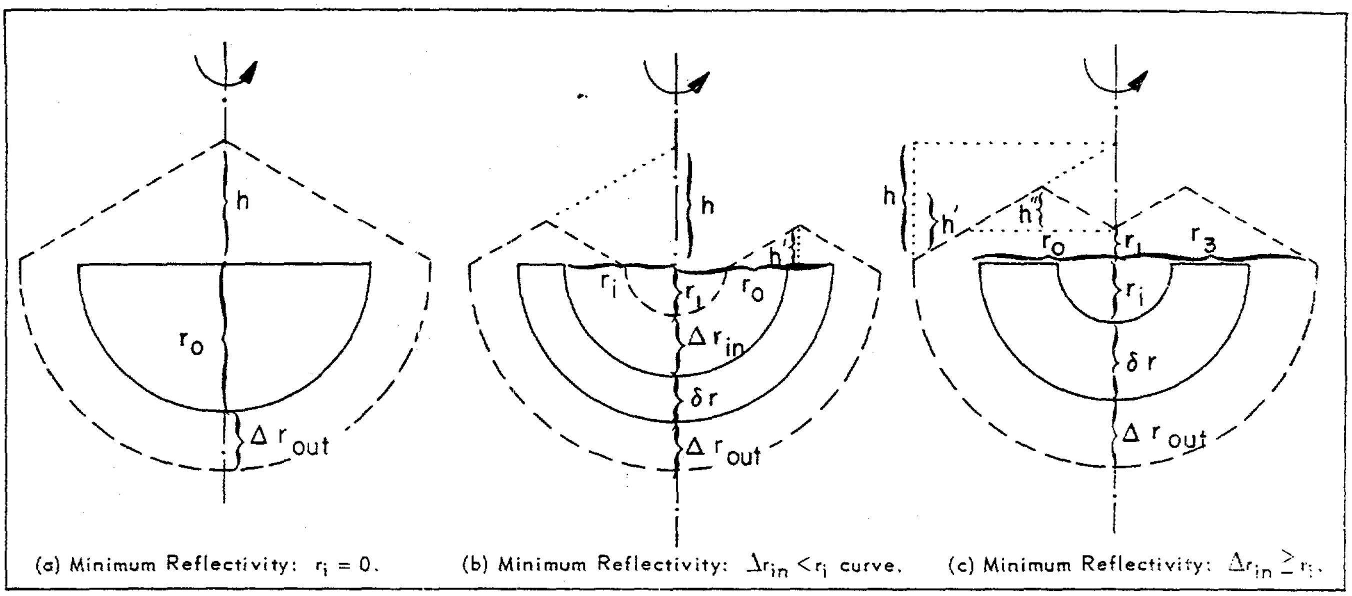
$$h' = h [1 - r_2 / r_o]$$

$$h'' = h' - r_1$$

$\cos \theta_o$ and Z_o as in (A-4)

The symbols for the above equations are shown in Figures 2-A (a), (b), and (c).

The values of Δr_{in}, Δr_{out}, and h are estimated from DTF calculations on reflected spherical shells and on reflected slabs. A plot of these values versus the surface radius of curvature is shown in Figure 3-A.



Legend

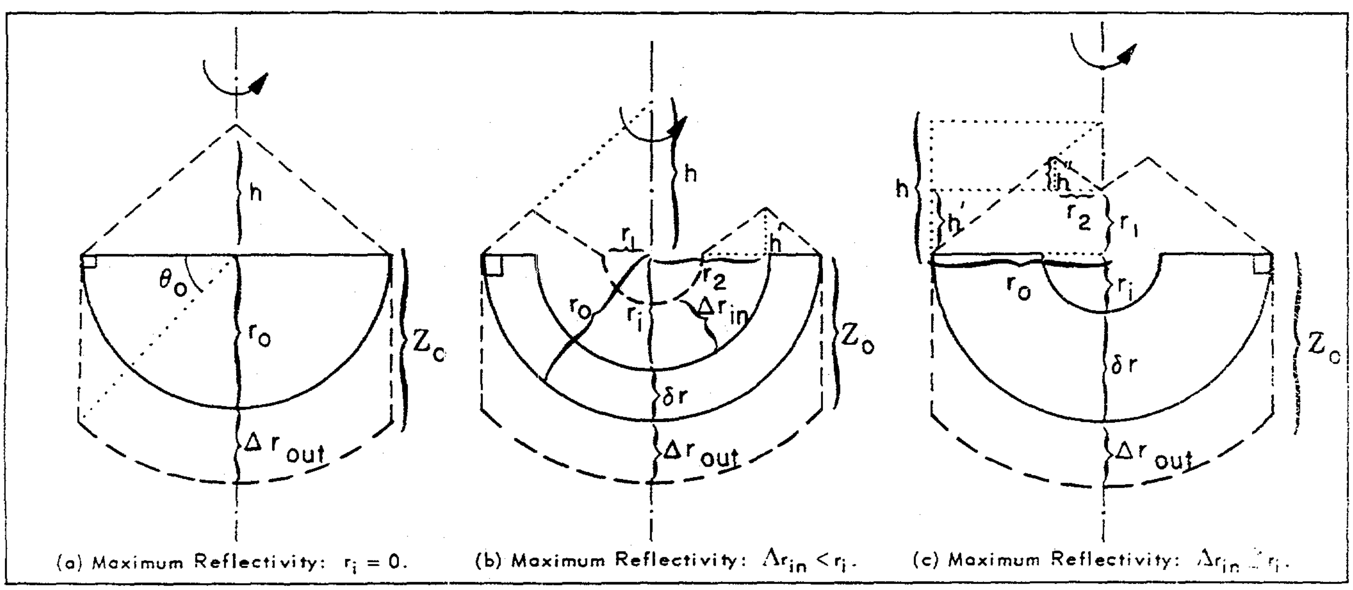
- · · · · · – Construction lines.
- —·— – Generating axis.
- – – – – – Reflector surface generating curve.
- ——— – Assembly generating curve.

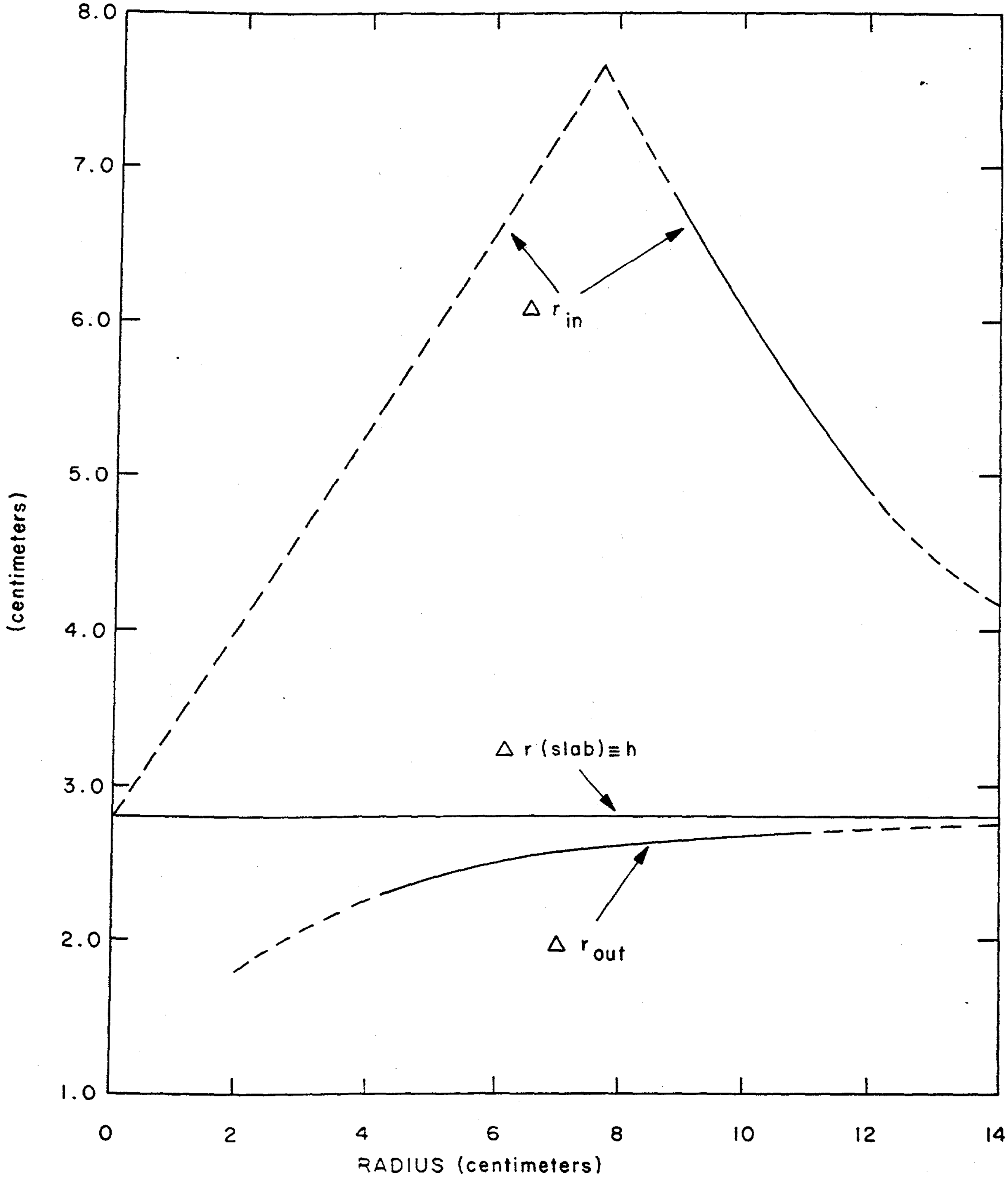
FIGURE 1-A. Minimum Albedo Reflector Surfaces: (a), (b), and (c).

FIGURE 2-A. Maximum Albedo Reflector Surfaces: (a), (b), and (c).

Legend

- · · · · · – Construction lines.
- —·— – Generating axis.
- – – – – – Reflector surface generating curve.
- ——— – Assembly generating curve.





Legend

– – – – – – Extrapolated values.

FIGURE 3-4 Parameters for Reflector Surface Specifications.

APPENDIX B. Collision-Probability Calculation of Critical Dimensions.

The procedure for obtaining critical hemishell properties with Equation 2, Page 18 is as follows. First, DTF-criticality calculations are done on a reflected plutonium sphere and a reflected slab. The fissile and reflector materials in the calculations have the same composition as a typical test assembly. These calculations give the values, $\phi_{r,j}$ for two significantly different geometries (see Equation 7, Page 19). The $\phi_{r,j}$ values do not vary significantly between the two geometries and so the ϕ_{rj} spectrum for the sphere is selected as *standard* and is used in all calculations. Equation 5, Page 19, is then used to find $\bar{\eta}$. A value of 1.892 is obtained. The value of β for the slab and sphere are now found from Equation 6, Page 19. The values of $\overline{P_c c}$ and $\overline{P_c}$ are calculated for the sphere and slab using Equations 3 and 4, Page 19. The $P_{c,j}$ values are obtained from Case, *et al.*[B-1] The correction factor K_m is then found using Equation 2 for the critical slab and sphere. These two values of K_m are used to form the plot of K_m versus mean chord length shown in Figure 19, Page 21. The calculational method from this point follows:

1. Specify a hemisphere and a reflector surface model. Compute $\bar{\beta}$ from Equation 8, Page 19, and the Appendix-A equations. Then use hemispherical values of $P_{c,j}$ and K_m values from Figure 19 to find k_{eff} from Equation 2.

[B-1]K. M. Case, *et al.* *Op. cit.* 1953.

2. Repeat the computation at several radii until enough points are obtained to form a curve of k_{eff} versus radius. From this curve find the critical ($k_{eff} = 1$) hemisphere radius. Note the $\overline{P_c}$ and $\overline{P_c c}$ values for $k_{eff} = 1$.

3. Repeat Steps 1 and 2 for the second reflector surface model.

4. Recall the values of $\overline{P_c}$ and $\overline{P_c c}$ for the reflected slab. Use these values and the values obtained from Steps 1, 2, and 3 (for hemispheres) to plot $\overline{P_c}$ and $\overline{P_c c}$ versus mean chord length. These plots are shown in Figure 19.

5. Compute a hemishell critical thickness from Equation 2. This calculation proceeds as in Steps 1 and 2 and uses the Figure 19 plots of $\overline{P_c c}$ and $\overline{P_c}$.

6. Repeat Step 5 for the other reflector surface model. This gives the limiting values for the hemishell critical thicknesses.

The quoted value of the hemishell critical thickness is now defined as the thickness which gives a critical mass half way between the limiting critical mass values.