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K-343
Special Hazards

CRITICAL MASS STUDIES

PART III

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CRITICAL MASS STUDIES PART III

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This paper reports a series of experiments performed in the Carbide and Carbon Research Laboratories, K-25 Plant, during 1948. It is the result of work by:

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Title: Critical Mass Studies
Part III

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A B S T R A C T

The conditions under which U-235, contained in aqueous solutions of uranyl fluoride, become critical in right cylindrical aluminum and stainless steel reactors, have been examined. The uranium-235 content of the uranium was 93.4%. Values of the critical masses of U-235 and of the corresponding heights of the solution in the reactors have been measured as functions of the chemical concentration of the fuel and the diameter of the reactors. Concentrations ranged from 2.5 to 43% U-235 by weight, corresponding to hydrogen to U-235 atomic ratios from about 1000 to 25, and reactor diameters varied from $5\frac{1}{2}$ inches to 20 inches. It was possible to enclose the reactors in water in order to observe the effect of adding a water reflector. A few data were obtained with cadmium sheet placed between the reactor and the reflector water.

The diameter of the largest reactor which could not be made critical under the most favorable conditions of these experiments was greater than $5\frac{1}{2}$ inches but less than 6 inches. Omission of the water reflector increased this diameter to 8 inches. The minimum critical mass measured was 893 gm, contained in a reactor 25.4 cm (10 inches) in diameter and 22.4 cm high with a chemical concentration corresponding to a hydrogen to U-235 atomic ratio of 329.

The absence of the water reflector increased the critical mass by about 100%; interposing cadmium between the reactor and the reflector water increased the critical mass by about 50%.

The results obtained are tabulated in the Appendix and are shown in a number of graphs. No attempt at correlation with theory is made in this report.

CRITICAL MASS STUDIES PART III

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CRITICAL MASS STUDIES, PART III.

I. INTRODUCTION

The first two series of critical mass experiments performed in these laboratories, on assemblies of one-inch UF_6 mock-up cubes interspersed among varying numbers of polyethylene cubes, were reported earlier.[1,2] The present report describes a third series of critical mass experiments, performed with aqueous solutions of uranyl fluoride of 93.4% U-235 isotopic content. Right circular cylinders of different diameters and lengths were used as reaction vessels. The experiments were intended to supply information on quantities of U-235 in solutions which would become critical under varying geometry, water content and reflector conditions. The maximum sized pipe which, when filled with a solution of a uranium salt, can not be made critical under the most favorable conditions could be ascertained from these experiments.

During the experimental program it has not been possible to consider adequately the interpretation of the data in terms of existing reactor theories. The limited amount of work which has been done points to the necessity for a more extensive investigation.

II. EXPERIMENTAL MATERIALS

A. Uranium Solution

An aqueous solution of uranyl fluoride, UO_2F_2, was chosen as the active material in these experiments because of these favorable properties:

1. Low nuclear absorption cross sections for thermal neutrons[3] of the associated atoms, oxygen ($< 0.001 \times 10^{-24}$ cm^2) and fluorine (0.01 x 10^{-24} cm^2). The relatively higher absorption cross sections of such atoms as chlorine (40 x 10^{-24} cm^2), sulfur (0.4 x 10^{-24} cm^2), nitrogen (1.7 x 10^{-24} cm^2), etc. precluded the use of the chloride, sulfate, nitrate, etc.

2. High solubility in water, allowing achievement of low hydro-

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1. Beck, C. K., D. Callihan, R. L. Murray, "Critical Mass Studies, Part I", Carbide and Carbon Chemicals Corporation, K-25 Plant, A-3691, Feb. 11, 1947.

2. Beck, C. K., D. Callihan, R. L. Murray, "Critical Mass Studies, Part II", Carbide and Carbon Chemicals Corporation, K-25 Plant, K-126, Jan. 23, 1948

3. Way, K. and G. Haines, "Thermal Neutron Cross Sections for Elements and Isotopes", AECD-2138, Feb. 29, 1948.

gen to uranium atomic ratios. A water solution of UO_2F_2 containing 43% U-235 by weight was prepared which corresponds to a hydrogen to U-235 atomic ratio (H:U-235) of 24.

3. Sufficiently low corrosion rates for readily available construction materials. Four types of stainless steel were corroded less than 0.7 mg/cm^2 day by uranyl fluoride solutions.[4] An accepted rate is 1.0 mg/cm^2 day.

Approximately 13.5 kg of uranium were converted into uranyl fluoride of 99.8% chemical purity. The isotopic content of this uranium was 93.4% U-235, 1.1% U-234 and 5.5% U-238. The following procedure was employed in this conversion: Uranium peroxide was converted to uranium trioxide by heating to 300°C in an atmosphere of oxygen for one hour. A mixture of anhydrous hydrogen fluoride and oxygen was then passed through the furnace for two hours at (300°C). The chamber was flushed with dry nitrogen and cooled. The reactions are:

$$2(UO_4 \cdot 4\,H_2O) \rightarrow 2\,UO_3 + O_2 + 8\,H_2O$$

$$UO_3 + H_2F_2 \rightarrow UO_2F_2 + H_2O$$

The addition of oxygen prevents the reduction or further fluorination of the compound, thus eliminating possible side reactions giving such products as U_3O_8 and UF_4.

Spectrographic analyses of the uranyl fluoride solution were made from time to time during the experiments. The maximum impurities found at the end of a series of experiments extending over eighteen months and the thermal neutron absorption cross section for the respective elements are listed in Table 4 of the Appendix. The analysis is given in parts per million of UO_2F_2. The macroscopic thermal neutron absorption cross section per gram of solid UO_2F_2 has been included. The effect of these impurities on the results of the experiments has been shown to be negligible ($<$ 0.4%) by comparing their combined absorption cross section with that of the uranium and the hydrogen normally present in the solution. The results of this comparison depends, of course, upon the concentration of the solution and are shown in the following table for two extremes of water content.

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4. Little, L. F. and C. D. Susano, "Corrosivity of Uranyl Fluoride to Certain Metals", Tennessee Eastman Corporation, Y-12 Plant, Report No. C-3.370.8, September 19, 1946

Table 1

Distribution of Neutron Absorption in the Core

Absorber	H:U-235 Atomic Ratio = 25	H:U-235 Atomic Ratio = 1000
U-235 fission	84.3%	57.0%
U-235 radiative capture	14.1	9.5
Hydrogen	1.2	33.3
Impurities	0.4	0.2

The relation between the concentration of the solution, in gm/cm^3, and the hydrogen to U-235 atomic ratio is shown in Fig. 1; that between the specific gravity of the solution and the atomic ratio is given in Fig. 2.

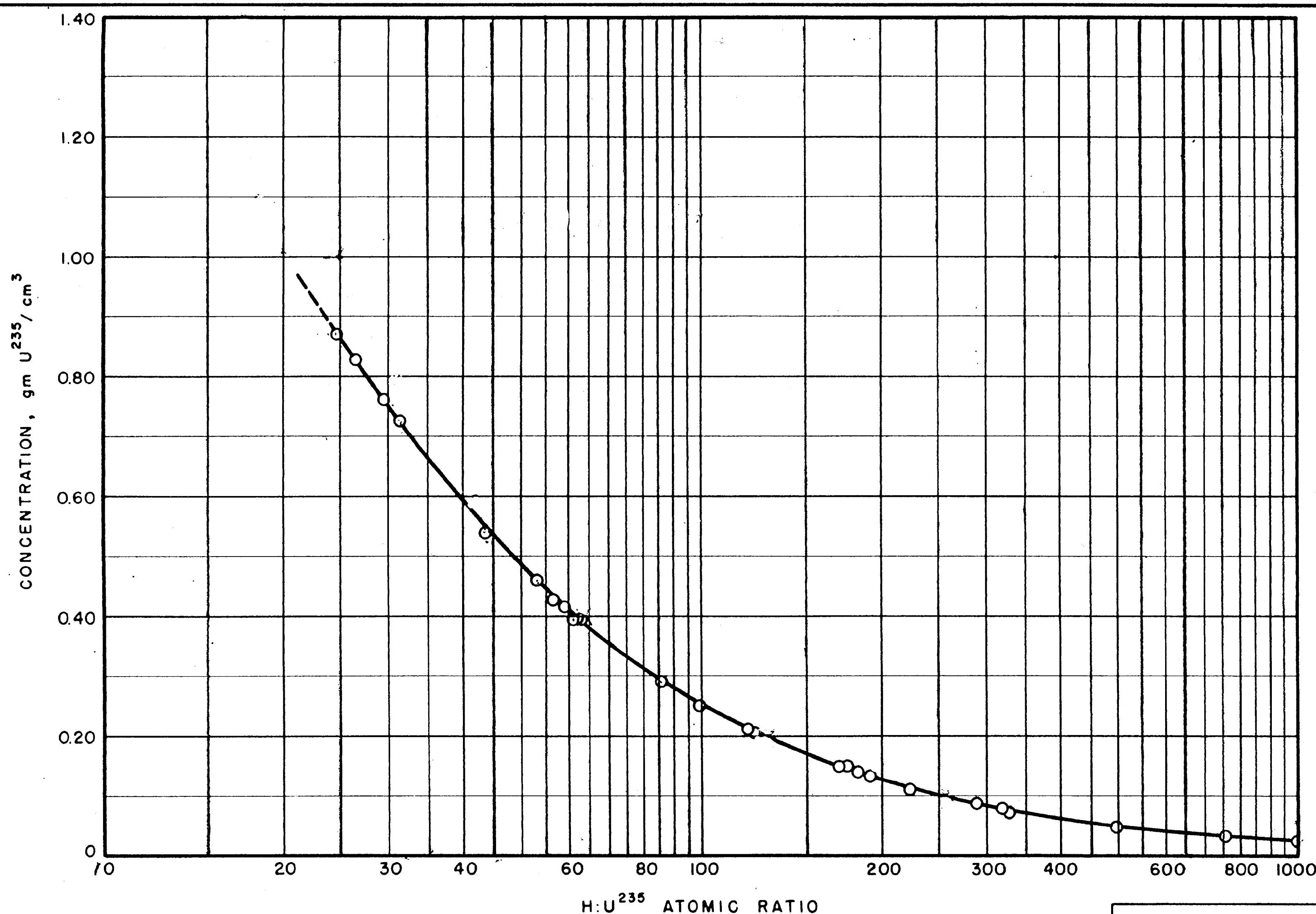
B. Materials of Construction

Stainless steel Type 321 was found to resist corrosion by uranyl fluoride solution and was used for storage cylinders, piping, etc. Type 347 was only slightly more corroded and was substituted for 321 when the latter was not available. Joints were either welded or brazed with "Silfos" or other cadmium free alloys. Pipe connections were welded or were threaded and sealed with Glyptal.

Fluorothene tubing (polymerized monochlorotrifluoroethylene) was used where flexible or transparent sections were required. Fluorothene is apparently quite inert and satisfactory flare connections can be made. Tygon tubing was also found suitable. It is more flexible than fluorothene of comparable diameter.

Some of the reactors were constructed of stainless steel and others of aluminum, Type 3-S, each of all-welded construction. It was found necessary to coat the aluminum to reduce corrosion. Bakelite varnish, air dried and baked, was found to give a satisfactory covering. In some instances Glyptal was used successfully.

The neutron absorption cross sections of the aluminum and of the elements in the stainless steel are significantly different. This effect of the reactor material on the critical mass was observable and is discussed below.



LABORATORY DIVISION

AQUEOUS UO_2F_2 SOLUTION CONCENTRATION, gm U^{235}/cm^3 VS $H:U^{235}$ ATOMIC RATIO

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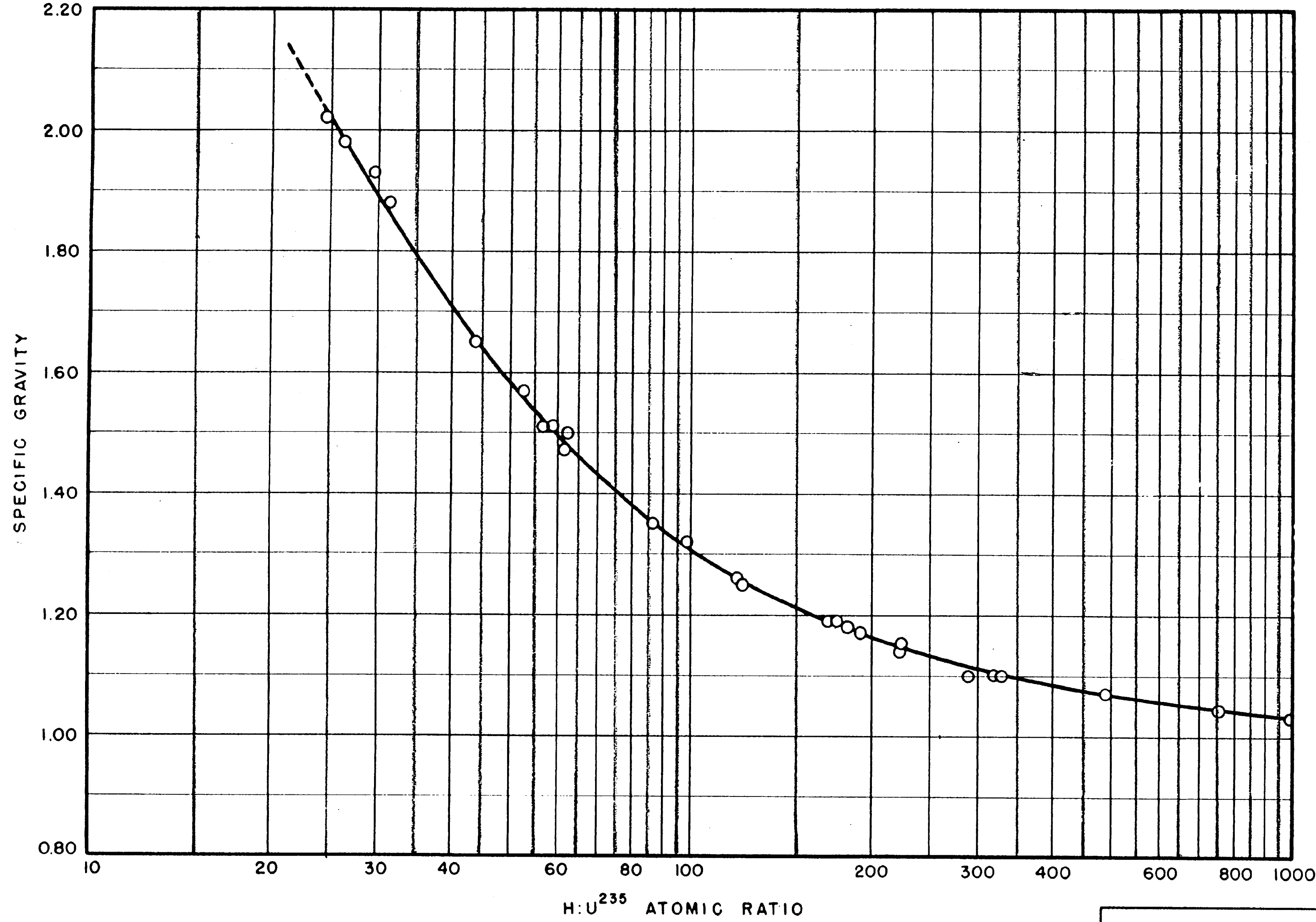
CARBIDE & CARBON CHEMICALS CORP

DRWN. F. C. Allen	APPV'D
DATE: APRIL 6, 1949	DWG NO: LD-B795

FIGURE 1



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AQUEOUS UO_2F_2 SOLUTION SPECIFIC GRAVITY VS $H:U^{235}$ ATOMIC RATIO

K-25 PLANT
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DRWN. B.Hammer	APPV'D. [illegible]
DATE: APRIL 5, 1949	DWG NO: LD-B794

FIGURE 2

III. APPARATUS

A. General Plan

The general experimental arrangement is shown schematically in Fig. 3. Briefly, uranyl fluoride solution, stored in small cylinders in the area marked "solution storage", is forced into the reactor located near one end of the Experimental Room by pneumatic pressure regulated from the Control Room. The Control Room is separated from the Experimental Room by a 16" concrete wall containing water-tank windows for observation. The experimenters assemble, by remote control, the active material in the reactor under prearranged conditions by operation of air valves and solution flow valves. Safety devices and radiation measuring instruments are located at appropriate points.

Detailed descriptions of the components of the system are given below.

B. Storage Cylinders and Solution Transport System

Vertical cadmium-coated, stainless steel cylinders four inches in diameter and 36 inches long, spaced in a row on fifteen inch centers, constituted the storage reservoir for the uranyl fluoride solution. Originally 3" cylinders were used but were replaced by 4" cylinders after early experiments showed the latter to be safe. The cylinders were located in a steel lined, concrete pit, equipped with a fire-proof cover which could be locked. A photograph of this storage facility is shown in Fig. 4.

Individual connections from a common header permitted regulated air pressure to be applied to the surface of the solution in each cylinder as shown in Fig. 5. Solution could thus be discharged through a line extending from the bottom of each cylinder through a diaphragm-sealed control valve and from there to a common feed line leading to the reactor at the other end of the room The valves were operated by handles extending through the concrete wall. The solution was returned to storage by gravity flow after releasing the air pressure. The return flow could be increased by reducing the air pressure in the manifold.

A fluorothene tube, mounted on a vertical scale in the Control Room, was connected to the reactor by a small stainless steel pipe thus allowing the position of the solution surface to be measured directly.

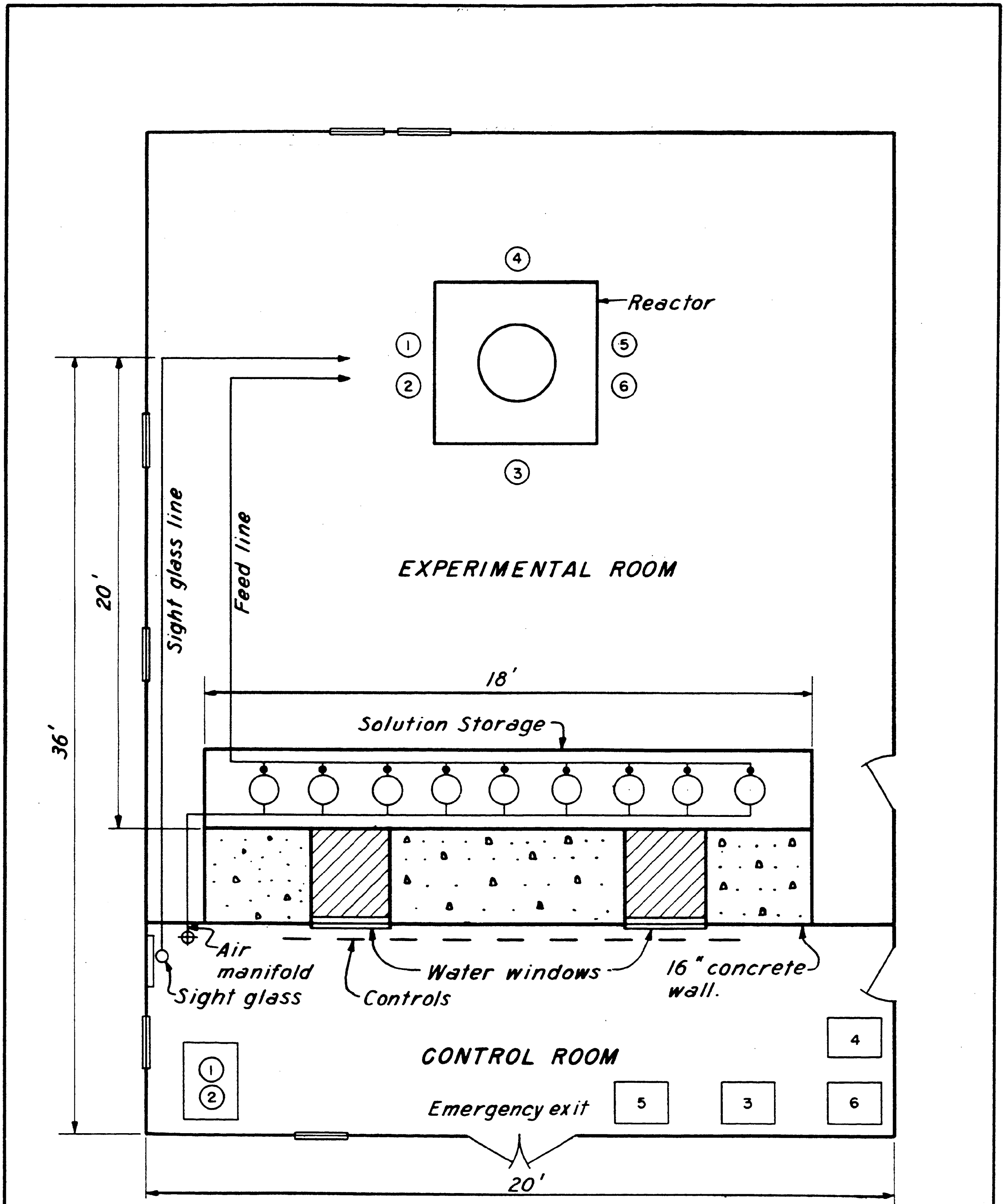
Fig. 6 shows the valve handles, air regulator, solution level "sight glass", and other controls in the Control Room.

C. Reactor Assembly

The arrangement of the reactor and its attendant parts are shown schematically in Fig. 7. Fig. 8 is a photograph of the assembly.

1. Reactors and Reflector

Eight interchangeable right circular cylinders, made of



NOTE:
1-2 ______ Boron lined counter
3-4-5 ___ BF_3 filled chambers
6 _______ Reed electrometer

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LAYOUT OF EXPERIMENTAL AREA	
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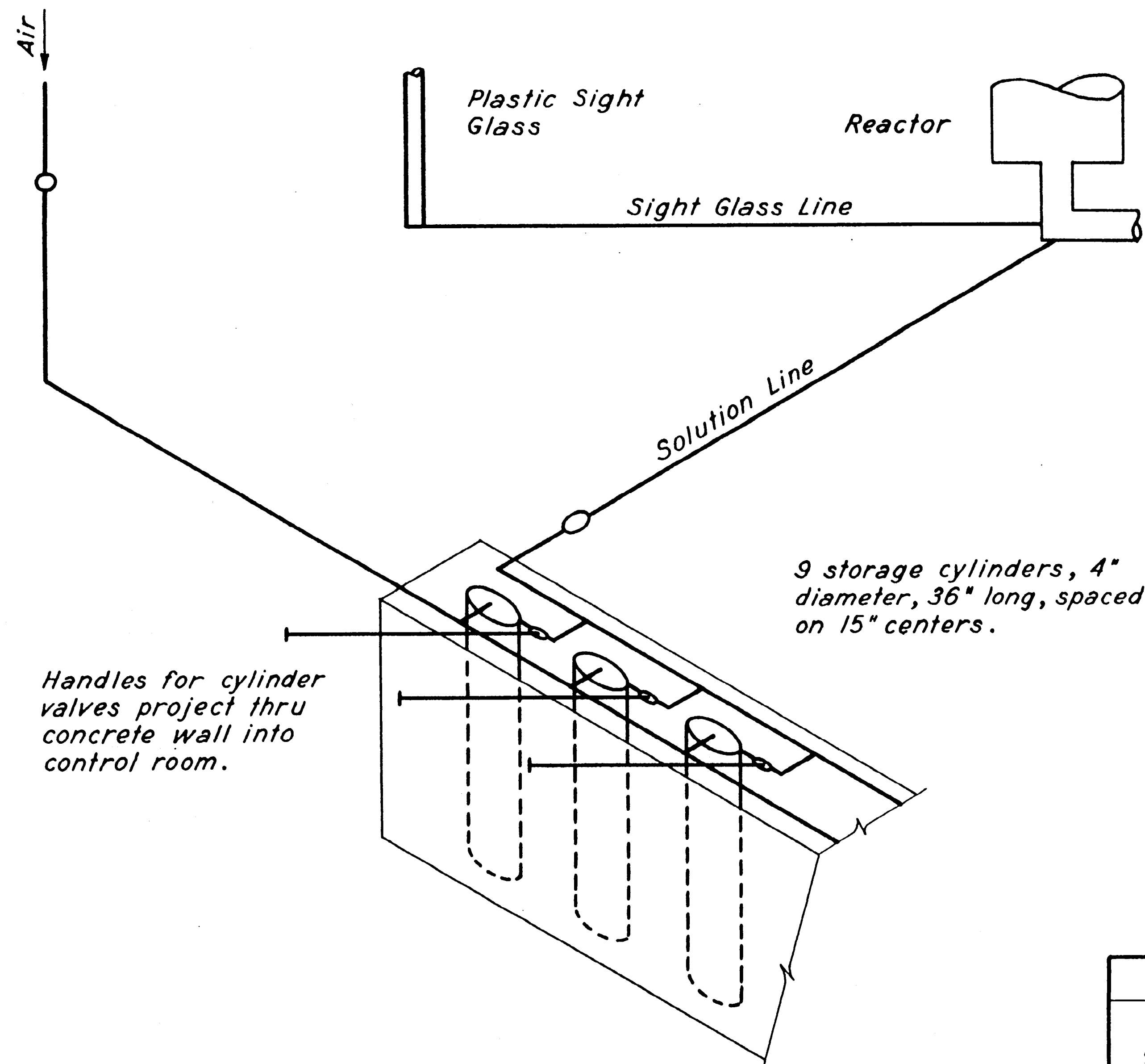
FIGURE 3

FIG. 4



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DETAIL OF STORAGE RESERVOIR

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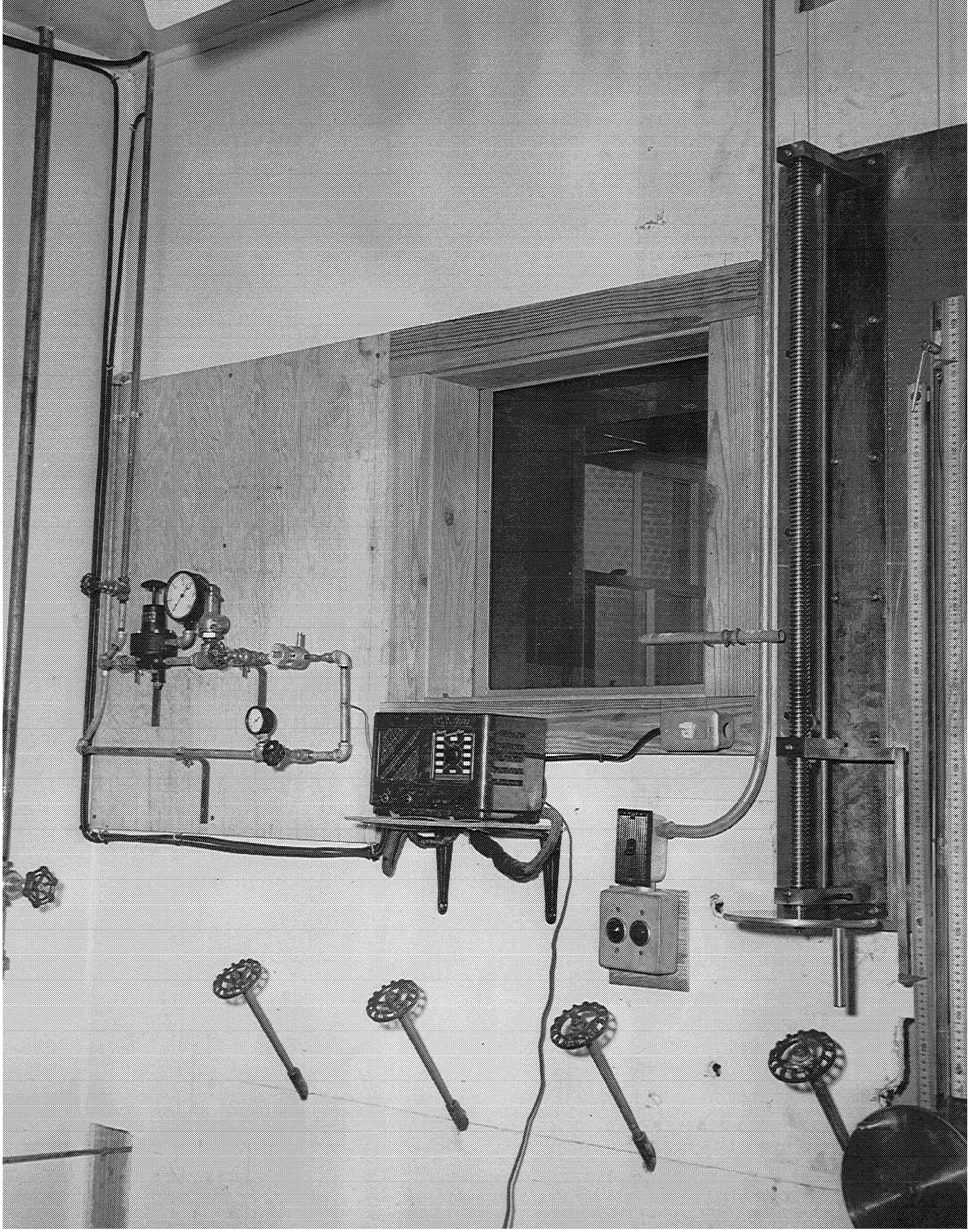
DATE: APR. 15, 1949	DWG NO: LD-B824

FIGURE 5



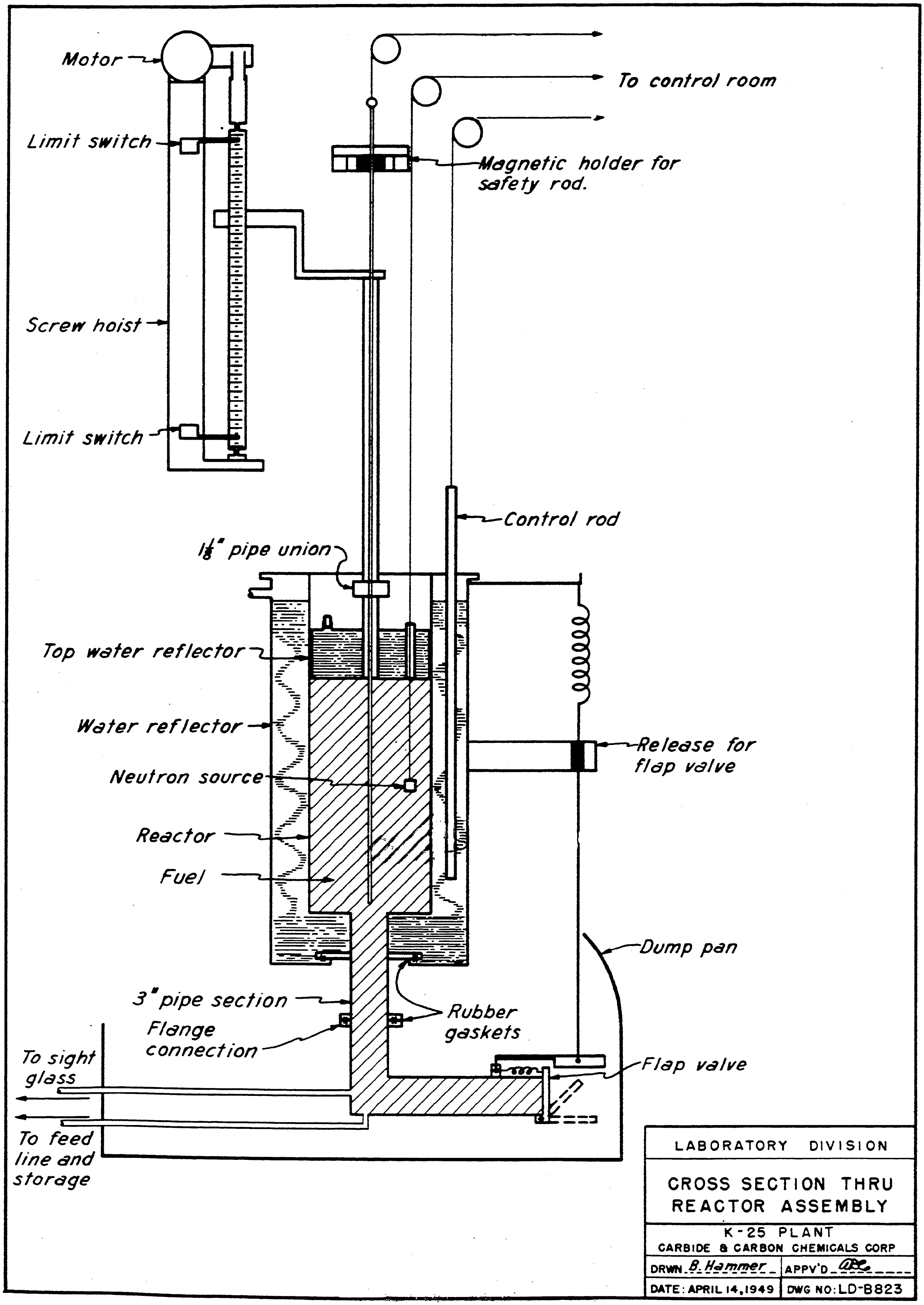
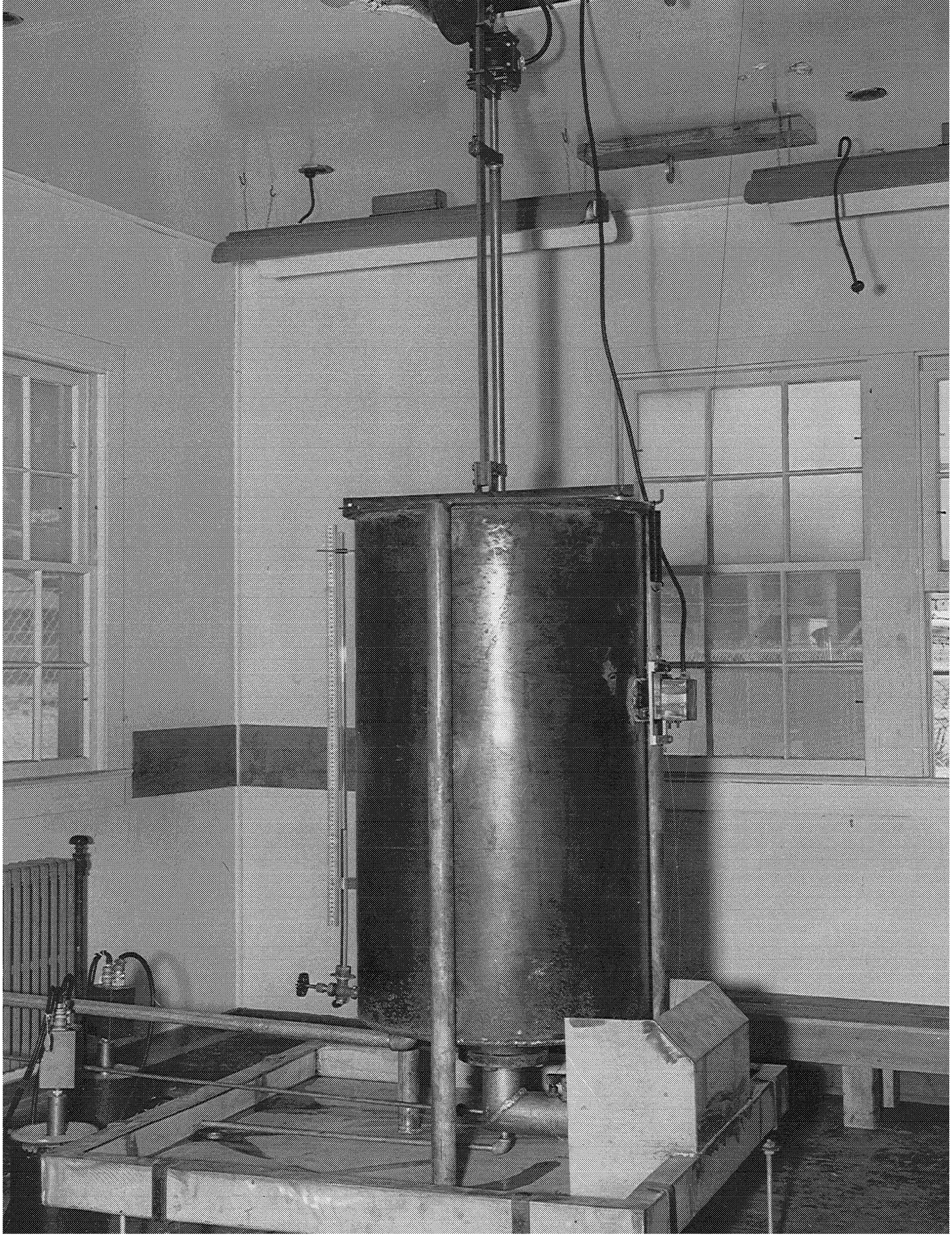

Motor
Limit switch
Screw hoist
Limit switch
To control room
Magnetic holder for safety rod.
Control rod
1⅛" pipe union
Top water reflector
Water reflector
Neutron source
Reactor
Fuel
Release for flap valve
Dump pan
3" pipe section
Flange connection
Rubber gaskets
Flap valve
To sight glass
To feed line and storage
LABORATORY DIVISION
CROSS SECTION THRU REACTOR ASSEMBLY
K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP
DRWN. B. Hammer
APPV'D
DATE: APRIL 14, 1949
DWG NO: LD-B823

FIGURE 7



Type 347 stainless steel and having diameters ranging from 6 to 20 inches were used as reactors. In addition, five cylinders, with diameters of $5\frac{1}{2}$ to 15 inches were made of Type 3-S aluminum. The cylinders were open at the top and carried two flanges at the bottom, as shown in Fig. 7, for connection to the permanent parts of the assembly. The wall thickness was 1/16 inch. The junction between the interchangeable reactors and the solution feed system was located outside of the water tank facilitating the detection of possible solution leaks at this point and minimizing loss of fuel into the reflector. A typical reactor is pictured in Fig. 9.

The experiments could be performed either with or without water reflector. An iron cylinder, 24 inches in diameter and concentric with the reactors could be filled with water to provide this reflector. At least 10 cm ($4\frac{1}{2}$ inches) of water surrounded the sides and bottom of the reactors used in experiments done with a reflector. This thickness was assumed to be effectively infinite.

The surface of the solution in each reactor could be covered by a thin-walled, smooth-fitting, stainless steel or aluminum water tank, 6 inches deep, which could be positioned by a motor driven screw operated from the Control Room. This "top reflector" tank was provided with suitable tubes through which safety and control devices could be inserted into the fuel.

Some experiments were performed with a cadmium sheet fitted around the outside and bottom of the reactor, and with cadmium shot placed in the top reflector tank, thus effectively enclosing the reactor in a sheath of approximately 0.44 grams of cadmium per square centimeter.

2. Safety and Control Devices

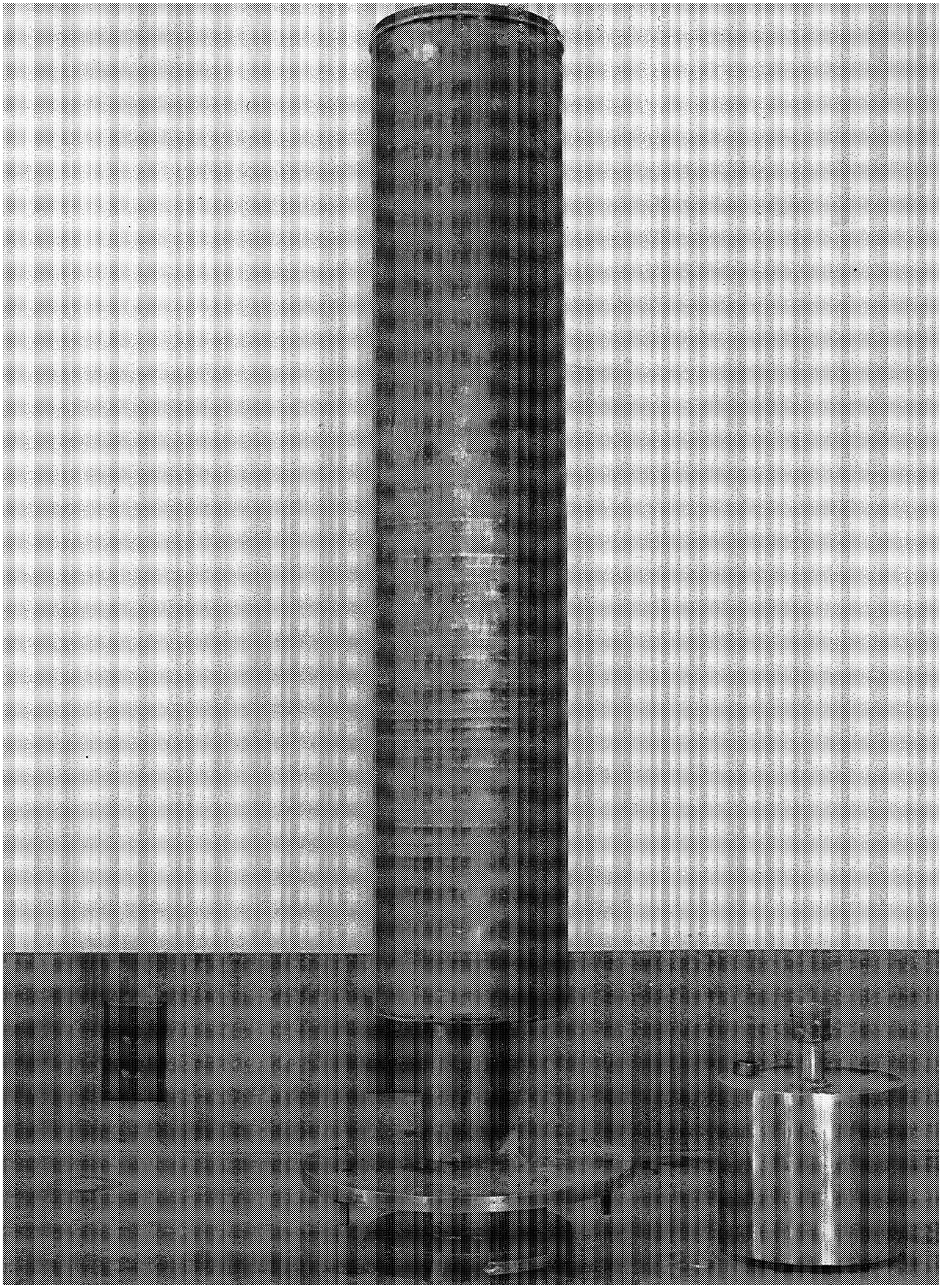
a. Cadmium Safety Rod

A safety rod, consisting of a roll of 1/16 inch cadmium sheet in a stainless steel tube 3/4 inch in diameter was suspended from an electromagnet above the center of the reactor. The support mechanism of the top reflector tank provided a guide through which the safety rod could fall, or be lowered by remote control, into the solution. The supporting magnet was automatically de-energized by an appropriate relay, allowing the rod to fall. This relay was tripped by an excessive neutron flux at either of two detectors or by a power failure. The magnet current could, of course, be interrupted manually.

When the system was near critical the poisoning effect of the safety rod was sufficient to offset the activity produced by the addition of approximately one centimeter of fuel in the reactor. Since the rate of solution addition was always low, one such rod was considered adequate.

b. Cadmium Control Rod

A second stainless steel-clad cadmium rod was supported by



a cable so it could be lowered into the reflector beside the reactors which were water enclosed. In experiments with no reflector, the rod was placed in the solution near the reactor wall. The poisoning effect of the rod in these positions was equivalent to at least a few millimeters of fuel and was adequate for control purposes. When large reactors were used, the rod was replaced by a flat cadmium sheet six inches wide, which was more effective, being equivalent to 2 cm of solution in some cases.

c. Solution Dump Valve

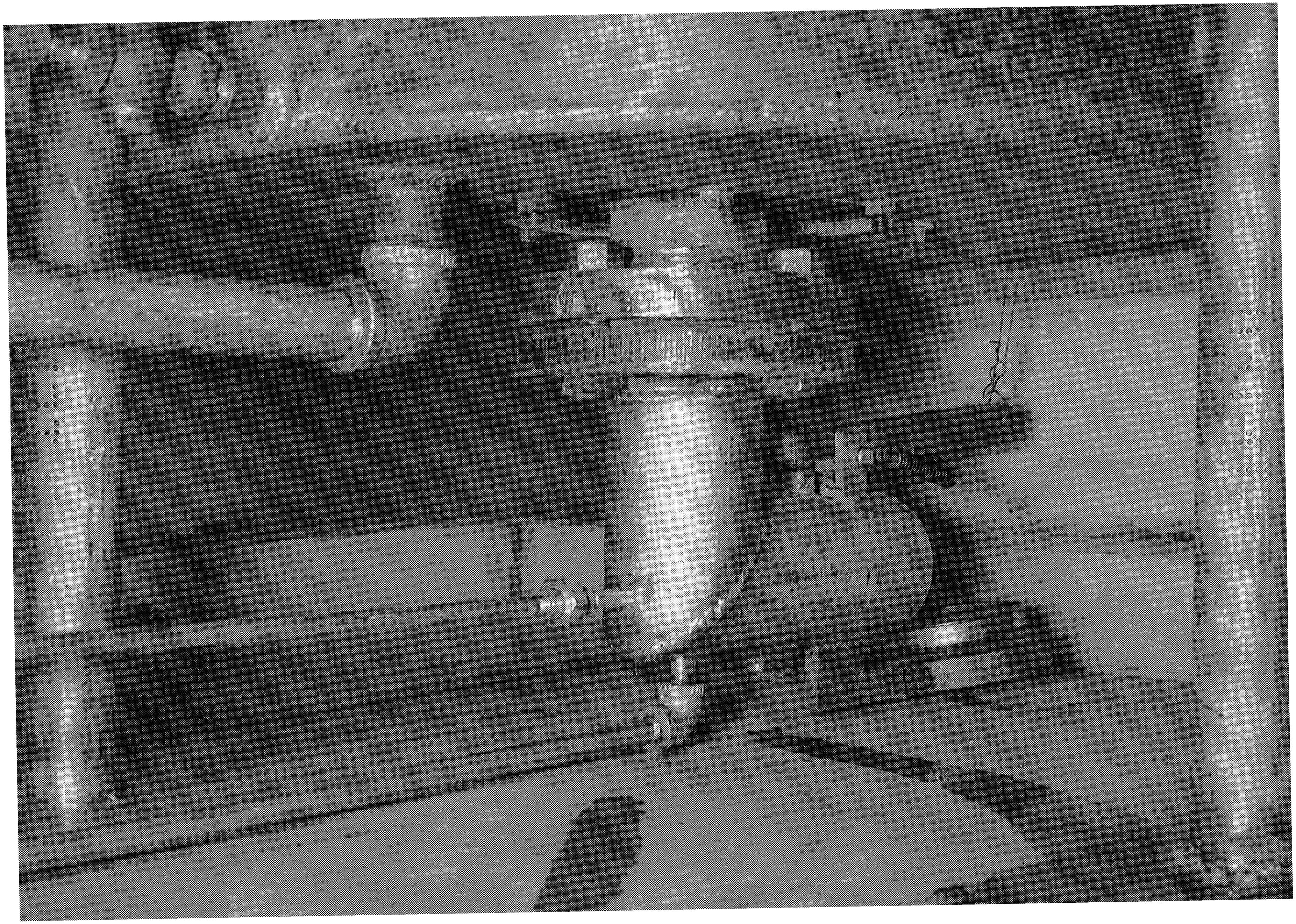
The three inch flanged extension on the lower end of the interchangeable reactors, shown in Fig. 10. was connected to a short three inch right angled pipe which was terminated by a flap-valve at the end of the horizontal section. The hinged flap-valve was spring-loaded to open, but was held in place by a latch connected to an electromagnet. The magnet core, in turn, was spring-loaded to open the latch but was prevented from doing so when the magnet was energized. If the magnet current was interrupted, by the monitoring devices or by power failure, the latch would be pulled and the flap-valve would open, emptying the solution from the reactor through the three inch pipe into a large, shallow tank underneath the assembly. The solution could then be returned to storage through a suitable connection. The flap-valve could also be released manually from the Control Room.

3. Neutron Source

Two polonium-beryllium neutron sources were used in these experiments. One, of about 10^7 neutrons/second strength, was used to check instrument response at the beginning of an experiment. The other, about 10^6 neutrons/second, was used in the assemblies to give a background for multiplication measurements. It was suspended inside the reactor cylinder from a cable extending to the Control Room.

D. Instrumentation

The level of reactivity was detected by several conventional type instruments. Three were boron trifluoride filled ionization chambers encased in paraffin connected through appropriate amplifiers to Brown or Leeds and Northrup recording potentiometers which indicated continuously the relative neutron level. Two of these circuits were connected into the energy supply of the magnets controlling the safety devices. If the neutron level at an ion chamber exceeded a predetermined value, the magnets became deenergized as previously described. This level was the order of 10^4 neutrons/second cm^2 at the detector. In the event of an emergency which would trip the safety mechanisms, the neutron flux at the operation position would be of the order of one-tenth the 8 hour daily tolerance level.



Two boron lined proportional counters enclosed in paraffin and connected to scalers were used for more quantitative measurement of the neutron activity. The gamma activity was measured by a freon filled ionization chamber near the reactor, the signals from which were amplified by a vibrating reed electrometer and recorded. A G-M tube with amplifier and recorder was used to monitor the gamma radiation in the vicinity of the operating personnel.

IV. EXPERIMENTAL PROCEDURE

A. Preparation

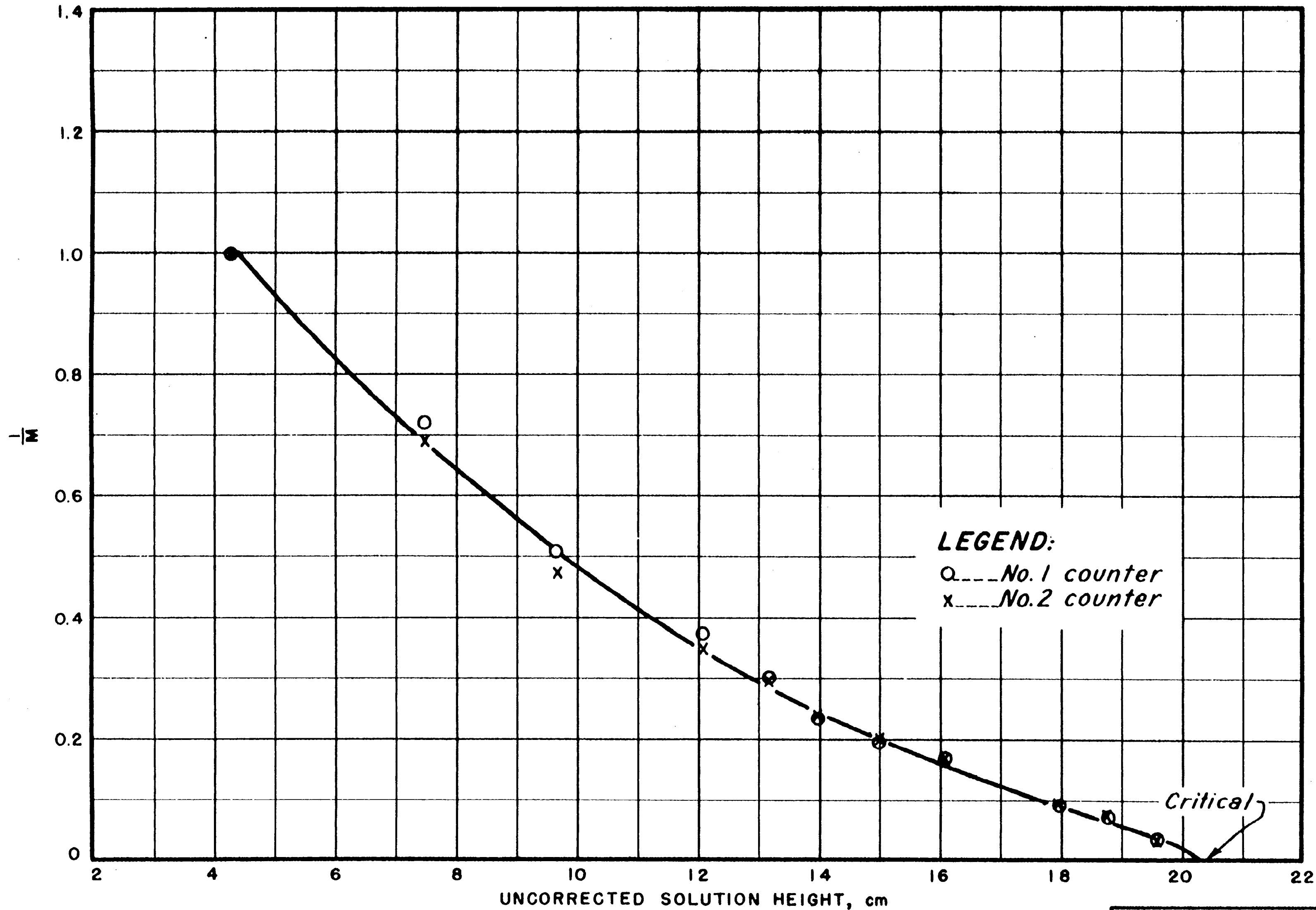
A sequence of operations was effected preparatory to each experiment, including investigation of instrument sensitivity, operation of safety devices, placement of source and of control and safety rods. The source was located above the reactor bottom at a distance about one third the estimated critical height. This is discussed more completely below. The safety rod was suspended above the reactor and the control rod was placed in the reactor or the reflector.

B. Critical Assemblies

Fuel was added in increments by applying pressure to an appropriate storage cylinder and controlling the flow with the valve. During the addition of fuel the neutron flux increases due to the multiplication of the source neutrons in the fission process. This increase in neutron flux was continuously observed on the recording instruments. Between additions, the control rod was removed and, since the system was sub-critical, the neutron flux came to equilibrium and was measured with the counters. The ratio of the count under these conditions to the count obtained at the beginning of the experiment is defined as the multiplication of the original source neutrons and is a measure of the reactivity. As the system approaches criticality, the multiplication increases without limit and its reciprocal, therefore, approaches zero. From a plot of the mass of material in the assembly, or, in this case the height of fuel in the reactor, against the reciprocal of the multiplication, a prediction can be made of the height at criticality by extrapolation to zero reciprocal multiplication. A typical curve is shown in Fig. 11 where data obtained from two counters are given. This plot serves as a guide to the rate at which the assembly can be built, but must be used with some caution. Reference is made to a discussion of the effects of geometry on multiplication curves given in Part IV,D.

While it is usually possible to estimate the critical height of an assembly by the extrapolation of a multiplication curve over the final few centimeters, it is more desirable to carry the system to criticality in order to better ascertain the limiting height. The neutron level in a critical system remains constant in the absence of any external source of neutrons.

Conversely, when a source of neutrons is removed from a sub-critical system, the neutron level decreases. The rate of decrease in the neutron intensity upon removal of the source is a measure of the near-



NOTE:
Experiment 22
10" Stainless Steel Reactor with water reflector at $H:U^{235}$ Atomic Ratio 31.6, Cadmium-Shielded.

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RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT	
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FIGURE 11

ness to critical conditions. It is to be noted, however, that it is imperative in this type of experiment to maintain an adequate neutron background to detect changes in multiplication. It is necessary to at least partially replace the source from time to time in order to keep this level up. The following is an outline of the procedure near criticality.

With a given mass of fuel in the reactor and the control rod in, it was ascertained that the system was sub-critical by removing the source and noting a decrease in the activity. As the control rod was removed the neutron flux continued to decrease, indicating the system to be sub-critical with the rod out. The rod was replaced, and a small quantity of solution was added, increasing the height two millimeters, for example. This procedure was repeated until a position of the control rod was found at which the neutron level remained constant with the source removed several feet from the reactor.

In each experiment which became critical an endeavor was made to evaluate the critical height to within ± 0.1 cm. This was done by determining a height at which the reactor was sub-critical but which upon the addition of two millimeters of solution would be supercritical with the control rod out.

C. Non-critical Assemblies, Experimental Limitations

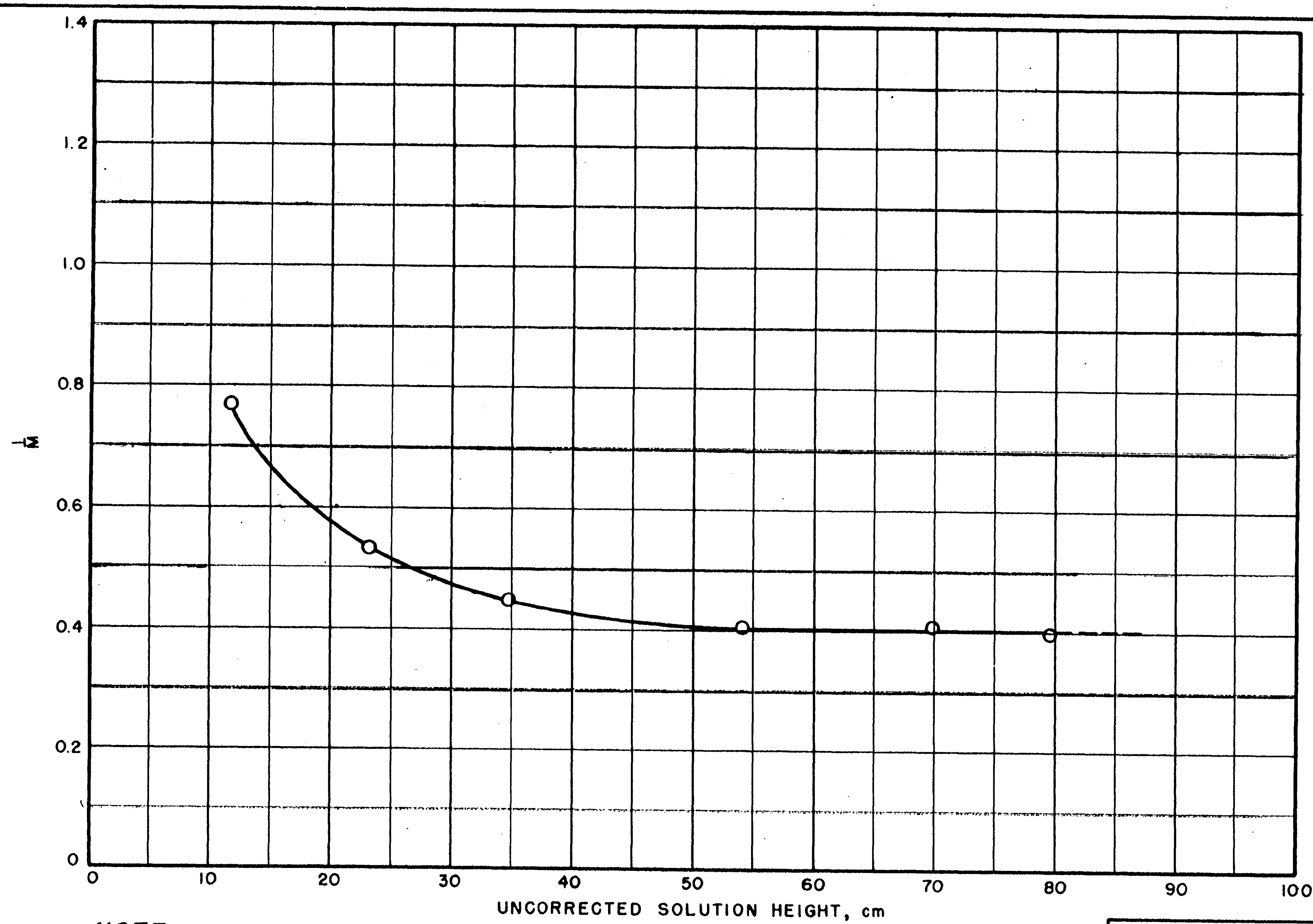
It was not possible to make every assembly critical because of one or more of the following limitations imposed by the apparatus or by the fuel.

1. Geometry

One of the purposes of this investigation was to determine the maximum diameter of a reactor of infinite length which could be filled with fuel and remain sub-critical. This diameter is, of course, dependent upon the concentration of the solution, the reflector and other variables. In the course of these experiments a number of conditions resulting in sub-criticality at infinite extension of reactor were found. That such a system will always be sub-critical is indicated by the shape of the reciprocal multiplication curve referred to above. In this group of experiments the geometrical conditions were such, essentially, that as the height of the solution was increased beyond a particular value, further additions of U-235 did not contribute significantly to the reactivity. These conditions resulted in a curve which showed an asymptotic approach to a finite multiplication. An example is shown in Fig. 12. The conditions of reactor diameter, concentration, etc., which yielded this shaped multiplication curve were said to represent assemblies which would be sub-critical at any reactor height.

2. Quantity of Fuel

Some assemblies did not become critical because insufficient U-235 was available. An example of the multiplication curve obtained in these instances is shown in Fig. 13. The curve has been extrapolated to give an estimate of the critical height.



NOTE:
Experiment 67
8" Stainless Steel Reactor
$H:U^{235}$ Atomic Ratio 86.3
No Reflector

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RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT	
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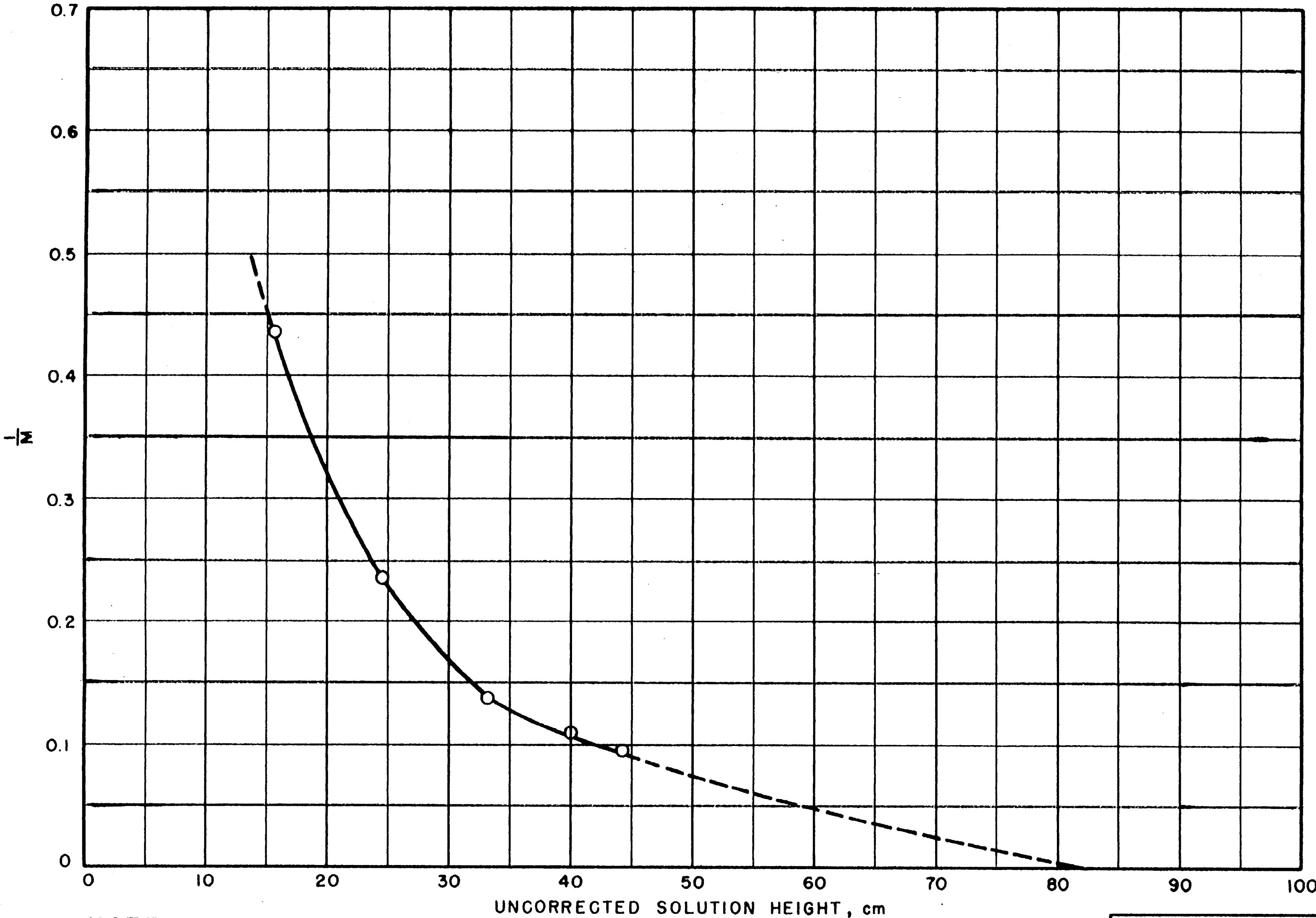
FIGURE 12



NOTE:
Experiment 55
9" Stainless Steel Reactor
$H:U^{235}$ Atomic Ratio 62.6
No Reflector

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FIGURE 13

3. Reactor Height

In certain cases the height of a reactor was insufficient to contain enough solution to be critical, though the reciprocal multiplication curve indicated the reactor would be critical at a finite height. The curve resembled that in Fig. 13 and could be extrapolated to a critical height.

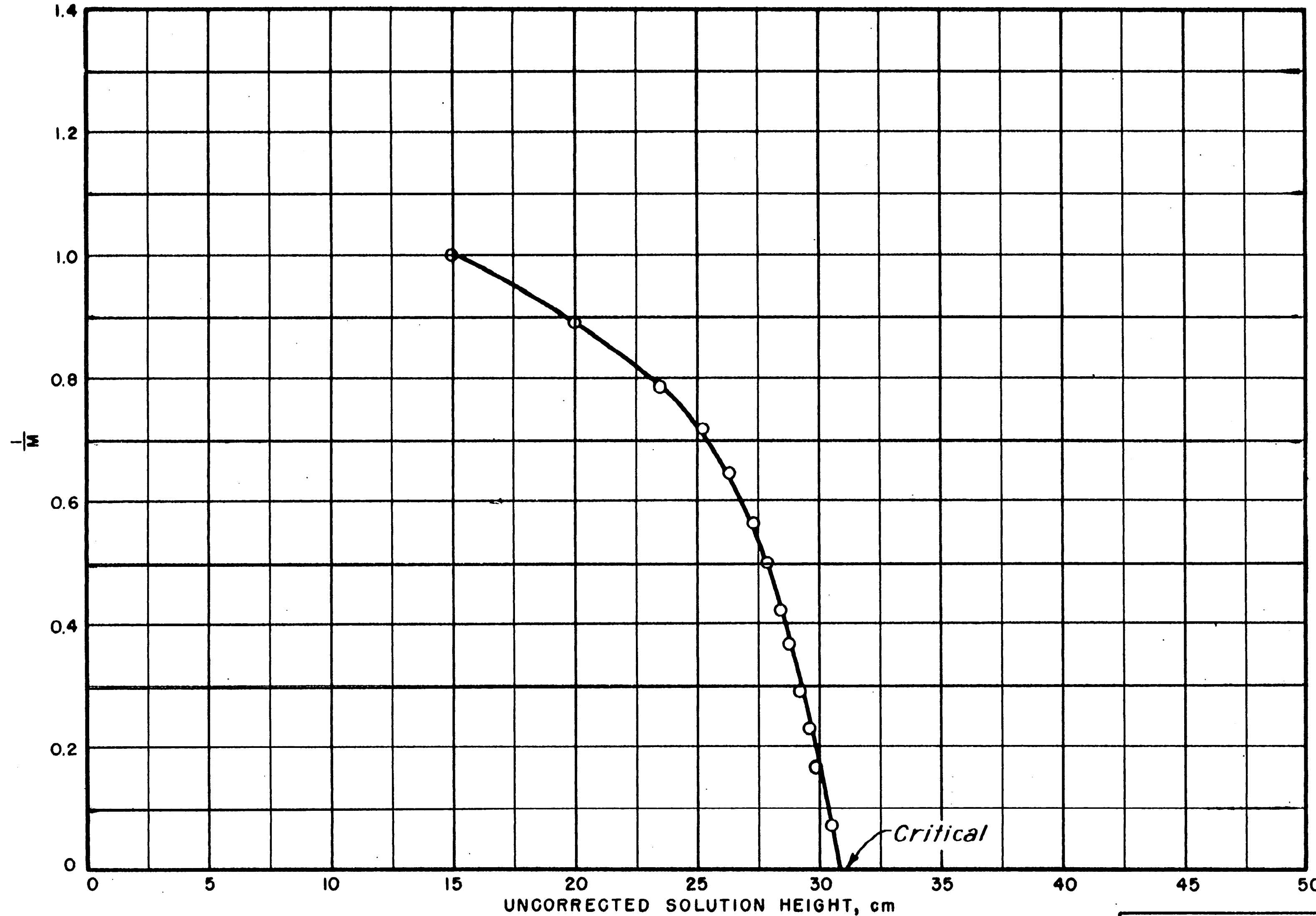
D. Effect of Neutron Source Strength and Source Geometry

It should be realized that while the strength and location of the neutron source do not affect the critical conditions, these factors do have a marked influence on the manner in which criticality is approached and the facility with which it is achieved. Ideally it is desirable to work with source geometries which (1) yield definite, reproducible neutron multiplications under identical conditions, (2) give rise to reciprocal multiplicative curves which are linear functions of the height and (3) introduce no marked perturbation in the multiplying medium when the source is withdrawn. The experimental conditions necessary to approximate such an ideal are discussed in the paragraphs that follow.

It is imperative that critical mass experiments must be performed in the presence of a neutron source. Dependence upon a neutron background from spontaneous fission and free neutrons to provide multiplication is dangerous since such multiplication is subject to wide statistical fluctuations and is too low to monitor successfully even near criticality. For this type of work a source producing approximately 10^6 neutrons per second is satisfactory.

It is likewise important to place the source within the multiplying medium. Otherwise, a signifcant fraction of the source neutrons will reach the counters without intercepting the active core. Hence, during the addition of the first increments of fuel, only a small fraction of the neutrons reaching the counters will be the result of neutron multiplication. As more solution is added and the critical condition is approached, the neutrons produced by multiplication increase rapidly in spite of the poor source location. These conditions yield a reciprocal multiplication curve that is initially flat. Since the curve must, however, intersect the height axis at criticality, the initial flatness must be compensated for by an extremely steep portion as criticality is approached. Such a curve, worthless as a guide to safe procedure, is shown in Fig. 14. It is to be compared with Fig. 11, in which the source was placed inside, rather than outside, the reactor.

The shape of the multiplication curve is also dependent upon the position of the source in the reactor and the height of solution at the time of the initial count selected for subsequent determination of the multiplication. If the source is placed too high in the reactor it may not become covered with solution by the time the system is at or near critical. Under these conditions, the sharp-breaking reactivity curves of the type discussed above are again obtained. If the source is placed too low, a similar, though less severe effect occurs because the source is in a relatively poor position for effective multiplication. In addition, if the source is located a few centimeters



NOTE:
Experiment 6A
7" Stainless Steel Reactor with Water Reflector at H:U^{235} Atomic Ratio 61.2.

LABORATORY DIVISION

RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN. B. Hammer	APPV'D. [illegible]
DATE: APRIL 5, 1949	DWG NO: LD-B792

FIGURE 14

from the bottom of the reactor and the initial count is taken with no solution in the reactor, then it will be found that as one adds solution the neutron count decreases at first since absorption and scattering initially overshadow neutron production. This phenomenon yields a "multiplication" less than one and the corresponding reciprocal multiplication becomes greater than one for a brief period with the remainder of the curve correspondingly steeper as illustrated by Fig. 15. In lieu of more idealized (and considerably less practical) geometries for linearizing reciprocal multiplication curves, a satisfactory rule of thumb is to set the source within the reactor at a height approximately one-third of estimated critical height. A satisfactory neutron count to be used in computing the multiplication is that obtained when the source is about one centimeter under the surface of solution.

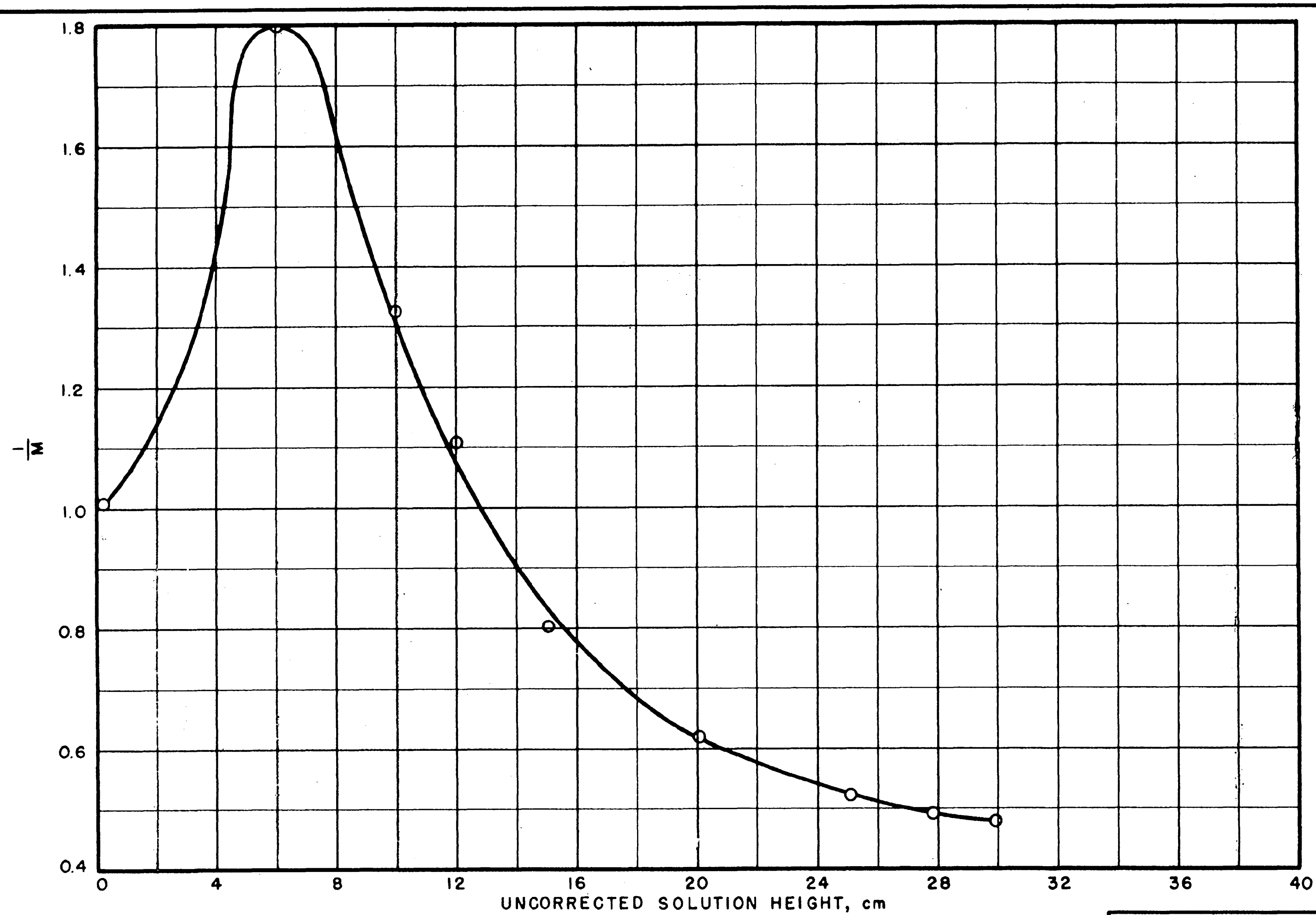
It is extremely desirable that the source and its container occupy as small a volume as possible. The reason for this requirement lies in the fact that, when the assembly is near critical, the presence of the void introduced into the solution by the physical size of the source may cause a greater perturbation in the neutron density of the reactor than the presence of the extra source neutrons. When the source is withdrawn under critical or near-critical conditions, the removal of this void from the body of solution may lead to a significant increase in reactivity. It is possible for a slightly sub-critical system to become supercritical upon removal of the source. There is no apparent effect on the reciprocal multiplication curve until the source is first removed upon entering the near critical region. The curve suddenly makes a short but steep decent, intersecting the height axis at a lower value than that predicted by an extrapolation of the linear portion of the curve. Thus the use of neutron sources of larger physical dimensions than necessary is an unsafe technique and is to be avoided.

An idea of the magnitude of the effect can be obtained from an experiment in which a simulated stainless steel source holder, approximately one inch in diameter and 5 inches long, occupying a volume of about 65 cm^3, was moved along the vertical axis of an 8" reactor at a radial distance of 4.5 cm from its center line, and the critical height determined as a function of its position. The results of the experiment as seen in Fig. 16, which shows a maximum of 2 cm difference in critical height. An extension of this method may constitute a convenient technique for determination of the spatial distribution of the neutron density in the core.

V. EXPERIMENTAL RESULTS

A. Introduction

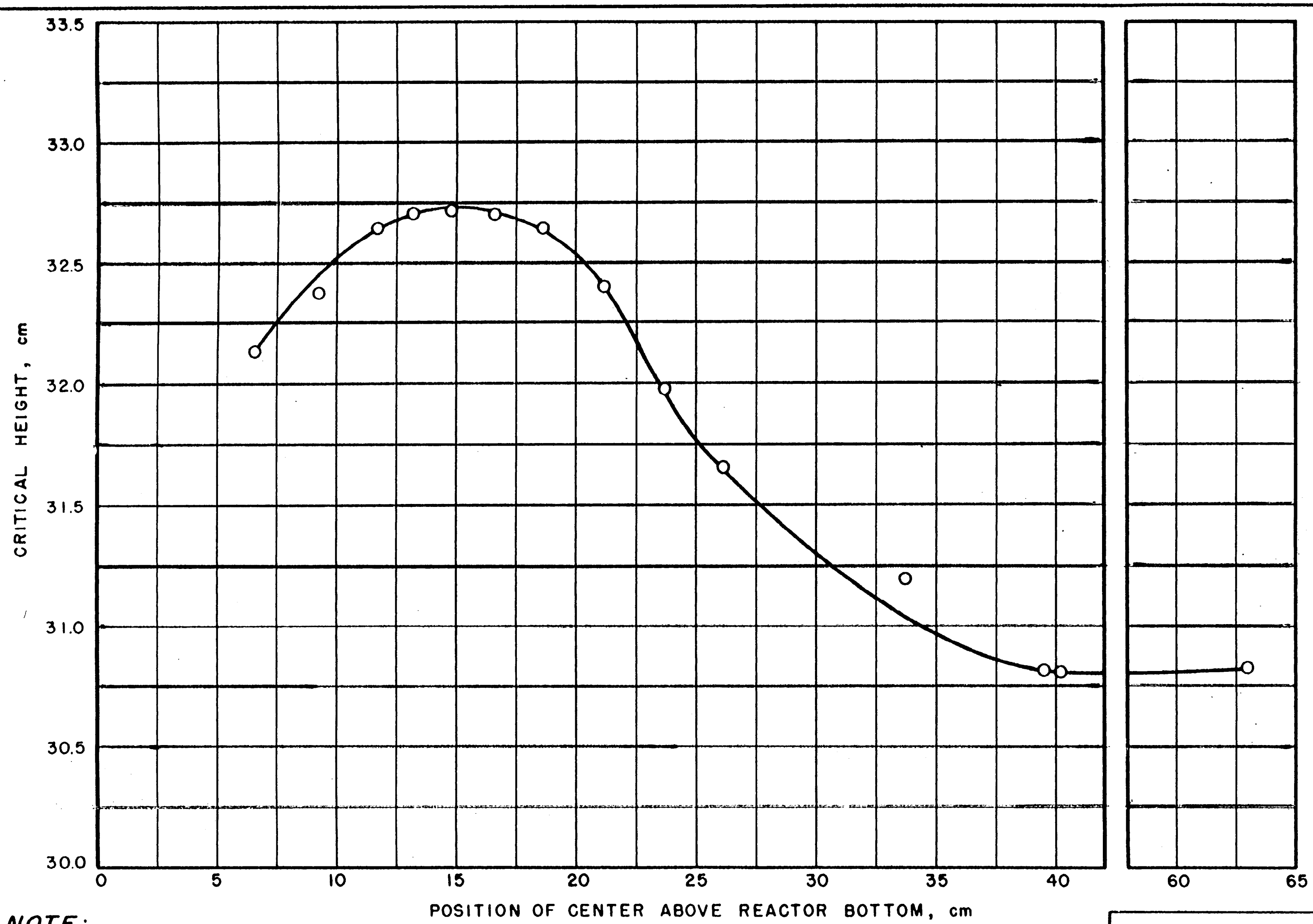
Data were obtained in these experiments on the conditions necessary for a solution of U-235 in right cylinders to become critical under a variety of conditions. The variables which were examined included the water content of fuel, the type of reflector, the diameter of reactor, and the reactor material. The data are recorded in detail in the Appendix. One set of tables gives the results from those assemblies which were critical. A second set reports the information derived from assemblies which did not become critical. In each of the latter are given



NOTE:
Experiment 14
8" Stainless Steel Reactor
H:U^{235} Atomic Ratio 24.3
No Reflector

LABORATORY DIVISION	
RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. Ben Hammer	APPV'D. ABC
DATE: APRIL 5, 1949	DWG NO: LD-B793

FIGURE 15



NOTE:
Experiment 86
Stainless Steel Reactor - 8" diameter
$H:U^{235}=174$
Water enclosed on sides only.

LABORATORY DIVISION

CRITICAL HEIGHT VS POSITION OF SIMULATED SOURCE HOLDER

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN B. Hammer	APPV'D [illegible]
DATE: APRIL 11, 1949	DWG NO: LD-B810

FIGURE 16

the maximum quantity of fuel added to the reactor and an estimate of the critical conditions. In general, large scale plots have been made of these data from critical assemblies and the best curves fitted. These curves, in turn, have been abstracted to show trends and are included in this report. It is believed that where uncertainties exist the interpretation is conservative, that is, the values given for the critical masses are low. The results may be duplicated in two or more graphs in order that relationships between different variables may be shown.

B. Reactors with Water Reflector

1. Aluminum

In Fig. 17 is shown a plot of uranyl fluoride solution height at criticality as a function of the moderation or hydrogen to U-235 atomic ratio in the fuel for several sizes of water enclosed aluminum reactors. These results are also shown in Fig. 18, a plot of the critical masses corresponding to these critical heights. The data are tabulated in the Appendix, Tables 5 and 6.

2. Stainless Steel

The data obtained with water enclosed stainless steel reactors of several diameters at various concentrations of uranyl fluoride solution appear in Tables 7 and 8 and are shown in Fig. 19 and Fig. 20. In these the height of the solution at criticality and the mass are plotted as a function of the moderation.

3. Stainless Steel, Cadmium Shielded

A few experiments were done in which a sheet of cadmium having a thickness of 0.44 gm Cd/cm^2 was wrapped around the stainless steel reactors which were then enclosed in water. Data obtained from these assemblies are shown in Fig. 21 and Fig. 22, where the critical heights and critical masses are plotted as functions of the H:U-235 atomic ratio. See also Tables 9 and 10 of the Appendix.

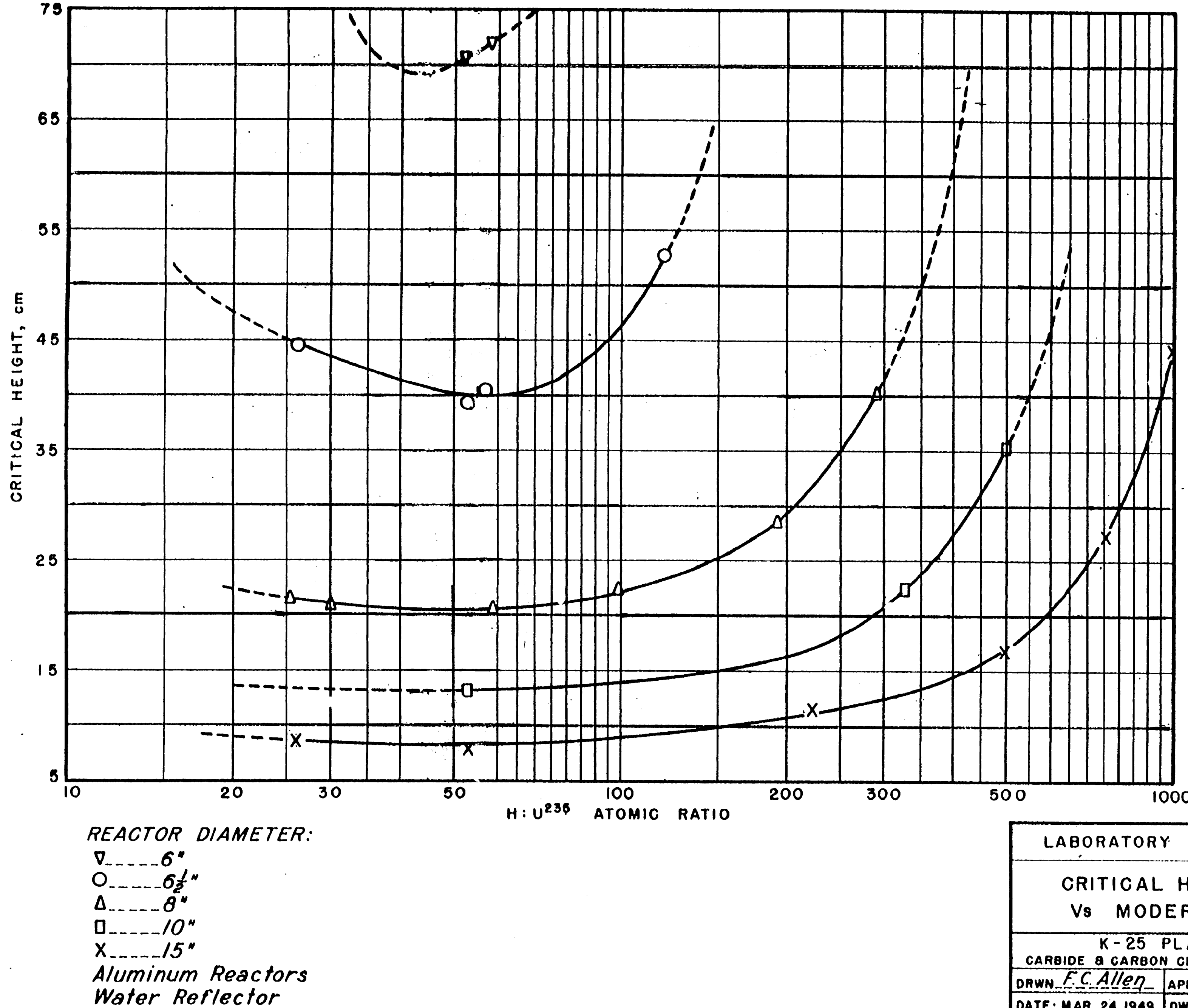
C. Reactors Without a Reflector

1. Aluminum

A few data were obtained with aluminum reactors having diameters of 10 and 15 inches with no reflector and are shown in Fig. 23 and Fig. 24 and in Tables 11 and 12.

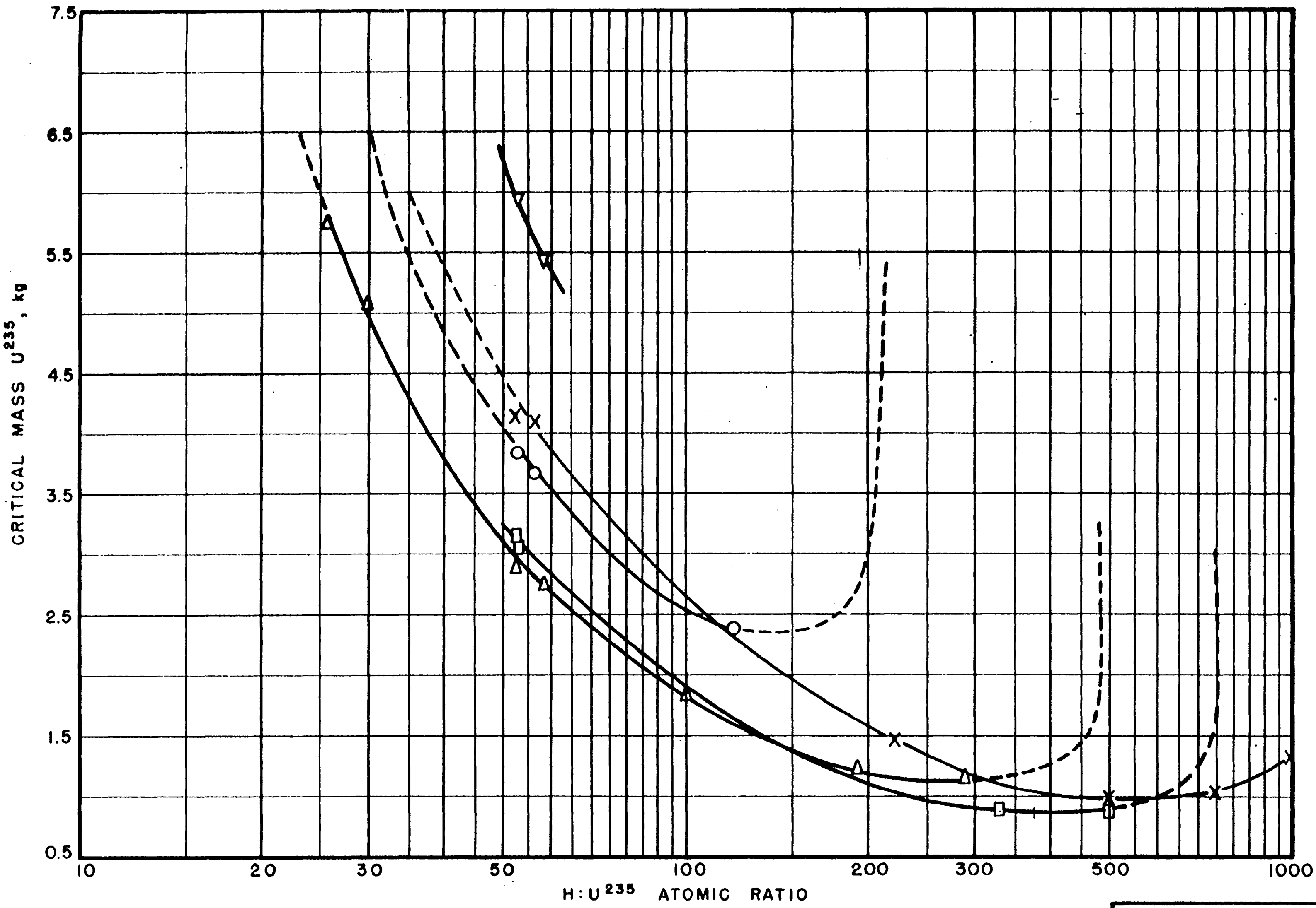
2. Stainless Steel

Stainless steel reactors having diameters of 10, 12, 15, and 20 inches became critical with the fuel at several concentrations and the data are given in Fig. 25 and Fig. 26. It was not possible to make a nine inch reactor critical, but, at some concentrations it was not shown conclusively to be subcritical at infinite length because of limitations imposed by the apparatus and quantity of U-235 available. On the curves are plotted some conservative



LABORATORY DIVISION	
CRITICAL HEIGHT Vs MODERATION	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN F.C. Allen	APPV'D [illegible]
DATE: MAR. 24, 1949	DWG NO: LD-B779

FIGURE 17



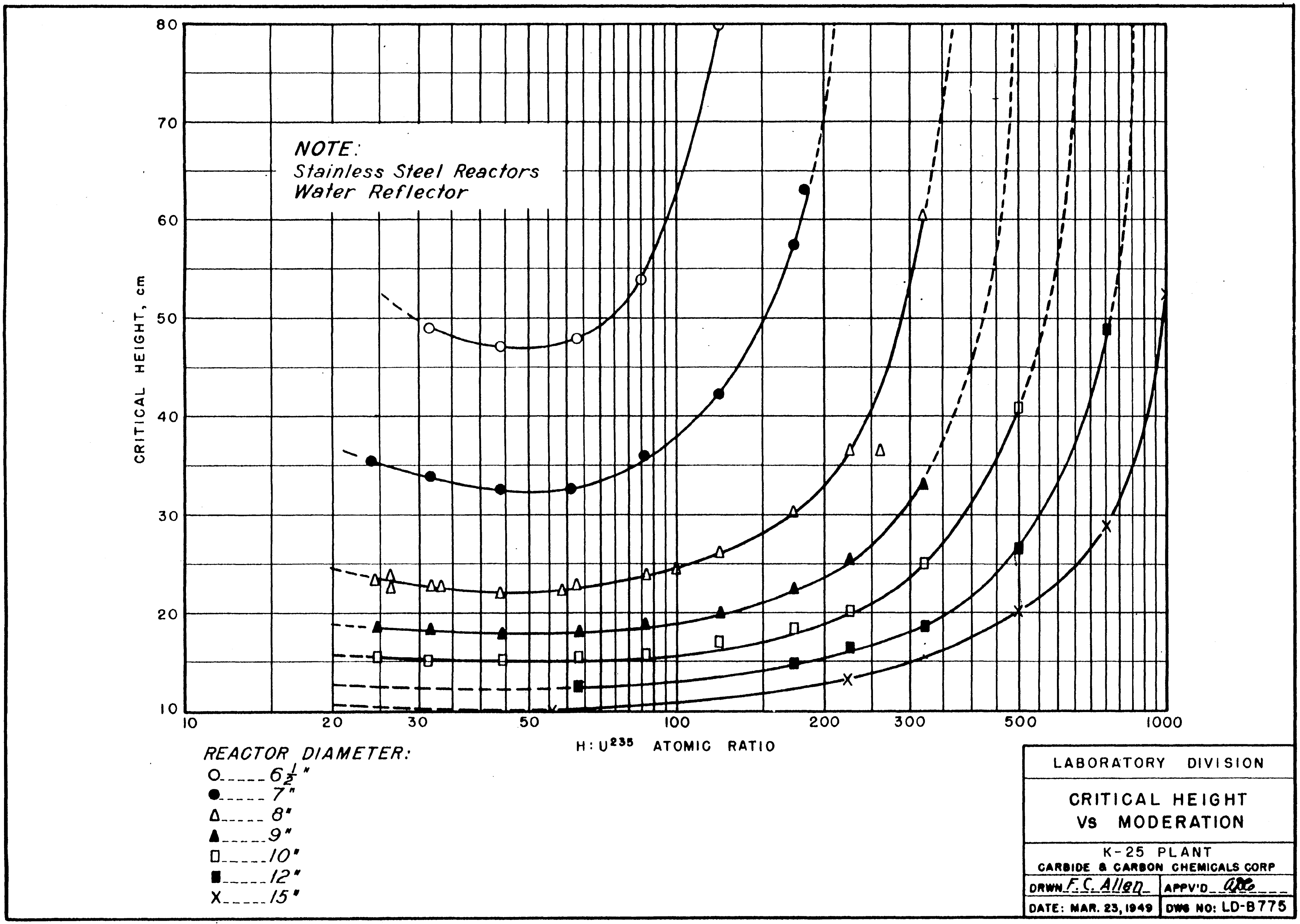
REACTOR DIAMETER:

- ▽ ------ 6"
- ⊙ ------ $6\frac{1}{2}$"
- △ ------ 8"
- □ ------ 10"
- X ------ 15"

Aluminum Reactors
Water Reflector

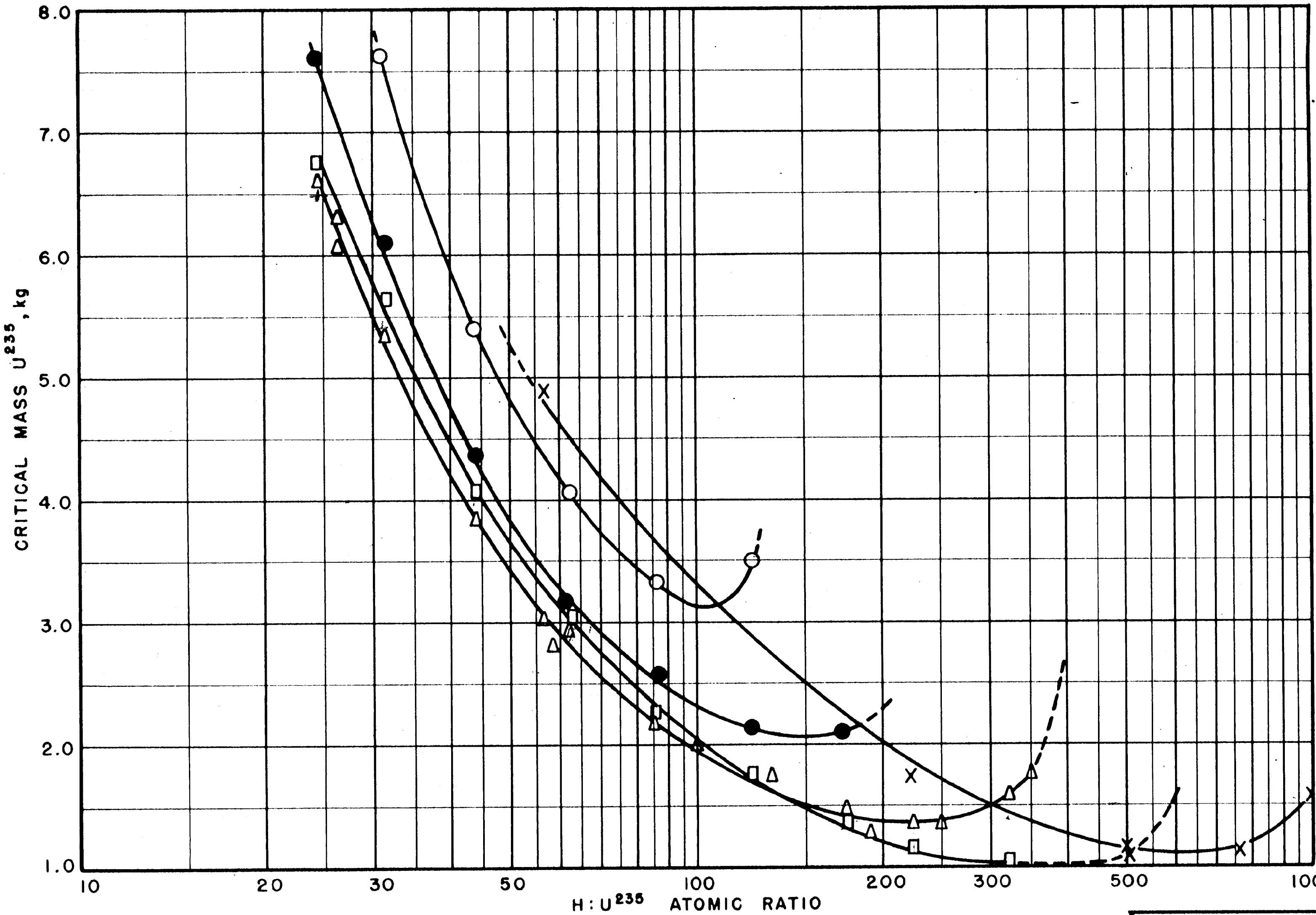
LABORATORY DIVISION	
CRITICAL MASS OF U^{235} VS MODERATION	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. F.C. Allen	APPV'D ADE
DATE: MAR. 24, 1949	DWG NO: LD-B777

FIGURE 18



NOTE:
Stainless Steel Reactors
Water Reflector
CRITICAL HEIGHT, cm
80
70
60
50
40
30
20
10
10
20
30
50
100
200
300
500
1000
H : U235 ATOMIC RATIO
REACTOR DIAMETER:
○ ----- 6½"
● ----- 7"
△ ----- 8"
▲ ----- 9"
□ ----- 10"
■ ----- 12"
X ----- 15"
LABORATORY DIVISION
CRITICAL HEIGHT
Vs MODERATION
K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP
DRWN. F. C. Allen
APPV'D
DATE: MAR. 23, 1949
DWG NO: LD-B775

FIGURE 19



REACTOR DIAMETER:

○ ----- 6½"

● ----- 7"

Δ ----- 8"

□ ----- 10"

X ----- 15"

Stainless Steel Reactors

Water Reflector

LABORATORY DIVISION

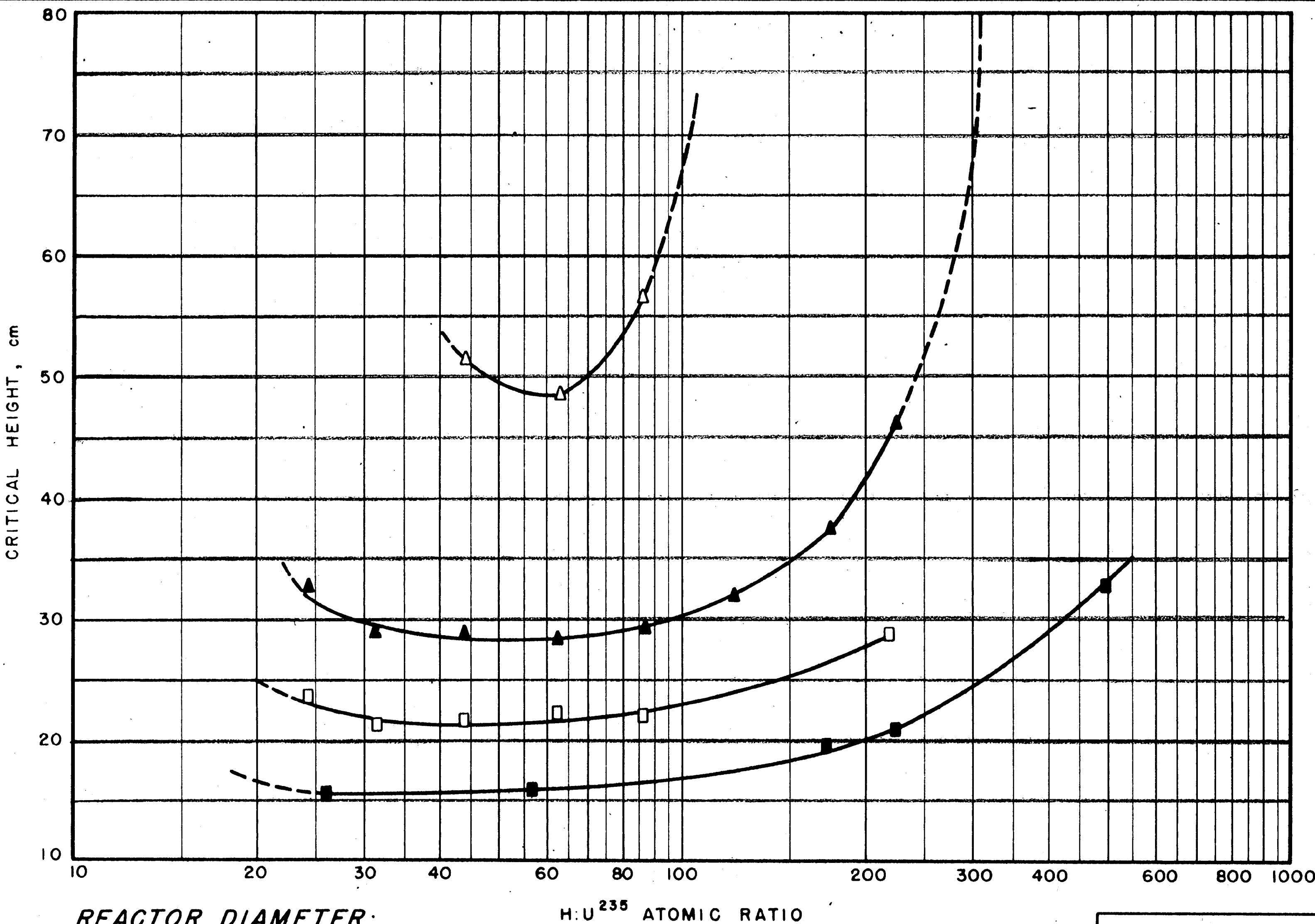
CRITICAL MASS OF U^{235} VS MODERATION

K-25 PLANT

CARBIDE & CARBON CHEMICALS CORP

DRWN F.C. Allen	APPV'D [illegible]
DATE: MAR. 24, 1949	DWG NO: LD-B781

FIGURE 20



REACTOR DIAMETER:

△ ________ 8"

▲ ________ 9"

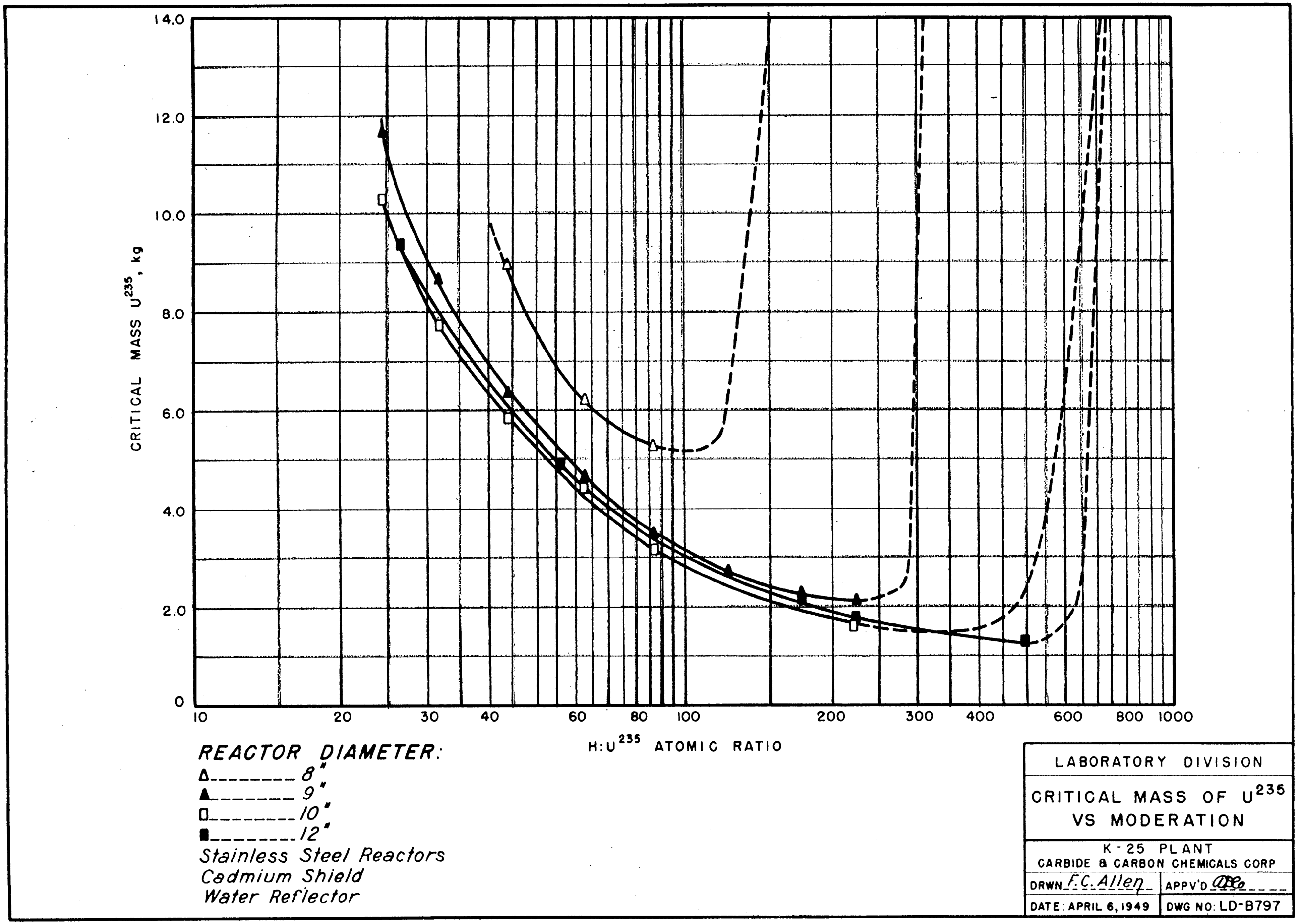
□ ________ 10"

■ ________ 12"

Stainless Steel Reactors
Cadmium Shielded
Water Reflector

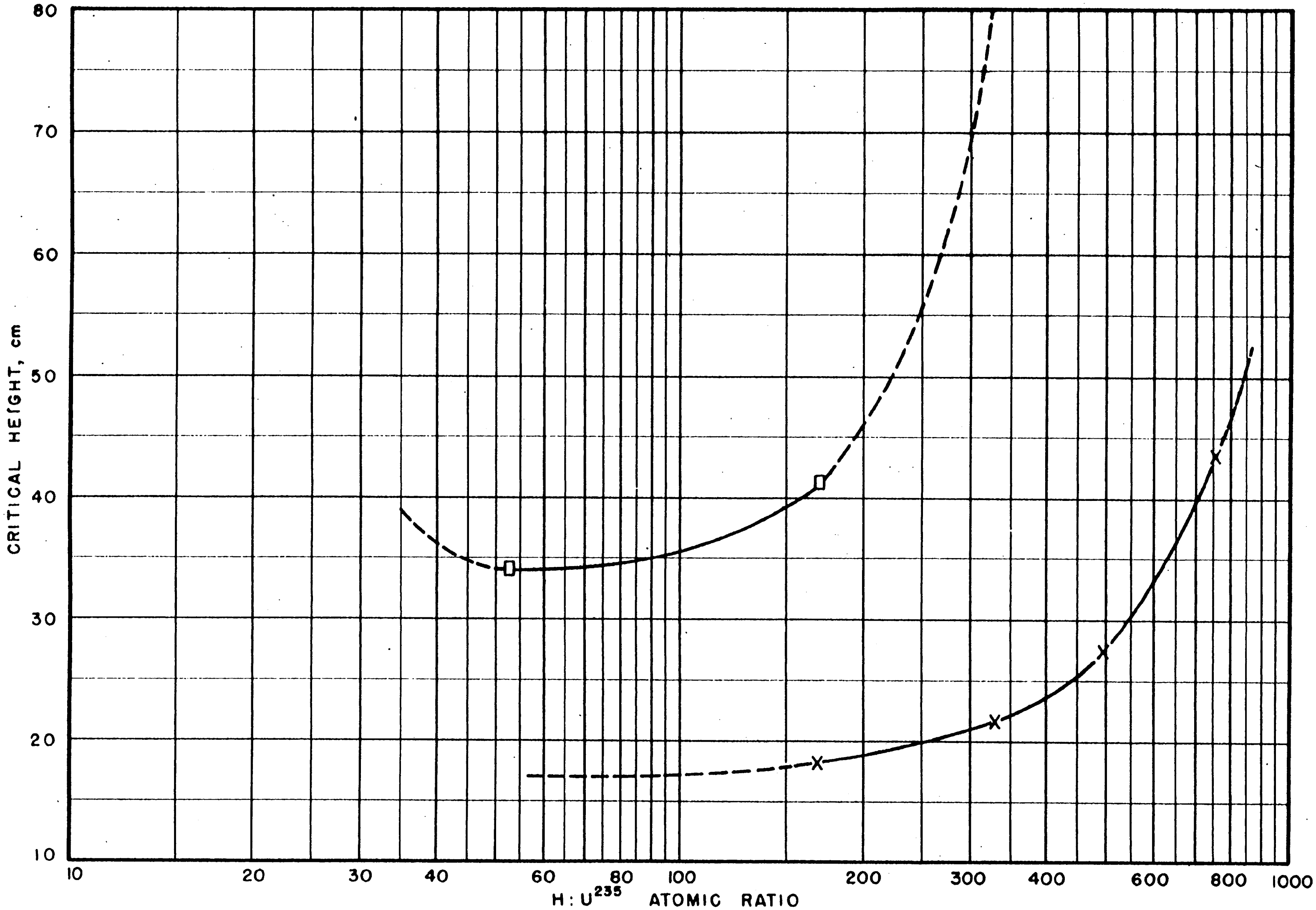
LABORATORY DIVISION	
CRITICAL HEIGHT Vs MODERATION	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN B. Hammer	APPV'D [illegible]
DATE: APRIL 6, 1949	DWG.NO: LD-B798

FIGURE 21



14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
CRITICAL MASS U^{235}, kg
10
20
30
40
60
80
100
200
300
400
600
800
1000
H:U^{235} ATOMIC RATIO
REACTOR DIAMETER:
Δ 8"
▲ 9"
□ 10"
■ 12"
Stainless Steel Reactors
Cadmium Shield
Water Reflector
LABORATORY DIVISION
CRITICAL MASS OF U^{235} VS MODERATION
K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP
DRWN F.C. Allen
APPV'D
DATE: APRIL 6, 1949
DWG NO: LD-B797

FIGURE 22



REACTOR DIAMETER:

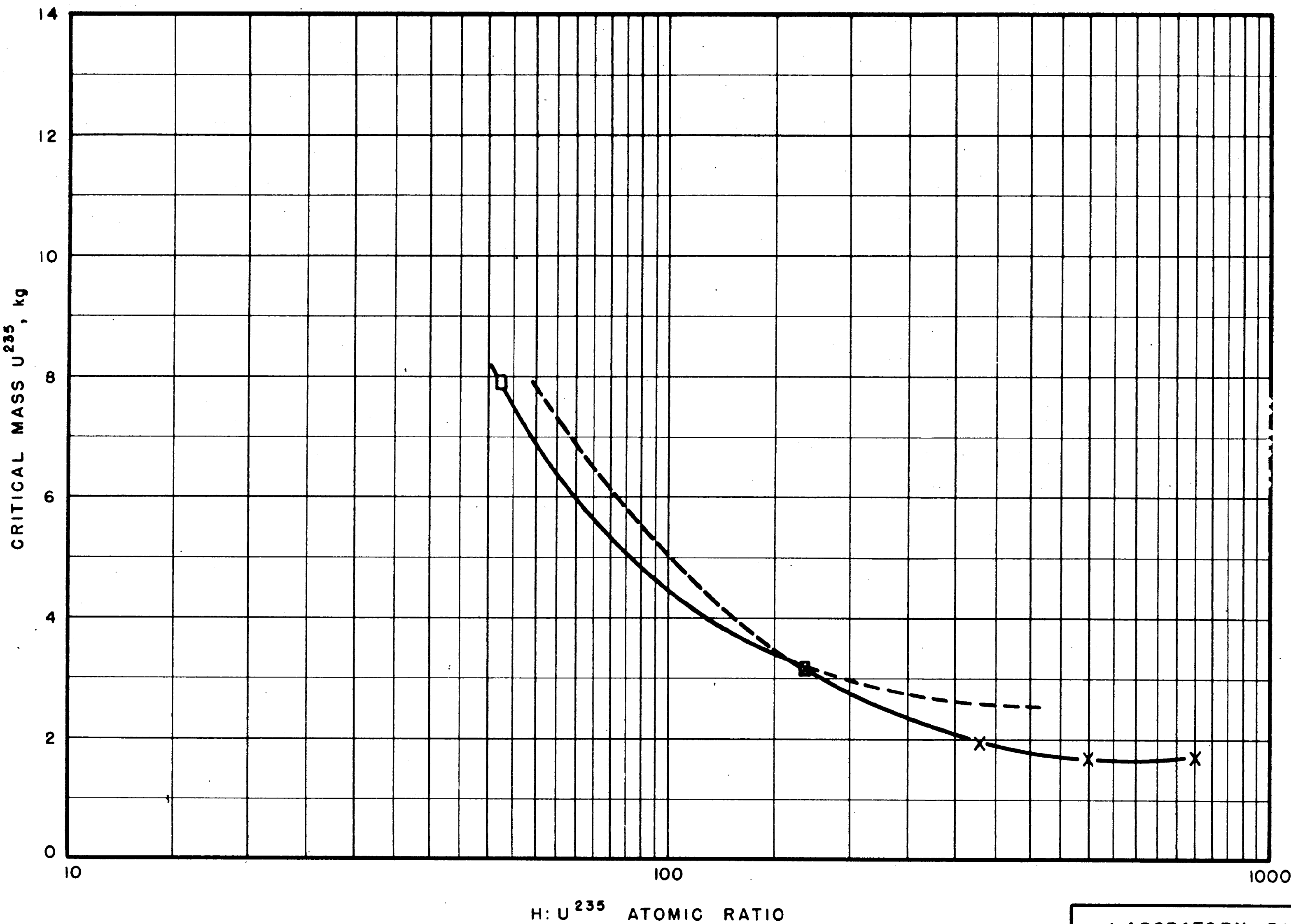
□ ------ *10"*

X ------ *15"*

Aluminum reactor
No reflector

LABORATORY DIVISION	
CRITICAL HEIGHT Vs MODERATION	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN *B. Hammer*	APPV'D *ACC*
DATE: MAR. 24, 1949	DWG NO: LD-B780

FIGURE 23



REACTOR DIAMETER:

□------ 10"

X------ 15"

Aluminum Reactor

No Reflector

LABORATORY DIVISION	
CRITICAL MASS OF U^{235} VS MODERATION	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN B. Hammer	APPV'D ABe
DATE: MAR. 25, 1949	DWG NO: LD-B782

FIGURE 24

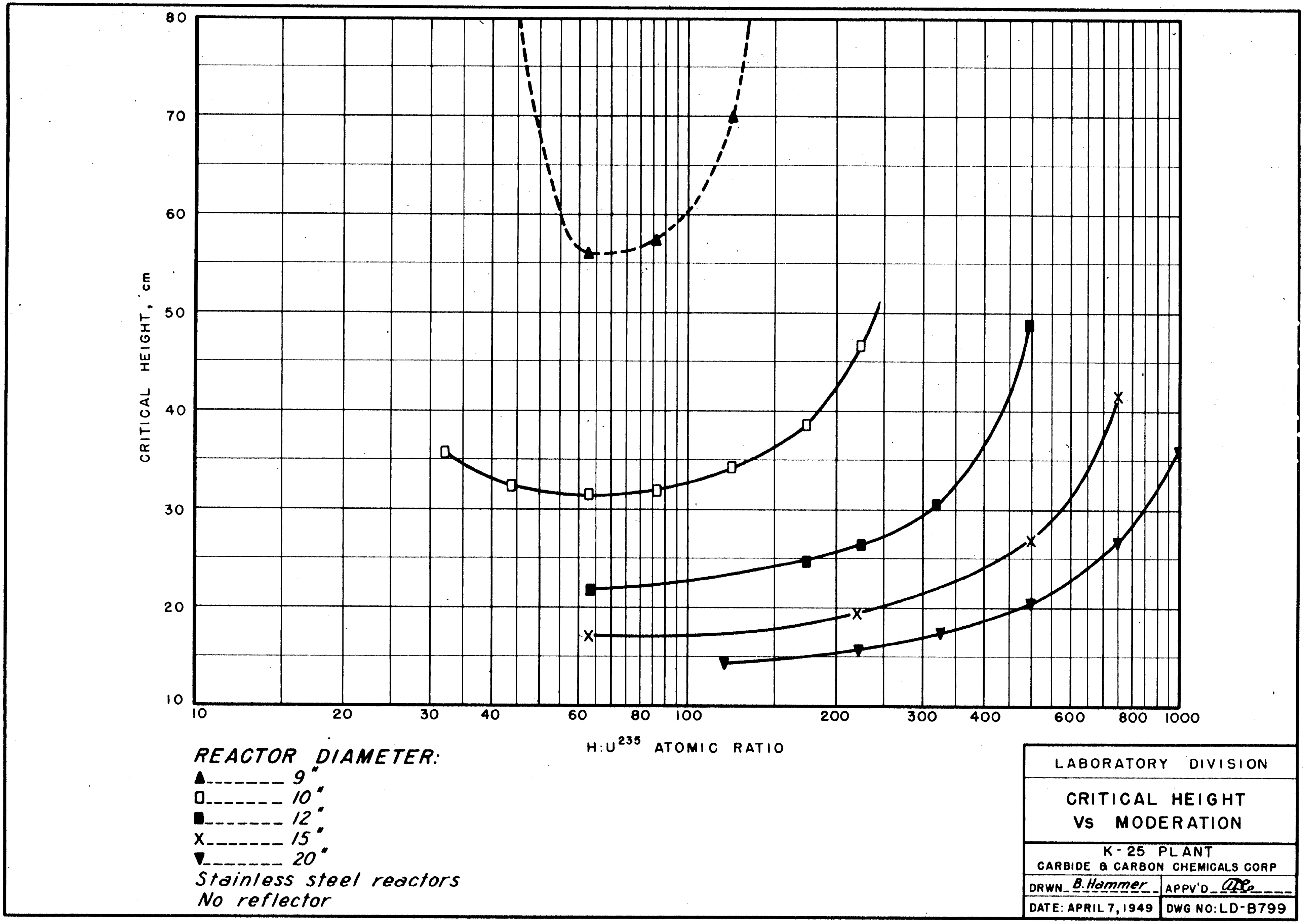
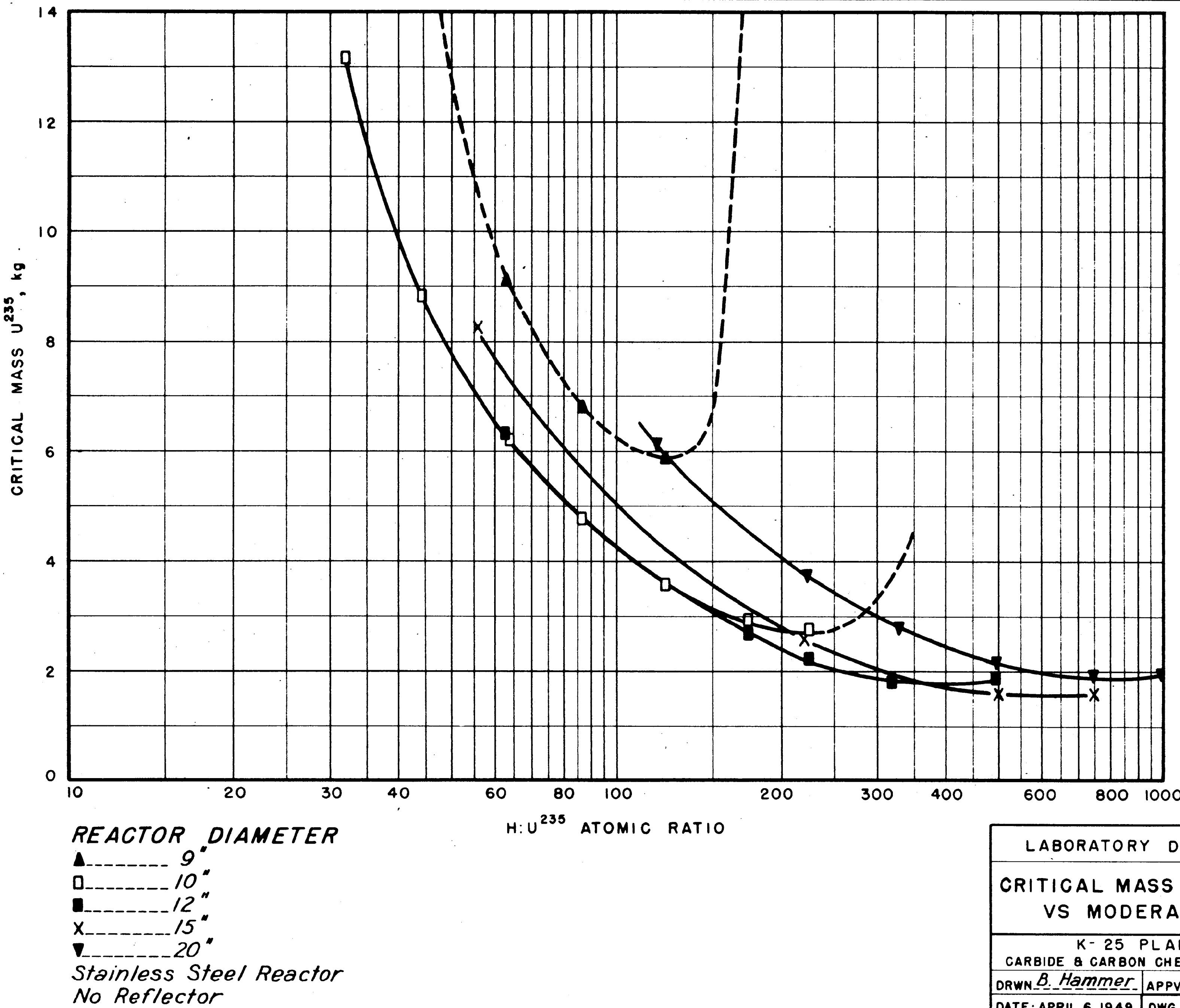

80
70
60
50
40
30
20
10
CRITICAL HEIGHT, cm
10
20
30
40
60
80
100
200
300
400
600
800
1000
H:U235 ATOMIC RATIO
REACTOR DIAMETER:
▲ 9"
□ 10"
■ 12"
X 15"
▼ 20"
Stainless steel reactors
No reflector
LABORATORY DIVISION
CRITICAL HEIGHT Vs MODERATION
K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP
DRWN. B. Hammer
APPV'D
DATE: APRIL 7, 1949
DWG NO: LD-B799

FIGURE 25



LABORATORY DIVISION

CRITICAL MASS OF U^{235} VS MODERATION

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN B. Hammer | APPV'D

DATE: APRIL 6, 1949 | DWG NO: LD-B796

FIGURE 26

estimates of the critical height and mass of the nine inch reactor. These values were obtained by extrapolation of the multiplication curves. All the data obtained under these conditions are listed in Tables 13 and 14 of the Appendix.

VI. DISCUSSION OF RESULTS

A. Moderation

Each critical height-moderation curve, for a particular reactor, shows a minimum at a H:U-235 atomic ratio of about fifty. The shape of the curve can be considered as resulting from several effects of increasing the water content of the fuel. Among these are (1) an increase in the hydrogen content or moderation resulting in the thermalization of more neutrons within the core and, consequently the loss of fewer by escape, an effect which decreases the critical mass. However, it should be pointed out that dilution beyond an H:U-235 ratio of approximately 100 does not materially increase the number of hydrogen atoms per unit volume of solution so the degree of thermalization per unit volume is essentially constant in this region. (2) An increase in the hydrogen content with increased neutron absorption which increases the critical mass. (3) A decrease in the density of the fuel, that is, a wider dispersion of the U-235, which increases the critical mass and (4) the necessity, with the decreased density, of supplying a greater volume of fuel per unit mass of U-235. This latter consideration is significant since these results were obtained with cylindrical reactors where, for a particular reactor, an increase in the volume of fuel means an increase in the core height. The result, in the case of filling cylinders which are long compared to their diameter, is that of adding successive increments of fuel into positions increasingly remote from the center of the reactor and which, therefore, contribute relatively less to the reactivity than would an equal mass placed at the center of the reactor. This increase in volume, however, results in a greater probability of capture of a neutron by a U-235 nucleus before leakage can occur, a small and competing process. In the limiting case, with cylinders of diameters small compared to their lengths, further increases in length do not contribute significantly to the reactivity leading to the concept of "always safe" pipes. A curve for one reactor is the resultant of these several effects, some of which are competitive. For instance, in Fig. 19 with a stainless steel reactor, 8 inches in diameter, as the atomic ratio is increased from thirty to fifty, by decreasing the chemical concentration, the reactor height at criticality decreases and the critical mass decreases. The mass change is shown in Fig. 20. This decrease in volume, and mass, is due to the predominance of the increase in moderation. As further dilution is made, the volume increases and the mass decreases until an atomic ratio of about 250 is reached. In the range H:U-235 = 50 to 250 the increased moderation further decreases the mass required, however, the decrease in density necessitates a greater volume of solution to contain the uranium. At an atomic ratio greater than 250 those factors which increase the mass, such as decreased density, increased hydrogen content and unfavorable geometry, become effective and the volume and mass both increase with further addition of water.

In the results reported here there is some uncertainty in the extrapolation of the critical mass and height curves but an endeavor has been made to keep them internally consistent and conservative. It is apparent from the curves that a reactor of a particular diameter will be critical at a finite height with the fuel having a range of moderations but may be sub-critical at infinite length with the fuel containing both more and less water.

B. Reactor Diameter

The investigation being reported here was partly directed towards determining the maximum diameter of a reactor which when filled with the uranyl fluoride solution to infinite height will remain sub-critical under the most favorable conditions. Since the dependence of critical mass and critical height on reactor diameter is of considerable interest, an endeavor was made to extend measurements with each reactor to a chemical concentration with which it was impossible to achieve criticality or until the program was limited by available U-235 or by apparatus dimensions. The curves showing the relations between moderation and critical height and critical mass have been extrapolated beyond experimentally measured critical conditions in a manner determined by these noncritical experiments. It is obvious that neither the reactor diameter nor the chemical concentration where changed continuously. Therefore, if a reactor ten inches in diameter was made critical at a particular moderation and a nine inch one was sub-critical at infinite length, it is not possible to comment with certainty on the probability of a $9\frac{1}{2}$ inch reactor always being sub-critical.

These geometric effects are also presented in Fig. 27 where the reciprocal of the multiplication has been plotted against the corresponding height for comparison of various water enclosed aluminum reactors at a fixed moderation. From this curve it is noted that a reactor of $5\frac{1}{2}$ inch diameter of any length is sub-critical while those of increased diameter become critical at successively lower heights*. Fig. 28 shows the corresponding data for stainless steel reactors without a water reflector.

The data can also be combined to show the dependence of critical height or critical mass on reactor diameter. In Fig. 29 is a plot of the height of fuel in water enclosed aluminum reactors as a function of their diameter for various degrees of moderation. Fig. 30 shows the corresponding relation for the water enclosed stainless steel reactors. It is to be noted again that, as the water content is increased, the critical height of a reactor goes through a minimum at an H:U-235 atomic ratio of about fifty. Each of these curves becomes asymptotic to a value of the height and to a value of the diameter and shows two limiting geometric conditions for the particular uranium solution. The asymptote parallel to the ordinate describes the cylinder

---

* It should be noted that the abscissa of some of these curves have been abnormally compressed in order to include them all on a single graph.

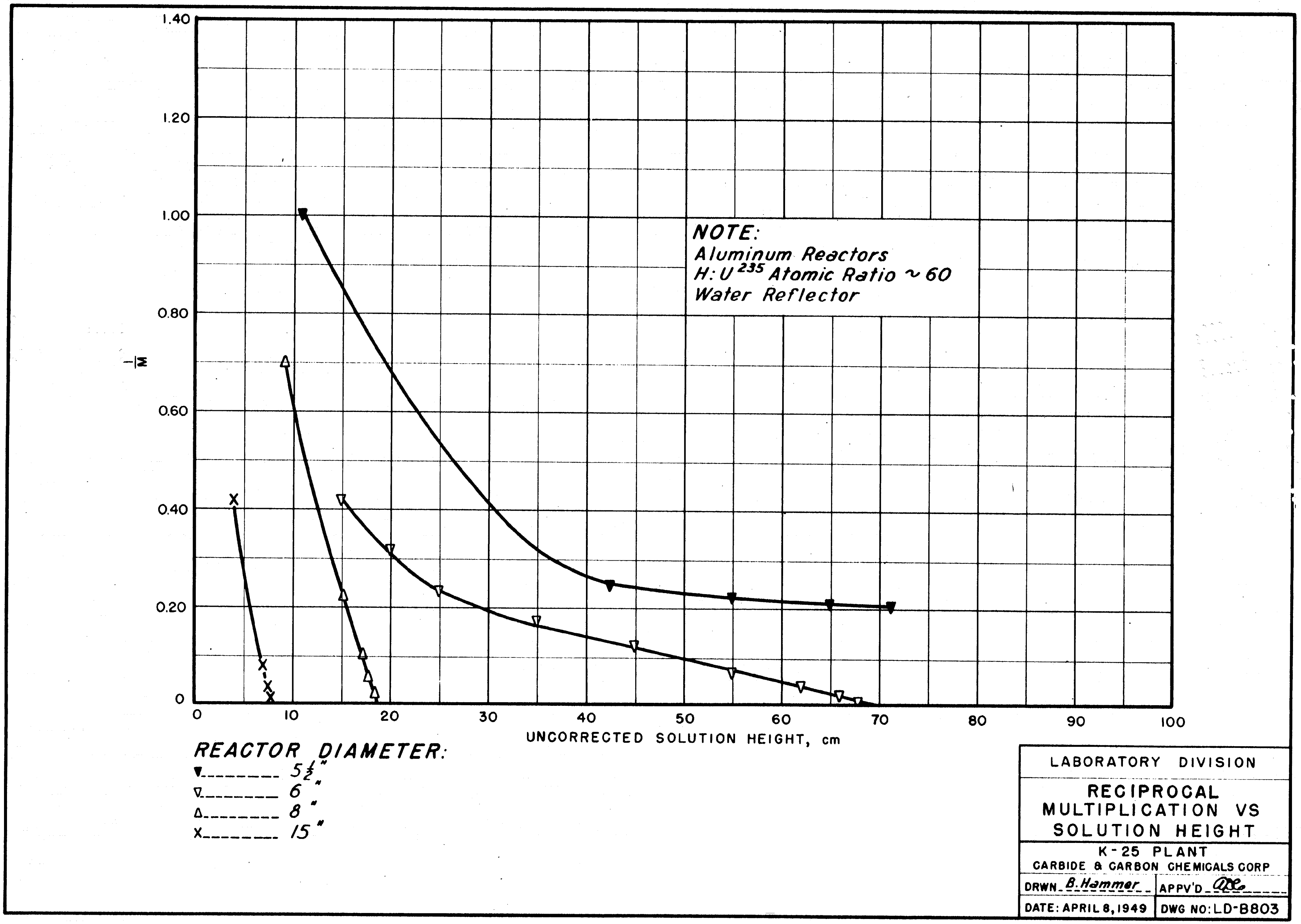
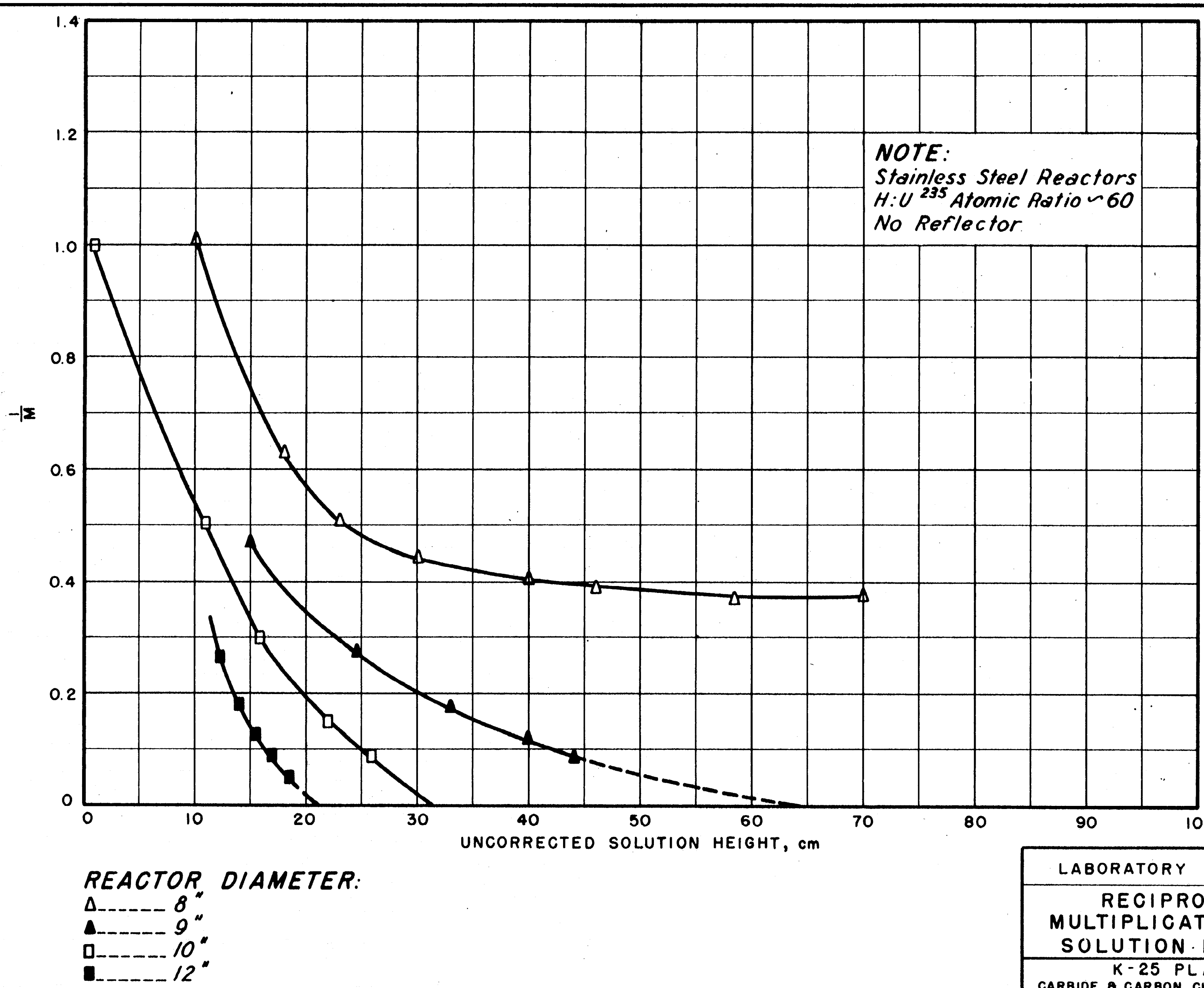

NOTE:
Aluminum Reactors
H:U235 Atomic Ratio ~60
Water Reflector
1/M
UNCORRECTED SOLUTION HEIGHT, cm
REACTOR DIAMETER:
▼ 5½"
▽ 6"
△ 8"
X 15"
LABORATORY DIVISION
RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT
K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP
DRWN. B. Hammer
APPV'D
DATE: APRIL 8, 1949
DWG NO: LD-B803

FIGURE 27



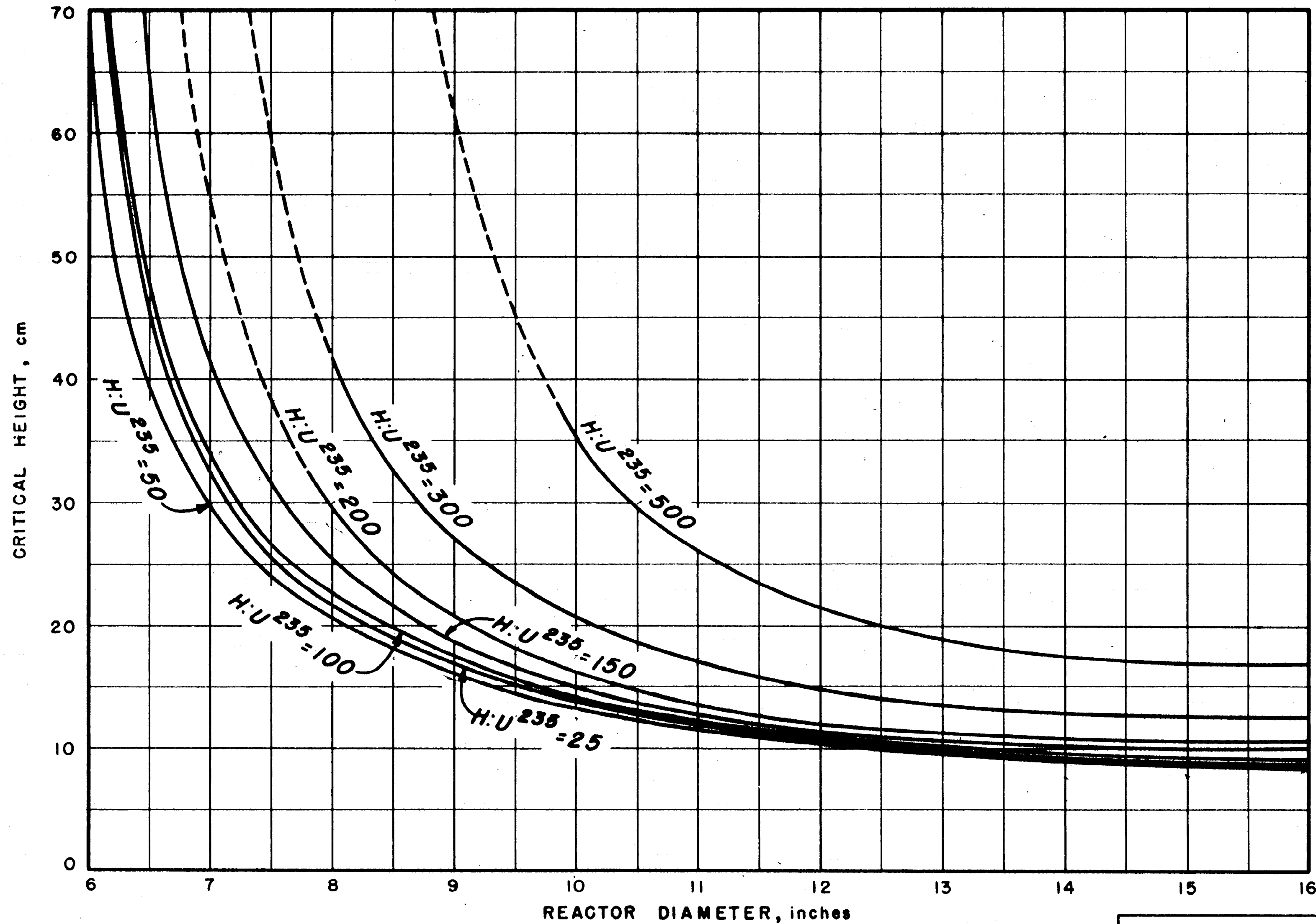
LABORATORY DIVISION

RECIPROCAL MULTIPLICATION VS SOLUTION HEIGHT

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN B. Hammer	APPV'D [illegible]
DATE: APRIL 7, 1949	DWG NO: LD-B801

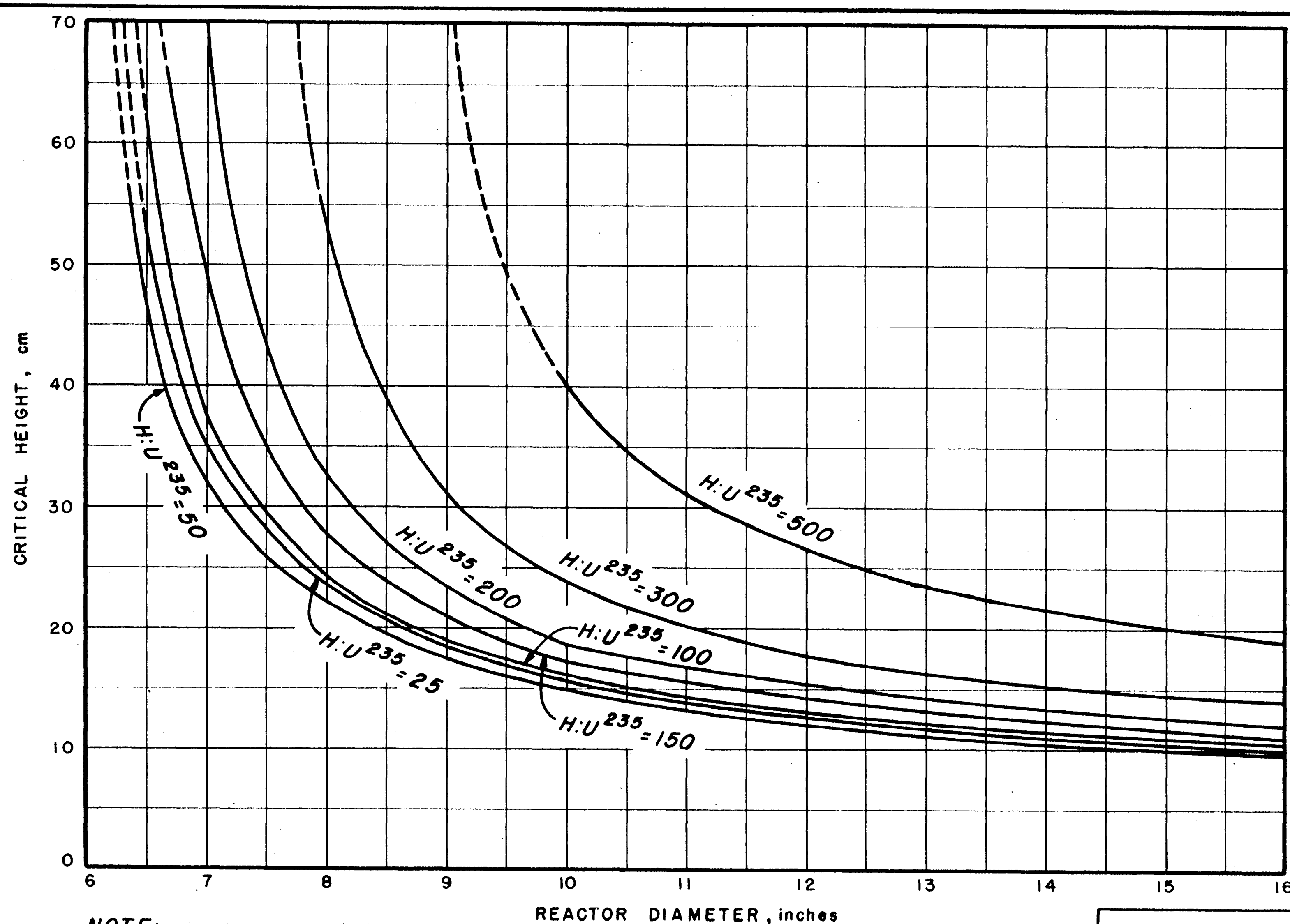
FIGURE 28



NOTE:
Aluminum Reactors
Water Reflector

LABORATORY DIVISION	
CRITICAL HEIGHT VS REACTOR DIAMETER	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. B. Hammer	APPV'D
DATE: APRIL 11, 1949	DWG NO: LD-B808

FIGURE 29



NOTE:
Stainless Steel Reactors
Water Reflector

LABORATORY DIVISION	
CRITICAL HEIGHT VS REACTOR DIAMETER	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN B. Hammer	APPV'D
DATE: APRIL 11, 1949	DWG NO: LD-8809

FIGURE 30

of maximum diameter which would be sub-critical at infinite length using materials of these experiments. The asymptote parallel to the abscissa gives the thickness of a slab of infinite size which would always be sub-critical under the conditions of the experiment. Selecting the optimum concentration it is noted in Fig. 31 that, for aluminum reactors, the "always safe" cylinder has a diameter less than 6 inches but greater than 5½ inches. The slab thickness is less well defined because of limitations imposed by the reactors available. The "always safe" slab appears to be at least 5 cm thick.

Similar graphs for stainless steel reactors without water reflector are shown in Fig. 32. The dimensions of the "safe" cylinders and slabs obtained from these data at optimum concentration are tabulated.

Table 2

"Always Safe" Dimensions

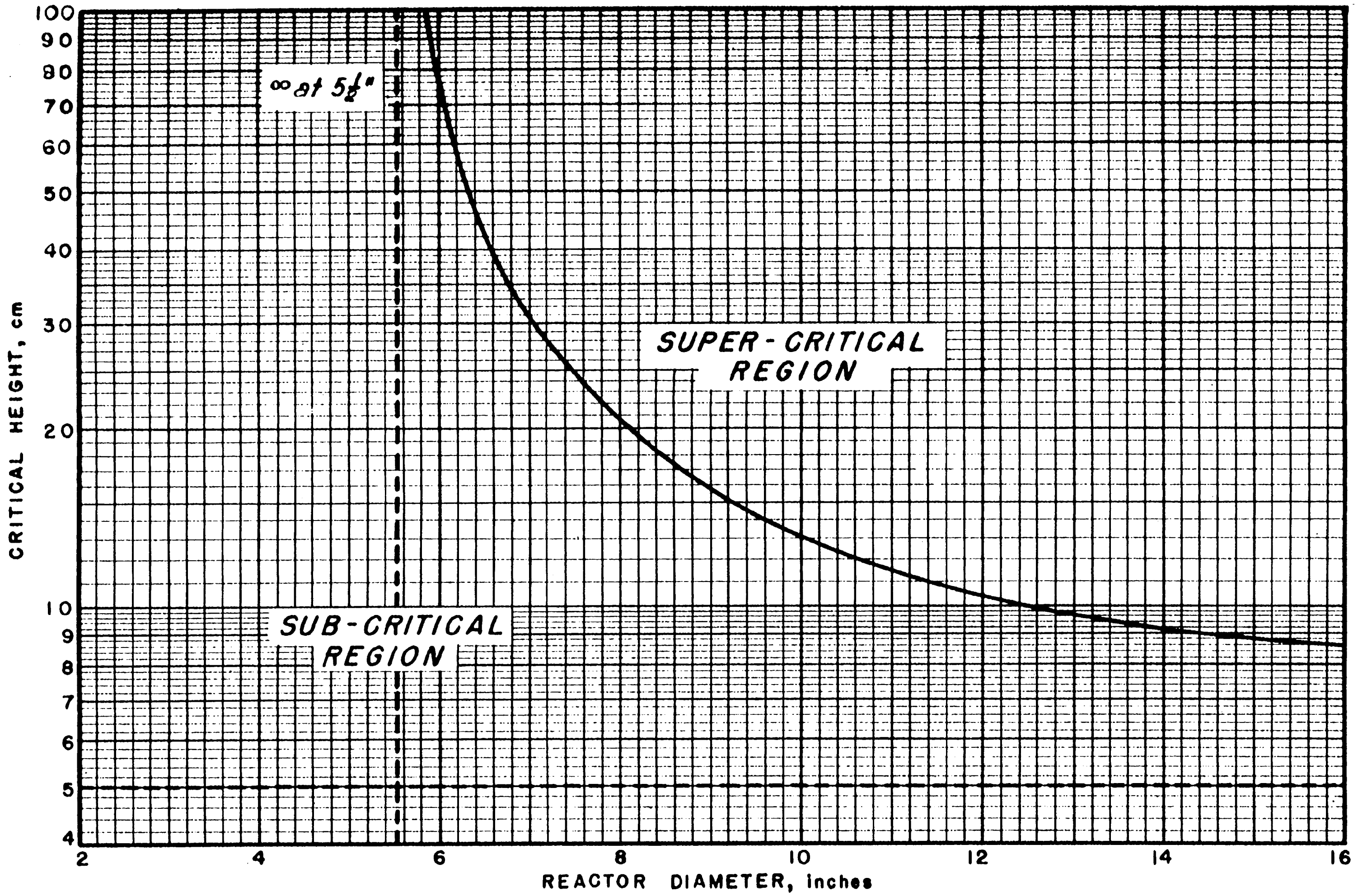
Reactor Material	Reflector	Cylinder Diameter inches	Slab Thickness cm
Aluminum	Water	5½	~ 5
Stainless Steel	Water	6	~ 5
Stainless Steel	Air	8	~10

The dependence of the critical mass on reactor diameter at constant moderation for water enclosed aluminum cylinders is shown in Fig. 33. It is to be noted that each curve has a minimum which was anticipated since the mass will be least in the geometrical configuration approximating equilateral cylinders. The minimum critical mass measured in this series of experiments was 893 gm U-235, and was contained, in a solution having an H:U-235 atomic ratio of 329, by a water enclosed aluminum cylinder 10 inches in diameter and 22.4 cm high. The minimum mass in a 15" reactor was somewhat greater. Since intermediate sized reactors were not examined, it is possible that a lower mass may be experimentally obtainable. It is to be expected that the minimum critical mass would be less were the fuel in a sphere of appropriate size, since a sphere has minimum surface to volume ratio. The mass-diameter relation for water enclosed stainless steel reactors is given in Fig. 34.

The minimum critical mass measured in each reactor has been plotted against the reactor diameter in Fig. 35.

C. Reactor Material

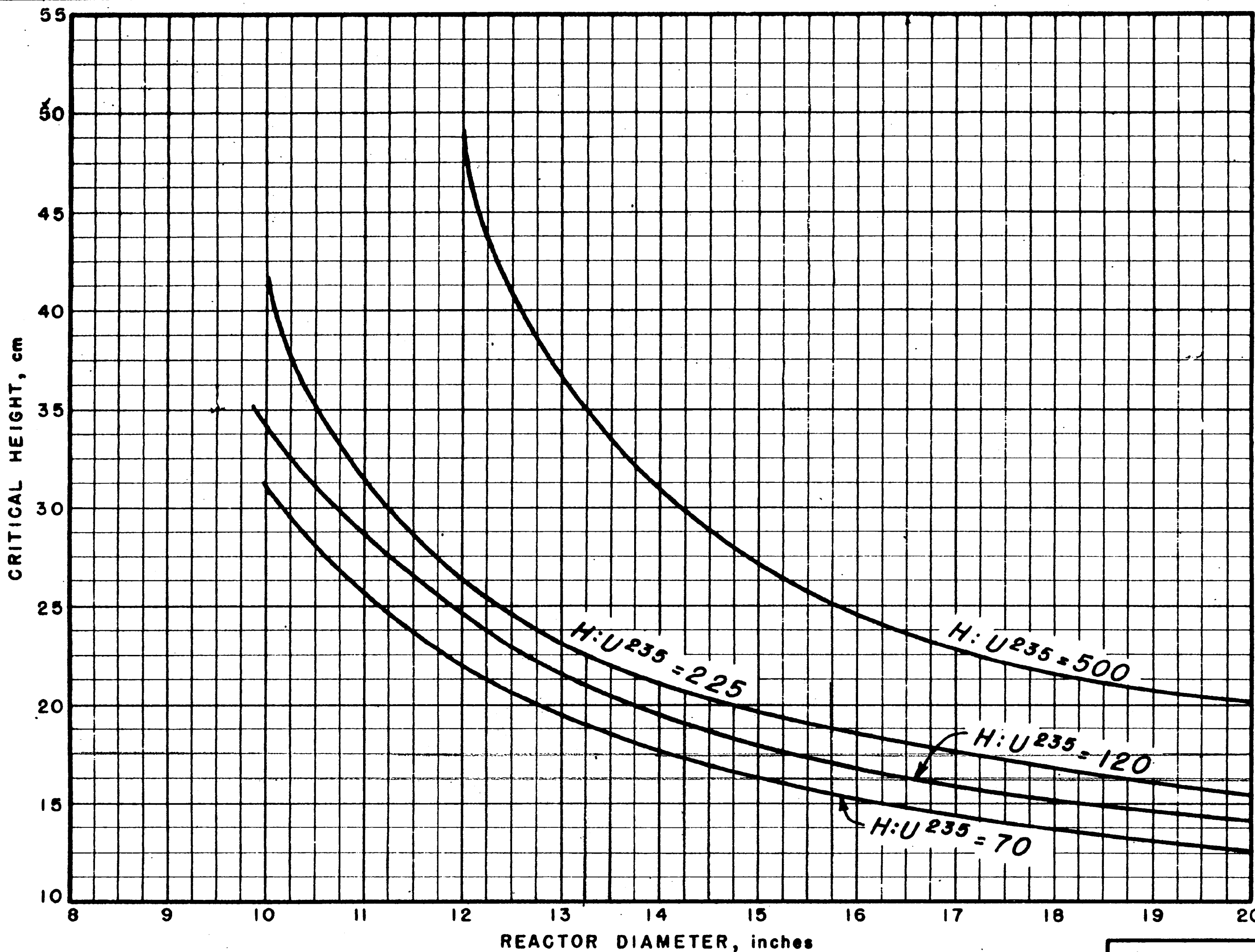
Reactors were fabricated from Type 3-S aluminum and Type 347 stainless steel and were used with fuel of a range of concentrations. A comparison of the results obtained with reactors of these materials enclosed in water are shown in Fig. 36. These data were obtained with reactors ten inches in diameter. The critical mass in the alumi-



NOTE:
Aluminum Reactors
Water Reflector

LABORATORY DIVISION
MINIMUM CRITICAL HEIGHT VS REACTOR DIAMETER
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP
DRWN F. C. Allen — APPV'D ABB
DATE: APR. 13, 1949 — DWG NO: LD-B818

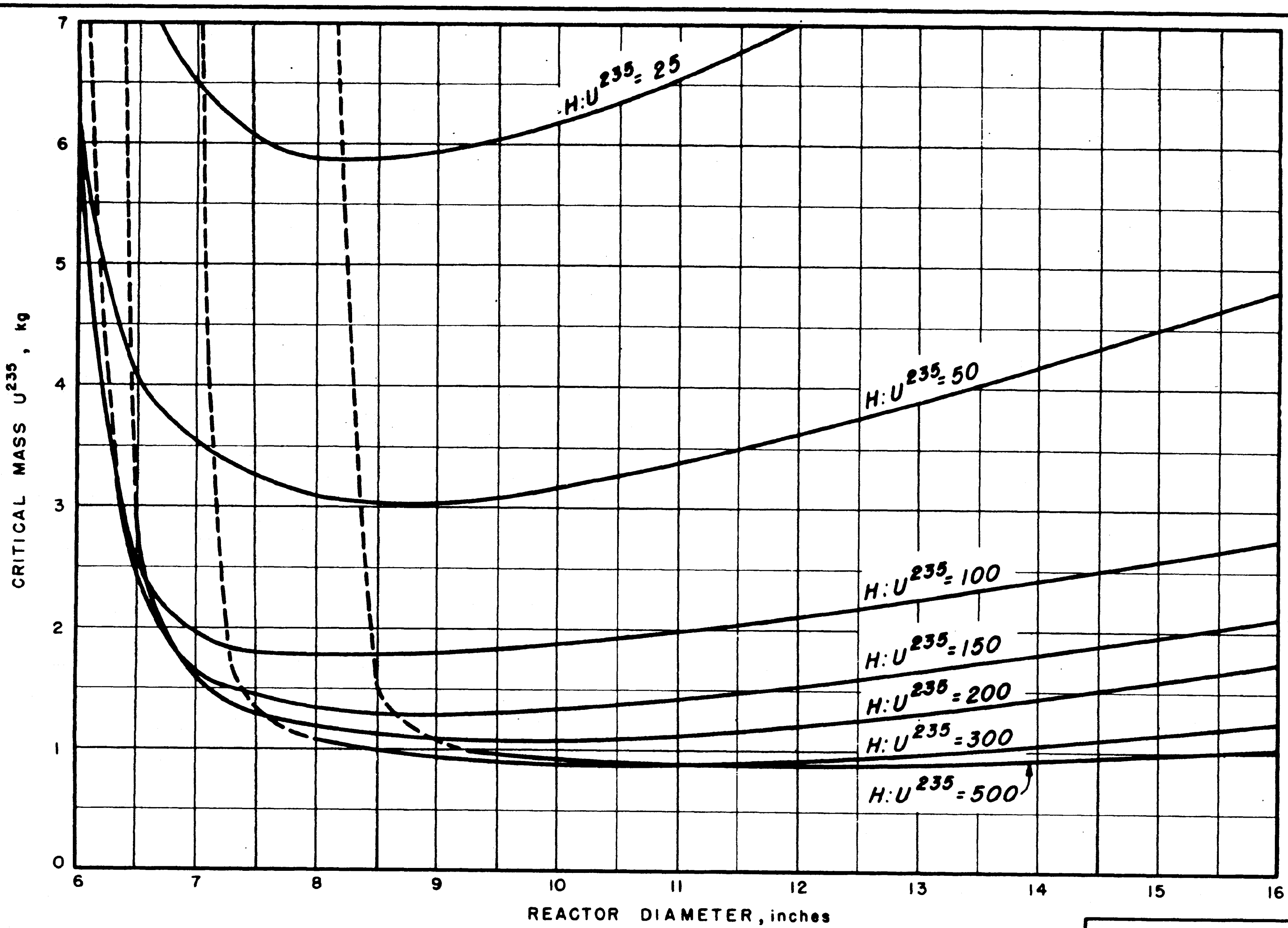
FIGURE 31



NOTE:
Stainless Steel Reactors
No Reflector

LABORATORY DIVISION
CRITICAL HEIGHT VS REACTOR DIAMETER
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP
DRWN F.C. Allen | APPV'D [illegible]
DATE: APR. 14, 1949 | DWG NO: LD-B821

FIGURE 32



NOTE:
Aluminum Reactors
Water Reflector

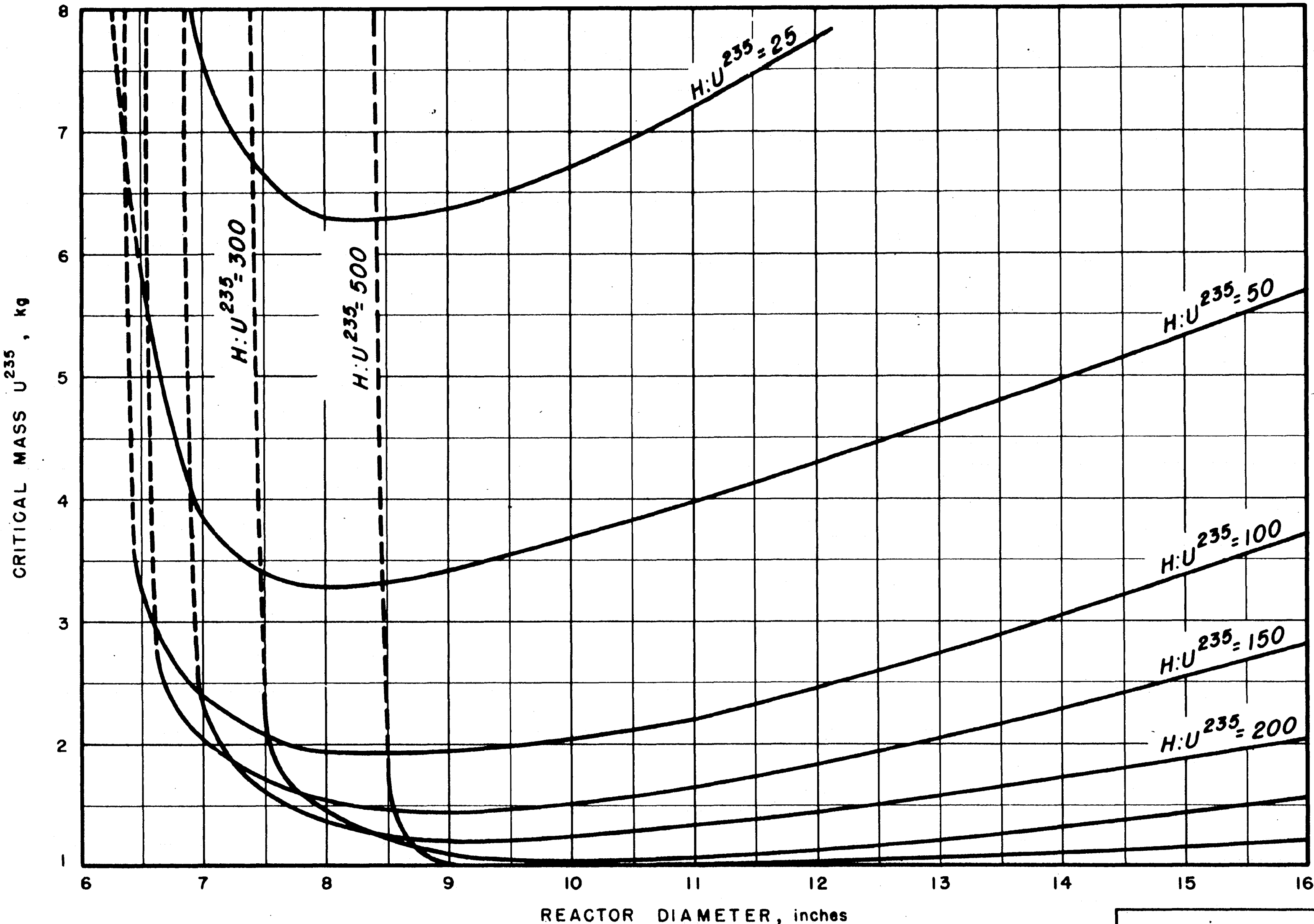
LABORATORY DIVISION

CRITICAL MASS OF U^{235} VS REACTOR DIAMETER

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN. B. Hammer	APPV'D ACL
DATE: APRIL 7, 1949	DWG NO: LD-B806

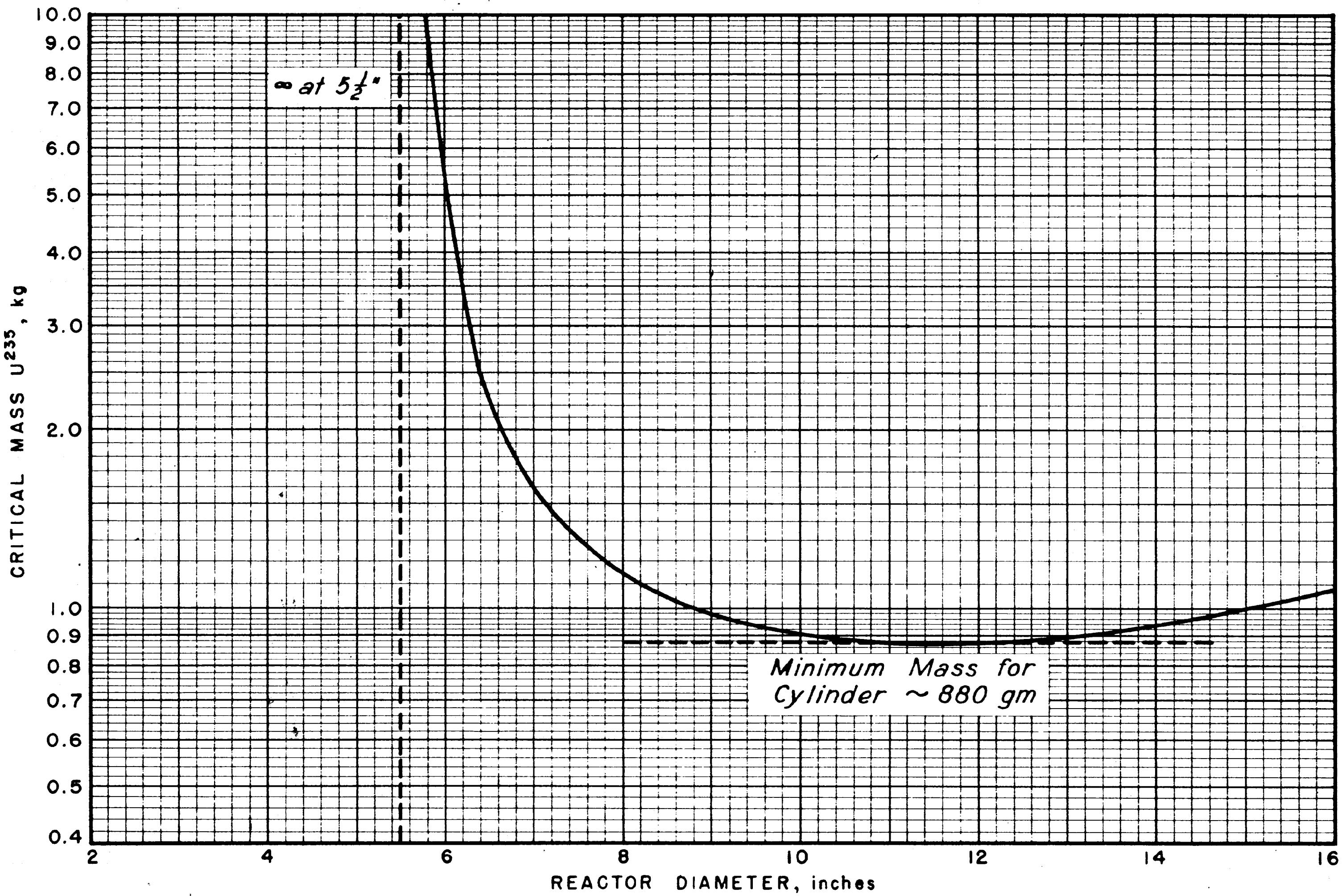
FIGURE 33



NOTE:
Stainless Steel Reactors
Water Reflector

LABORATORY DIVISION	
CRITICAL MASS OF U^{235} VS REACTOR DIAMETER	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. B. Hammer	APPV'D ABC
DATE: APRIL 7, 1949	DWG NO: LD-B805

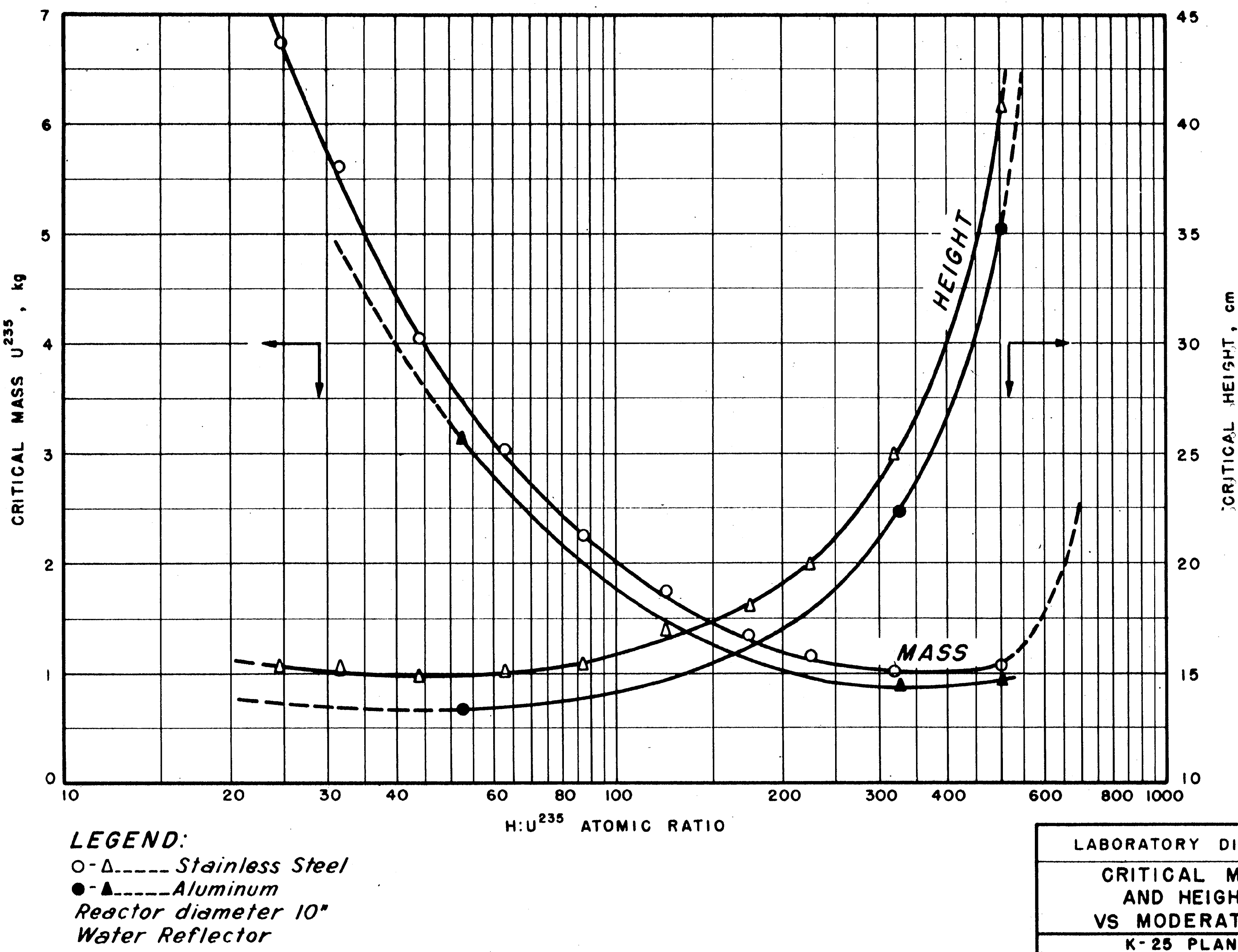
FIGURE 34



NOTE:
Aluminum Reactors
Water Reflector

LABORATORY DIVISION	
MINIMUM CRITICAL MASS VS REACTOR DIAMETER	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN *F.C. Allen*	APPV'D *OBC*
DATE: APR. 13, 1949	DWG NO: LD-B816

FIGURE 35



LABORATORY DIVISION

CRITICAL MASS AND HEIGHT VS MODERATION

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN B. Hammer	APPV'D
DATE: APRIL 13, 1949	DWG NO: LD-B817

FIGURE 36

num reactor is significantly less than that in the stainless steel due to the absorption by the components of the stainless steel of the thermal neutrons reflected by the water.

A similar comparison is made between ten inch diameter reactors without water reflector in Fig. 37. The difference between the two materials is significant. In other instances, with reactors of greater diameter the critical mass with the stainless steel reactor was only slightly less than that obtained with aluminum under the same conditions. The above effect is attributed to the greater reflection of neutrons by the stainless steel than by the aluminum.

D. Reflector

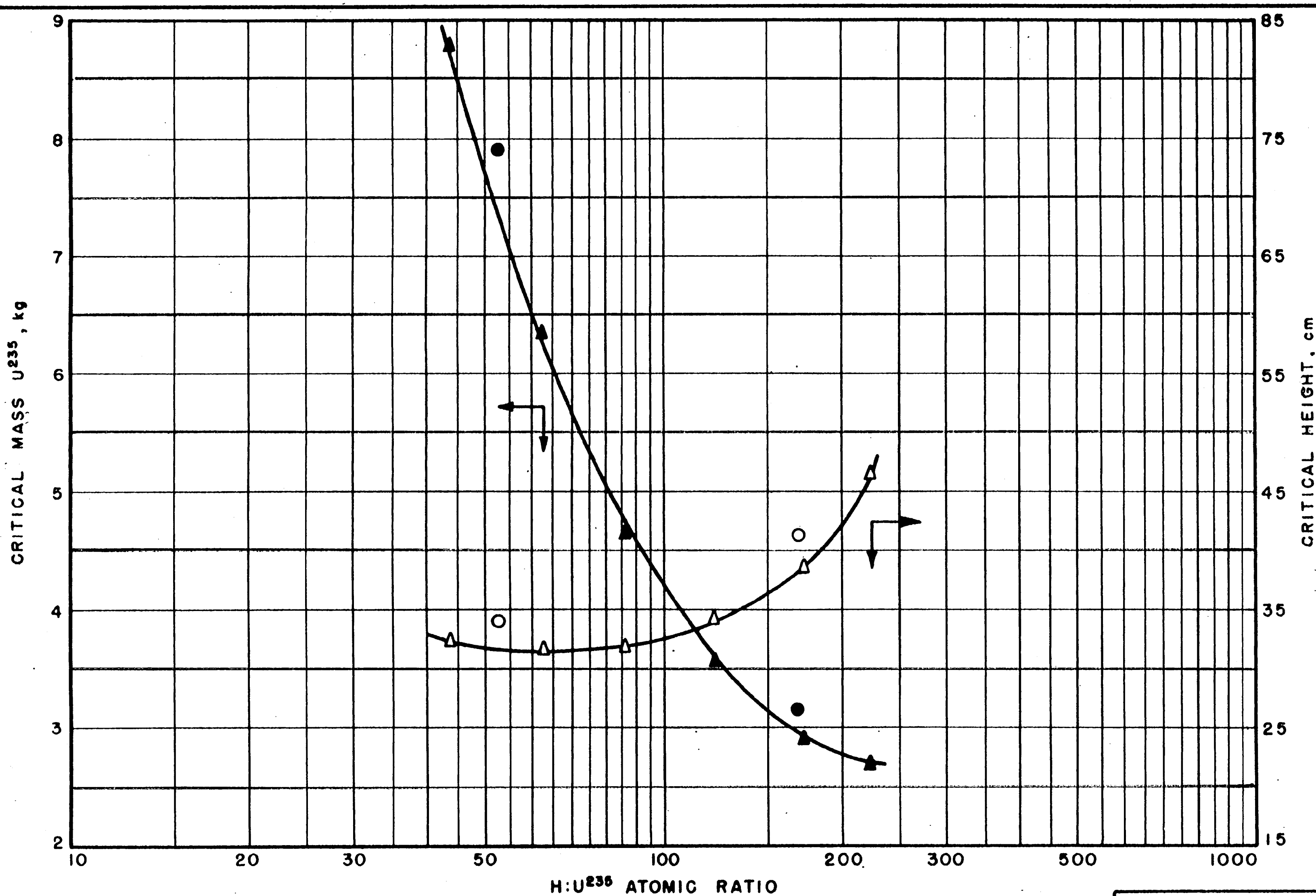
A limited amount of data were obtained on the effect of the reflector on critical conditions. The cases examined with stainless steel reactors were, a) with complete water enclosure, b) with cadmium sheet of thickness 0.44 gm Cd/cm^2 between the reactor and the water, c) without the water reflector. The data obtained from a 12 inch stainless steel reactor are shown in Fig. 38 where the critical mass and critical height for each is plotted as a function of moderation. It is observed that the absence of the water reflector approximately doubles the critical mass. The interposition of cadmium between the reactor and reflector increases the critical mass by about 50%.

The effect of the water reflector is also shown in Fig. 39 where the ratio of the critical masses with and without reflector is plotted against the diameter of the reactor. For reactors of small diameter the number of neutrons reaching the surface is a relatively large fraction of the total. If a reflector for these neutrons is provided it is more effective for reactors of small diameter than for larger ones. Therefore cylinders of small diameter which have no good reflector around them require a considerably increased U-235 content to become critical. In larger reactors, on the other hand, relatively fewer neutrons reach the surface so the masses with and without a reflector are more nearly equal.

The results of a single experiment in which the critical height of fuel in an aluminum reactor was determined as a function of the height of water reflector surrounding it are shown in Fig. 40 as a matter of general interest. It gives a qualitative picture of the value of the top reflector and the relative ineffectiveness of additional amounts of water reflector at a height of fifteen or more centimeters above the top surface of the fuel. The relation between fuel height and reflector height has not been determined under a sufficient number of experimental variables to permit any generalized conclusion to be drawn.

E. Accuracy and Precision

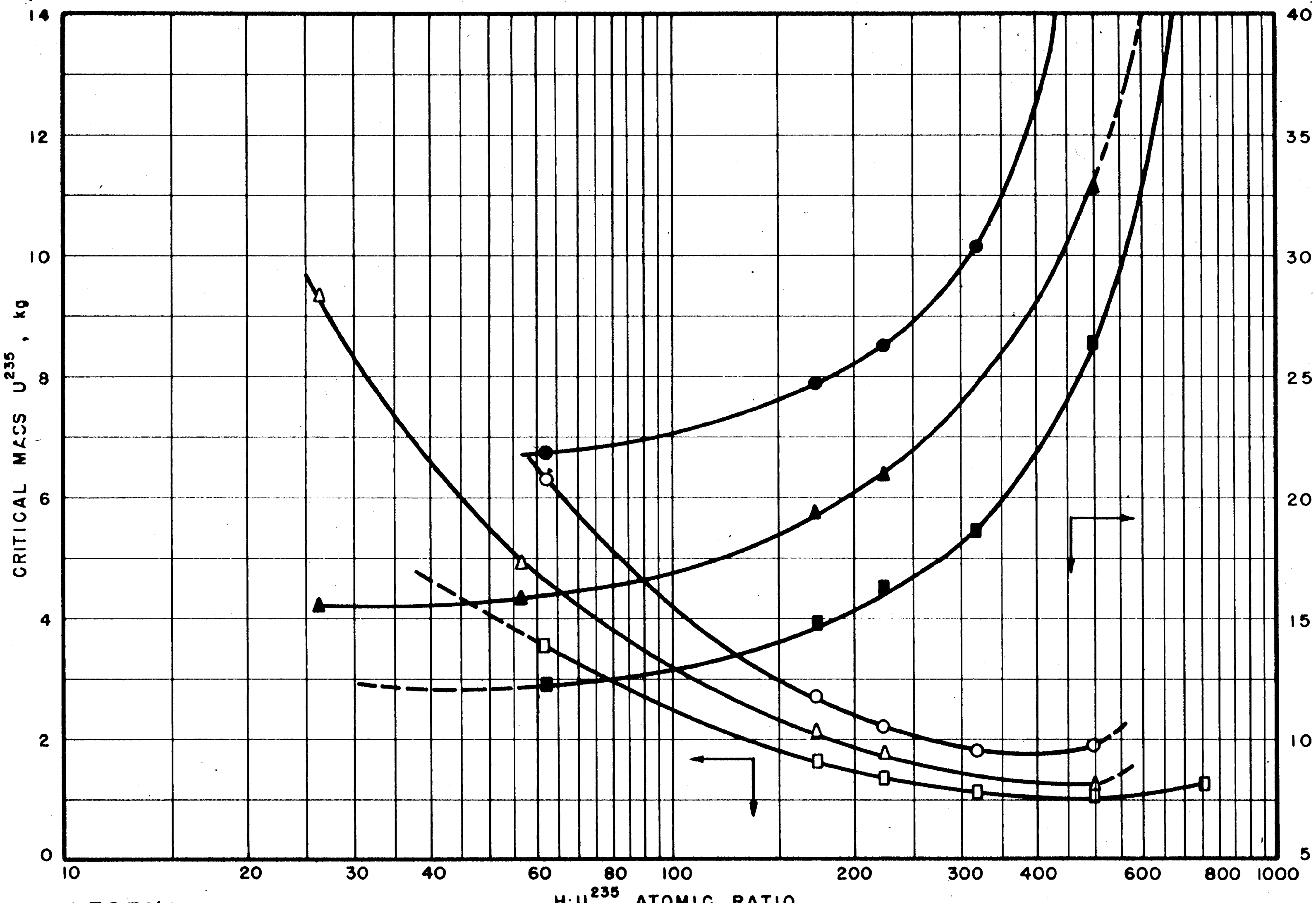
It is appropriate to consider the accuracy with which the results of these experiments are known and the reproducibility of the measures. An estimate of the overall accuracy of the critical masses and heights is ± 5% L. E. Some of the uncertainties will now be noted.



NOTE:
Reactor Diameter 10"
No Reflector
▲-△ ----- *Stainless Steel*
●-○ ----- *Aluminum*

LABORATORY DIVISION	
CRITICAL HEIGHT AND MASS VS $H:U^{235}$ ATOMIC RATIO	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN F.C. Allen	APPV'D ACC
DATE: APR. 14, 1949	DWG NO: LD-B822

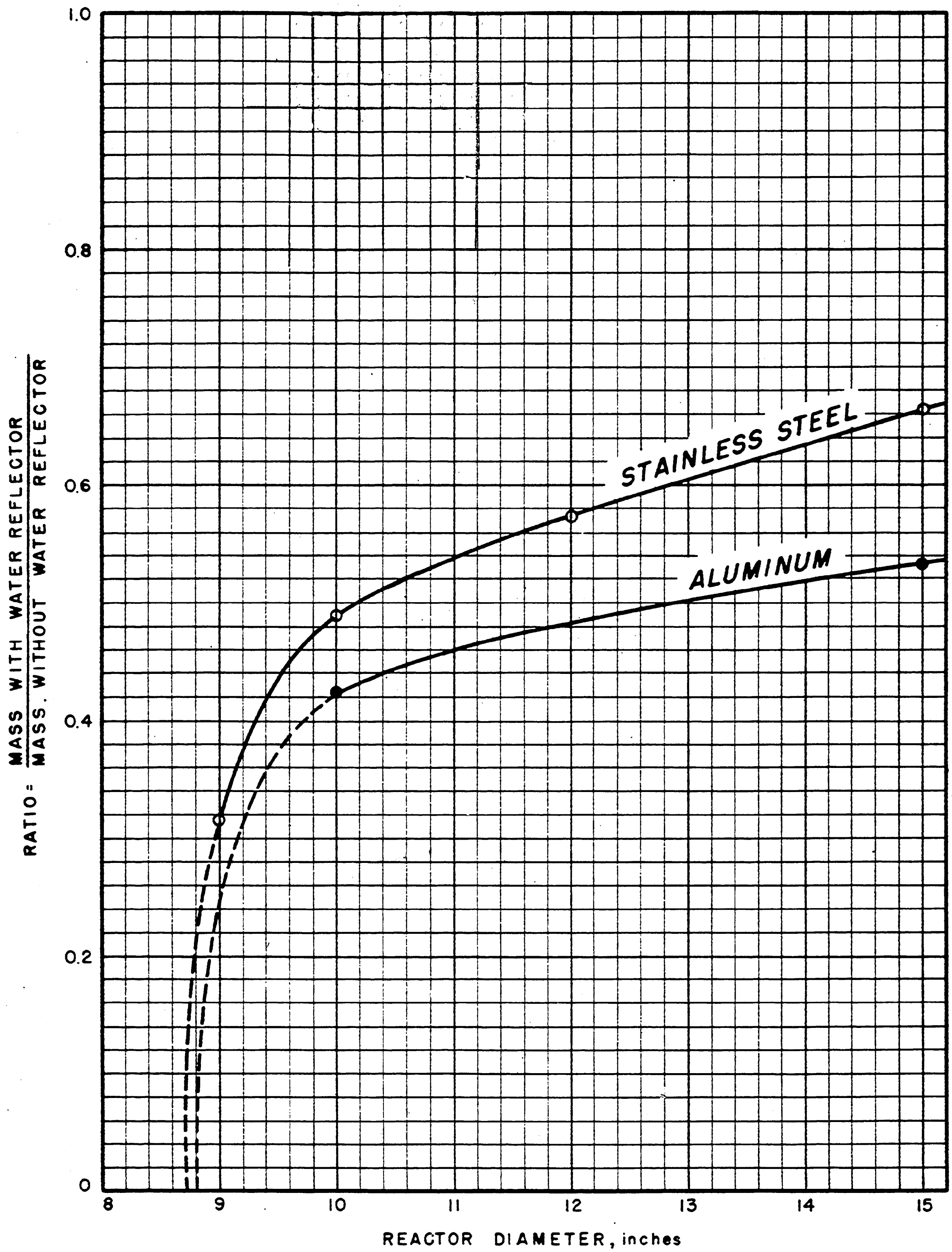
FIGURE 37



LEGEND:
○ - ● .... No reflector
△ - ▲ .... Water reflector - Cadmium shielded
□ - ■ .... Water reflector
Reactor diameter = 12"

LABORATORY DIVISION	
CRITICAL MASS & HEIGHT VS H:U^{235} ATOMIC RATIO	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. B. Hammer	APPV'D. [illegible]
DATE: APRIL 14, 1949	DWG. NO: LD-B819

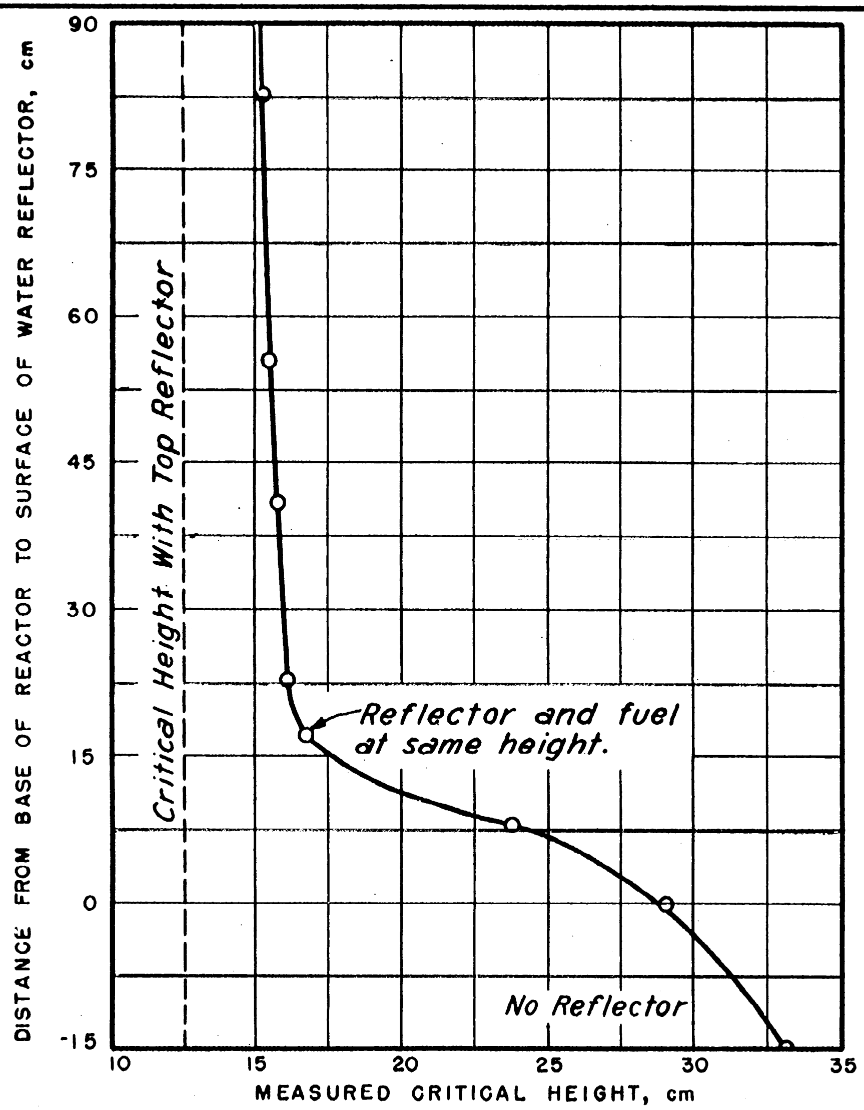
FIGURE 38

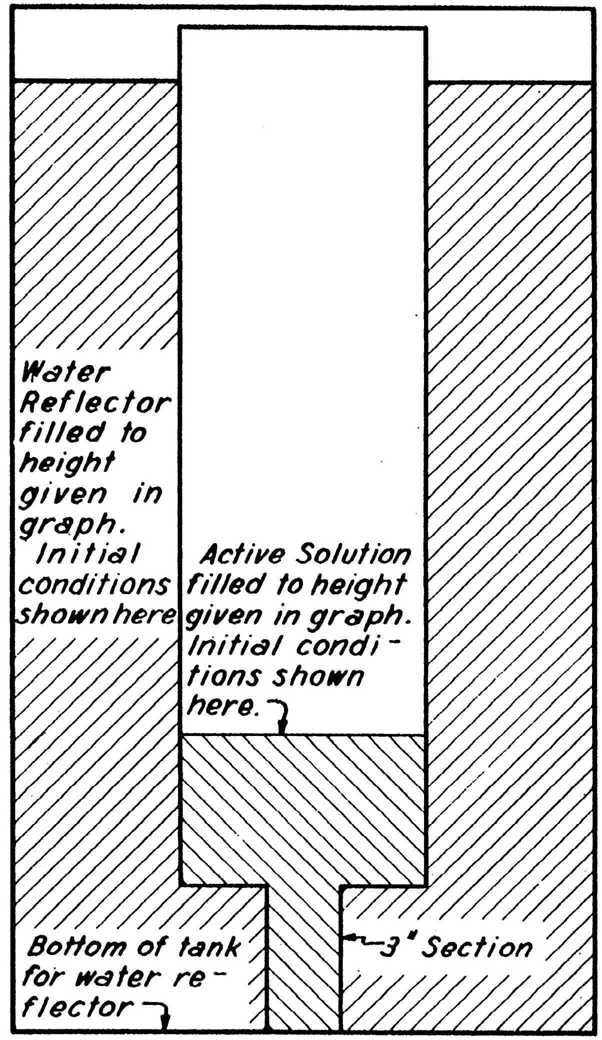


NOTE:
H:U^{235} Atomic Ratio = 100 for various reactor diameters.

LABORATORY DIVISION
RATIO OF CRITICAL MASSES WITH AND WITHOUT WATER REFLECTOR
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP
DRWN *B. Hammer* — APPV'D *[illegible]*
DATE: APRIL 12, 1949 — DWG NO: LD-B814

FIGURE 39





NOTE:
Experiment #209
$H:U^{235} = 52.9$
No top reflector
10" diameter Aluminum reactor
Water Reflector

LABORATORY DIVISION	
MEASURED CRITICAL HEIGHT VS HEIGHT OF WATER REFLECTOR	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN B. Hammer	APPV'D. ADK
DATE: APRIL 12, 1949	DWG NO: LD-B811

FIGURE 40

1. Volume of Solution

The height of uranyl fluoride solution in a reactor at criticality under fixed conditions was reproducible to ± 0.1 cm. However, the accuracy of the values is not greater than ± 0.2 cm because of scale zero variations due to constructional irregularities. The actual diameters of the reactors were equal to the nominal values to one percent.

2. Mass of U-235

The mass of U-235 was determined from the volume of the UO_2F_2 solution, its specific gravity and a gravimetric analysis of uranium in the solution, reported as weight percent. The specific gravity was not corrected for temperature and may be in error by a few tenths of a percent. The analysis error, including sampling, is estimated at ± 2% L. E.

3. Feed Line

Fuel was fed into the reactors through a vertical section of three inch pipe as shown in Fig. 7. The purpose of the large diameter was to permit rapid disassembly in case of emergency. When filled, each reactor had, therefore, appended to its bottom a column of fuel three inches in diameter and approximately one foot long. The sides of this section were partially surrounded by water in appropriate experiments. It was recognized that the uranium solution in this appendage contributed to the reactivity, both as fuel and as reflector, making the critical mass obtained from the volume contained in the reactor erroneous. A correction term was evaluated by duplicating this geometric perturbation at the top of the reactor in the following manner. A height of solution at criticality in a seven inch reactor, water enclosed, was first determined in the usual way with the small water tank in contact with the top surface. For this top water tank, which was six inches deep, was then substituted one 15 inches deep having an axial opening three inches in diameter. The tank was filled with water equivalent to the amount of feed line which was water enclosed. The experiment was repeated with other conditions remaining the same and the height of fluoride solution in the seven inch diameter section at criticality was redetermined when the surface of the solution in the three inch hole in the top tank was 30 cm above the top of the seven inch diameter column of liquid. The arrangement is shown in Fig. 41. The resulting height, h_2, was less than h_1, that normally measured, by an amount attributed to the contribution to the reactivity by this top appendage. The difference in critical height, $h_1 - h2$, represents, in a seven inch diameter reactor, a volume of fuel equivalent to the effective part of the contents of the top three inch section.* It was assumed that the similar extension to the bottom of the seven inch liquid cylinder contributed equally to the system and, therefore, that it was necessary to increase the normally

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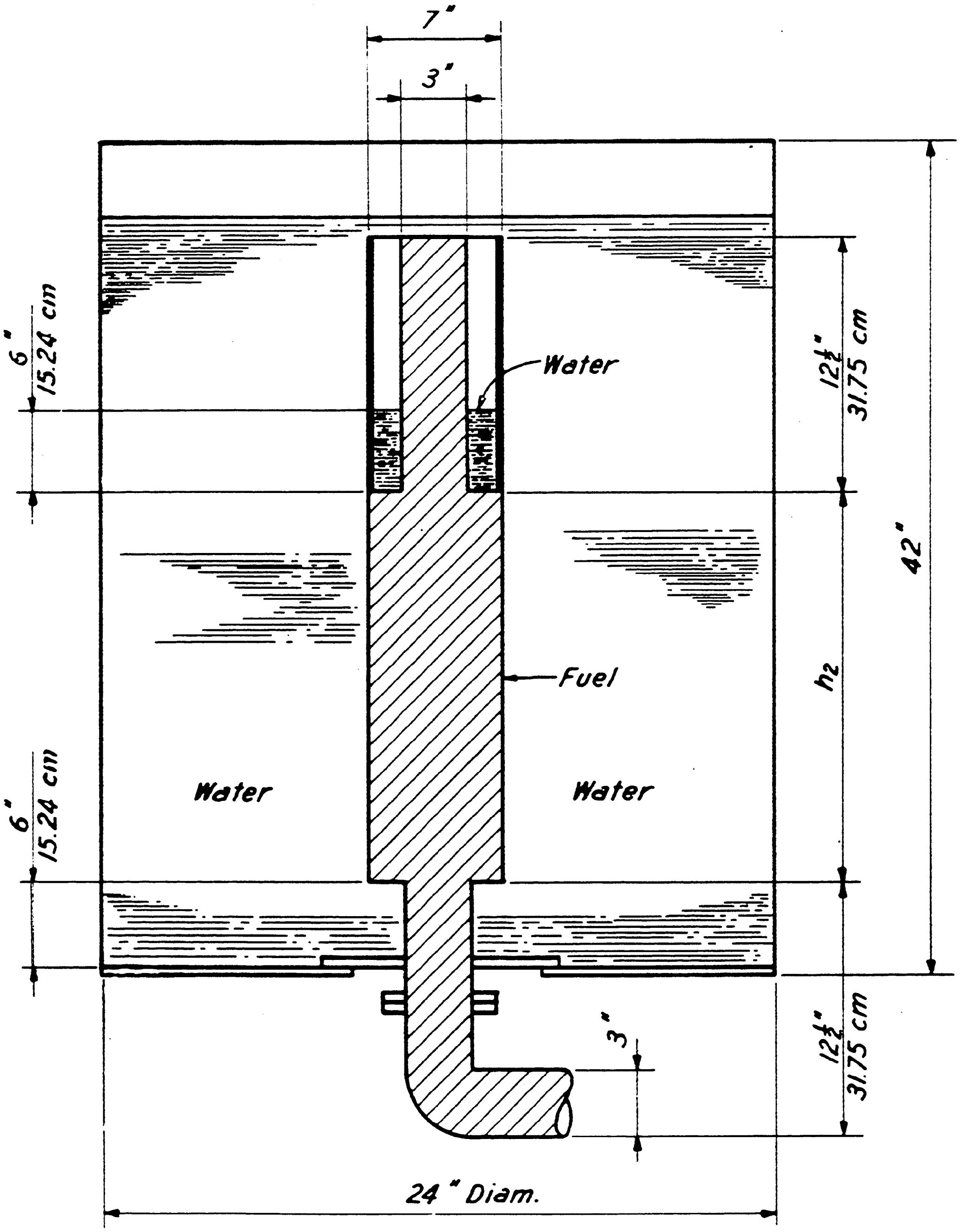
* It was found that the height of this top appendage, three inches in diameter, could be reduced to 15 cm before the reactivity decreased, showing that at greater heights the material in this small section does not contribute further to the reactor either as fuel or as reflector.



LABORATORY DIVISION

APPARATUS FOR MEASURING END CORRECTION

K-25 PLANT
CARBIDE & CARBON CHEMICALS CORP

DRWN B. Hammer	APPV'D
DATE: APRIL 14, 1949	DWG NO: LD-8820

FIGURE 41

measured height by $(h_1 - h_2)$. Height corrections for reactors of other diameters were determined on the assumption that the volume correction was the same for all.

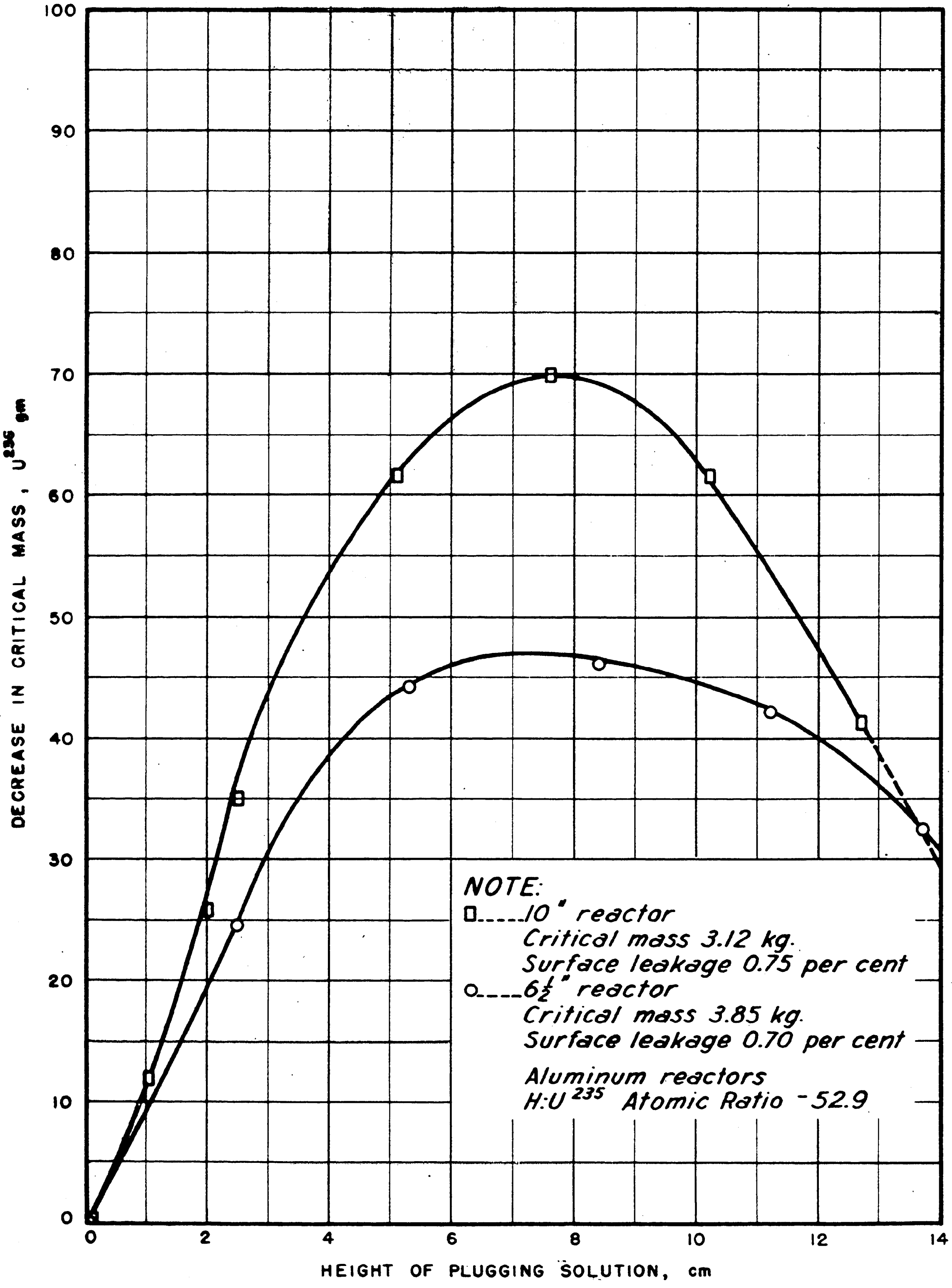
In the course of a subsequent series of experiments it has been possible to measure critical heights in reactors with essentially flat bottoms. The values of the above corrections have been verified by comparison of the later measurements with results reported here.

4. Reflector

The accuracy of the results obtained from water-enclosed reactors will be affected by neutron leakage through the water reflector. Leakage could be due to an inadequate thickness of water surrounding the reactors and to holes in the reflector. A layer of water at least 10 cm thick was used in each experiment. In the course of a subsequent program it was possible to increase by 30% the thickness of the water enclosing the sides of the largest reactor, keeping other conditions constant. No significant difference was observed in the results.

In all water enclosed experiments the surface of the fuel was covered by a container of water six inches deep which was traversed by vertical tubes through which control devices could be inserted. Neutron leakage through these apertures was investigated by lowering the water container below the fuel surface, displacing some liquid into these openings and into the annulus at the perimeter of the reactor. The displaced liquid served as a reflector. As the bottom of the water container was lowered below the surface, the critical mass decreased until the height of solution in the aperatures was about 8 cm. Further lowering the container increased the critical mass of the system. These observations are interpreted as showing that the initially displaced fuel serves predominately as a plug in the holes in the reflector. However, when the height of this plug exceeds about 8 cm the increase in critical mass, which includes the uranium in the displaced solution, is due to the onset of less favorable geometrical arrangement of the fuel. A plot of the mass decrease in the system at criticality against the height of the solution displaced into the water tank aperatures is shown in Fig. 42. The decrease in critical mass in a 10 inch and in a $6\frac{1}{2}$ inch diameter reactor effected by introducing fuel into the openings in and around the top water tank was about 2% in each case and represents an estimate of the error introduced by leakage in typical experiments. The surface area through which the leakage responsible for the increase in mass could occur is about 0.7% of the total of each reactor.

The iron tank, 24 inches in diameter, which was coaxial with the reactors and contained the reflector water, was in place during the experiments with no reflector. Due to its proximity to the surface of the large reactors, this iron shell could possibly reflect neutrons into the fuel. At the end of the program the iron tank was removed and an experiment repeated with no observable change in the result.



LABORATORY DIVISION	
EFFECT OF PLUGGING PORTS IN TOP WATER REFLECTOR	
K-25 PLANT CARBIDE & CARBON CHEMICALS CORP	
DRWN. B. Hammer	APPV'D. [illegible]
DATE: APRIL 12, 1949	DWG NO: LD-B813

FIGURE 42

5. Temperature

The uranyl fluoride solution and the reflector water used in these experiments were subject to seasonal variations in temperature which could amount to as much as 15 C$^{\circ}$. No measure was made of a temperature coefficient of reactivity and the data have not been normalized to constant temperature. Some of the scatter in the results may be attributed to this cause.

VII. SUMMARY

The results of these experiments which are of interest in the specification of safe handling procedures for solutions are summarized below. The examples of cylindrical reactors which have been selected represent 1) the reactors of maximum diameter which were sub-critical near optimum moderation and 2) the reactors of minimum diameter which were critical at minimum solution height, i.e. optimum moderation for cylinders.

Table 3

Material	Reactor Diameter inches	Reflector	H:U-235	Critical Height cm	Critical Mass U-235 kg
Aluminum	$5\frac{1}{2}$	water	57	∞	∞
Aluminum	6	water	59	71.8	5.4
Stainless Steel	6	water	61	∞	∞
Stainless Steel	$6\frac{1}{2}$	water	44	47.1	4.1
Stainless Steel	8	air	63	∞	∞
Stainless Steel	10	air	63	31.7	6.4
Stainless Steel	7	Cd shield water	86	∞	∞
Stainless Steel	8	Cd shield water	63	48.4	6.2

A treatment of the data allows an estimate to be made of the thickness of a slab of fuel of infinite extent which will be sub-critical under all conditions. This thickness is 5 cm for a water-enclosed slab and 10 cm for one without water reflector.

The minimum critical mass observed in these experiments was 893 gr U-235 contained in a water-enclosed aluminum reactor of 25.4 cm (10 inches) diameter and 22.4 cm height. The concentration of the fuel corresponded to H:U-235 = 329.

VIII. ACKNOWLEDGMENTS

The authors are indebted to Dr. Eugene Greuling of Duke University, Dr. E. T. Booth of Columbia University and Dr. Phil Morrison of Cornell University for helpful discussions during the progress of these experiments. The UO_2F_2 was prepared at Y-12 under the direction of Mr. N. H. MacKay whose assistance is gratefully acknowledged. The instrumentation was the result of the cooperation of Mr. Elmer Olsen and Mr. Robert Quinn of Y-12 and Mr. M. L. Bartkus, Mr. H. A. Kermicle and Mr. James H. Lykins of K-25. Mr. Lee Schuske of Y-12 assisted in the compilation of the data.

APPENDIX

TABLE 4

MAXIMUM IMPURITIES IN URANYL FLUORIDE SOLUTIONS

AND THEIR THERMAL NEUTRON ABSORPTION CROSS SECTIONS

Element	ppm *	$\sigma_a \times 10^{24}$ cm^2	$\frac{N\sigma_a \times 10^7 \text{ cm}^2}{\text{gm } UO_2F_2}$
Ag	0.5	60	1.7
Al	2000	0.21	93.7
As	< 10	4.3	3.4
Au	< 0.1	95	0.3
B	15	715	6000
Ba	<10	1.3	0.5
Be	< 0.1	0.01	0.1
Bi	< 1	0.015	0
Cd	200	2900	31060
Ca	20	36	73.4
Cr	120	2.5	34.7
Cu	500	3.0	142.0
Fe	2000	2.5	538.5
Ge	< 1	2.8	0.2
Hg	<10	430	129.1
In	< 1	194	10.2
Mg	60	0.3	4.5
Mn	40	13	51.0
Mo	<10	2.6	1.6
Ni	10,000	4.5	4615
P	<10	0.23	0.4
Pb	40	0.2	0.2
Sb	<10	4.5	2.2
Si	1	~ 0.2	0.1
Sn	20	0.55	0.5
Tl	< 1	3.0	0.1
V	<10	4.5	5.3
Zn	300	0.9	24.9

* Reported as parts per million of solute.

TABLE 5

CRITICAL CONDITIONS FOR ALUMINUM REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm	Critical Volume Liters	Critical Mass kg U-235
	52.9	0.293	1.566	0.459	70.9	12.93	5.93
6	58.8	0.2745	1.51	0.415	71.8	13.10	5.44
$6\frac{1}{2}$	26.2	0.4179	1.98	0.827	44.5	9.56	7.91
	52.9	0.293	1.566	0.459	39.2	8.39	3.85
	56.7	0.281	1.51	0.424	40.4	8.65	3.67
	119.0	0.1685	1.26	0.212	52.6	11.26	2.39
8	26.2	0.4179	1.98	0.827	21.5	6.92	5.76
	29.9	0.394	1.926	0.759	20.7	6.71	5.09
	52.9	0.293	1.566	0.459	19.5	6.32	2.90
	58.8	0.2745	1.51	0.415	20.5	6.65	2.76
	99.5	0.1924	1.32	0.254	22.4	7.26	1.84
	192.0	0.1145	1.17	0.134	28.1	9.11	1.22
	290.0	0.0801	1.10	0.0881	40.1	13.00	1.15
10	52.9	0.293	1.566	0.459	13.4	6.79	3.12
	328.7	0.715	1.101	0.0787	22.4	11.35	0.893
	499	0.0488	1.070	0.0522	35.2	17.83	0.930
15	52.9	0.293	1.566	0.459	7.90	9.01	4.14
	56.7	0.281	1.51	0.424	8.50	9.69	4.11
	221.0	0.1014	1.14	0.116	11.30	12.88	1.49
	499.0	0.0488	1.070	0.0522	16.90	19.27	1.01
	755.0	0.033	1.04	0.0343	27.10	29.75	1.02
	999.0	0.0252	1.03	0.0260	44.30	50.50	1.31

TABLE 6

NON-CRITICAL ALUMINUM REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Maximum Experimental Attainable Height (cm)	Maximum Experimental Attainable Mass U-235 kg	Estimated Critical Height (cm)	Estimated Critical Mass U-235 kg.
$5\frac{1}{2}$	56.7	0.281	1.51	0.424	74.3	4.83	∞	∞
6	26.2	0.4179	1.98	0.827	51.6	7.79	>75	>11.3
	119.0	0.1685	1.26	0.212	72.6	2.81	∞	∞
$6\frac{1}{2}$	221	0.1014	1.14	0.116	61.6	1.47	∞	∞
8	499	0.0488	1.07	0.0522	74.5	1.26	∞	∞
10	755	0.033	1.04	0.0343	56.4	0.98	∞	∞
15	26.2	0.4179	1.98	0.827	7.5	7.07	8.60	8.10

TABLE 7

CRITICAL CONDITIONS FOR STAINLESS STEEL REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H : U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Sol'n. Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm	Critical Volume Liters	Critical Mass kg. U-235
$6\frac{1}{2}$	31.6	0.385	1.88	0.724	49.0	10.49	7.59
	43.9	0.326	1.65	0.538	47.1	10.08	5.42
	62.7	0.264	1.50	0.396	47.9	10.25	4.06
	86.4	0.213	1.35	0.288	53.8	11.51	3.31
7	24.4	0.430	2.02	0.869	35.4	8.79	7.63
	31.6	0.385	1.88	0.724	34.0	8.44	6.11
	43.9	0.326	1.65	0.538	32.7	8.12	4.37
	61.1	0.268	1.47	0.394	32.6	8.09	3.19
	86.4	0.213	1.35	0.288	36.0	8.94	2.57
	123.2	0.164	1.25	0.205	42.3	10.50	2.15
	174	0.124	1.19	0.148	57.3	14.22	2.10
8	24.4	0.430	2.02	0.869	23.4	7.59	6.59
	26.2	0.418	1.98	0.827	23.5	7.62	6.30
	31.6	0.385	1.88	0.724	22.6	7.33	5.31
	43.9	0.326	1.65	0.538	21.9	7.10	3.82
	56.7	0.281	1.51	0.424	22.2	7.20	3.05
	58.8	0.275	1.51	0.415	20.8	6.74	2.80
	62.7	0.264	1.50	0.396	22.9	7.42	2.94
	86.4	0.213	1.35	0.288	23.8	7.72	2.22
	99.5	0.192	1.32	0.254	24.2	7.85	1.99
	123.2	0.164	1.25	0.205	26.0	8.43	1.73
	174	0.124	1.19	0.148	30.1	9.76	1.44
	192	0.115	1.17	0.134	29.4	9.53	1.28
	226	0.0995	1.15	0.114	36.3	11.77	1.34
	320	0.0732	1.10	0.0805	60.1	19.48	1.57
9	24.4	0.430	2.02	0.869	18.4	7.55	6.56
	31.6	0.385	1.88	0.724	18.1	7.43	5.38
	43.9	0.326	1.65	0.538	17.8	7.30	3.93
	62.7	0.264	1.50	0.396	18.0	7.39	2.93
	86.4	0.213	1.35	0.288	18.7	7.67	2.21
	123.2	0.164	1.25	0.205	19.9	8.16	1.67
	174	0.124	1.19	0.148	22.2	9.11	1.35
	226	0.0995	1.15	0.114	25.3	10.38	1.18
	320	0.0732	1.10	0.0805	33.0	13.54	1.09

TABLE 7 (Continued)

CRITICAL CONDITIONS FOR STAINLESS STEEL REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H : U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Sol'n. Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm	Critical Volume Liters	Critical Mass kg. U-235
10	24.4	0.430	2.02	0.869	15.3	7.75	6.73
	31.6	0.385	1.88	0.724	15.3	7.75	5.61
	43.9	0.326	1.65	0.538	14.9	7.55	4.06
	62.7	0.264	1.50	0.396	15.2	7.70	3.05
	86.4	0.213	1.35	0.288	15.4	7.80	2.25
	123.2	0.164	1.25	0.205	16.8	8.51	1.74
	174	0.124	1.19	0.148	18.1	9.17	1.36
	226	0.0995	1.15	0.114	20.0	10.13	1.15
	320	0.0732	1.10	0.0805	25.0	12.67	1.02
12	62.6	0.264	1.49	0.394	12.3	8.97	3.53
	174	0.124	1.19	0.148	14.9	10.87	1.61
	226	0.0995	1.15	0.114	16.5	12.04	1.37
	320	0.0732	1.10	0.0805	18.5	13.50	1.09
	499	0.0488	1.07	0.0522	26.3	19.19	1.00
	755	0.0330	1.04	0.0343	48.7	35.53	1.22
15	56.7	0.281	1.51	0.424	10.1	11.51	4.88
	221	0.1014	1.14	0.116	13.0	14.82	1.72
	499	0.0488	1.07	0.0522	20.0	22.12	1.15
	755	0.0330	1.04	0.0343	28.8	32.83	1.13

TABLE 8

NON-CRITICAL STAINLESS STEEL REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Maximum Experimental Attainable Height (cm)	Maximum Experimental Attainable Mass U-235 kg.	Estimated Critical Height (cm)	Estimated Critical Mass U-235 kg.
6	24.4	0.4301	2.02	0.8688	56.9	9.02	∞	∞
	31.6	0.385	1.88	0.724	66.6	8.80	∞	∞
	61.1	0.268	1.47	0.394	87.6	6.30	∞	∞
	86.4	0.213	1.35	0.288	72.9	3.83	∞	∞
$6\frac{1}{2}$	123.2	0.164	1.25	0.205	77.2	3.39	80	3.50
	174.0	0.124	1.19	0.148	72.3	2.29	∞	∞
7	183.0	0.1194	1.18	0.141	54.4	1.90	63	2.20
	226.0	0.0995	1.15	0.114	69.9	1.98	>100	> 2.80
9	499.0	0.0488	1.07	0.0522	40.5	0.87	>75	>1.60
10	499.0	0.0488	1.07	0.0522	39.4	1.04	40.7	1.08
12	999.0	0.0252	1.03	0.0260	69.0	1.31	∞	∞
15	999.0	0.0252	1.03	0.0262	50.2	1.49	52.4	1.55

TABLE 9

CRITICAL CONDITIONS FOR CADMIUM-SHIELDED STAINLESS STEEL REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H : U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm	Critical Volume Liters	Critical Mass kg. U-235
8	43.9	0.326	1.65	0.538	51.5	16.70	8.98
	62.7	0.264	1.50	0.396	48.4	15.69	6.21
	86.4	0.213	1.35	0.288	56.5	18.32	5.28
9	31.6	0.385	1.88	0.724	29.0	11.90	8.62
	43.9	0.326	1.65	0.538	28.8	11.82	6.36
	62.7	0.264	1.50	0.396	28.3	11.64	4.61
	86.4	0.213	1.35	0.288	29.2	11.98	3.45
	123.2	0.164	1.25	0.205	32.0	13.13	2.69
	174.0	0.124	1.19	0.148	37.3	15.30	2.26
10	31.6	0.385	1.88	0.724	21.1	10.69	7.74
	43.9	0.326	1.65	0.538	21.4	10.84	5.83
	62.7	0.264	1.50	0.396	22.0	11.15	4.42
	86.4	0.213	1.35	0.288	22.0	11.15	3.21
	221	0.1014	1.14	0.116	28.7	14.54	1.69
12	56.7	0.281	1.51	0.424	15.8	11.53	4.89
	174	0.124	1.19	0.148	19.5	14.22	2.10
	226	0.0995	1.15	0.114	20.9	15.25	1.74
	499	0.0488	1.07	0.052	32.8	23.93	1.25

TABLE 10

NON-CRITICAL CADMIUM SHIELDED STAINLESS STEEL REACTORS WITH WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Maximum Experimental Attainable Height (cm)	Maximum Experimental Attainable Mass U-235 kg.	Estimated Critical Height (cm)	Estimated Critical Mass U-235 kg.
7	31.6	0.385	1.88	0.724	50.3	9.04	∞	∞
	86.4	0.213	1.35	0.288	71.9	5.15	∞	∞
8	24.4	0.4301	2.02	0.8688	30.8	8.68	>47	>13.2
	31.6	0.385	1.88	0.724	35.9	8.43	∞	∞
9	24.4	0.4301	2.02	0.8688	24.7	8.80	>32	>11.4
	226.0	0.0995	1.15	0.114	41.2	1.93	>46.2	> 2.16
	320	0.0732	1.10	0.0805	40.5	1.34	∞	∞
10	24.4	0.4301	2.02	0.8688	19.6	8.63	23.4	10.3
12	26.2	0.4179	1.98	0.827	13.2	7.96	15.5	9.35
	755	0.033	1.04	0.0343	58.3	1.46	∞	∞

TABLE 11

CRITICAL CONDITIONS FOR ALUMINUM REACTORS WITHOUT WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm.	Critical Volume Liters	Critical Mass U-235 kg.
10	52.9	0.293	1.566	0.459	34.0	17.22	7.90
	169.0	0.127	1.187	0.151	41.2	20.87	3.15
15	169.0	0.127	1.187	0.151	18.5	21.09	3.18
	328.7	0.0715	1.101	0.0787	21.7	24.73	1.95
	499.0	0.0488	1.070	0.0522	27.4	31.24	1.63
	755	0.033	1.04	0.0343	43.6	49.7	1.70

TABLE 12

NON-CRITICAL ALUMINUM REACTORS WITHOUT WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Maximum Experimental Attainable Height (cm)	Maximum Experimental Attainable Mass U-235 kg.	Estimated Critical Height (cm)	Estimated Critical Mass U-235 kg.
8	52.9	0.293	1.566	0.459	46.7	6.95		
10	499	0.0488	1.07	0.0522	61.9	1.64		

TABLE 13

CRITICAL CONDITIONS FOR

STAINLESS STEEL REACTORS WITHOUT WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Critical Height cm.	Critical Volume Liters	Critical Mass U-235 kg.
10	43.9	0.326	1.65	0.538	32.3	16.36	8.80
	62.7	0.264	1.50	0.396	31.7	16.05	6.36
	86.4	0.213	1.35	0.288	31.9	16.16	4.65
	123.2	0.164	1.25	0.205	34.3	17.38	3.56
	174	0.124	1.19	0.148	38.7	19.61	2.90
	226	0.0995	1.15	0.114	46.6	23.61	2.69
12	174	0.124	1.19	0.148	24.7	18.02	2.67
	226	0.0995	1.15	0.114	26.2	19.11	2.18
	320	0.0732	1.10	0.0805	30.3	22.10	1.78
	499	0.0488	1.07	0.0522	48.9	35.67	1.86
15	56.7	0.281	1.51	0.424	17.1	19.49	8.26
	221	0.1014	1.14	0.116	19.5	22.23	2.58
	499	0.0488	1.07	0.0522	27.0	30.78	1.61
	755	0.0330	1.04	0.0343	41.7	47.54	1.63
20	119	0.168	1.26	0.212	14.3	28.98	6.14
	221	0.1014	1.14	0.116	15.7	31.81	3.69
	329	0.0715	1.10	0.0787	17.4	35.25	2.77
	499	0.0488	1.07	0.0522	20.5	41.45	2.17
	755	0.0330	1.04	0.0343	26.7	54.10	1.86

TABLE 14

NON-CRITICAL STAINLESS STEEL REACTORS WITHOUT WATER REFLECTOR

Reactor Diameter Inches	H:U-235 Atomic Ratio	gm U-235 / gm Sol'n.	Solution Density gm/cm^3	gm U-235 / cm^3 Sol'n.	Maximum Experimental Attainable Height (cm)	Maximum Experimental Attainable Mass U-235 kg.	Estimated Critical Height (cm)	Estimated Critical Mass U-235 kg.
6	24.4	0.4301	2.02	0.8688	63.1	10.0	∞	∞
7	24.4	0.4301	2.02	0.8688	43.5	9.38	∞	∞
	31.6	0.385	1.88	0.724	47.9	8.61	∞	∞
	43.9	0.326	1.65	0.538	62.0	8.28	∞	∞
	61.1	0.268	1.47	0.394	87.1	8.52	∞	∞
8	24.4	0.4301	2.02	0.8688	31.2	8.79	∞	∞
	31.6	0.385	1.88	0.724	39.3	9.22	∞	∞
	43.9	0.326	1.65	0.538	54.8	9.56	∞	∞
	62.7	0.264	1.50	0.396	71.5	9.18	∞	∞
	86.4	0.213	1.35	0.288	81.2	7.58	∞	∞
	123.2	0.164	1.25	0.205	81.7	5.43	∞	∞
	174	0.124	1.19	0.148	85.8	4.12	∞	∞
	226	0.0995	1.15	0.114	85.8	3.17	∞	∞
9	24.4	0.4301	2.02	0.8688	24.9	8.88	∞	∞
	31.6	0.385	1.88	0.724	32.0	9.51	∞	∞
	43.9	0.326	1.65	0.538	40.7	8.98	>90	>20.4
	62.7	0.264	1.50	0.396	45.3	7.36	>56	>9.1
	86.4	0.213	1.35	0.288	46.3	5.47	>57.5	>6.80
	123.2	0.164	1.25	0.205	46.0	3.87	>70	>5.9
	174.0	0.124	1.19	0.148	46.2	2.81	∞	∞
10	24.4	0.4301	2.02	0.8688	19.4	8.54	>28	>12.4
	26.2	0.4179	1.98	0.827	19.0	7.96	>25	>10.5
	31.6	0.385	1.88	0.724	27.1	9.94	>35	>12.8
	320	0.0732	1.10	0.0805	46.7	1.90	>75	>3.0
	499	0.0488	1.07	0.0522	45.9	1.21	∞	∞
12	62.6	0.2641	1.49	0.394	18.5	5.32	21.7	6.24
20	999.0	0.0252	1.03	0.0260	9.5	1.55	36	1.90