REFERENCE 44

A. D. CALLIHAN, D. F. CRONIN, J. K. FOX, AND J. W. MORFITT, "CRITICAL MASS STUDIES, PART V," CARBIDE AND CHEMICALS CORP., K-25 PLANT REPORT K-643 (JUNE 1950).

K-643
Criticality Hazards (Special)

CRITICAL MASS STUDIES, PART V

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E R R A T A

to

Report K-643, Critical Mass Studies, Part V

It is requested that the following corrections be made in Report K-643, Critical Mass Studies, Part V:

1. Page 29, Table VI, last line, reflector thickness should be 2.50" instead of 3.50. The line should read

10.0	493	2.50	38.9	1.04

2. Graph 10, the symbol for the two nitrogen concentrations should be reversed, i.e., the legend should read:

Line	N:U-235 Atomic Ratio
———	0 Part III
- - - - - -	2.86
—·—·—	7.48

3. Graph 16, delete the point, represented by a square, at 3.5" and 1.08. The thickness limit of stainless steel reflector added to the 10" reactor was 2.5".

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Approved for issue: Frank W. Hurd
Frank W. Hurd

SUBJECT CATEGORY: Criticality Hazards (Special)

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CARBIDE AND CARBON CHEMICALS DIVISION
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A B S T R A C T

An investigation has been made of the conditions under which aqueous solutions of enriched uranyl nitrate become critical in right cylindrical reactors.

A comparison was made of the neutron reflectivity of stainless steel, bismuth subcarbonate both dry and as a water slurry, aqueous solutions of natural uranyl nitrate and phosphoric acid. The materials tested, with the exception of dry bismuth subcarbonate, were about as effective reflectors as water. Dry bismuth subcarbonate was considerably less effective.

The free nitrogen content of the nitrate solution and the addition of phosphoric acid and metallic bismuth to the reactor core were among the variables studied. Nitric and phosphoric acid when introduced into the core material were effectively mild poisons when compared with aqueous solutions at the same hydrogen to U-235 ratio. Bismuth was introduced into the core as an array of aluminum clad bismuth rods. The critical mass of this array was only slightly less than that measured when the bismuth was replaced by a similar array of voids.

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I. INTRODUCTION

The experimental work described in this report was designed to determine the parameters necessary for criticality of uranium 235 under conditions simulating those arising in the separation and purification of plutonium. The concentrations, types of solution, and reflectors or poisons, were selected on the basis of a feasibility study[1]. Plutonium is most frequently encountered as the nitrate solution, and handling equipment is fabricated mainly of stainless steel. Bismuth and phosphoric acid are present in large amounts.

Uranium enriched to 93.3% U-235 was chosen in preference to plutonium because of the availability of materials and equipment, and because of the facility with which the desired experiments could be performed. It is believed that the signs, if not the magnitudes, of the effects investigated are the same as those which would be found with plutonium solutions. Uranium does not introduce the severe health hazard associated with plutonium.

No attempt has been made in this report to apply these results to the problems related to the processing of plutonium.

II. APPARATUS

A plan of the control and experimental rooms is shown in Fig. 3 of an earlier report[2] and, in general, the equipment is the same as that described previously[3]. In the present program, a single reactor was used, so the apparatus shown schematically in Fig. 1, Part IV was modified by eliminating the movable reactor assembly.

A. Materials of Construction

Since the uranyl nitrate solution contained free acid, it was necessary to use corrosion resistant materials. The storage cylinder and feed system were made of type 347 stainless steel except for sections of fluorothene plastic tubing which provided visibility of solution flow. The reactors were made of type 3-S

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1. Beck, C. K., A. D. Callihan, E. Greuling, J. W. Morfitt, "Feasibility Study of Uranium Experiments for Obtaining Data Needed in Hanford Operations", Carbide and Carbon Chemicals Division, K-25 Plant; K-320, April 19, 1949.

2. Beck, C. K., A. D. Callihan, J. W. Morfitt, R. L. Murray, "Critical Mass Studies, Part III", Carbide and Carbon Chemicals Division, K-25 Plant; K-343, April 19, 1949

3. Callihan, A. D., D. F. Cronin, J. K. Fox, R. L. Macklin, J. W. Morfitt, "Critical Mass Studies, Part IV", Carbide and Carbon Chemicals Division, K-25 Plant; K-406, November 28, 1949. In subsequent references, these two reports will be designated as Parts III and IV respectively.

aluminum because of its low thermal neutron absorption. It was necessary, however, to apply two or three coats of Bakelite varnish to them for corrosion protection. A series of concentric nesting cylindrical shells, split longitudinally along a diameter, were constructed of type 3-S aluminum, 1/16" thick to contain the liquid reflectors. The outside thickness of some of the shells, measured along a radius, was 1". Four of these were made to fit around the 10" diameter reactor. An additional shell, 2" wide, was made to fit outside the 1" shells. These shells were also used for the experiments in which an air gap separated the reactor from the reflector by leaving the shells empty and filling the outer tank with water.

For the inhomogeneous poison experiments, a tube bundle was fabricated as shown in Fig. 1. The aluminum tubes were 1" outside diameter placed in a hexagonal lattice with uniform distances between tubes as shown in Fig. 2. Three sets of tubes were made. One set was open at both ends, and was used to determine the effect of the aluminum. Two sets were made with the lower end closed, one set being used for liquids and the other for containers into which bismuth metal was poured.

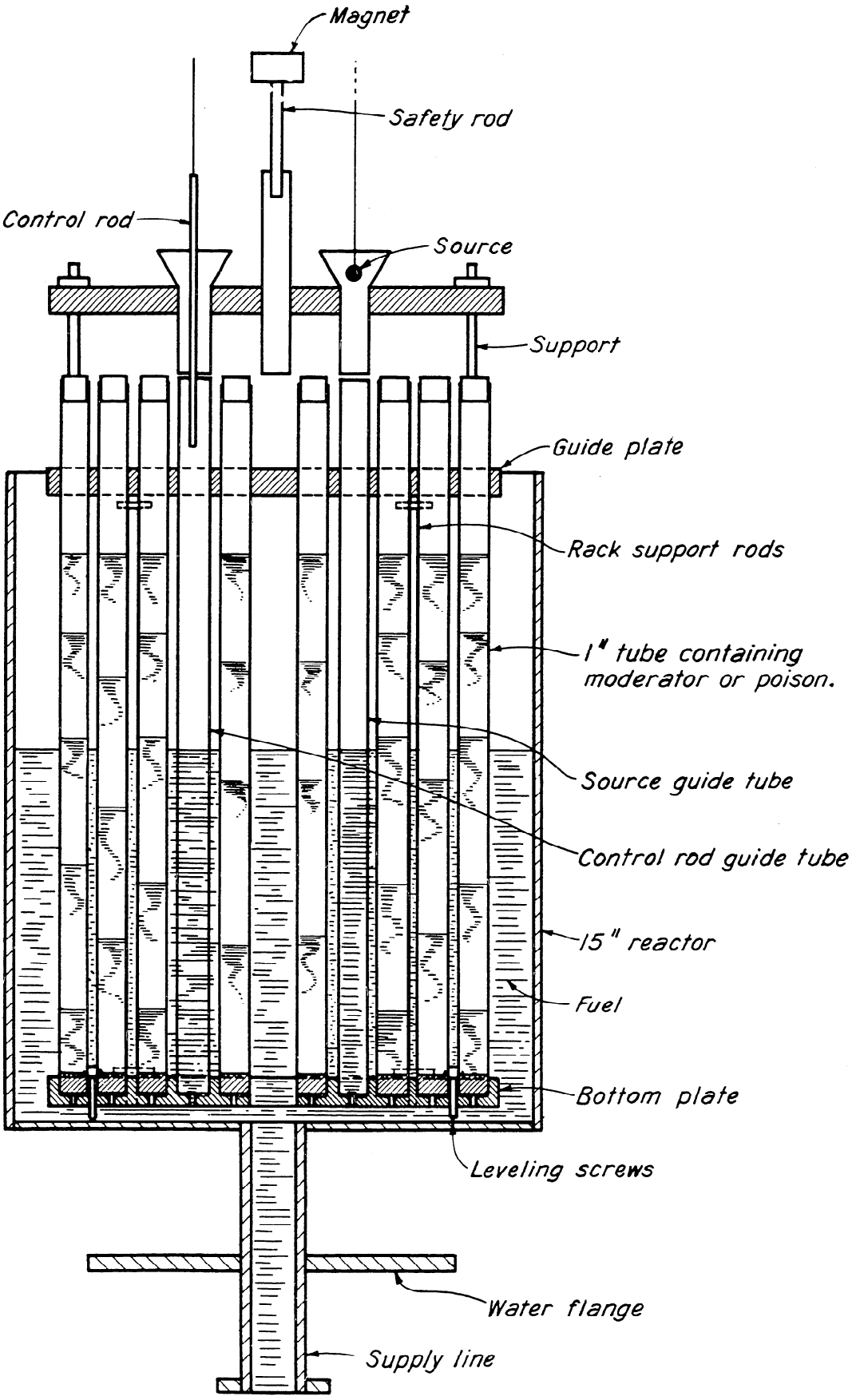
B. Solution Transport and Reactor System

As described in Part III, the storage system consisted of nine 4" diameter stainless steel cylinders 36" long, mounted on 15" centers. The storage cylinders were connected to a common header, permitting regulated air pressure to be applied to the surface of the solution. Solution could then be discharged from individual cylinders into a manifold and thence to the reactor. Stainless steel valves with fluorothene packing, for controlling the solution flow were operated by handles extending through the 16" concrete wall into the control room. The solution was returned to storage by reducing the pressure on the line with a vacuum pump.

Interchangeable reactors, used in previous experiments were retained without alterations. The six-inch deep top water tanks were altered to permit the entry into the reactor of a control rod consisting of a 3/4" stainless steel tube containing cadmium. The tanks also had holes for the safety rod and source. A reactor could be surrounded by water by filling the top water tank and the outer large rectangular tank. Conversely, the water could be readily drained and an experiment performed without reflector.

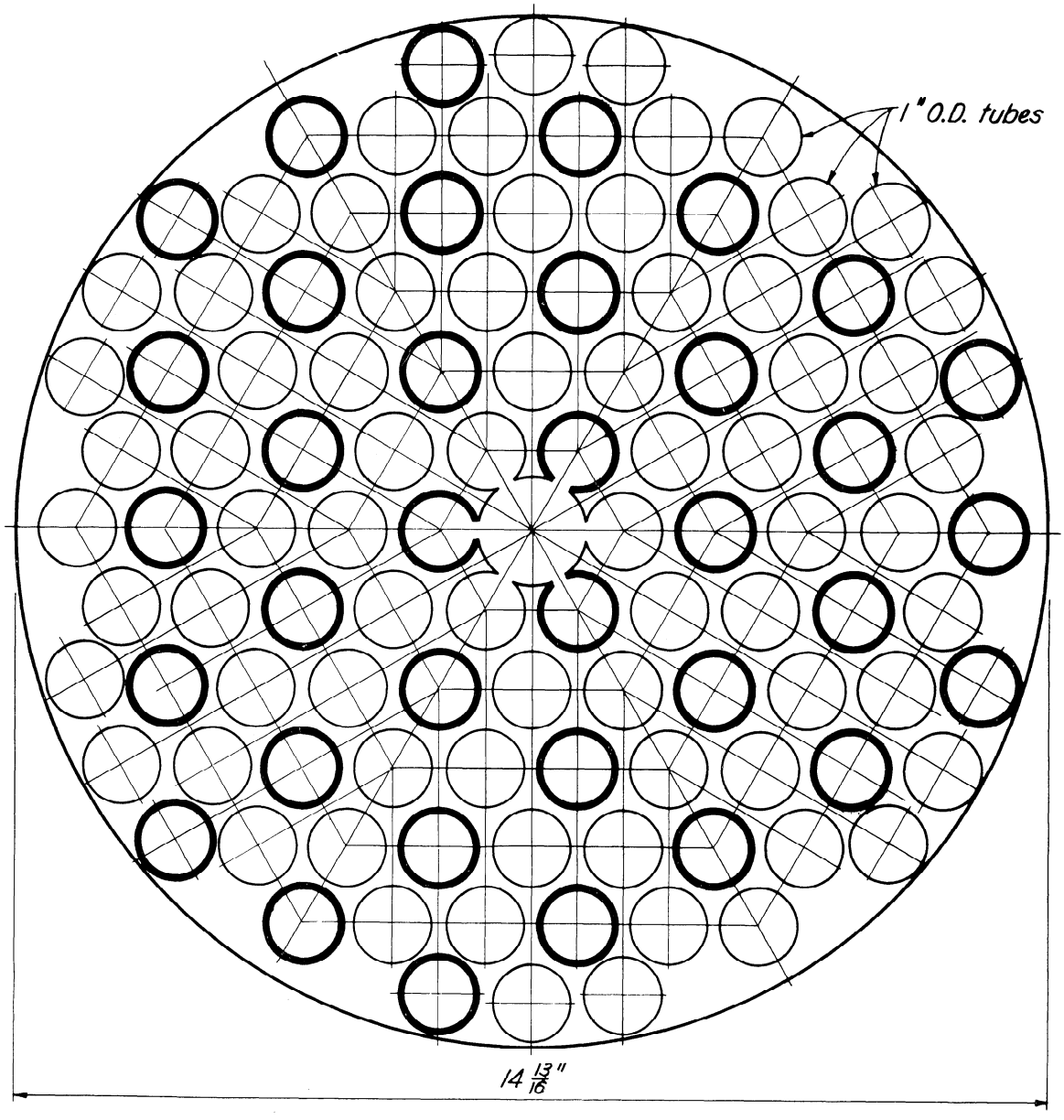
C. Instrumentation

In general the instrumentation was similar to that used in Parts III and IV. One of the counters was placed in an improved type of neutron



SCHEMATIC VIEW OF TUBE RACK ASSEMBLY

FIGURE 1



NOTE:
Heavy circles are $\frac{1}{3}$ lattice.

TUBE ARRAY

FIGURE 2

shield developed at Los Alamos[4] and gave more linear reciprocal multiplication curves than the counter enclosed in a single block of paraffin. A photomultiplier type alarm circuit was added[5] and used only as an additional signal detector for the safety circuits and not as a flux level indicator.

III. EXPERIMENTAL MATERIALS

A. Fuel Solutions

The uranium employed in these experiments was initially prepared as uranium trioxide of spectrographic purity equivalent to the fuel used in Part III. The isotopic assay of the uranium was 93.3% U-235, 1.1% U-234, and 5.6% U-238.

The uranyl nitrate solution was prepared by dissolving the oxide in a slight excess of reagent nitric acid and adding double-distilled water. Excess reagent nitric acid and reagent phosphoric acid were subsequently deliberately added to the nitrate solution to examine the effects of phosphorus and nitrogen on the critical mass. Four basic fuel solutions were prepared having the compositions shown by the following atomic ratios:

Solution	N:U-235	P:U-235	H:U-235
#1	2.86	0	61.8, 240, 352, 493, 733
2	7.48	0	88, 230, 327
3	2.90	53.1	376
4	5.37	15.8	~156

Spectroscopic analyses of the solution showed insignificant amounts of impurities. Further data on these fuels are given in Table I of the Appendix.

In some cases, the overall composition of the material contained in the reactor was considerably modified by the insertion into the uranyl nitrate solution of additional moderators and absorbers in the tube rack already described. In addition to nitric and phosphoric acids and distilled water, pure bismuth metal was introduced into the core as billets cast in aluminum tubes.

B. Reflecting Materials

The external reflector tank was filled from the laboratory water line. Analyses of the water have shown it to be essentially free from elements with high neutron absorption cross-sections. Natural

4. Hanson, A. O. and J. L. McKibben, "A Neutron Detector Having Uniform Sensitivity from 10 Kev to 3 Mev", Los Alamos Scientific Laboratory MDDC-972, May 29, 1947.

5. Macklin, R. L. and E. R. Rohrer, Rev. of Sci. Instr. 20, 965, (1949).

uranyl nitrate solution, spectroscopically free from interfering elements; bismuth subcarbonate, U.S.P. grade as a tamped powder, and as a water slurry; and an 86.7% aqueous solution of phosphoric acid were used as reflectors. Concentric hemi-cylindrical sheets of type 347 stainless steel, 1/8" thick and 35" long, were formed to nest around the 8" diameter reactor. Enough of these were made to enclose the 8" reactor with a thickness of 3-1/2" of reflector. The assembled sheets were held in place by steel straps. Further data on all materials used as reflectors may be found in Table II of the Appendix.

IV. EXPERIMENTAL PROCEDURE

The experimental procedure was essentially the same as that used in Part III. The most important steps may be summarized as follows:

1. A careful review was made of all apparatus and instrumentation, using a check list to assure that no item had been overlooked.

2. Solution was added stepwise with the control rod in the assembly and safety rod out.

3. The level of activity was followed during each addition by the response of the ion-chamber recorders and the audible counter.

4. From quantitative measures of the activity after each addition, a curve of reciprocal multiplication vs. height was plotted with extrapolation being used as a guide to the approach to criticality. Points were more closely spaced in the region of high multiplication.

5. Most assemblies were made critical as indicated by the constancy of the neutron flux upon removal of the source. Were it impossible to attain criticality, because of insufficient uranium or of geometry conditions, an estimate of the critical mass was made from the curve of step 4.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The variables examined in this study included the reactor core composition, reactor diameter, and thickness of various reflecting media. In addition to adjusting the water content of the fuel to provide appropriate amounts of moderation, critical data were obtained for two nitrate ion concentrations. Several experiments were performed with phosphorus or bismuth added to the core. The reflectors studied were water, stainless steel, aqueous solutions of natural uranyl nitrate at two concentrations, phosphoric acid and bismuth subcarbonate.

The data are recorded in detail in the Appendix and are presented there in graphical form. Results may be duplicated in two or more tables in order to make certain relationships more evident. Some data from Part III have also been included for comparison. The time limits imposed necessitated that the experimental results be indicative rather than exhaustive.

A. Comparison of Critical Conditions for Uranyl Nitrate and Uranyl Fluoride

1. Experimental

The basic fuel used in all these experiments was uranyl nitrate containing uranium of 93.3% U-235 isotopic assay. The nitrate was selected in preference to the fluoride because of the large amounts of nitrate ion in the Hanford process, and because the nitrate is more compatible with phosphoric acid and the other core materials. The first experiments in this series were done to determine conditions under which uranyl nitrate solution became critical when contained in right circular cylinders. Data were obtained at two nitrate ion concentrations for comparison with the data from the fluoride solutions reported in Part III.

A plot of uranyl nitrate solution height at criticality as a function of its moderation is shown in Graph 1 for the water-enclosed reactors and in Graph 3 for the bare reactors. The critical masses of U-235 corresponding to these reactor heights are shown in Graphs 2 and 4 respectively. Data are recorded in Table III of the Appendix. The nitrogen to uranium atomic ratio was 2.67, equal to N:U-235 of 2.86, indicating that the solution contained some free nitric acid.

A second set of experiments was done with the nitrogen to uranium atomic ratio increased to approximately seven by the addition of nitric acid. The critical height and critical mass for water enclosed reactors are presented in Graphs 5 and 6 and the data are given in Table IV together with a few experiments on reactors having no reflector.

An alternative presentation of the above data is recorded in Graphs 7 and 9 in which the critical mass of U-235 in uranyl nitrate is plotted as a function of reactor diameter for various amounts of moderation. Graph 8 presents similar data with excess nitric acid in the fuel.

A comparison of the critical masses obtained from both nitrate concentrations and from uranyl fluoride solutions under otherwise identical conditions is given in Graph 10.

In general, the curve shapes are the same as those obtained in Part III. In all of the experiments, the presence of the nitrate ion increased the critical height and mass by an amount depending upon the quantity of nitrate ion present. Nitrogen thus acts as a weak poison. The lowest critical masses measured with uranyl nitrate solutions of N:U-235 equal to 2.86 were 960 gm for a 10" reactor at a height of 24.6 cm and an H:U-235 ratio of 350, and 950 gm for a 12" reactor at a height of 24.6 cm and an H:U-235 ratio of 493. The minimum critical mass for uranyl nitrate in cylindrical geometry is estimated to be 930 gm in a reactor approximately 11" in diameter at a H:U-235 ratio of about 400. This is 50 grams more than the estimated minimum of 880 gm for uranyl fluoride. The smallest mass measured for a bare aluminum reactor using uranyl nitrate was 1.72 kg of U-235 in a 15" diameter cylinder at H:U-235 of 493 as contrasted with 1.64 kg U-235 in a 15" diameter cylinder when uranyl fluoride was used, a difference of 80 gm.

It has been possible to draw curve shapes with some degree of confidence by the application of various curve-fitting techniques. Thus, the locations of the minima in the critical height vs. moderation curves shown in Graphs 1 and 5 were obtained from interpolations of the critical mass curves since the latter are known to be monotonic in the region under investigation. By such techniques, a set of curves is obtained which is internally consistent and which permits some qualitative observations to be made.

2. Discussion

The poisoning of the reactor by nitrogen is the only study in this program which lends itself to a theoretical discussion. The interposition of the discussion within that part of the report which recounts the experimental results has been done deliberately in order to provide continuity of the particular topic.

It is seen from comparison of Graphs 1 and 5 with the data of Part III* that the minimum critical volumes occur at a higher moderation when a mild poison is added, the increase being larger for larger amounts of poison. It appears that a similar shift occurs in the moderation corresponding to the minimum critical mass. Absorption of neutrons by a mild poison can be treated as an increased leakage and this "leakage" can be compensated for by an appropriate increase in the dimensions of the reactors. Conversely, for a reactor of fixed dimensions, the H:U-235 ratio of fuels which may become critical decreases with addition of poison. The addition of a poison to a critical system lowers the reactivity which can be restored,

* Figs. 17 and 19, Part III for example.

without significant change in volume, only by the addition of fissionable material, thereby decreasing the moderation. With sufficiently large amounts of poison, the lowered H:U-235 ratio will eventually result in such poor moderation that the given reactors of either finite or infinite dimensions cannot sustain a chain reaction. The data here do not permit such limiting concentrations to be determined.

The effect of nitrogen poisoning on the critical mass as determined by these experiments can be compared with that predicted by theory. Several treatments were considered, all of which gave predictions of roughly the same order of magnitude. One such approximation will be discussed.

Problems of this type in which the reflector and moderator are of the same material, can be treated by an integral equation method[6]. Greuling[7] has observed that the continuity equation for neutrons can be solved for the H:U-235 ratio at criticality in constant geometry on the assumption that the amount of absorber is sufficiently small so that only second order changes occur in the H and G functions. If the region of application is also limited to cases in which the variation of the displacement with the amount of poison can be neglected the relation can be written:

$$\frac{N_H}{N_{25}} = \left[\frac{\nu \sigma_{25}}{\sigma_H} H - \left(\frac{\sigma_{25}}{\sigma_H} - D\right) G\right] - \left[\frac{\sigma_{25}}{\sigma_H} G\right] y \quad (1)$$

where ν is the number of neutrons produced per neutron absorbed in U-235, D is the displacement $\left(= \frac{(N_H)\text{reflector} - (N_H)\text{core}}{(N_{25})\text{core}}\right)$, σ is the microscopic neutron absorption cross-section, H and G are the non-escape probabilities for neutrons during slowing down and thermal diffusion respectively, y is the quantity $\frac{N_P \sigma_P}{N_{25} \sigma_{25}}$, N is the number of atoms/cm^3 and the subscripts H, 25 and P refer to hydrogen, U-235 and poison respectively. Equation (1) can be written as

$$\frac{N_H}{N_{25}} = A - By \quad (2)$$

where A and B are the terms in brackets.

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6. Greuling, E., "Theory of Water-Tamped Water Boiler", Los Alamos Scientific Laboratory, LA-399, September 27, 1945.

7. Greuling, E., Private Communication, October 18, 1949.

Under the assumptions made above, A and B are constants and thus equation (2) is linear, having an intercept A, the critical H:U-235 ratio when no poison is present, and slope equal to -B. The negative slope is in agreement with the previous qualitative discussion.

In the table below, the amount of poison, the moderation at criticality and the value of y are tabulated for three reactors for which sufficient experimental data are available. These data are plotted in Graph 11 and it is seen that, at least for the small amounts of poison added in these experiments, the curves are linear.

Variation of Critical H:U-235 Ratio
With N:U-235 Ratio in Fixed Geometries

Water Reflector

Reactor Diameter in.	Critical Height cm	N:U-235	Critical H:U-235	Critical Mass kg	$y \times 10^3$
10.0	26.6	0	380	0.89	0.00
		2.86	352	0.95	7.58
		7.48	310	1.05	19.8
10.0	23.2	0	350	0.90	0.00
		2.86	303	0.97	7.58
		7.48	250	1.12	19.8
15.0	12.2	0	285	1.25	0.00
		2.86	240	1.45	7.58
		7.48	145	2.15	19.8

By assuming that the ratio G/H is the same for an essentially equilateral cylinder (10" diameter, 26.6 cm high) as for a sphere of the same volume, equation (1) can be solved for G and hence for a theoretical value of the slope B. Values of H:U-235 ratios can be calculated from equation (2) and plotted as a function of the amount of poison and compared with experiment. This has been done in Graph 11 and it is apparent that, although experimentally the critical moderation drops off linearly as required, the rate of change is much greater than theoretically predicted.

The rate of change of the calculated values is not sufficiently increased even if G = 1, its maximum possible value. Since the critical mass in a given volume is, to a close approximation, inversely proportional to the H:U-235 ratio, the theoretically

calculated masses are too low. The discrepancy is increased for the lower H:U-235 ratios where the effect of displacement cannot be ignored. Thus, calculation of the poisoned critical mass will be conservative in the region investigated. It may be that the agreement is much closer for H:U-235 ratios of approximately 1000. Some of the discrepancy can perhaps be explained by the fact that the nitrate molecule displaces uranium as well as hydrogen from the core, i.e., the mass of U-235 per unit volume of uranyl nitrate solution is less than that of uranyl fluoride solution at the same H:U-235 ratio.

The usual theoretical treatments based on pile theory, in which either ν or the thermal utilization is modified, give approximately the same results and can be shown to be virtually equivalent to the above treatment with G = 1.

B. Effect of Special Reflectors

A number of experiments were done to determine the effect of surrounding the lateral surfaces of a reactor with layers of various materials to simulate conditions of reflection that might be expected to arise in the processing of plutonium at Hanford. The materials tested were stainless steel, phosphoric acid, uranyl nitrate of natural isotopic concentration, and bismuth subcarbonate. The densities of the constituents under test are given in Table II. The results of reflector tests are plotted in Graphs 12, 13, 14, 15 and 17 in which the critical mass is shown as a function of the reflector thickness for 10" and 12" reactors with the core at various moderations. The corresponding data are given in Tables V, VII, VIII and IX. The masses obtained under the various reflector conditions are to be compared to those measured with a water reflector of the same dimensions bounding the lateral surfaces of the reactors.

To a first approximation, the curves of critical mass vs. reflector thickness are essentially the same for water, stainless steel, uranyl nitrate solution, and phosphoric acid and their shape is relatively independent of the moderation. At the lowest moderation, Graph 12, the differences in mass for the various media tested is greatest, water being the most effective, but at the higher moderations, Graphs 13, 14 and 15, the curves are, for practical purposes, indistinguishable. The thicknesses of reflectors employed were not effectively infinite, but further increases would not have significantly affected the critical mass. Reference will now be made to the results obtained from particular reflectors.

1. Natural Uranyl Nitrate

The variation in critical mass with the thickness of a solution of natural uranyl nitrate reflector, placed on the lateral surfaces of the reactors, is shown for various H:U-235 ratios in

Graphs 12, 13 and 14. Data on two chemical concentrations of reflector were obtained, one being approximately twice that which occurs in routine processing at Hanford and the other approximately equal to the Hanford concentration. The difference between them is small at all thicknesses and moderations of the core. For thin layers and low H:U-235 ratios, water is a more effective reflector. At higher H:U-235 ratios, Graphs 13 and 14, the curves are almost indistinguishable. As expected, the characteristics of the dilute uranyl nitrate were even more like those of water than the more concentrated material. Simple theory predicts that uranyl nitrate solution should be somewhat less effective than water and that the difference should be small.

2. Phosphoric Acid

The effect on the critical mass of various thicknesses of an 86.7% aqueous solution of phosphoric acid on the lateral reactor surfaces is presented in Graphs 12 and 13. For thin layers of reflector, this material was also less effective than water. In thicker layers, at an H:U-235 ratio of 61.8, the phosphoric acid was more effective. Since the phosphoric acid has a hydrogen content of 0.07 gm/cm^3 compared with 0.11 gm/cm^3 for water, a measurement was made with the phosphoric acid surrounded by an infinite water reflector. The critical mass with the composite reflector was lower than that for an infinite water reflector alone. Furthermore, water was a better reflector than phosphoric acid at higher moderations. Therefore, it seems possible that the effectiveness of the phosphoric acid at low H:U-235 ratios is due to the forward scattering of neutrons being reduced by a material of higher atomic weight.

3. Stainless Steel

The effectiveness of stainless steel when used as a reflector on the lateral surfaces of a reactor is shown in Graphs 12, 13, 14 and 15. Stainless steel and water behave similarly as reflectors in thicknesses up to three inches. The effect is relatively independent of the H:U-235 ratio. Although experiments with stainless steel thicker than 3-1/2 inches were not performed, it appears that an effectively infinite layer is a slightly better reflector than water. A second series of reflector experiments in which the reactor and its lateral reflector of stainless steel were enclosed in an infinite water reflector leads to the same conclusion, although the curve shapes are quite different.

As shown in Graph 16, thicknesses of stainless steel up to 0.5 inches increased the critical mass. Further increasing the thickness decreased the critical mass until at 3 inches, the mass was approximately equal to that measured with a water reflector alone. Additions to the stainless steel annulus decreased the critical mass below that of the water-reflected reactor. The maximum thickness of stainless steel tested was not large enough to be effectively infinite but the curve shape indicates that further increases will not greatly reduce the critical mass. The position of the maximum critical mass is relatively independent of the concentration, although the curves become flatter as the amount of moderation is increased. Control experiments showed the presence of thin films of water between successive layers of the steel to have no significant effect upon the criticalmass.

These results can be partially explained by assuming that thin layers of steel are relatively transparent to epithermal neutrons and the major effect is absorption of neutrons thermalized by the water reflector. At greater thicknesses the water is effectively isolated from the reactor. Inelastic scattering plus a decrease in the number of neutrons scattered forward undoubtedly accounts for much of the effectiveness of the stainless steel. The problem has not been treated quantitatively.

4. Bismuth Subcarbonate

The effect on critical conditions of bismuth subcarbonate as a reflector was also investigated in much the same manner as described for the other materials. The data obtained with dry bismuth subcarbonate powder tamped to a density of 0.52 gm Bi/cm^3 are shown in Graphs 17 and 18 and Table IX. As in the experiments with stainless steel, data were obtained both with and without an external water reflector.

The bismuth density was increased by the preparation of a water slurry and a second series of tests was made. The slurry having the highest density and adequate mechanical stability contained 0.85 gm Bi/cm^3 and 0.82 gm $water/cm^3$. The data obtained using this slurry as a reflector are presented in Graph 17 and Table IX. The critical mass was equal to that obtained using an equal thickness of water under otherwise identical conditions. This behavior was observed in three experiments at two moderations.

An indication of the relative effectiveness of bismuth and water as reflectors can be obtained by interpreting the above experiments as showing that 0.85 gm Bi/cm^3 has the same reflectivity as 0.18 gm H_2O/cm^3. Assuming this ratio of relative effectiveness to hold at other densities, 4.7 gm Bi/cm^3 would be a reflector equal to water.

Experiments were also performed with a compound reflector of dry bismuth subcarbonate and water. The bismuth compound was adjacent to the lateral surfaces of the reactors and was surrounded by water. The critical masses were much higher than those obtained with complete water reflector suggesting that the main function of the bismuth subcarbonate was to displace water from the lateral surfaces of the reactor. Accordingly, a third type of reflector study was made with water alone but with an air annulus, of variable width, surrounding the reactor. The results, given in Graph 18 and in Table X, show dry bismuth subcarbonate to be a weak reflector. The data also give some indication of the way in which the critical mass changes with the approach of a reflecting body to an assembly of fissionable material.

C. Effect of Special Core Materials

A limited number of experiments were done with phosphorus and bismuth added to the core. The large amounts of these elements required to approximate plutonium processing conditions necessitated introducing all the bismuth and some of the phosphorus into the core as an hexagonal array of vertical tubes described in section II-A. Two standard arrays were used: a full hexagonal lattice of 106 tubes positioned into a reactor 15" in diameter as shown in Fig. 2 and a 36 tube lattice formed by removing nearest neighbors from the above configuration. The 36 tube array is shown by the heavy circles in Fig. 2. The spacing in the 106 tube matrix was determined by the requirement that bismuth densities up to 4 gm/cm^3 of core be attainable. No top reflector was used in any of the experiments.

Since phosphorus or bismuth added in this way introduced inhomogeneities into the core, the magnitude of the inhomogeneity was estimated by filling the tubes with water, obtaining the critical mass and comparing it with that which would have been obtained had the water in the tubes below the surface of the fuel at criticality been homogeneously mixed with the core. The results of these experiments are given in Table XII and a comparison with the homogeneous core is presented in Graph 20.

The inhomogeneity in the core resulting from lumping the phosphorus and bismuth increases the critical mass only slightly in the range of concentration under investigation. The added inhomogeneity due to the aluminum containers of the phosphorus and bismuth was evaluated by observing that when 106 aluminum tubes, open at both ends, were placed in the solution, the effect of the aluminum alone was to raise the critical mass by 4 to 5%. No correction has been applied to the data reported in Table XII.

1. Phosphorus

Some experiments were performed to determine the effect on critical conditions of phosphorus additions to the core and the data are given in Tables XI and XII. In some instances, phosphoric acid was added directly to the uranyl nitrate to give a homogeneous core. Phosphorus to U-235 ratios of 15.8 and 53.1 were obtained in this manner. In two cases, additional phosphoric acid was added to the tube lattice to make P:U-235 = 64 and 106, respectively.

It was necessary to add 5% nitric acid to the core tubes to increase the corrosion resistance of the aluminum to the phosphoric acid. A like amount of nitric acid was added to the water in the tubes during the control experiments. Nitric acid was also added to the fuel to inhibit the precipitation of uranyl phosphate. The hydrogen contents of all nitric and phosphoric acids added to the core were included in the calculation of H:U-235 ratios. When phosphoric acid was added to a fuel of hydrogen content less than the optimum, the increased moderation from the associated hydrogen more than compensates for the small poisoning effect of the phosphorus. This behavior was found to be true for both homogeneous and inhomogeneous cores.

A comparison of the data obtained from uranyl nitrate solutions with those from uranyl nitrate-phosphoric acid mixtures shows the critical mass of the latter to be greater, provided the comparison is made at the same total H:U-235 ratio, as shown in Graph 19. Thus phosphorus behaves as a mild poison. When an attempt is made to treat phosphorus in the same manner as the homogeneous nitrogen poison in section V-A, the "poisoning" is much greater than predicted. This discrepancy, much larger than for nitrogen, is perhaps due to the fact that the phosphorus was added in such large quantities that the effect of the attendent reduced uranium density in the core cannot be ignored. The data obtained are sufficient to show that phosphorus exhibits no unexpected moderating ability in an essentially thermal system.

2. Bismuth

Bismuth was added to the core only as a metal lattice. For some of the systems tested, the presence of the bismuth in a 106 tube lattice increased the critical mass to a point such that the mass had to be obtained by extrapolation of the reciprocal multiplication curves. The bismuth density within the core was decreased from 4.1 gm/cm^3 to 1.4 gm/cm^3 by replacing the 106 tube lattice by a 36 tube lattice in the manner previously described. The data in Table XII show that bismuth has a small

moderating effect. For example, the critical mass of a water enclosed 15" reactor with no top reflector is 1.86 kg U-235. The addition of 36 bismuth slugs increased the mass to 1.96 kg; replacing the 36 bismuth slugs by 36 voids increased the critical mass to 2.17 kg; substituting water for bismuth decreased the mass to 1.72 kg U-235. From the above typical result, it is seen that although bismuth exhibits some moderating power, it is significantly less than that of water.

D. Investigation of Design Details of Hanford Equipment

A series of tests was done to compare the effectiveness of the control rods used in these experiments with that designed in the Hanford criticality equipment. The usual control rod in the Oak Ridge apparatus is a single stainless steel tube, 3/4" O.D. with 1/16" wall containing a closely fitting cylindrical insert of 1/16" thick cadmium sheet. The rod is mounted vertically and, depending on the conditions of the experiment, is placed either in the water reflector close to the wall of the reactor or in the fuel itself 2-1/4" from the center of the reactor. A secondary control rod, similar to that included in the design of the Hanford apparatus[8] was built into the equipment. It consisted of sheet cadmium contained in a 1" stainless steel tube which moved in a horizontal reentrant aluminum tube, 1-7/16" in diameter. The reentrant tube was placed below the reactor and coplanar with a diameter.

The tests were run at a H:U-235 atomic ratio of 240 using 8", 10" and 15" reactors. At this fuel concentration the 10" reactor was nearly equilateral at criticality, the 8" reactor relatively tall and the 15" less than a diameter high. The results of these investigations are shown in Table XIII and in Graph 21, which show the relative effectiveness of the control rods in various positions for the different reactors. In the case of the rod inserted in the fuel, the critical value obtained was corrected for the displacement caused by the rod itself. As expected, the horizontal rod was more effective when the height at critical was less than the diameter, while the vertical rods were more effective on the taller reactors.

A second operational detail designed into the Hanford equipment was also investigated. The neutron source, in the Hanford apparatus, is to be placed at the bottom of a reentrant vertical stainless steel tube coaxial with the reactor and extending below the water container serving as the top reflector. A fission chamber is to be placed in the same tube above the source and separated from it by an hydrogenous material. The tube will form a void in the fuel solution, increasing the critical mass above its value in a regular cylinder. The purpose of the experiment was to evaluate the increase.

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8. Kruesi, F. E., "Outline of Proposed Experiments P-11 Project", Hanford Engineering Works, HW-1409, August 2, 1949.

The mock-up of the source holder was a stainless steel tube, 0.50" O.D. and 0.41" I.D. and containing, in order from bottom to top, a closely fitting cylinder of steel, 1-1/2" long, one of polyethylene 2" long, and one of brass 3" long. The first and third were to simulate the source and the fission chamber, respectively.

At an H:U-235 of 350, in a completely water reflected 10" reactor, introducing the rod to a depth of 25.0 cm caused an increase in critical height of 0.6 cm, corresponding to a volume of 300 cm^3 and to a mass of 40 gm of U-235. The rod displaced a volume of only 31.2 cm^3. Thus, the source tube, when placed in the center of a reactor, will have a significant effect upon the critical mass for which correction should be made. A similar effect was noted in Part III where small changes in critical mass were effected by introducing a cylinder of stainless steel into the reactor.

VI. SUMMARY

In the range of conditions recorded in this report, the following core and reflector effects were noted:

1. Nitrogen in the core acts as a weak poison. The minimum critical mass measured with uranyl nitrate was 950 gm U-235 in a 12" reactor at an H:U-235 ratio of 493, compared to a value of 893 gm in a 10" reactor at an H:U-235 ratio of 329 using uranyl fluoride.

2. Phosphorus in the core acts as a weak poison similar to nitrogen. The data are too limited for a quantitative comparison with uranyl fluoride results.

3. Bismuth, added to the core in the form of metal rods, gave a lower critical mass than a similar array of aluminum tubes filled with air, indicating, qualitatively, some moderating effect. As a moderator, however, bismuth is not as effective as water or phosphoric acid.

4. Equal thicknesses of stainless steel, phosphoric acid and natural uranyl nitrate solutions, and a slurry of bismuth subcarbonate are comparable with water as a reflector. Dry bismuth subcarbonate powder reflector is somewhat less effective due perhaps to its low density.

5. Experiments with various thicknesses of stainless steel reflector and with composite reflectors of stainless steel and water show that an effectively infinite steel reflector is more efficient than one of water.

6. An air gap between a reactor and its water reflector raises the critical mass somewhat. In one experiment the critical mass was increased 50% by interposing a four inch wide air annulus between the reactor and the reflector. Complete removal of the water increased the mass to 3.5 times the value with a complete reflector.

VII. ACKNOWLEDGMENTS

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Table I

PROPERTIES OF FUEL SOLUTIONS

Atomic Ratios			Concentration		Density
H:U-235	N:U-235	P:U-235	gm U / gm soln.	gm U-235 / cm³ soln	gm/cm³
61.8	2.86	-	0.2485	0.359	1.55
88.0	7.48	-	0.1680	0.236	1.51
115	10.53	-	0.1339	0.187	1.50
128	6.97	15.8	0.0854	0.12	1.5
131	6.97	15.8	0.0846	0.120	1.52
157	5.37	15.8	0.0805	0.11	1.5
180	5.50	12.4	0.0812	0.11	1.5
230	7.48	-	0.0887	0.102	1.23
240	2.86	-	0.0963	0.105	1.16
316	2.90	53.1	0.0356	0.055	1.67
327	7.48	-	0.0673	0.073	1.17
352	2.86	-	0.0698	0.073	1.11
493	2.86	-	0.0524	0.053	1.08
733	2.86	-	0.0357	0.036	1.06

Table II

PROPERTIES OF REFLECTORS AND MODERATORS

Material	Density	Remarks
$UO_2(NO_3)_2$ (soln)	0.426 gm U/cm^3	Natural isotopic concentration
$UO_2(NO_3)_2$ (soln)	0.217 gm U/cm^3	Natural isotopic concentration
$Bi_2O_2CO_3$ (dry)	0.52 gm Bi/cm^3	USP powder
$Bi_2O_2CO_3$ (slurry)	0.85 gm Bi/cm^3 0.82 gm H_2O/cm^3	Water slurry
Bi metal	9.8 gm Bi/cm^3	
H_3PO_4(soln)	0.465 gm P/cm^3	86.7% H_3PO_4
Stainless Steel	7.9 gm/cm^3	AISI type 347

Table III

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTIONS

N:U-235 = 2.86

	Reactor Diameter, Inches									
	8.0		9.0		10.0		12.0		15.0	
	Hc	Mc	Hc	Mc	Hc	Mc	Hc	Mc	Hc	Mc
H:U-235	cm	kg	cm	kg	cm	kg	cm	kg	cm	kg
Water Reflector										
61.8	25.5	2.97	19.7	2.90	16.6	3.02	-	-	9.4	3.85
240	36.7	1.24	25.3	1.08	20.1	1.06	15.1	1.15	12.2	1.45
352	-	-	35.0	1.04	26.2	0.96	19.3	1.02	14.4	1.20
493	-	-	-	-	37.0	1.00	24.6	0.95	17.9	1.08
733	-	-	-	-	-	-	43.2	1.11	26.7	1.07
No Reflector										
61.8	∞	∞	∞	∞	>40 *	>7.3*	-	-	>18.0	>7.5
240	-	-	-	-	72.4	3.82	29.2	2.23	20.9	2.49
352	-	-	-	-	∞	∞	36.8	1.94	24.0	1.99
493	-	-	-	-	-	-	49.5	1.91	28.3	1.71
733	-	-	-	-	-	-	∞	∞	44.6	1.79

* This system may be subcritical at infinite length, however insufficient uranium precluded extension of measurement above 27 cm and 4.8 kg.

Table IV

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE-NITRIC ACID SOLUTIONS

N:U-235 = 7.48

	Reactor Diameter, Inches							
	9.0		10.0		12.0		15.0	
	Hc	Mc	Hc	Mc	Hc	Mc	Hc	Mc
H:U-235	cm	kg	cm	kg	cm	kg	cm	kg
Water Reflector								
88.0	27.7	2.69	22.4	2.67	16.3	2.81	12.7	3.42
230	-	-	22.6	1.17	16.8	1.25	13.2	1.53
327	-	-	28.2	1.05	20.0	1.07	15.1	1.26
No Reflector								
88.0	-	-	> 81.0	> 9.7	35.2	6.06	22.6	6.09
230	-	-	>105.	> 5.4	32.9	2.44	22.7	2.63
327	-	-	∞	∞	40.2	2.15	25.1	2.09

Table V

CRITICAL HEIGHT AND CRITICAL MASS OF U-235
IN URANYL NITRATE SOLUTION
WITH STAINLESS STEEL REFLECTOR

N:U-235 = 2.86

H:U-235	Reflector Thickness Inches	Hc cm	Mc kg
	Reactor Diameter 8.0 Inches		
61.8	0.00	∞	∞
	1.50	47.8	5.56
	2.00	39.7	4.63
	3.00	33.2	3.86
	3.50	31.5	3.66
	Reactor Diameter 10.0 Inches		
61.8	0.00	> 40.	> 7.3
	1.00	28.0	5.09
	2.50	21.2	3.85
240	0.00	72.4	3.82
	0.25	47.3	2.51
	0.50	39.5	2.09
	1.00	32.8	1.73
	2.50	26.8	1.42
352	0.00	∞	∞
	0.50	58.7	2.15
	0.75	48.6	1.78
	1.50	37.3	1.37
	2.50	33.1	1.22
493	2.50	47.6	1.28

Table VI

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION WITH LATERAL COMPOSITE REFLECTOR OF WATER AND STAINLESS STEEL

N:U-235 = 2.86

Reactor Diameter Inches	H:U-235	Reflector Thickness Inches	Hc cm	Mc kg
8.0	61.8	0.00	25.5	2.97
		0.12	29.6	3.44
		0.25	32.8	3.81
		0.50	34.7	4.04
		0.75	34.0	3.96
		1.00	33.1	3.85
		1.50	29.5	3.43
		2.00	27.4	3.18
		3.50	24.2	2.82
10.0	61.8	0.00	16.6	3.02
		0.50	18.6	3.39
		1.00	18.0	3.27
		2.50	16.4	2.98
10.0	240	0.00	20.1	1.06
		0.25	23.4	1.24
		0.50	23.6	1.25
		1.00	22.8	1.20
		2.50	20.4	1.08
10.0	352	0.00	26.2	0.96
		0.50	31.3	1.15
		0.75	30.7	1.13
		1.50	28.4	1.04
		2.50	26.5	0.97
10.0	493	0.00	37.0	1.00
			38.9	1.04

Table VII

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION WITH LATERAL WATER REFLECTOR

N:U-235 = 2.86

Reactor Diameter Inches	H:U-235	Reflector Thickness Inches	Hc cm	Mc kg
10.0	61.8	0.00	> 40.	> 7.3
		0.88	28.6	5.20
		1.75	24.6	4.47
		2.63	23.3	4.24
		3.50	22.9	4.16
10.0	240	0.00	72.4	3.82
		0.88	33.6	1.78
		1.75	28.4	1.51
		2.63	26.9	1.42
		3.50	26.6	1.41
10.0	352	0.00	∞	∞
		0.88	43.9	1.61
		1.75	35.3	1.30
		3.50	32.5	1.20
12.0	352	0.00	36.8	1.94
		0.88	28.6	1.52
		1.75	26.0	1.38
		4.50	24.8	1.31
12.0	493	0.00	49.5	1.91
		0.88	35.2	1.36
		4.50	30.0	1.16

Table VIII

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION WITH LATERAL REFLECTOR OF NATURAL URANYL NITRATE SOLUTION

N:U-235 = 2.86

Reactor Diameter Inches	Reflector Concentration gm U/cm³	Reflector Thickness Inches	Fuel H:U-235	Fuel Hc cm	Fuel Mc kg
10.0	0.426	0.00	61.8	> 40.	> 7.3
		0.88		29.9	5.40
		1.75		25.3	4.60
		2.63		23.6	4.29
		3.50		23.0	4.17
10.0	0.426	0.00	240	72.4	3.82
		0.88		34.8	1.84
		1.75		29.0	1.53
		2.63		27.3	1.45
		3.50		26.4	1.40
10.0	0.426	0.00	352	∞	∞
		0.88		47.1	1.73
		1.75		36.1	1.33
		3.50		32.0	1.17
10.0	0.217	0.00	352	∞	∞
		0.88		44.7	1.64
		1.75		35.7	1.31
		3.50		32.5	1.20
12.0	0.217	0.00	493	49.5	1.91
		0.88		35.2	1.36
		4.50		29.8	1.15

Table IX

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION WITH LATERAL REFLECTOR OF PHOSPHORUS AND BISMUTH

N:U-235 = 2.86

Reactor Diameter Inches	H:U-235	Reflector Thickness Inches	Hc cm	Mc kg
		Phosphoric Acid, 0.465 gm P/cm^3		
10.0	61.8	0.00	>40.	>7.3
		0.88	>31.1	>5.6
		1.75	25.8	4.68
		2.63	23.6	4.28
		3.50	22.6	4.11
		3.50	16.0*	2.91*
10.0	240	0.00	72.4	3.82
		0.88	34.6	1.83
		1.75	29.2	1.55
		3.50	28.3	1.50
		Bismuth Sub-carbonate, dry, 0.52 gm Bi/cm^3		
10.0	61.8	0.00	>40.	>7.3
		3.50	>36.	>6.4
		3.50	21.8*	3.96*
10.0	240	0.00	72.4	3.82
		1.75	53.6	2.84
		3.50	48.8	2.58
12.0	352	0.00	36.8	1.94
		0.88	35.4	1.87
		4.50	33.5	1.77
		Bismuth Sub-carbonate Slurry, 0.85 gm Bi/cm^3; 0.82 gm H_2O/cm^3		
12.0	352	0.00	36.8	1.94
		0.88	28.7	1.52
		4.50	24.7	1.31
12.0	493	0.00	49.5	1.91
		4.50	30.1	1.17

*Values obtained with core and reflector enclosed in water.

Table X

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION WITH ANNULAR VOID SEPARATING WATER REFLECTOR FROM REACTOR

N:U-235 = 2.86

Reactor Diameter 10.0"

H:U-235	Thickness of Void Inches	Hc cm	Mc kg
61.8	0.0	16.6	3.02
	1.0	19.0	3.45
	2.0	21.0	3.81
	3.0	22.4	4.08
	4.0	23.6	4.28
	∞	> 40.	> 7.3
240	0.0	20.1	1.06
	1.0	24.0	1.27
	2.0	26.5	1.40
	4.0	29.6	1.57
	∞	72.4	3.82

Table XI

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE-PHOSPHORIC ACID-NITRIC ACID SOLUTIONS

Reactor Diameter inches	N:U-235	H:U-235	P:U-235	Hc cm	Mc kg
		Water Reflector			
10.0	5.4	157	15.8	> 27.	>1.5
	5.4	157	15.8	> 27. *	>1.6 *
	2.9	316	53.1	>105.	>2.9
12.0	2.9	316	53.1	43.5	1.75
15.0	2.9	316	53.1	26.8	1.69
	2.9	316	53.1	29.5*	1.86 *
	5.5	180	12.4	18.9*	2.5 *
	5.5	180	12.4	15.4	2.0
		No Reflector			
10.0	5.4	157	15.8	> 57.	> 3.2
15.0	2.9	316	53.1	43.2	2.72
15.0	5.5	180	12.4	> 25.	> 3.3

* Without top water reflector.

Table XII

CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN INHOMOGENEOUS CORES

Reactor Diameter 15.0"
Water Reflector

Fuel Composition H:U-235	Fuel Composition N:U-235	Tubes	Bismuth Filled Bi:U-235	Bismuth Filled Hc cm	Bismuth Filled Mc kg	Air Filled Hc cm	Air Filled Mc kg	Fuel Filled Hc cm	Fuel Filled Mc kg
88	7.48	106	---	---	---	>54.	>7.7	17.3	4.39
115	10.53	106	45.3	>44.	>5.0	--	--	--	--
230	7.48	106	83.5	>45.	>2.8	>85.	>5.2	17.4	1.90
230	7.48	36	18.5	20.2	1.96	22.3	2.17	--	--

Fuel Composition H:U-235	Fuel Composition N:U-235	Fuel Composition P:U-235	Tubes	Core Composition H:U-235	Core Composition N:U-235	Core Composition P:U-235	Water Filled Hc cm	Water Filled Mc kg	Phosphoric Acid Filled Hc cm	Phosphoric Acid Filled Mc kg
115	10.53	--	106	224	10.53	--	17.6	1.99	--	--
230	7.48	--	106	430	7.48	--	23.6	1.44	--	--
230	7.48	--	36	273	7.48	--	17.6	1.72	--	--
128	6.97	15.8	106*	291	8.16	15.8	24.1*	1.8	--	--
128**	6.97	15.8	106*	291	8.16	15.8	35.2	2.6	--	--
128	6.97	15.8	36*	163	7.22	15.8	19.6	2.3	--	--
128**	6.97	15.8	36*	163	7.22	15.8	25.9	3.0	--	--
131**	6.97	15.8	36*	155	7.22	20.7	--	--	26.9	3.1
131	6.97	15.8	36*	155	7.22	20.7	--	--	20.8	2.4
131	6.97	15.8	106*	244	8.16	39.0	--	--	29.0	2.1
131**	6.97	15.8	106*	244	8.16	39.0	--	--	>46.	>3.3
316	2.90	53.1	106*	711	5.69	53.1	∞	∞	--	--
316	2.90	53.1	106*	565	5.69	106.4	--	--	∞	∞
316	2.90	53.1	36*	368	3.46	63.9	--	--	35.8	1.90

* with 5% nitric acid solution.
** without water reflector.

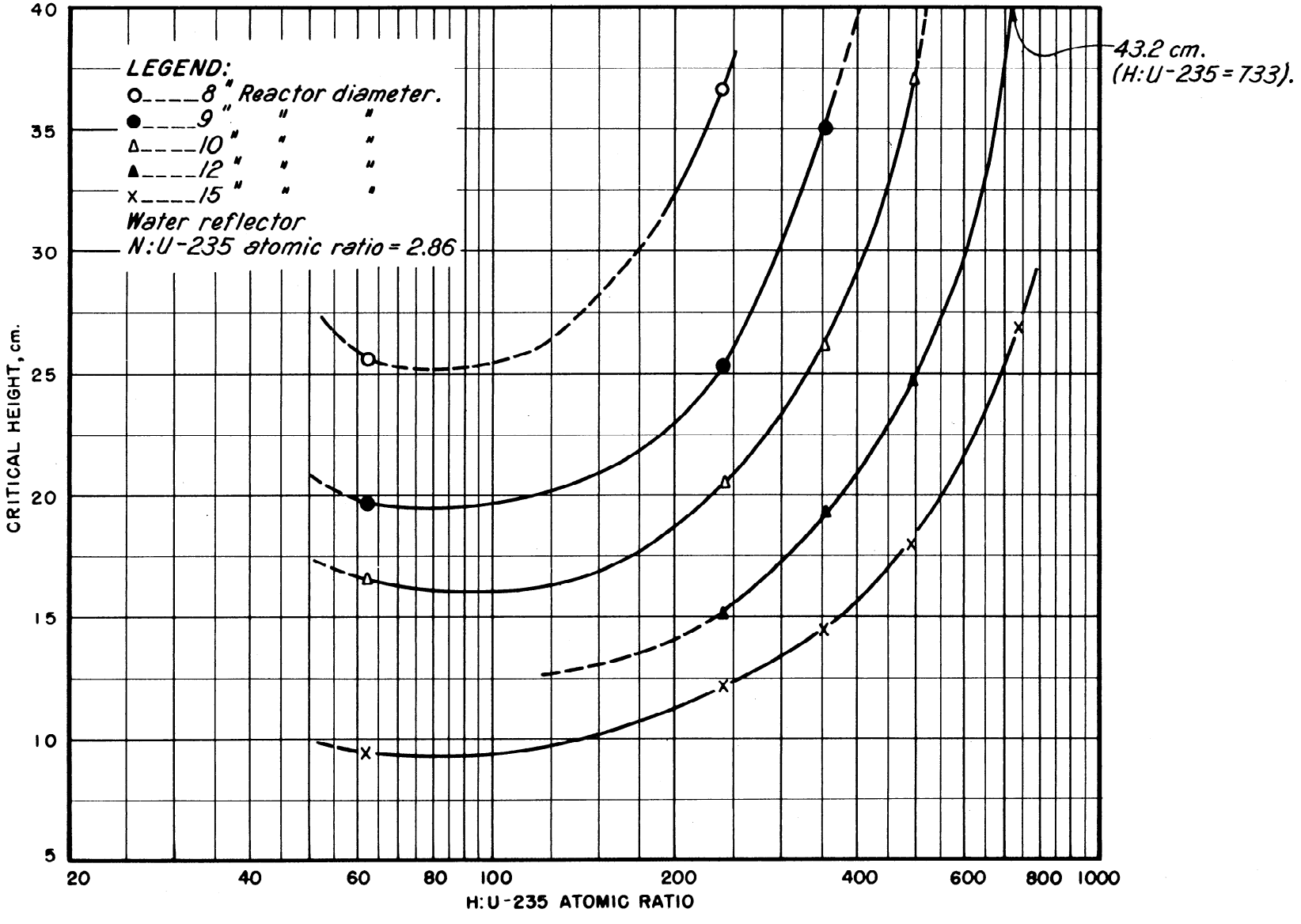
Table XIII

EFFECT OF CONTROL RODS ON CRITICAL HEIGHT AND CRITICAL MASS OF U-235 IN URANYL NITRATE SOLUTION

H:U-235 = 240
N:U-235 = 2.86

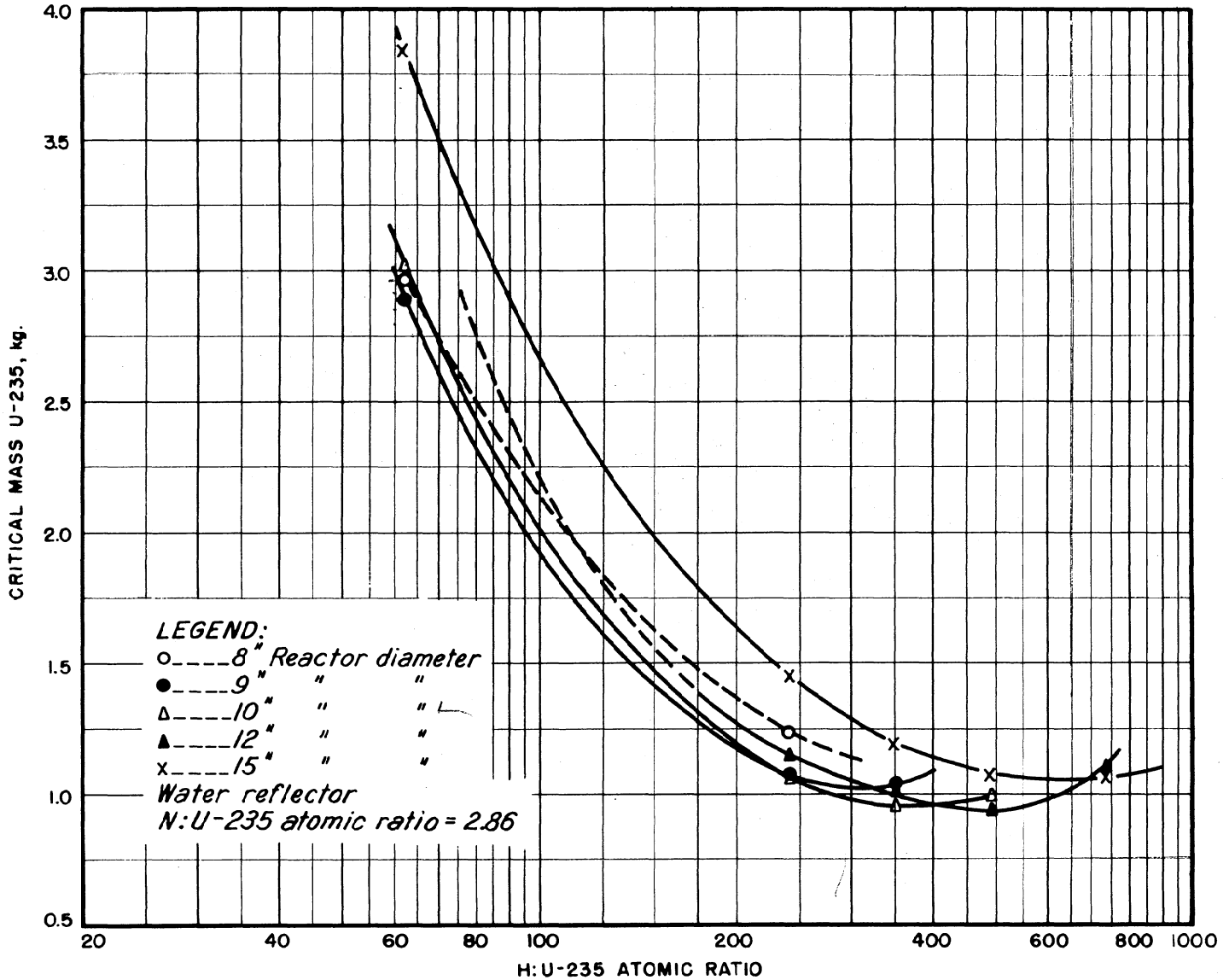
Rod	Position*	Reactor Diameter Inches 8.0 Hc cm	8.0 Mc kg	10.0 Hc cm	10.0 Mc kg	15.0 Hc cm	15.0 Mc kg
None	Out	36.7	1.24	20.10	1.06	12.15	1.45
1" rod with 1-7/16" sheath	Horizontal	37.1	1.26	20.6	1.09	12.55	1.50
1-7/16" sheath	Horizontal	36.7	1.24	20.25	1.07	12.25	1.46
1" rod only	Vertical	39.4	1.33	---	---	---	---
1-7/16" sheath	Vertical	37.2	1.26	---	---	---	---
3/4" rod	Vertical	37.9	1.29	20.45	1.08	12.30	1.47
3/4" rod	Vertical (in fuel)	43.3	1.47	---	---	12.50	1.49

* Control rod in reflector touching reactor wall except where noted.



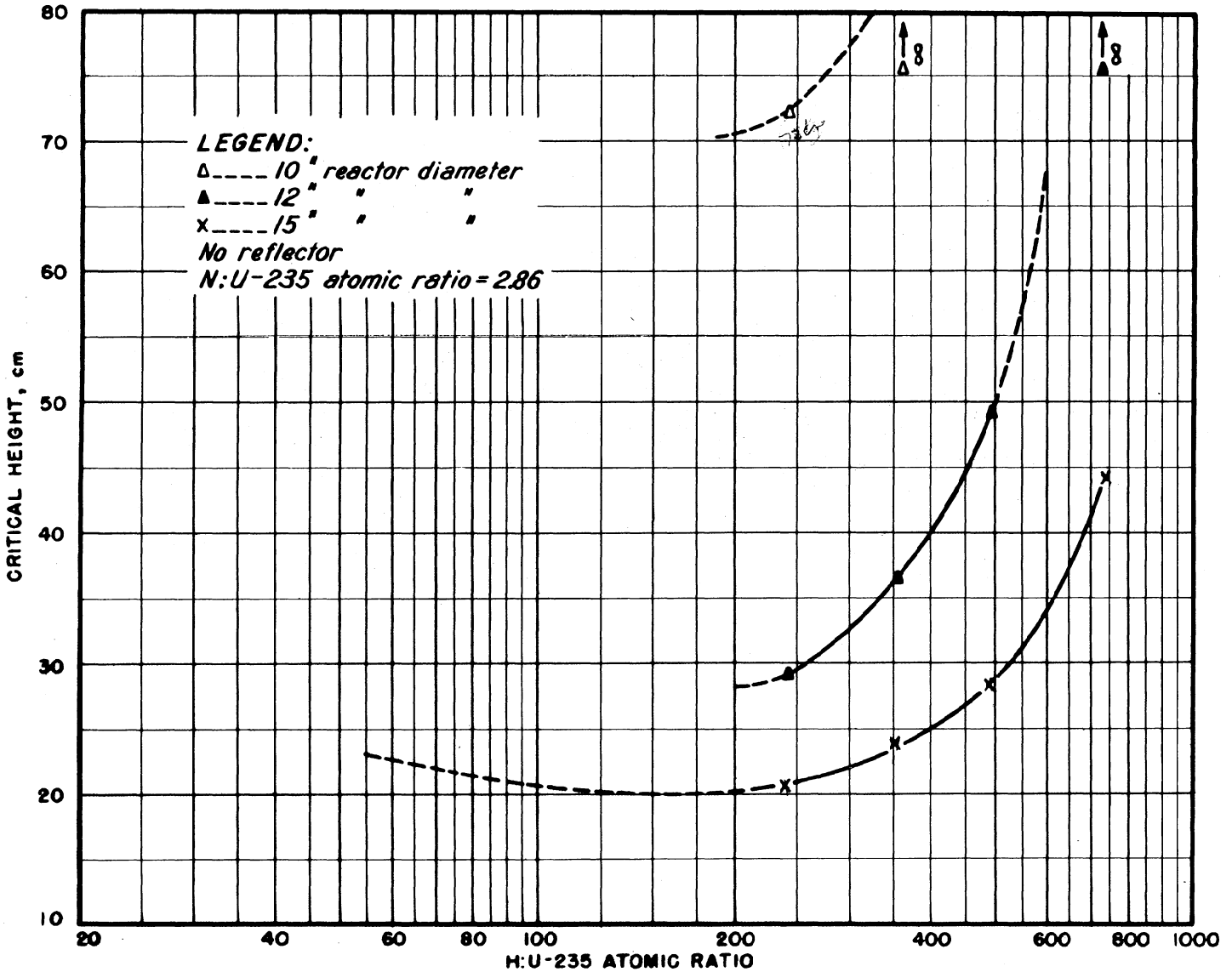
CRITICAL HEIGHT Vs MODERATION

GRAPH 1



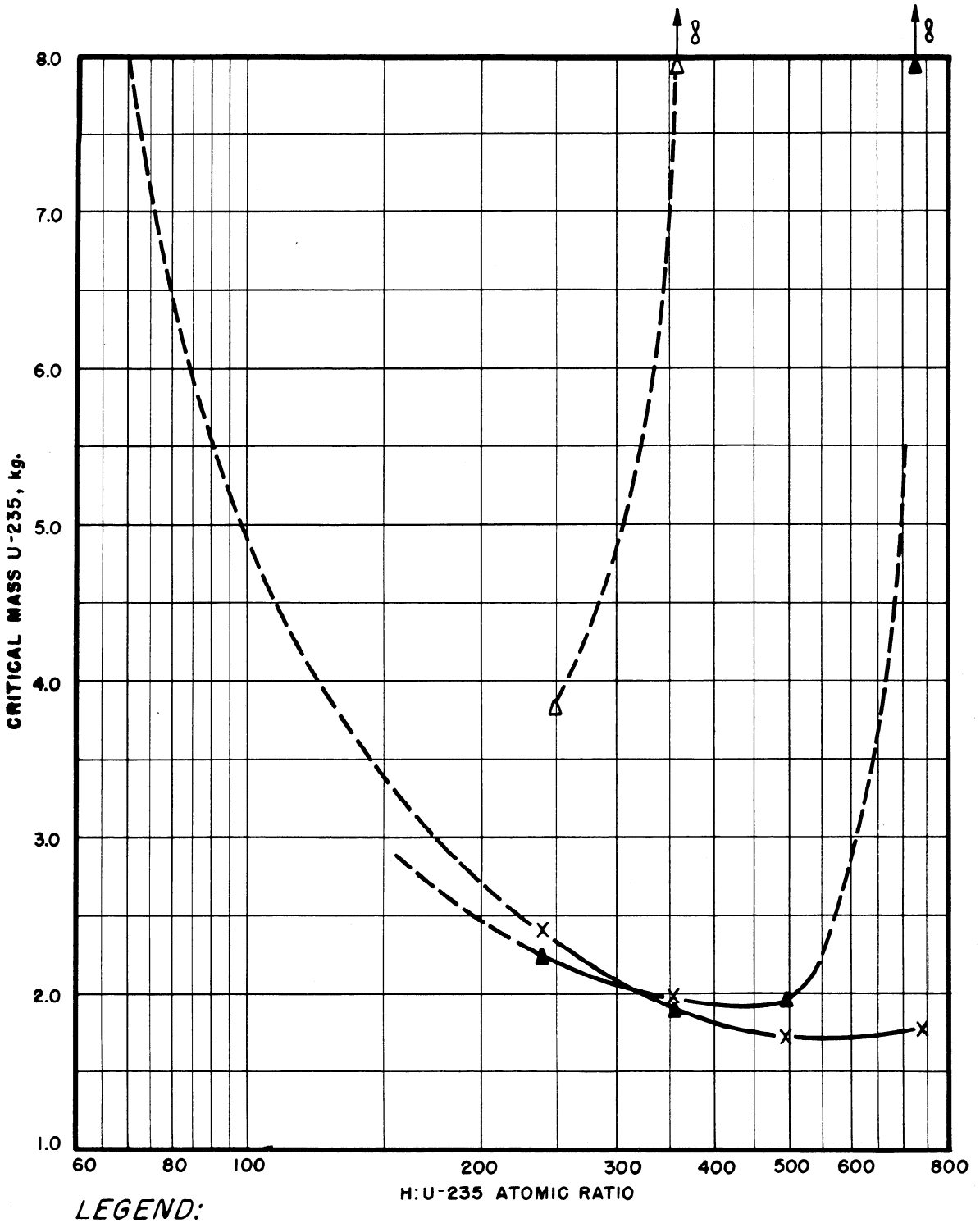
CRITICAL MASS OF U-235 Vs MODERATION

GRAPH 2



CRITICAL HEIGHT Vs MODERATION

GRAPH 3



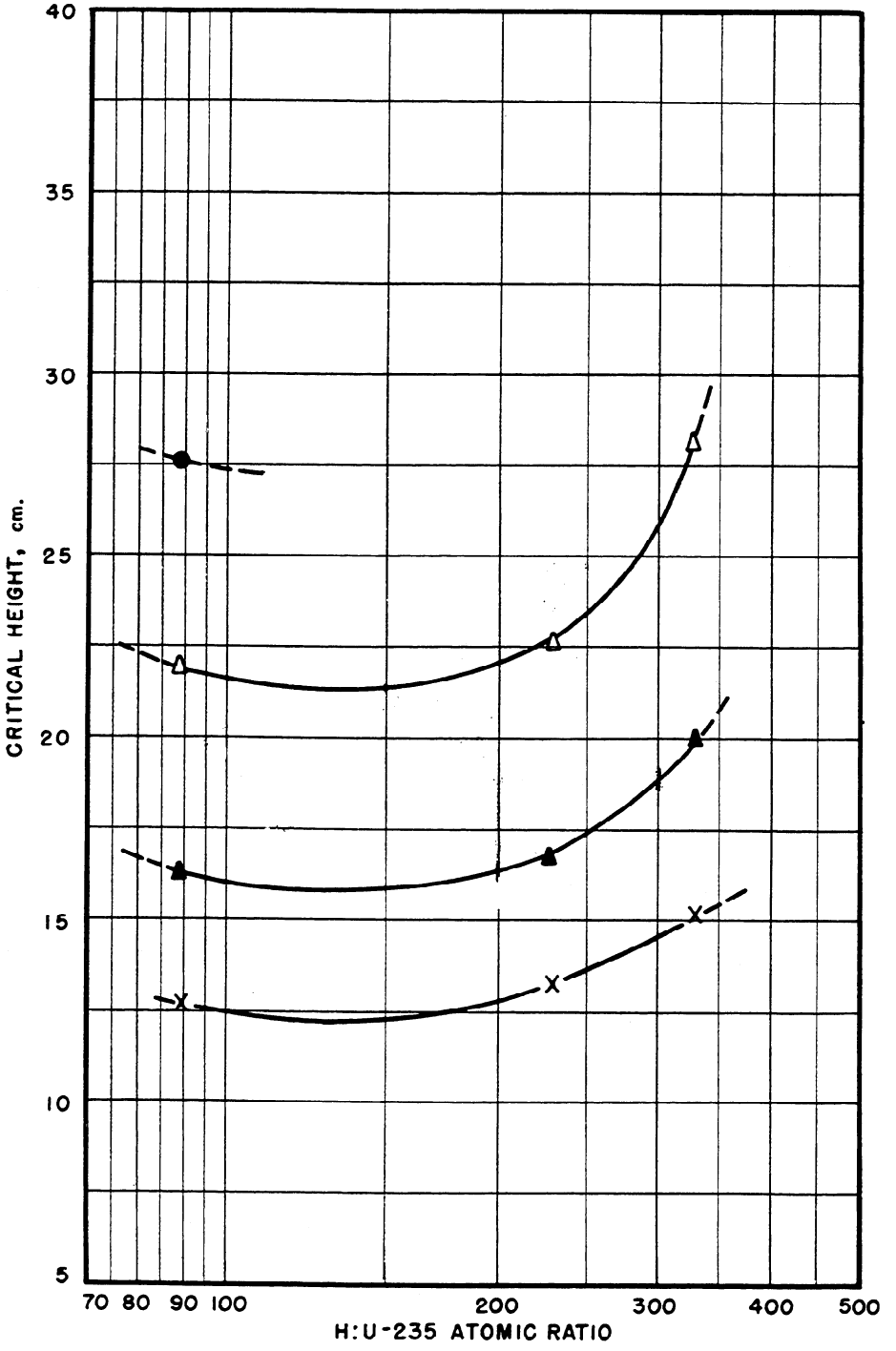
LEGEND:

Δ----10" reactor diameter.
▲----12" " "
X----15" " "

No reflector
N:U-235 atomic ratio = 2.86

CRITICAL MASS OF U-235 Vs MODERATION

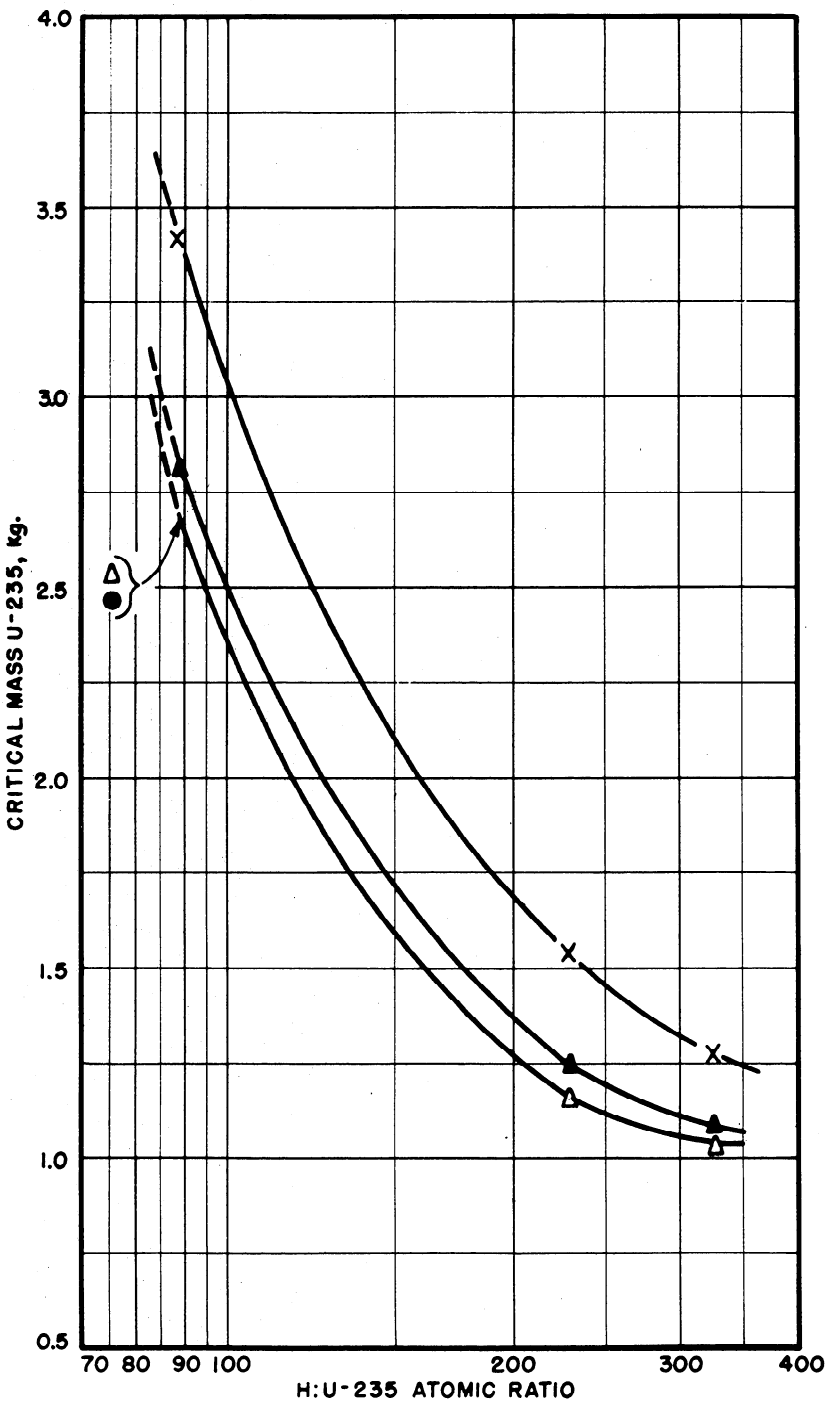
GRAPH 4



LEGEND:
●____ 9" reactor diameter.
Δ____ 10" " "
▲____ 12" " "
X____ 15" " "
Water reflector
N:U-235 atomic ratio = 7.48

CRITICAL HEIGHT VS MODERATION

GRAPH 5

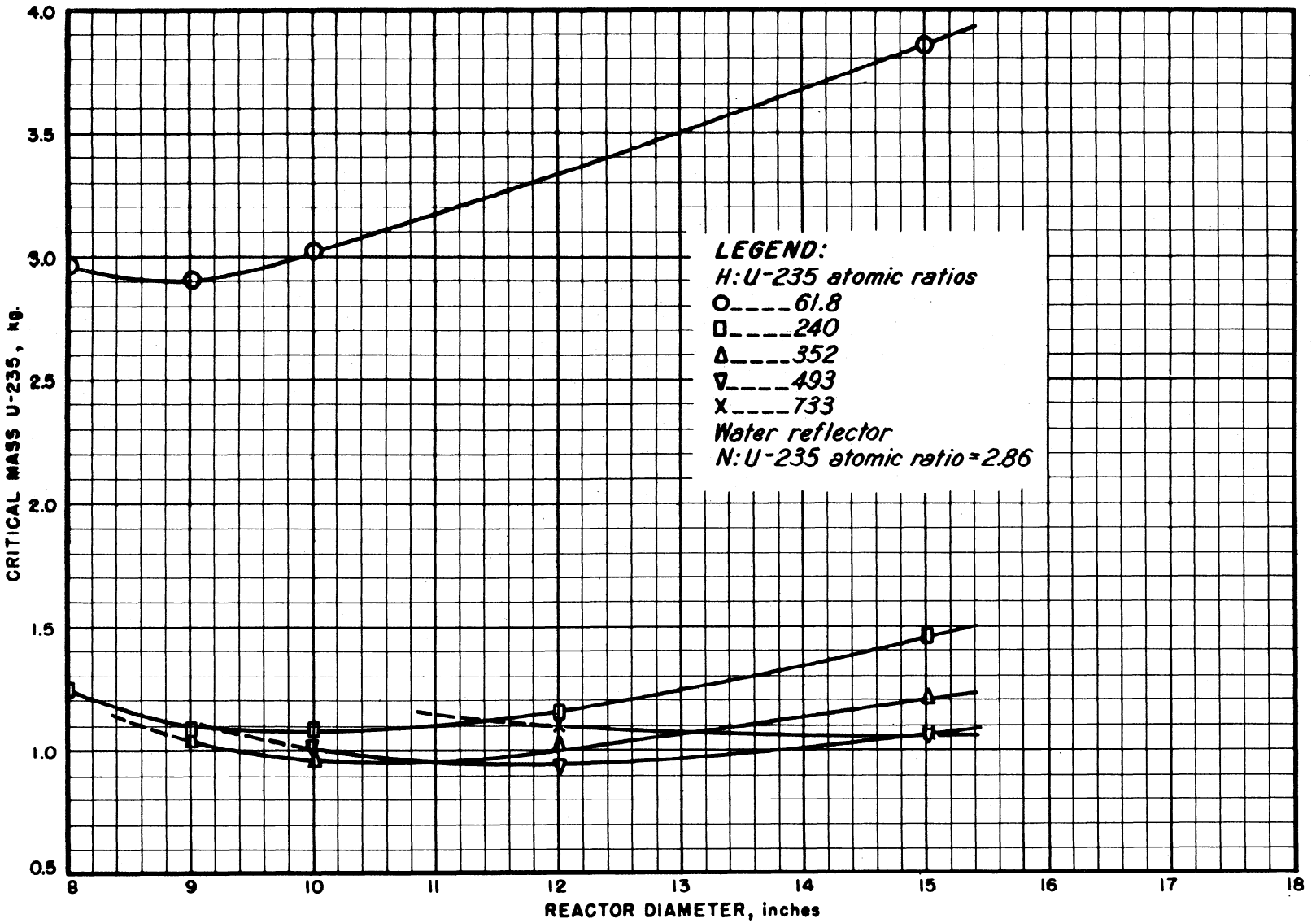


LEGEND:

●____ 9" reactor diameter.
Δ____ 10" " "
▲____ 12" " "
x____ 15" " "
Water reflector
N:U-235 atomic ratio = 7.48

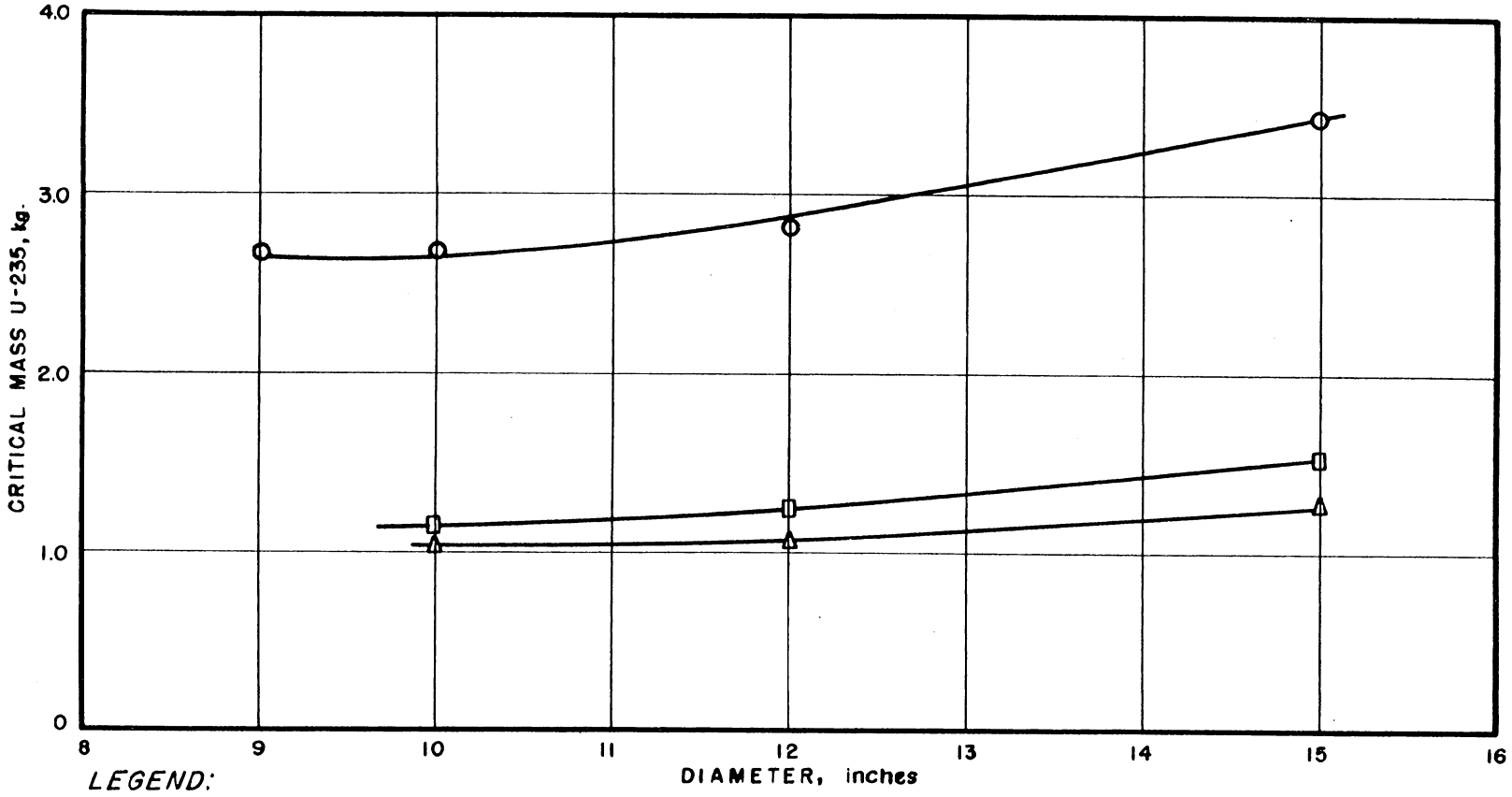
CRITICAL MASS OF U-235 Vs MODERATION

GRAPH 6



CRITICAL MASS OF U-235 Vs REACTOR DIAMETER

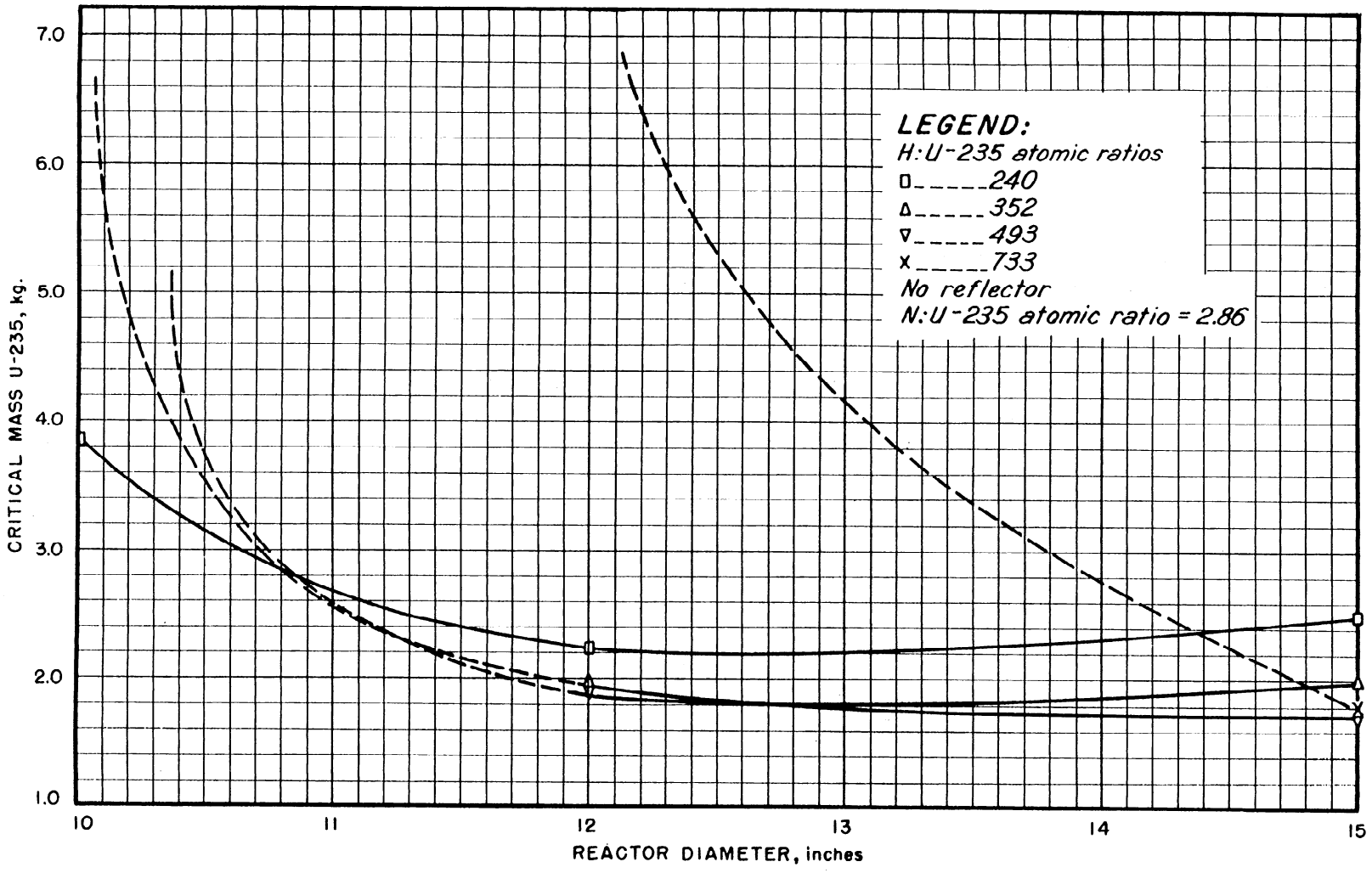
GRAPH 7



LEGEND:
H: U-235 atomic ratios:
O____88
□____230
Δ____327
Water reflector
N: U-235 atomic ratio = 7.48

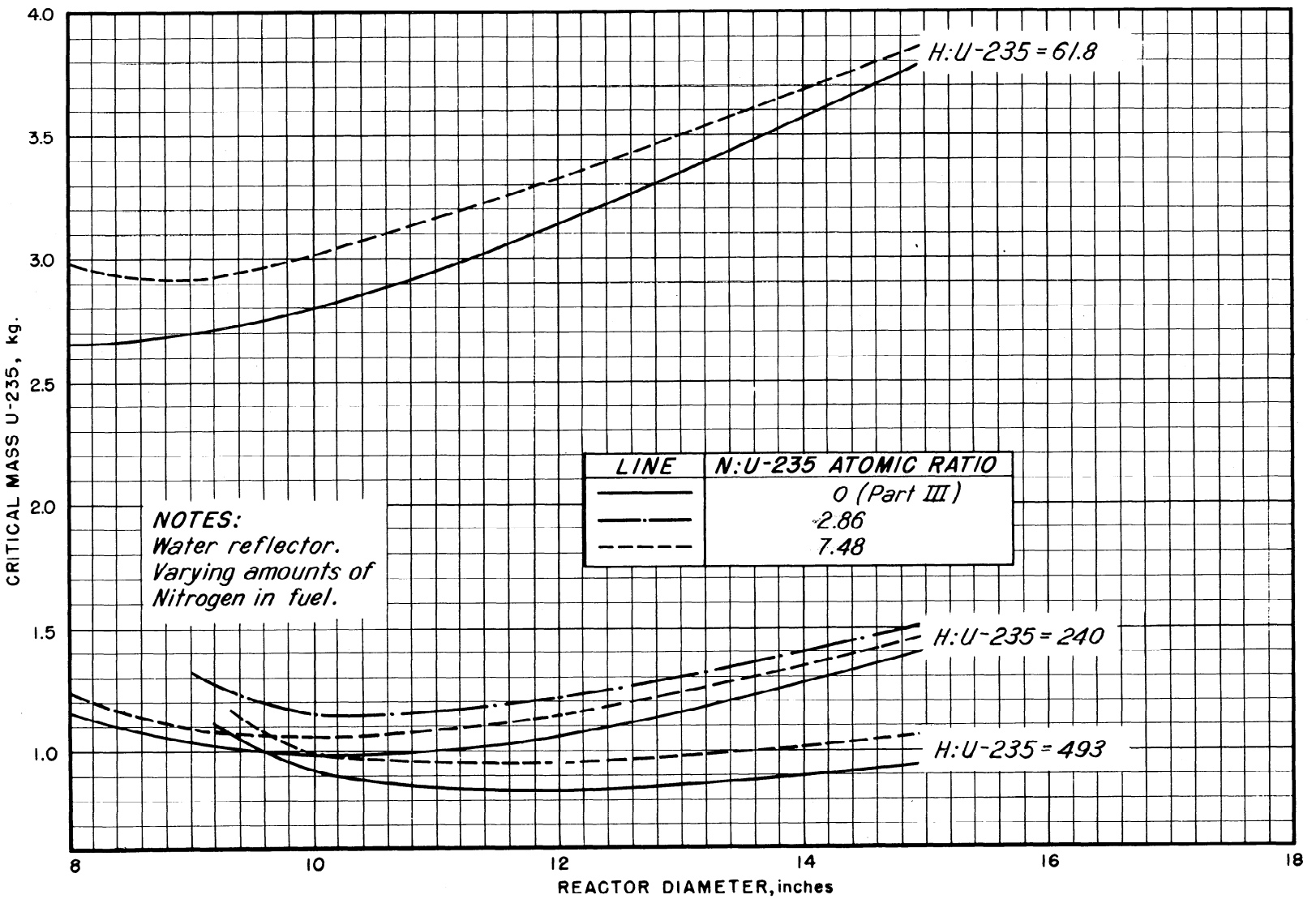
CRITICAL MASS OF U-235 Vs REACTOR DIAMETER

GRAPH 8



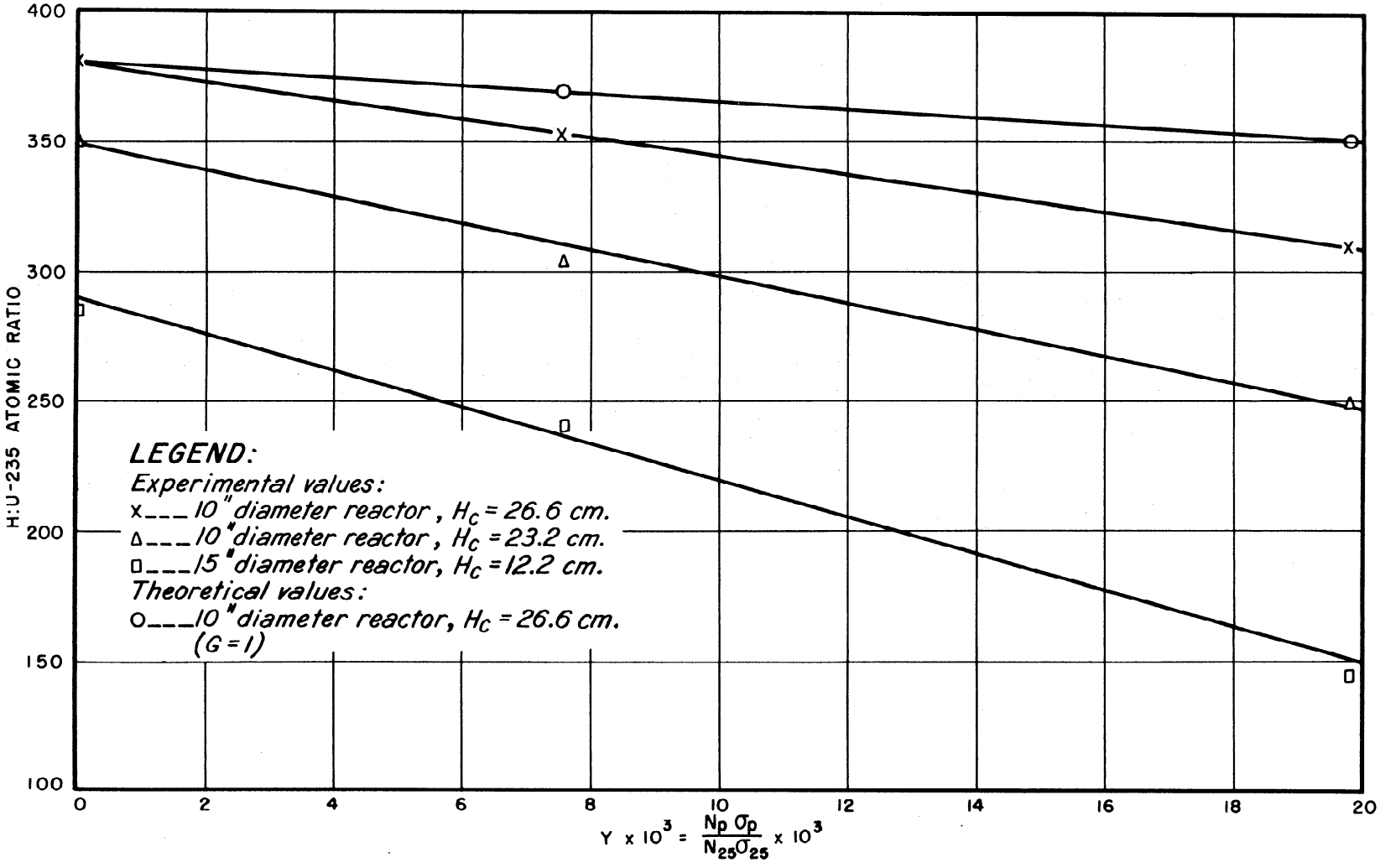
CRITICAL MASS OF U-235 Vs REACTOR DIAMETER

GRAPH 9



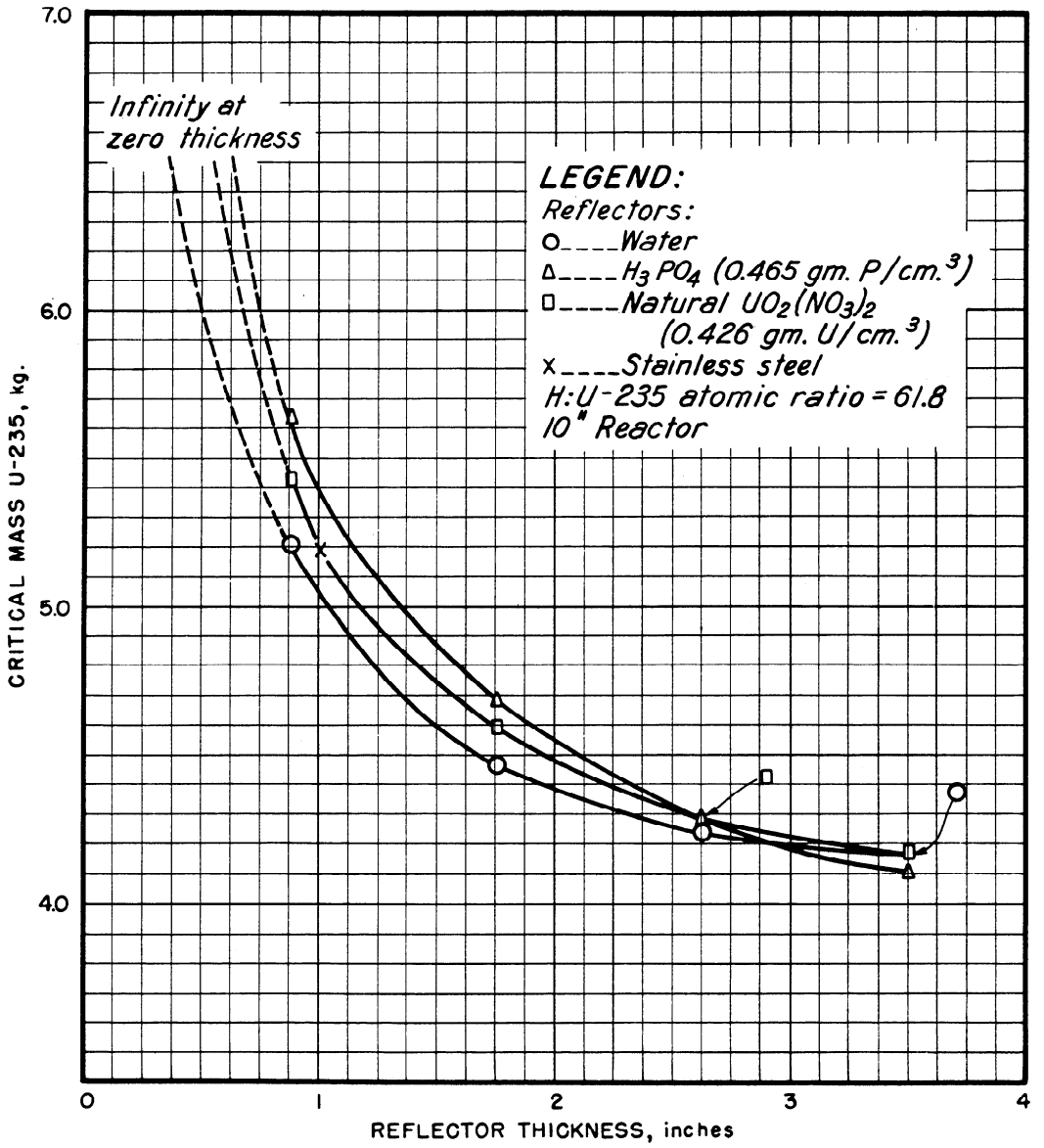
CRITICAL MASS OF U-235 Vs REACTOR DIAMETER

GRAPH 10



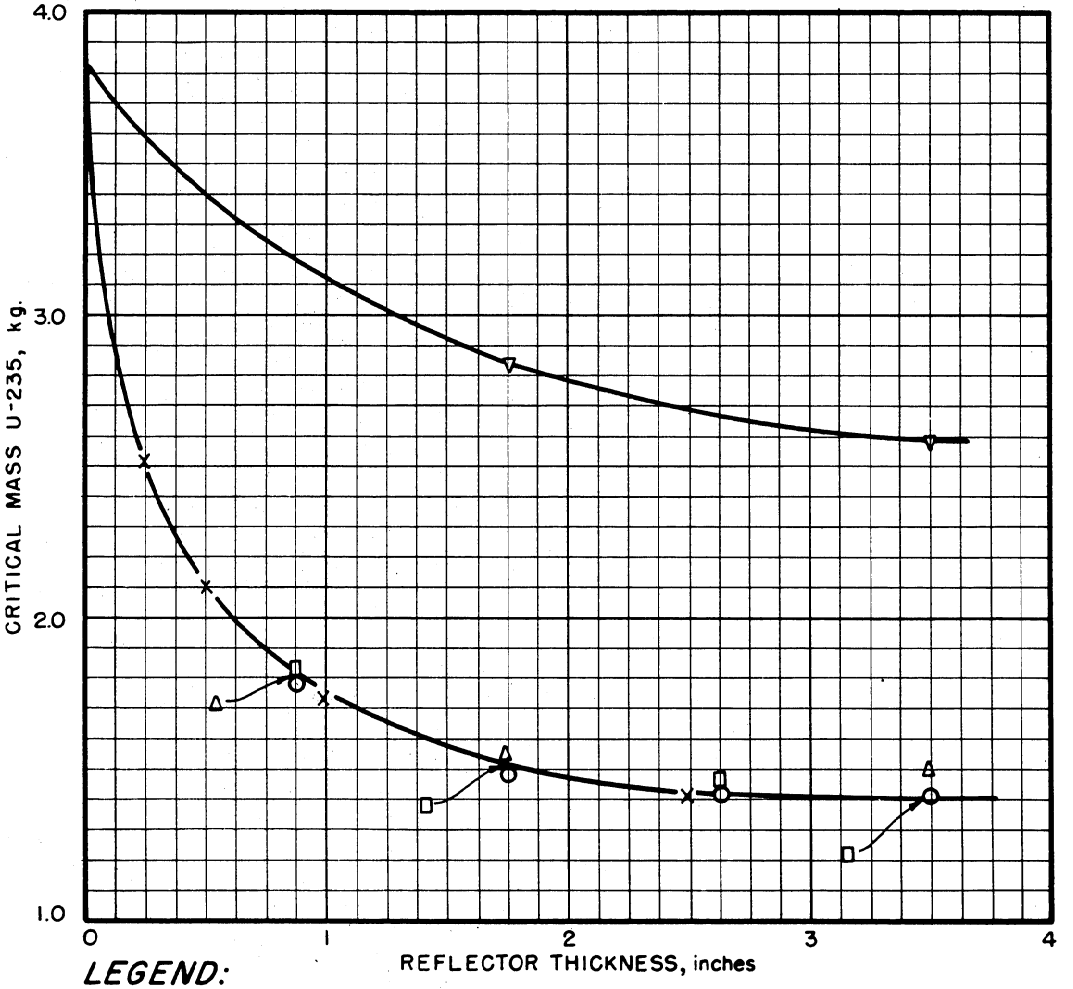
MODERATION Vs $\frac{Np\ \sigma p}{N_{25}\ \sigma_{25}} \times 10^3$

GRAPH II



CRITICAL MASS OF U-235 Vs LATERAL REFLECTOR THICKNESS

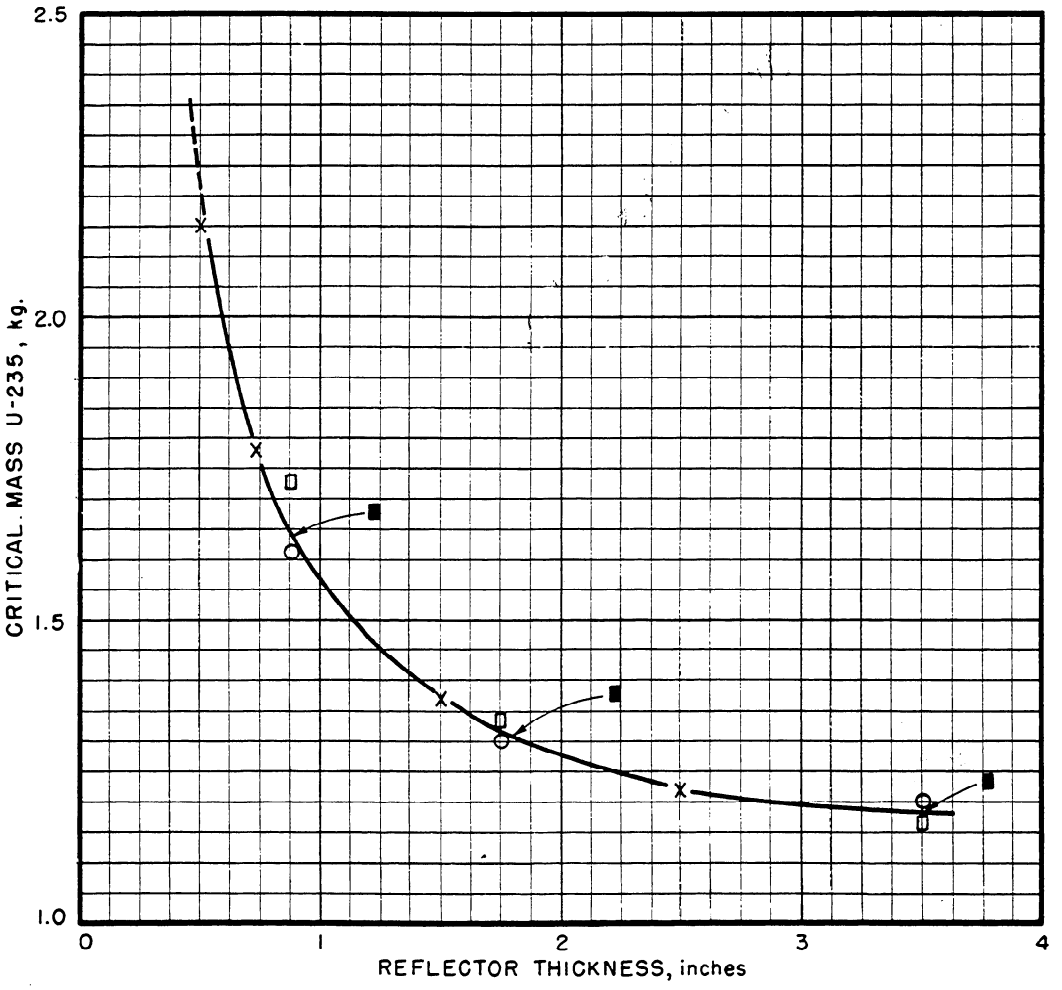
GRAPH 12



LEGEND:
Reflectors:
O____ *Water*
▽____ $Bi_2O_2CO_3$ *dry (0.529 Bi/cm.*^{3}*)*
□____ $UO_2(NO_3)_2$ *solution (0.476 gm. U/cm.*^{3}*)*
△____ H_3PO_4 *solution (0.465 g. P/cm.*^{3}*)*
x____ *Stainless steel*
H:U-235 atomic ratio = 240
10" Reactor

CRITICAL MASS OF U-235 Vs LATERAL REFLECTOR THICKNESS

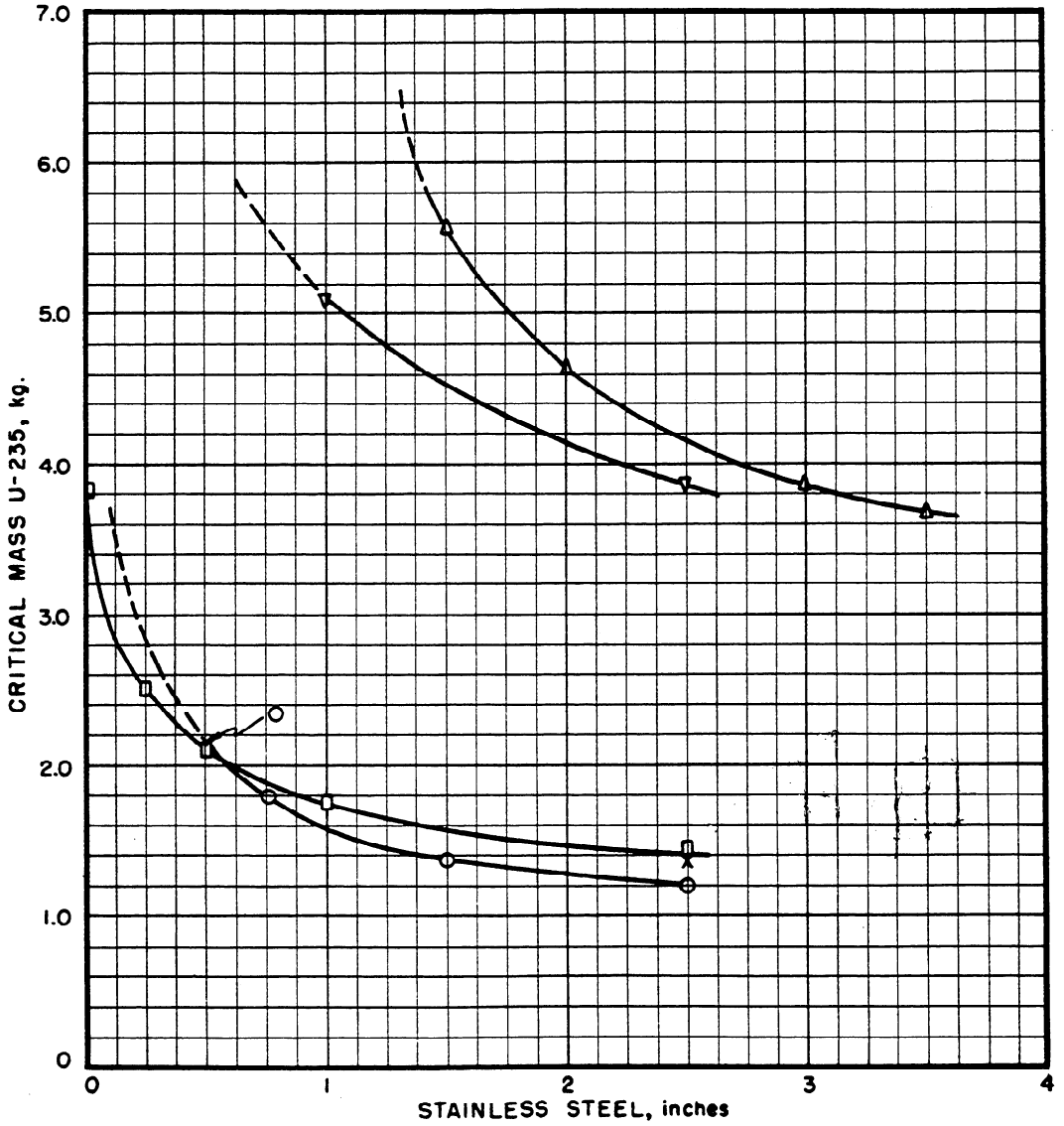
GRAPH 13



LEGEND:
Reflectors:
○_____ *Water.*
□_____ $UO_2(NO_3)_2$ *solution (0.426 gm. U/cm.*^{3}*)*
■_____ $UO_2(NO_3)_2$ *solution (0.217 gm. U/cm.*^{3}*)*
x_____ *Stainless steel.*
H:U-235 atomic ratio = 352
10" Reactor

CRITICAL MASS OF U-235 Vs LATERAL REFLECTOR THICKNESS

GRAPH 14

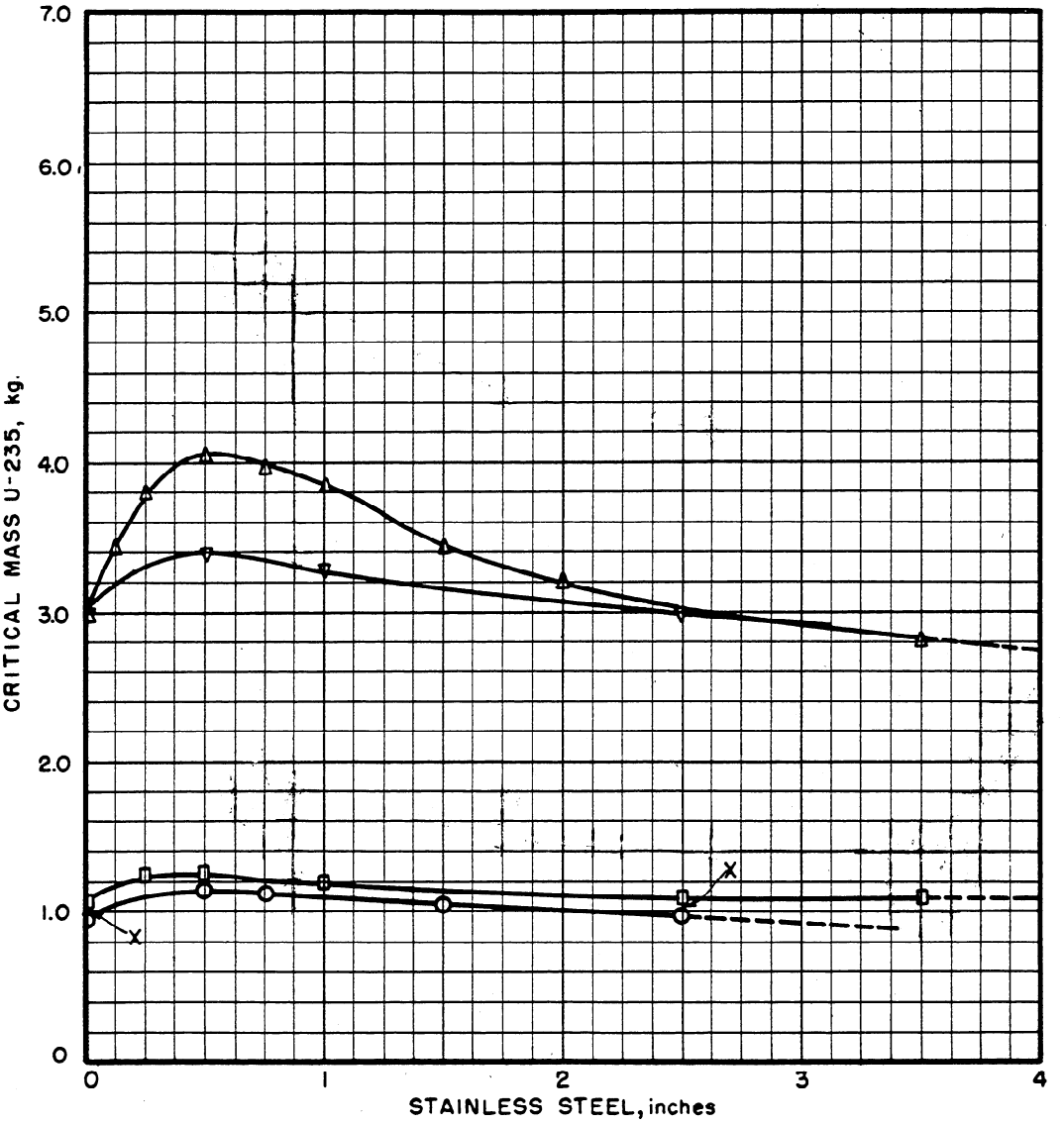


REACTOR	H:U-235 ATOMIC RATIO	SYMBOL
8"	61.8	Δ
10"	61.8	∇
10"	240	□
10"	352	○
10"	493	×

N:U-235 atomic ratio = 2.86

CRITICAL MASS OF U-235 Vs LATERAL THICKNESS OF STAINLESS STEEL REFLECTOR

GRAPH 15

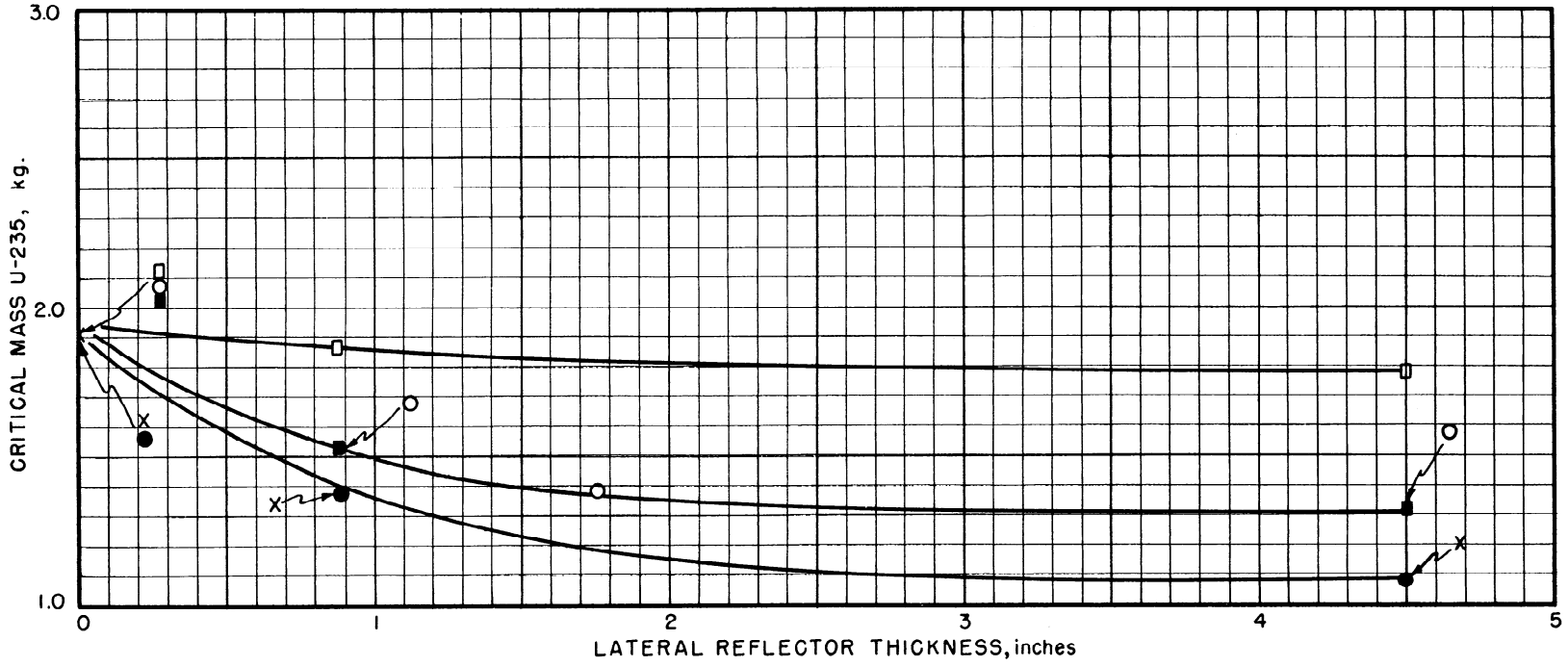


REACTOR	H:U-235 ATOMIC RATIO	SYMBOL
8"	61.8	△
10"	61.8	▽
10"	240	□
10"	352	○
10"	493	x

Enclosed in water reflector.

CRITICAL MASS OF U-235 Vs LATERAL THICKNESS OF STAINLESS STEEL REFLECTOR

GRAPH 16

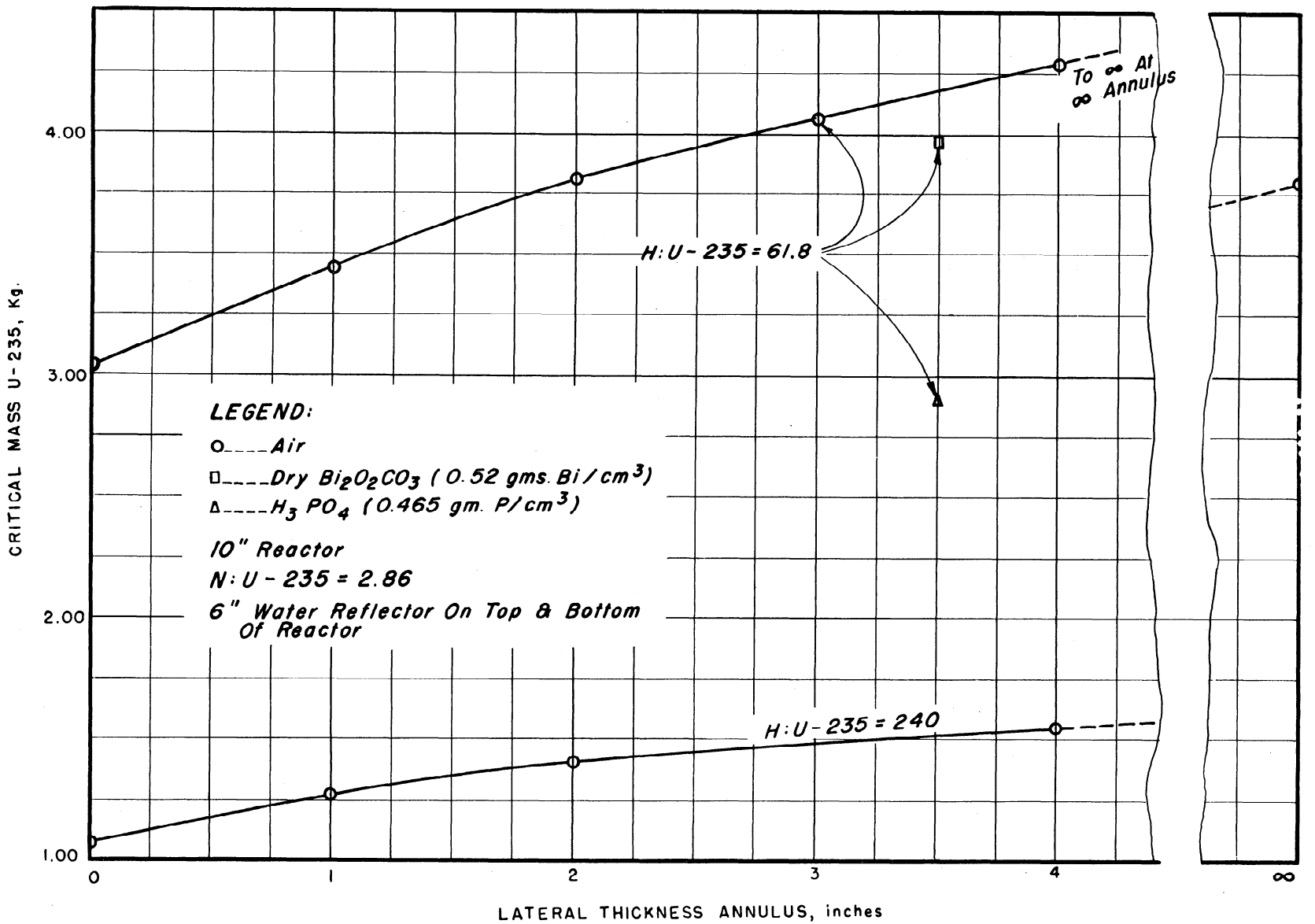


SYMBOL	H:U-235 ATOMIC RATIO	REFLECTOR
□	352	Dry $Bi_2O_2CO_3$
■	352	Slurry $Bi_2O_2CO_3$
○	352	Water
×	493	Nat'l. uranyl nitrate solution
●	493	Water

NOTE:
12" Reactor.

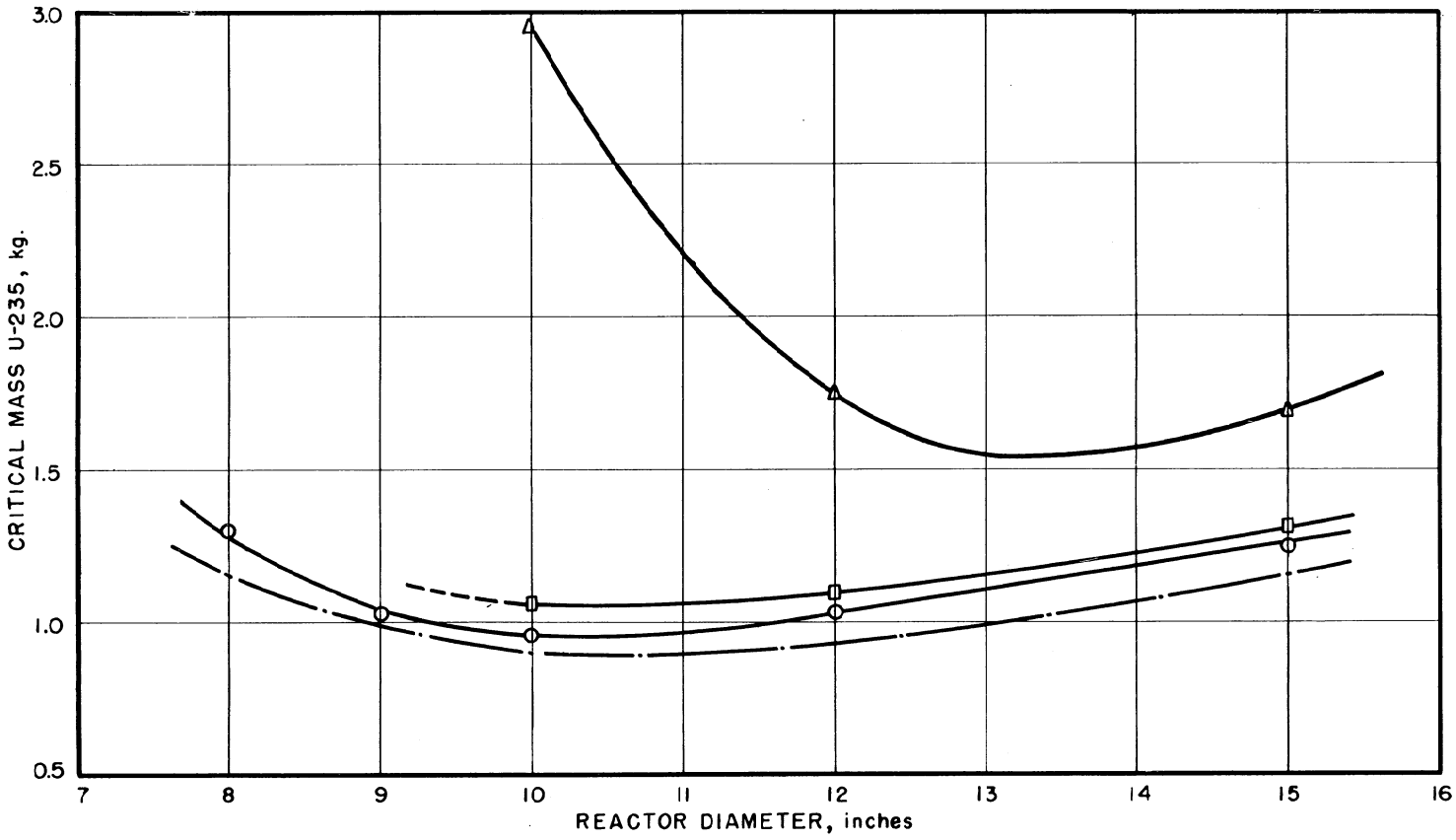
CRITICAL MASS OF U-235 Vs LATERAL REFLECTOR THICKNESS

GRAPH 17



CRITICAL MASS OF U-235 VS LATERAL THICKNESS OF ANNULUS SEPARATING REACTOR FROM WATER REFLECTOR

GRAPH 18

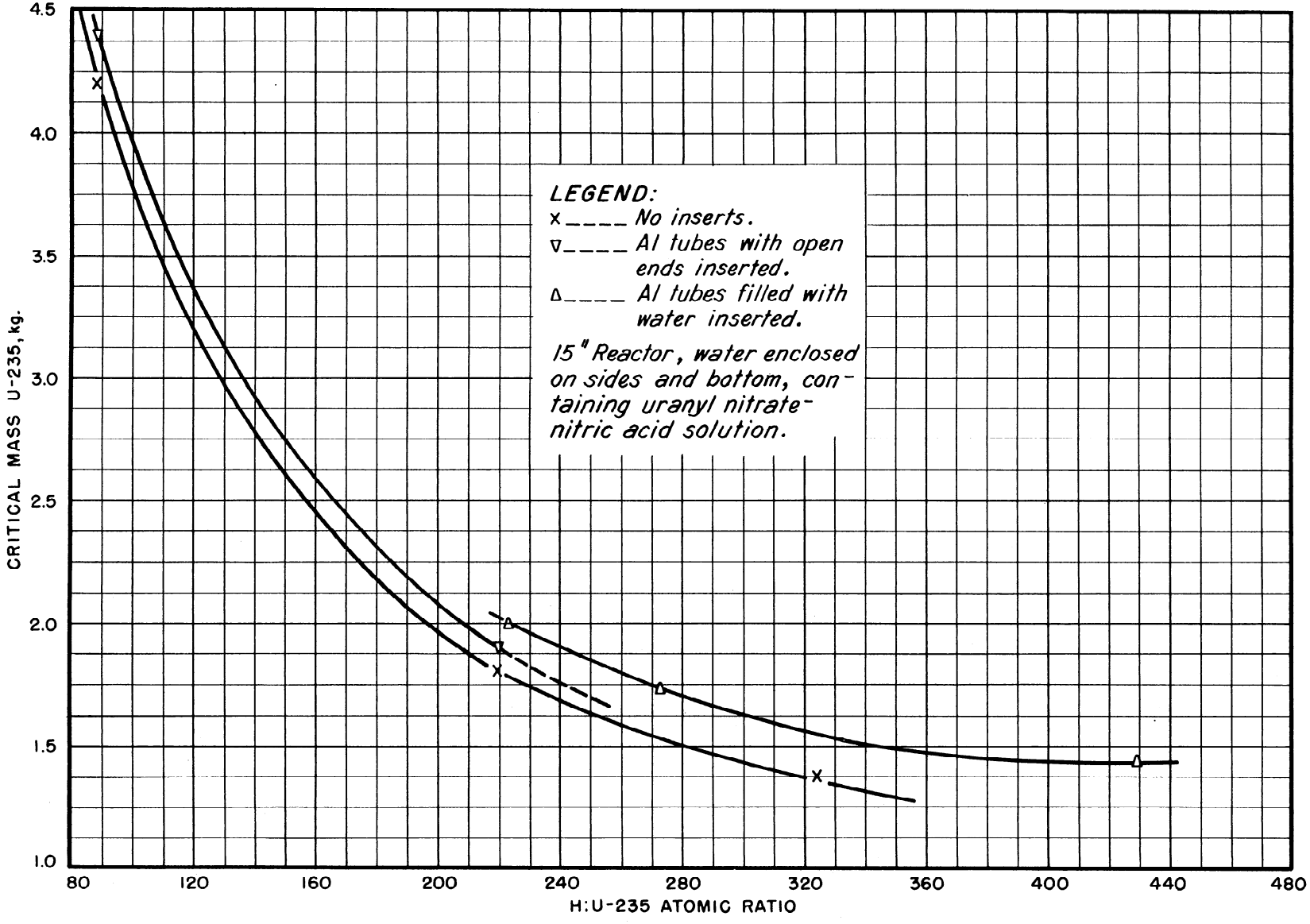


H:U-235 ATOMIC RATIOS	N:U-235 ATOMIC RATIOS	P:U-235 ATOMIC RATIOS	SYMBOL
316	2.9	53.1	△
316	7.5	0	□
316	2.9	0	○
316	0 (Part III)	0	—·—

NOTE:
Water reflector.

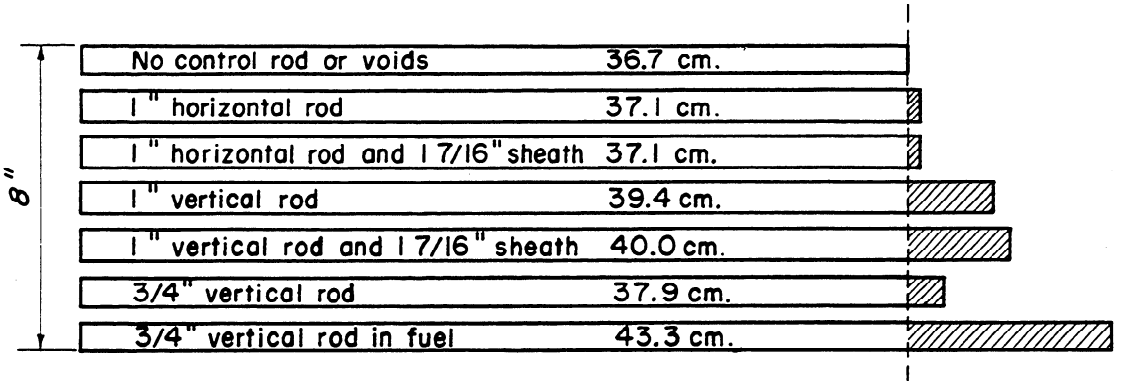
CRITICAL MASS OF U-235 IN PRESENCE OF POISONS Vs REACTOR DIAMETER

GRAPH 19

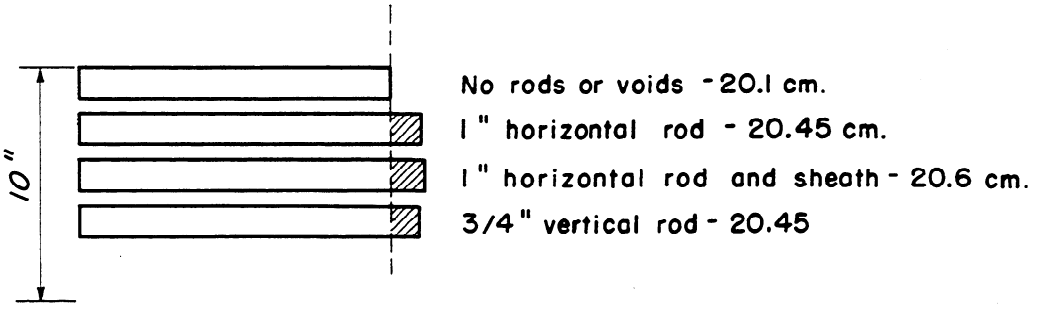


EFFECT OF WATER INHOMOGENIETY ON CRITICAL MASS

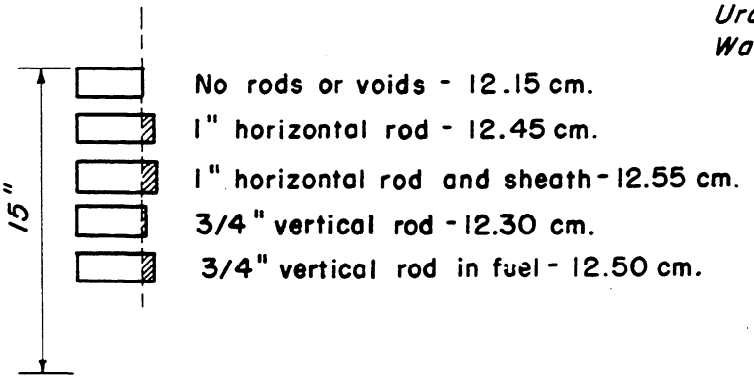
GRAPH 20



REACTOR DIAMETER



NOTES:
H:U-235 = 240
N:U-235 = 2.86
Uranyl nitrate solution
Water reflector



VALUES OF CRITICAL HEIGHT OBTAINED WITH VARIOUS CONTROL RODS INSERTED

GRAPH 21