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OF THE UNIVERSITY OF CALIFORNIA

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CRITICAL MASSES OF FISSIONABLE METALS AS BASIC NUCLEAR SAFETY DATA

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CRITICALITY HAZARDS
(M-3679, 16th edition)

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Abstract

Pajarito data on critical configurations of fissionable metals are summarized in a form that emphasizes the influence of conditions that are commonly met in nuclear safety questions.

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Enriched Uranium

The bulk of the data on critical configurations of fissionable metal exists for uranium enriched, in most cases, to about 93.5 atomic percent U^{235} [Oy(93.5)]. A summary of such information includes the influence upon critical mass of various reflectors, of shape of the fissionable material, of variations in U^{235} concentration and density, or, more generally, the effect of a diluent, and, finally, the extent of interaction between separate U^{235} systems.

Reflectors. Neutron reflectors which are incidental to processing include water (as cleaning and plating baths), oxide refractories and graphite (in casting furnaces), steel (of rolls and presses), and molten salts (heating baths). The critical mass of a bare, isolated sphere of Oy(93.5) metal, 52 kg, would be reduced to 20 - 25 kg by a thick reflector of nearly any common material (e.g., Al, Fe, Cu, water). Reflectors known to be exceptionally effective are Be, D_2O, and graphite at large thicknesses, U, and W (or WC). Dependence of critical mass upon reflector thickness is illustrated by Figure 1 for Al, Fe, graphite, H_2O, and D_2O. The striking difference between shapes of the curves for H_2O and D_2O reflects, of course, the small capture cross

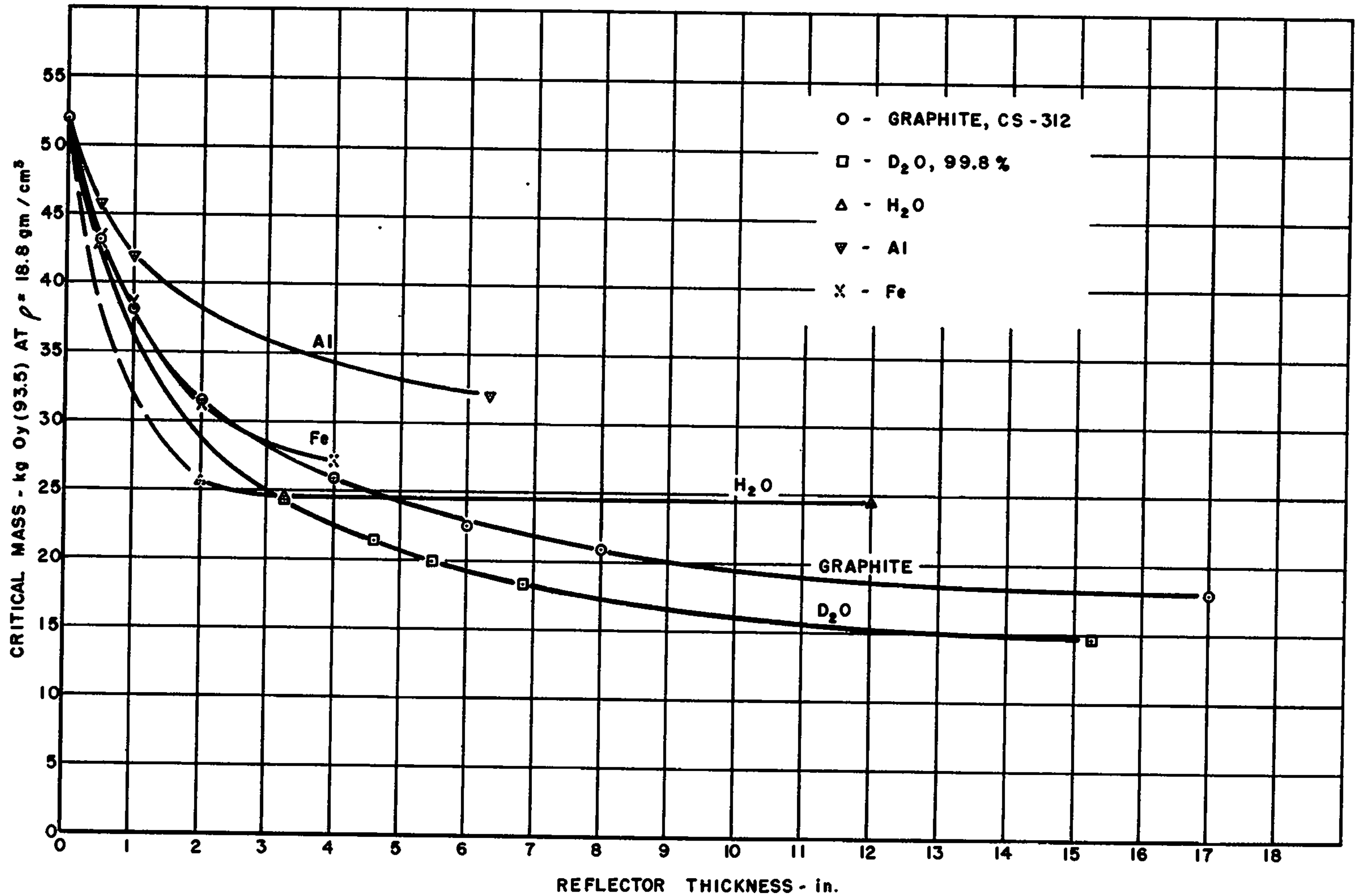

FIG. 1. Illustrations of critical mass of oralloy vs. reflector thickness.

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section of D relative to H. Where direct information is unavailable, the relative effectiveness of a neutron reflector (at least for modest thickness) may be judged by comparing the macroscopic transport cross section[1] with those of materials with known reflection efficiencies. Table I lists critical masses for standard thicknesses of various reflectors and transport cross sections of the reflector materials.

Shape. The critical mass of oralloy metal is insensitive to minor changes of shape. For example, it may be seen in Figure 2 that critical masses of oralloy cylinders with thick graphite or water (or paraffin) reflectors change only 20% as the ratio of oralloy height to diameter ranges from 1/3 to 2. As reflector effectiveness is decreased, critical mass does become somewhat more dependent upon shape, as shown by data for oralloy cylinders with normal uranium reflectors of various thicknesses, Figure 3.

Limiting critical dimensions of Oy(93.5) metal cylinders, obtained by R. E. Gwin[2] from guided extrapolations of the data of Figures 2 and 3, are:

reflector	diam. of just critical infinite rod	thickness of just critical infinite plate
none	4.9"	2.4 "
thick water	2.9"	0.75"
thick graphite or U	2.3"	0.5 "

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TABLE I.

CRITICAL MASSES OF SPHERICAL ORALLOY WITH VARIOUS REFLECTORS
(adjusted to several standard reflector thicknesses)

Reflector (ρ-gm/cm^3)	Critical mass - kg Oy(93.5) at ρ = 18.8 gm/cm^3				effective
reflector thickness:	1"	2"	4"	infinite	σ_{tr} - cm^{-1}
Be (QMV, ρ = 1.84)	31.2	22.3	15.1		~ 0.25
BeO (ρ = 2.69)		22.8	16.6	~ 9.5	
WC (ρ = 14.7)		22.8	17.7	~ 17.1	
U (ρ = 19.0)	33.0	25.2	19.7	17.2	0.25
W-alloy(~ 92% W, ρ=17.4)	33.4	25.8	20.8		~ 0.25
paraffin				23.3	
H_2O		~ 25.7	24.5	24.4	
D_2O		(29)	22.5	~ 14.6	
Cu (ρ = 8.88)	34.7	27.2	22.2		0.23
Ni (ρ = 8.35)		28.7	(23.5)	~ 21	0.23
Al_2O_3 (ρ = 2.76)	37.6				
graphite (CS-312, ρ=1.69)	38.0	31.5	25.9	~ 17.9	0.18
Fe (ρ = 7.87)	38.5	31.3	27.1	24.8	0.19
Zn (ρ = 7.04)		31.9	26.7		0.18
Th (ρ = 11.48)		35.6			~ 0.14
Al (2S, ρ = 2.70)	42.0	(38)	(34)	< 32.1	0.13
Ti (ρ = 4.50)	42.5				0.12
Mg (ρ = 1.77)	43.9				0.10

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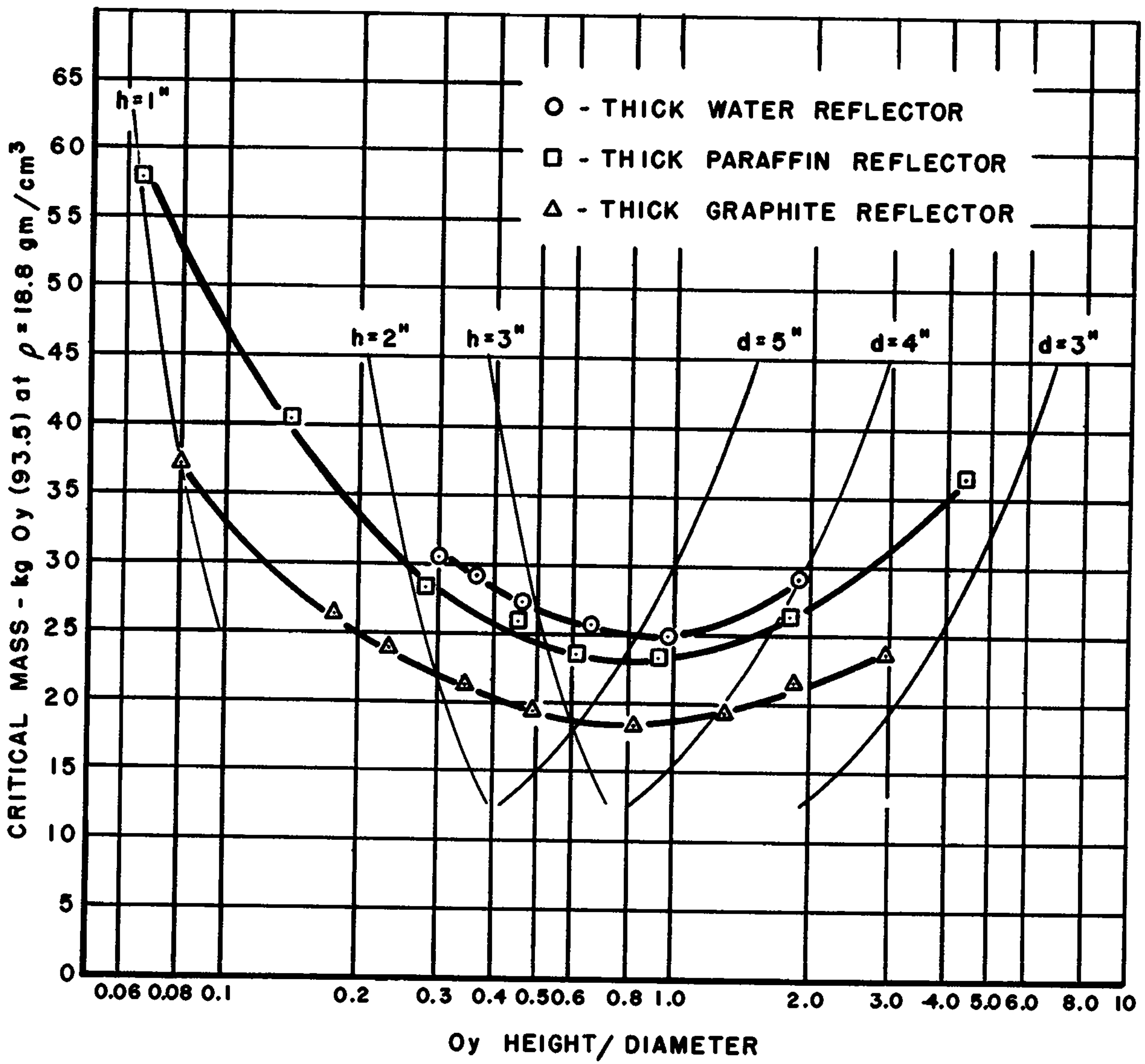

FIG. 2. Critical mass of cylindrical oralloy as function of height/diameter, with reflector of ~ 12" thick water, ~ 8" thick paraffin, and of ~ 17" thick graphite.

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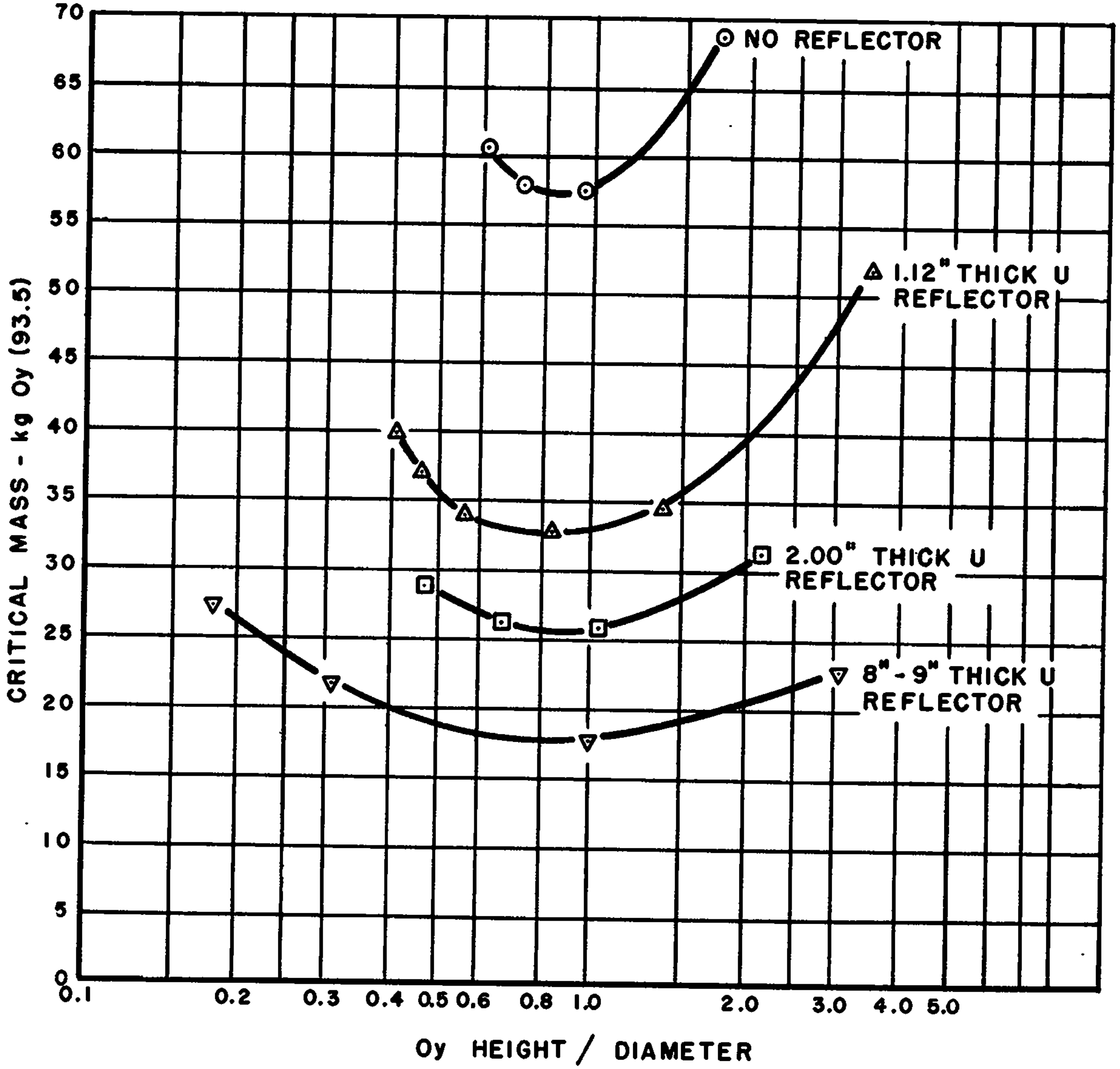

FIG. 3. Critical mass of cylindrical oralloy as function of height/diameter, without reflector and with several thicknesses of normal uranium reflector.

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These dimensions, less useful than corresponding values for solutions, are considered more suitable for orientation than as gospel.

U^{235} Concentration. The critical mass of oralloy metal as a function of average U^{235} concentration has been determined for nearly spherical oralloy in a reflector of thick normal uranium, and for a series of oralloy cylinders without reflector. After the data for the bare cylinders are corrected to apply to spheres, both sets of data are of the form

$$\text{Oy critical mass} \propto (\text{U-235 concentration})^{-1.7}$$

Figure 4 shows the two relations, and includes data in the very low concentration range which come indirectly from measurements in exponential columns. The shaded region represents the estimated uncertainty in the limiting critical U^{235} concentration (at which an infinite mass would be just critical).

Oralloy Density. Critical masses of Oy(93.5) spheres in thick normal uranium have been measured at various average densities of the oralloy. The resulting relation, Figure 5, is of the form

$$\text{Oy critical mass} \propto (\text{Oy density})^{-1.2}.$$

From the proportionality of critical radius and mean free path of neutrons, which in turn is inversely proportional

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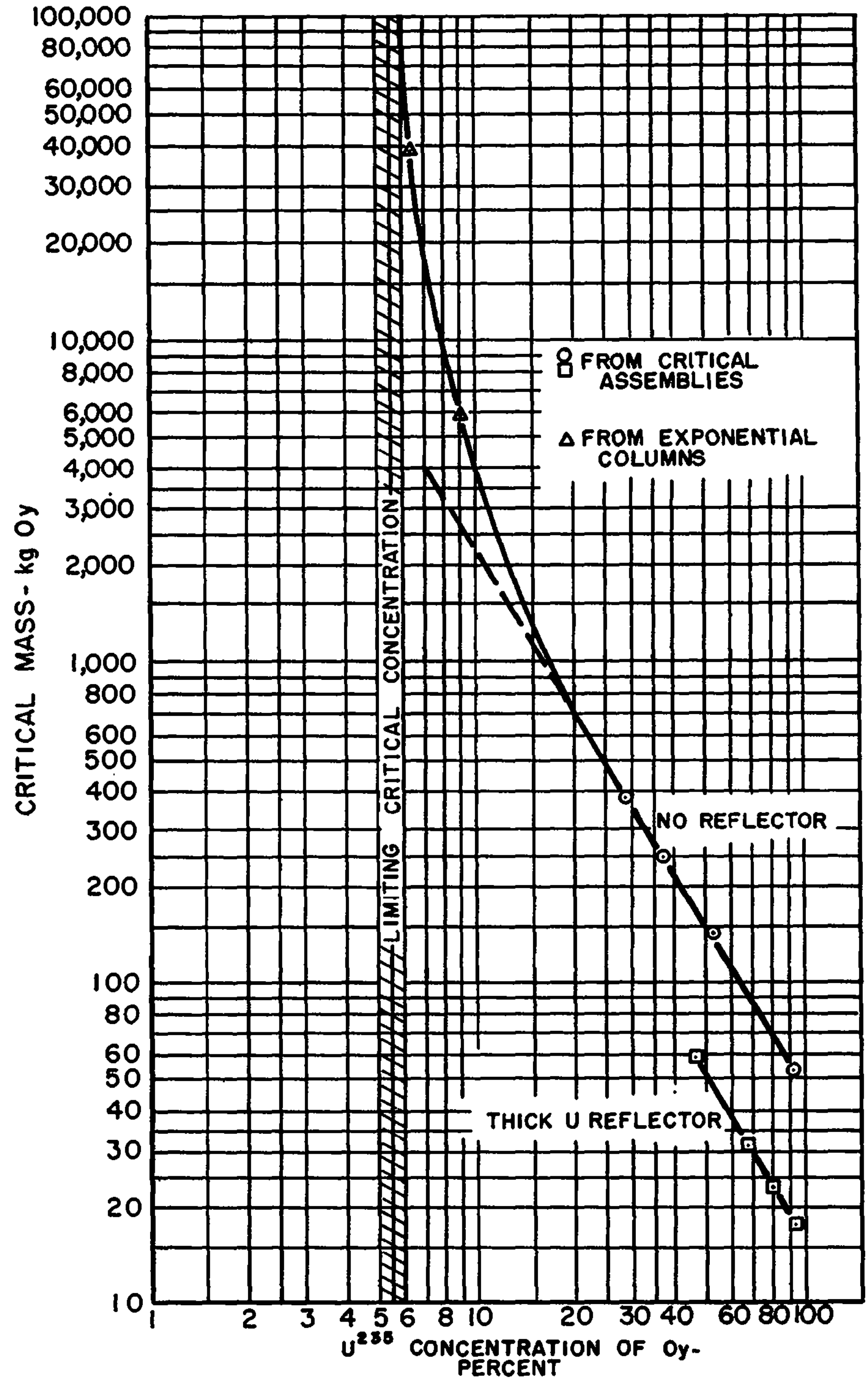

FIG. 4. Oralloy critical mass vs. U^{235} concentration. The shaded strip represents the range of uncertainty in the value of U^{235} concentration below which oralloy metal cannot be made critical.

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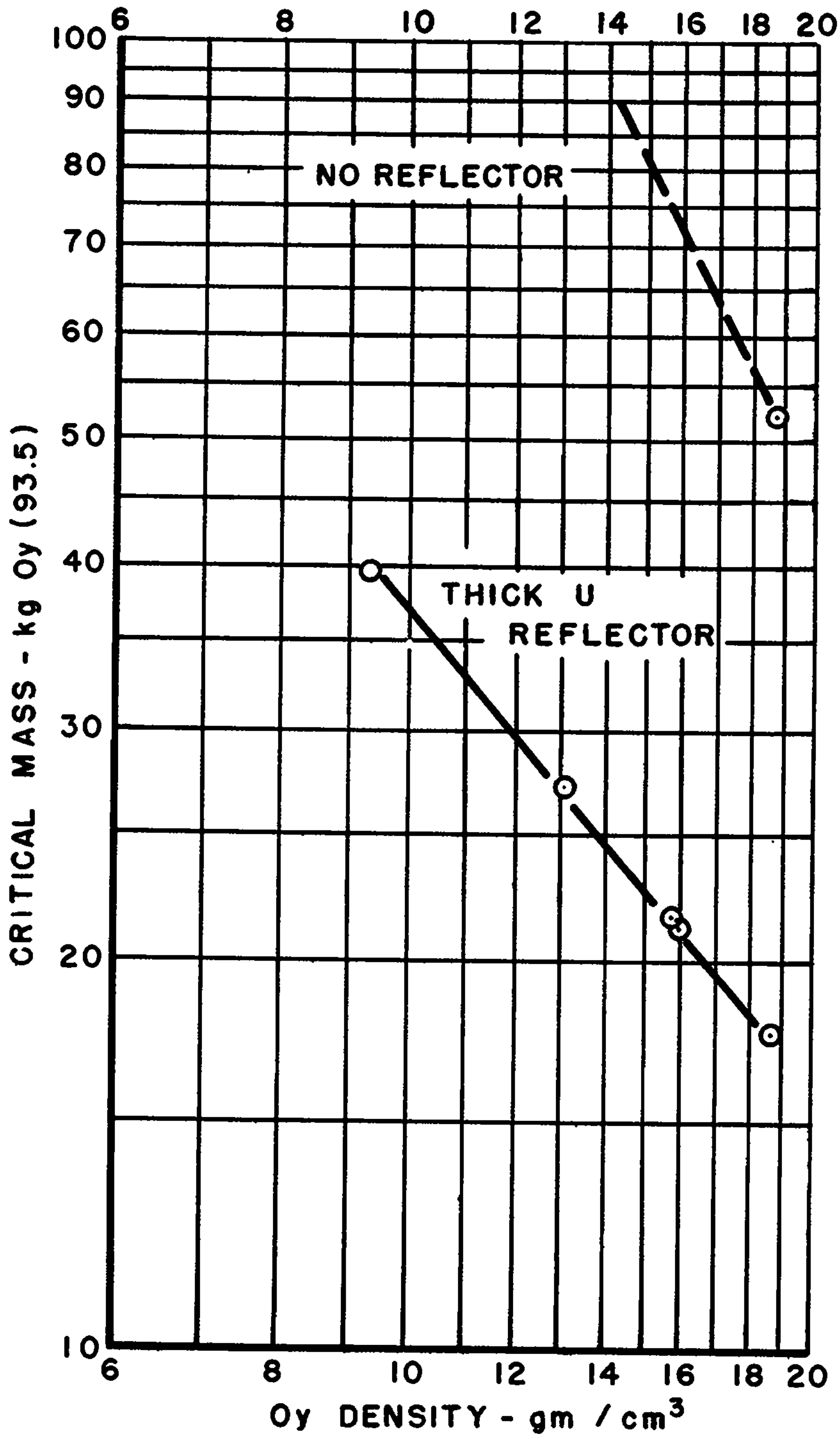

FIG. 5. Critical mass vs. density of oralloy metal -- with normal uranium reflector at full metal density. The broken line represents the computed relation for bare oralloy.

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to an over-all density change, it follows that the above expression for oralloy in thick normal uranium may be expanded to

$$\text{Oy critical mass } \alpha \text{ (Oy density)}^{-1.2}\text{(Tu density)}^{-0.8}$$

i.e., the sum of the exponents must be - 2. For a bare oralloy assembly, the indicated relation is

$$\text{Oy critical mass } \alpha \text{ (Oy density)}^{-2}.$$

<u>General Dilution of Oralloy</u>. The oralloy diluent most likely to be of concern is, of course, water (or other hydrogenous materials). The way in which the minimum critical mass of Oy(93.5) - water mixtures depends upon the size of oralloy units is shown in Figure 6. For each size of unit, the minimum critical mass occurs at an edge-to-edge spacing of about 5/8" between oralloy units. These results underline the need for precautions against water or oil flooding of accumulations of oralloy machine turnings, loose coils of wire, or similar pseudolattices of thin oralloy.

The case of oralloy-graphite mixtures can be of interest as a prototype of a multiple casting in a graphite mold. Figure 7 gives critical masses of various stacks of 10-1/2" diameter oralloy plates separated by graphite and surrounded by a 2" thick graphite reflector.(3) It is seen that, for oralloy plates of 0.315", 0.630", and 0.945" thicknesses,

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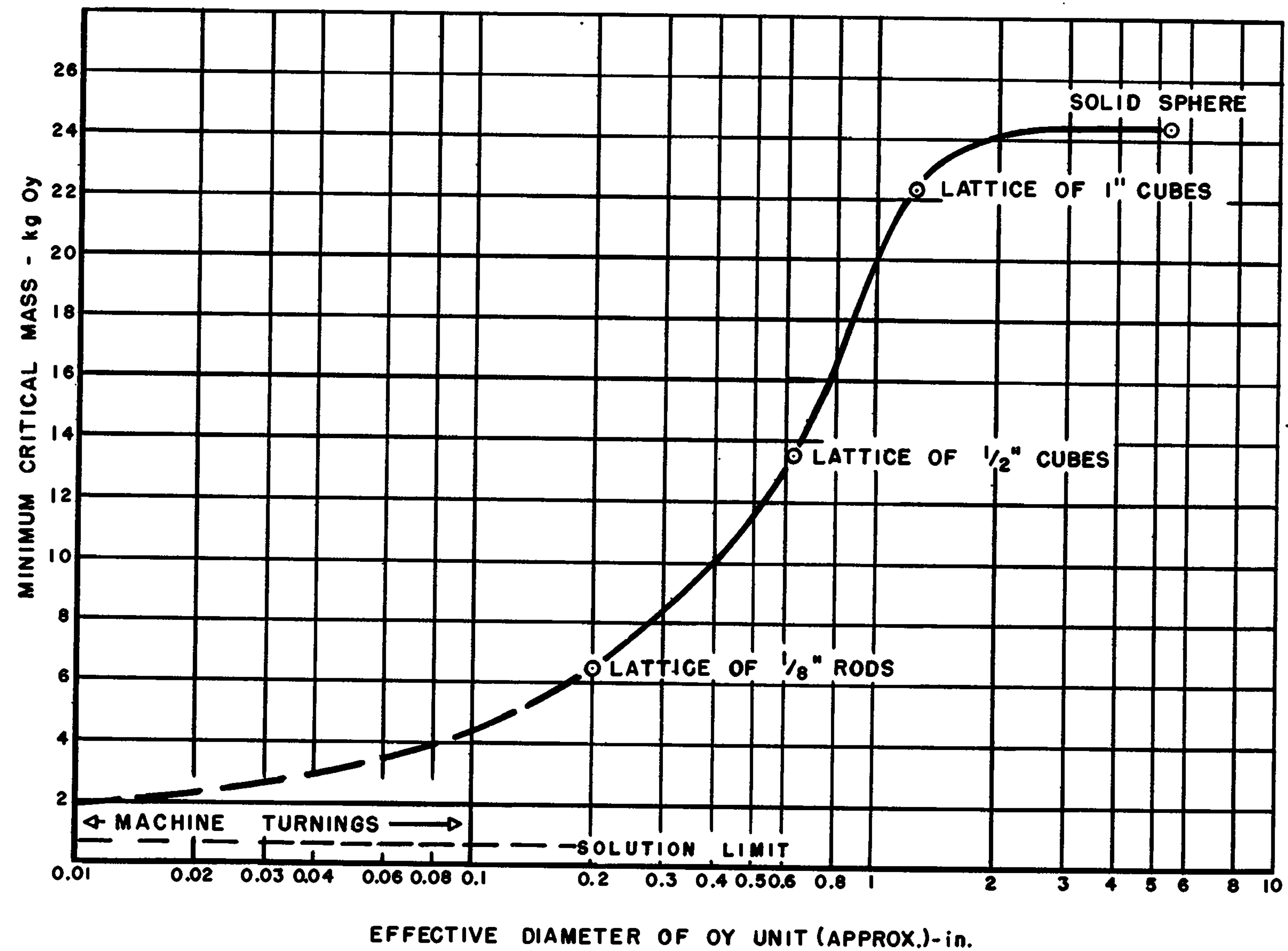

FIG. 6. Minimum critical mass of flooded oralloy lattice as a function of size of oralloy unit.

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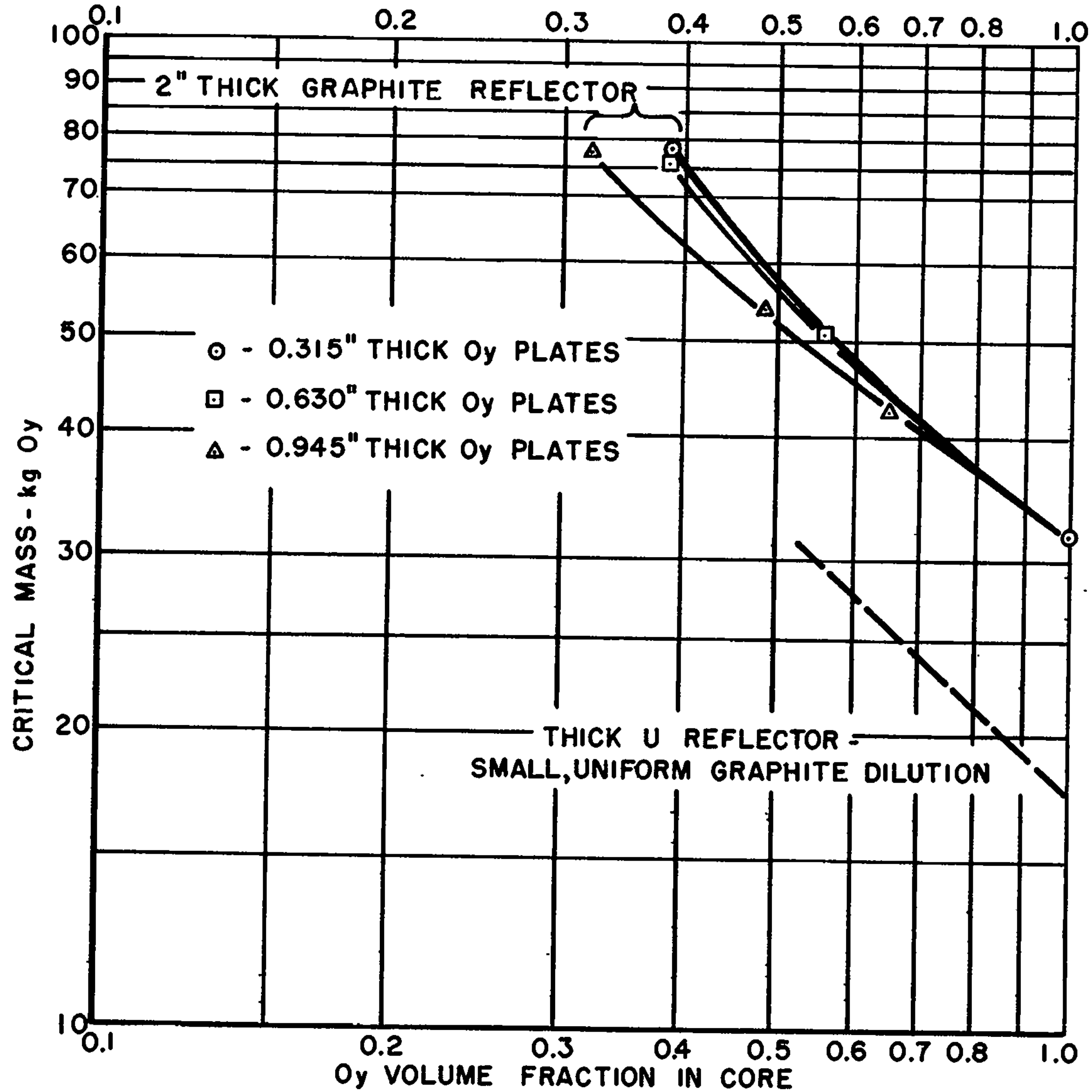

FIG. 7. Critical masses of oralloy-graphite systems -- data were obtained from cylinders but reduced to spherical equivalents.

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the effect of moderation by the graphite is outweighed by the decrease in oralloy density (naturally, this does not remain true for much thinner oralloy - e.g., the low-mass KAPL Thermal Test Reactor of oralloy and graphite with water coolant[4]).

The dotted line of Figure 7 is deduced from measurements of the relative effectiveness of graphite and oralloy at various positions within a fast-neutron critical assembly.[1] Strictly, this curve is valid only for small dilution by dispersed graphite. Data for similar computations exist for a large number of elements.[1]

Interaction. The existing data on assemblages of similar Oy(93.5) units, though somewhat crude, provide a basis for establishing safe storage limits for Oy metal.[5] The upper curve of Figure 8 was obtained from measurements on spheres, each equivalent to ∼ 20 kg oralloy, which were arranged in various 27-unit cubic arrays in cubic concrete enclosures (the inside edge of the enclosure was three times the center-to-center spacing of closest units). The lower curve represents extrapolations of measurements on four spheres, each equivalent to ∼ 32 kg oralloy, arranged in square arrays, with centers 10" above a concrete floor; it is assumed that the extrapolations apply to a cubic lattice.

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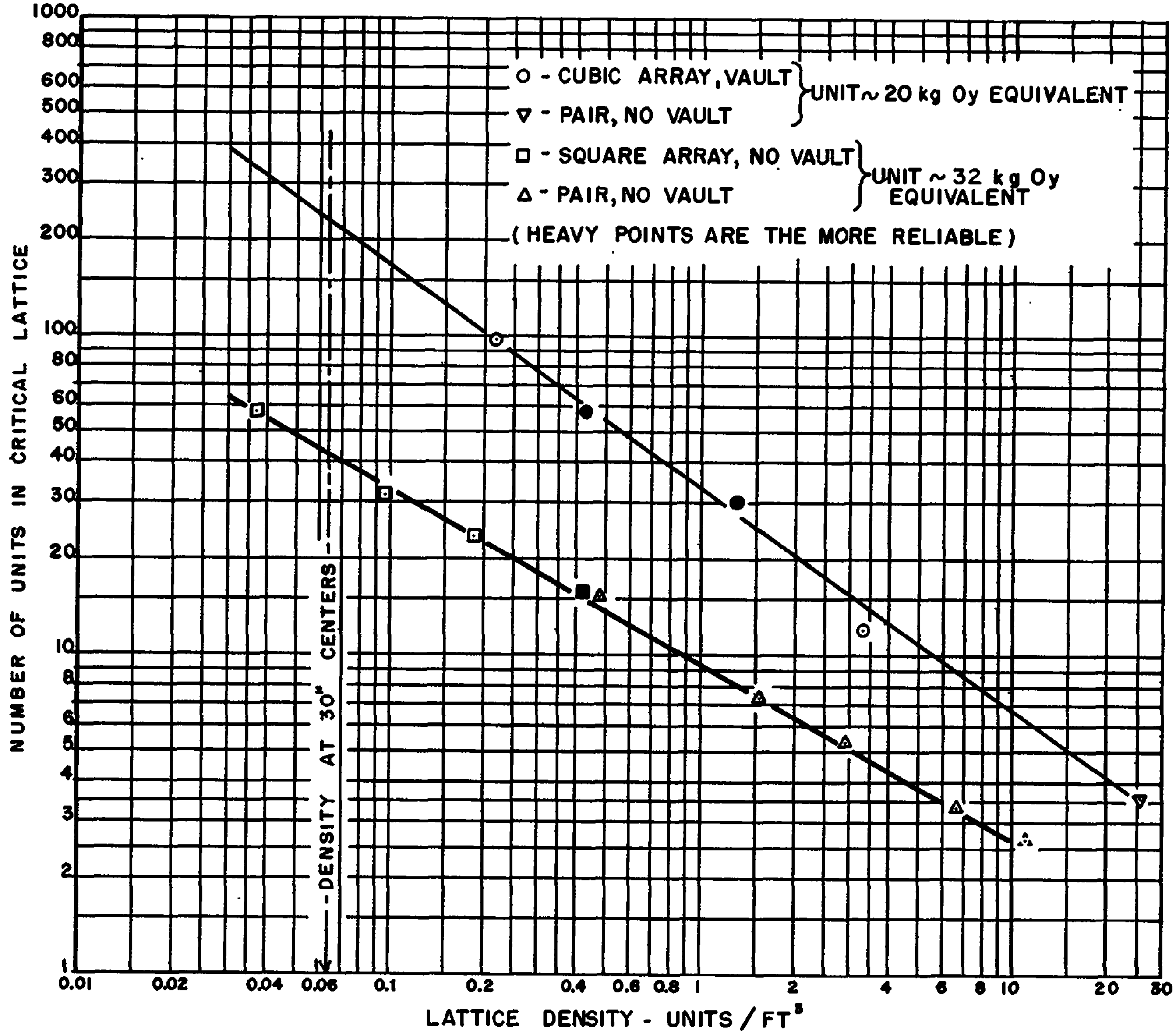

FIG. 8. Approximate critical arrays of similar oralloy metal units.

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Effects of flooding arrays of oralloy metal must be judged by measurements on pairs of similar units. Examples of interaction of pairs of Oy(93.5) metal spheres are given in Figure 9. The increase in the apparent fraction of a critical mass of one sphere is shown as a second similar sphere approaches it. In water, it is apparent that interaction is minor where the edge-to-edge separation is greater than three inches.

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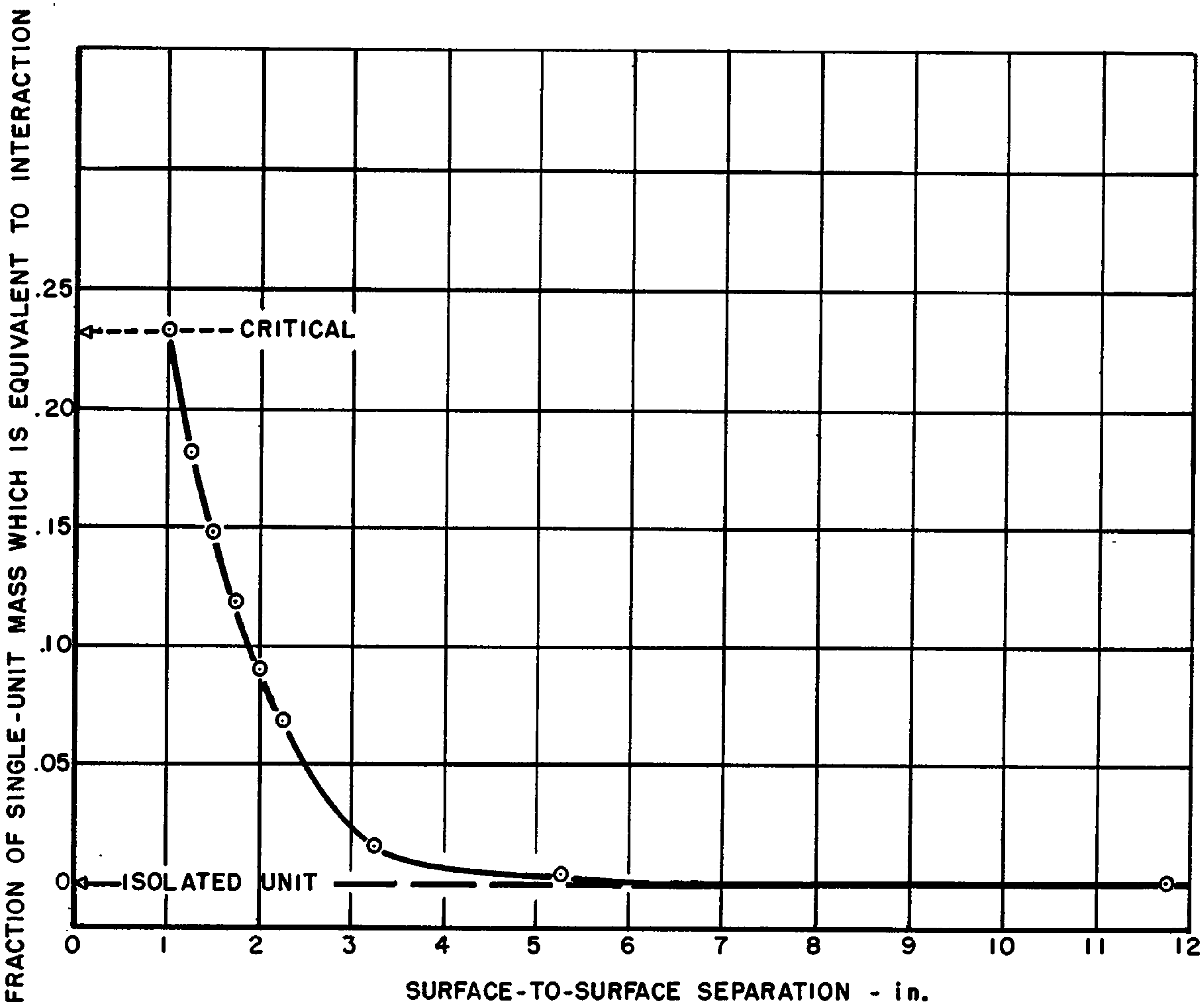

FIG. 9. Interaction between a flooded pair of oralloy metal spheres.

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Pu-239 and U-233

Critical masses of plutonium metal (at a density of 15.8 gm/cm^3) and Oy(93.5) have been compared for bare spheres and spheres in a few reflectors, Table II. In these cases the plutonium critical mass is roughly one-third that of oralloy. Not only is this ratio confirmed by effectiveness measurements in fast critical assemblies, but it is further deduced that the critical masses of plutonium and U^{233} (at a density of 18.5 gm/cm^3) will be nearly identical. A few additional comments about unmoderated plutonium and U^{233} systems are:

1) The relation, critical mass $\propto$ (density)$^{-2}$, stated before for bare oralloy, applies also to bare plutonium or U^{233} metal.

2) The ratio of the critical mass of a plutonium metal cylinder of height/diameter = 0.4, in a thick U reflector, to that of a sphere in the same reflector, was observed to be identical to the corresponding ratio for oralloy.

3) Less than ~ 10% Pu^{240} in plutonium metal may be considered equivalent to Pu^{239} for estimating critical mass, as measurements in fast critical assemblies indicate that the two isotopes differ by only 5-10% in net fission production.

For lack of more detailed information, then, critical masses of plutonium (ρ = 15.8 gm/cm^3) and U^{233} metal are estimated by scaling oralloy values downward by a factor of three. In nuclear safety considerations, the resulting uncertainties should be covered by generous safety margins.

TABLE II.

COMPARISON OF CRITICAL MASSES OF PLUTONIUM AND ORALLOY METAL SPHERES

(Pu density 15.8 gm/cm^3, Oy(93.5) density 18.8 gm/cm^3)

Reflector	m_c(Pu) - kg	m_c(Oy) - kg	m_c(Pu)/m_c(Oy)
None	16.2	52.0	0.31_1
Tu--9-1/2" thick	5.80	17.3	0.33_5
Tu--4.60" thick	6.28	19.2	0.32_7
Cu--5.00" thick	6.95	~ 21.2	~ 0.33
Water--infinite	~ 8.0	24.4	~ 0.33

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Remarks About Nuclear Safety Rules

With the critical mass information which exists, questions of nuclear safety under many specific conditions may be answered realistically. Frequently, however, it is difficult to define a completely appropriate set of conditions. For storage, transportation, and other operations where immediate surroundings are readily controlled, it is a straightforward matter to specify and implement general nuclear safety rules. For material processing, however, where a great variety of techniques may be represented, over-all regulations are likely to be so cumbersome as to be easily misapplied. Consequences of an unforseen non-nuclear accident, for example, may add to the nuclear risk. Misapplication may work the other way, too. Blind observance of rules, with insufficient attention to extenuating conditions, may easily lead to considerable unnecessary expense, especially in the design of a large-volume processing plant.

[redacted]

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(1) LA-1708, Material Replacement Measurements in Topsy and Godiva Assemblies; Engle, Hansen, Paxton; July 1954.

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(4) TID-2010, Reactor Data Table (Revision 2), Morgan; Reactor Science and Technology 3, September 1953.

(5) LA-1875, Safety Tests for the Storage of Fissile Units; Mallary, Paxton, White; February 1955.

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