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CRITICAL MASS OF A WATER-REFLECTED PLUTONIUM SPHERE

REACTORS

KEYWORDS: *criticality, mass, spheres, plutonium, water, reflectors, abundance, isotope ratio*

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We have determined the critical mass of a water-reflected plutonium sphere. The experimental data are:

1. *Properties of metal: (a) all alpha-phase, (b) high purity, and (c) 94.5% ^{239}Pu, 5.18% ^{240}Pu*
2. *Measurements: (a) mass—5546 g, (b) diameter—8.126 cm at 20°C, (c) density—19.74 g/cm^3 at 20°C, and (d) neutron multiplication—71 (based on unreflected value of 5)*
3. *Reflector—effectively infinite water*
4. *Results: (a) critical mass, our experiment—5790 ± 25 g (extrapolated from appropriately adjusted data), (b) DTF calculation, our experiment—k_{eff} = 1.0037, and (c) applying above normalizing factor to DTF, critical mass of pure ^{239}Pu—5430 (±25) g.*

QUESTION AND ANSWER

Q: "What is the critical mass of a water-reflected sphere of plutonium?" was asked for two reasons:

1. Computists could use information about this basic configuration.
2. Safety considerations frequently postulate flooding and there was concern that the computational methods should be verified.

A: A 5790-g sphere is critical under the following conditions:

1. The metal—electro-refined, high purity alpha-phase plutonium (isotopic abundances listed in Table I and chemical analysis in Table II), chill-cast at a density of 19.74 g/cm^3.
2. The experiment—the sphere at the center of an effectively infinite tank of water.

MACHINE CALCULATIONS

Pre-Test

Before this experiment, data for other reflector materials provided the only checks on

TABLE I

Isotopic Abundances

(Mass spectrometer)

Isotope	Atom %
238	<0.01
239	94.5
240	5.18
241	0.30
242	0.02

TABLE II

Chemical Analysis

(Average, two hemispheres)

Pu	99.9 ± 0.06%
Am	90 ppm
W	60 ppm
C	25 ppm
O	20 ppm
37 others	<35 ppm total

calculations. All of our calculations were one-dimensional, using Hansen-Roach 16-group cross sections, anisotropic scattering, and the S_8 angular approximation. Using the density of our castings, DTF predicted criticality at 5635 g (calculation No. 1, Table III) with the sphere encapsulated in thin Plexiglas and reflected by infinite water. Aiming at a k_{eff} of 0.995 for our first sphere, it was machined to 5546 g.

TABLE III

Some DTF Calculations

No.	Core			Reflector		k_{eff}
	Composition	Mass	Density	Lucite	Water	
1	Table I	5635	19.74	0.175 in.	infinite	1.0000
2	Table I	5790	19.74	none	infinite	1.0037
3	^{239}Pu	5430	19.74	none	infinite	1.0037

Post-Test

DTF (calculation No. 2, Table III) gave k_{eff} = 1.0037 for the empirically critical sphere of 5790 g. Applying this 0.37% normalizing factor, DTF predicted the critical mass of pure ^{239}Pu to be 5430 g (calculation No. 3, Table III). Based on previous experience and consistency of calculations we estimate the uncertainty to be $\pm\frac{1}{2}\%$ or ±25 g.

FABRICATION OF PLUTONIUM

Fabrication of the metal sphere deserves mention because of its relatively high purity and exceptionally high density for pieces of this size. Electrorefining produced metal with a total of 230 ppm impurities. Casting this high purity metal in a (tantalum) mold, chilled to -90°C, resulted in the unusually high density of 19.74 g/cm^3. Casting the metal in two split ingots (Fig. 1), one-half of each being used for one hemisphere, gave more uniform properties in the two hemispheres.

These were shrink-fitted together (Fig. 2): the male piece was cooled with dry ice while the female piece self-heated. Then the final machining cut was made.

Lastly, a set of 0.175-in.-thick close fitting Plexiglas hemishells was placed over the bare metal and sealed. Copper, 0.0005 in. thick, had been previously electroplated on the inside of the Plexiglas to protect it from decomposition (and to lessen consequent hydrogen pressure inside the shell) by alpha particles from the plutonium.

After the first criticality run, for reasons discussed later, the sphere was machined down to a mass of 5343 g. Oxide had formed on all metal surfaces including the equatorial parting plane. A radiograph showed a low density region, ~0.4

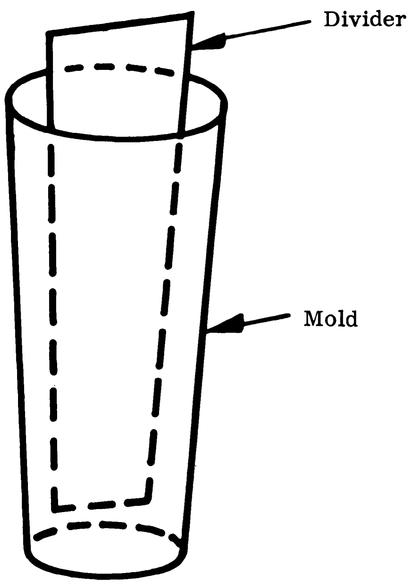

Fig. 1. Split ingots.

Fig. 2. Cooled lower hemisphere being shrink-fitted into self-heating upper piece.

mm thick, at the equator. Therefore, the average density of the new sphere was calculated to be 19.68 g/cm^3, down from 19.74 g/cm^3.

EXPERIMENT

Figure 3 shows the main components of the experimental setup. The fill tank, 2 ft in diameter and filled to a depth of 2 ft, rode on a hydraulic lift and was connected by a flexible hose to an identical run tank. Raising the fill tank 2 in. raised the run-tank water level 1 in.

The plutonium sphere rested on a Plexiglas stool. Two detectors were located in wells 3 in. below the sphere and two others were strapped to the outside of the run tank. The operator could remove water from the run tank either by lowering the lift or by draining through a large valve into a catch tank (not shown).

In the first of four series of measurements, we calibrated the control room indicator of hydraulic lift position for exact water level in the run tank. The next series, with a ^{252}Cf neutron source at the center of a dummy aluminum ball, was to obtain detector response as a function of water height. Figure 4 shows the response of one of the detectors in the well below the ball. This curve provided an unmultiplied count-rate reference during measurements with the plutonium spheres.

A DTF calculation for the unreflected sphere gave k_{eff} = 0.85. The value M = 5 was arbitrarily assigned for the initial count rate with run tank empty. Since the final determination of critical mass is made by extrapolation, this assignment did not affect accuracy, nor did the use of the point-source reference cause a meaningful error.

We added small amounts of water to the run tank between recorded count rates as the level approached the sphere and then covered it. After ~2 in. of water covered the sphere, leakage multiplication increased little, so larger increments of water were added. During this operation a plot of inverse multiplication ($1/M$) vs water level (Fig. 5) guided us in choosing succeeding steps which were always less than halfway to extrapolated delayed critical ($1/M$ = zero).

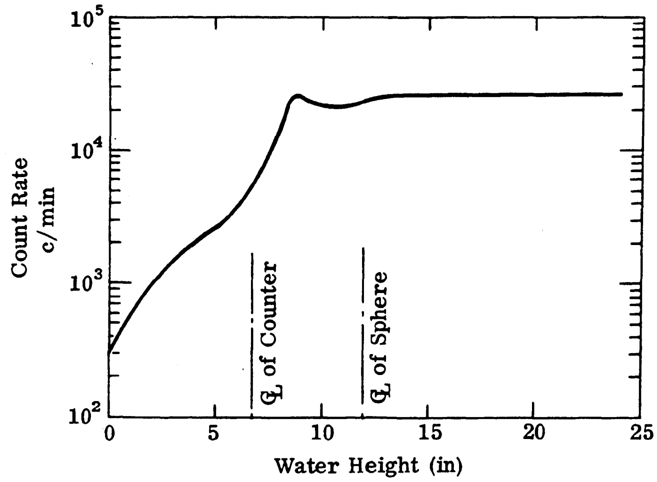

Fig. 4. Detector calibration run with californium source.

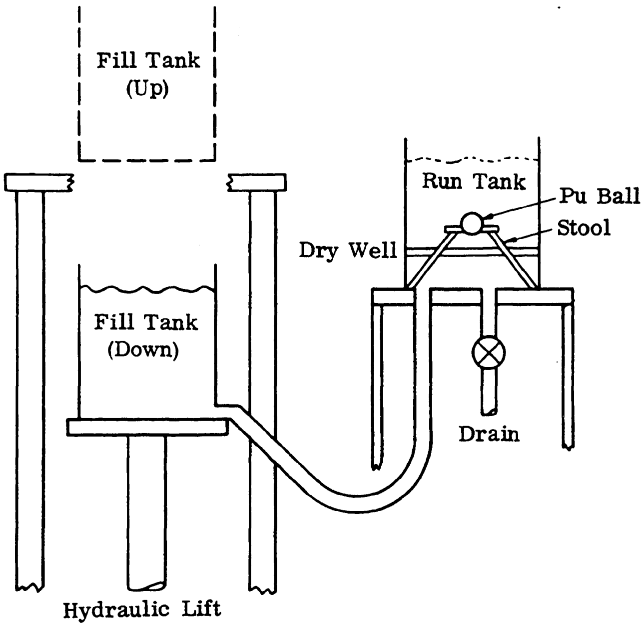

Fig. 3. Experimental set-up at LASL's critical assembly facility.

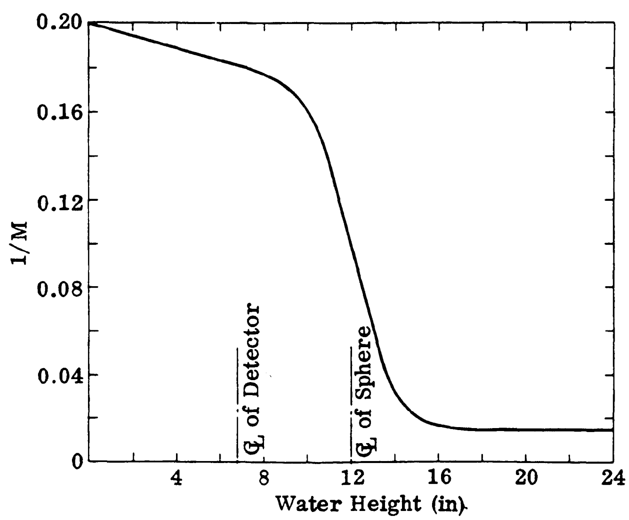

Fig. 5. Plutonium ball with 0.150-in.-thick Lucite shell on stool.

The stool (Plexiglas is a better reflector than water) added reactivity, $\Delta\ 1/M = 0.0024$, and the shell added $\Delta\ 1/M = 0.0020$. These were measured by placing a second stool, then a second shell in the assembly. Figure 6 shows the corrections and the adjusted $1/M$ for this sphere.

Following intended procedure, the plutonium then would have been refabricated into a new, larger sphere, with a mass halfway between the first one and the new empirical estimate of critical size. For two reasons this plan was revised:

1. Final count rate of the first sphere was so high that doubling it would saturate the system.
2. If the metal were recast, the density might be different.

Given the value of k_{eff} of ~0.99, DTF estimated that our first sphere was 200 g below delayed critical. So, rather than halve the margin below critical, we doubled it.

After remachining and encapsulation, we made the last series of measurements and applied the previous corrections for stool and shell (Fig. 6). A third correction, for density, was calculated using the approximation that critical mass is proportional to density to the 1.6 power. (This came from a separate series of DTF calculations.) This correction was treated as a uniform density change, which introduced a negligible error in our situation.

Finally, Fig. 6 and Table IV show the adjusted $1/M$ values of the two spheres, fully reflected, and the extrapolation to critical at 5790 g. Experience with many sub-critical and critical systems is that a straight-line extrapolation by radius is appropriate over a narrow range such as this.

TABLE IV

Extrapolation

	Mass	$1/M$
Second sphere	5343	---
(density adjusted)	5316	0.03604
First sphere	4546	0.01844
Critical	5790	0

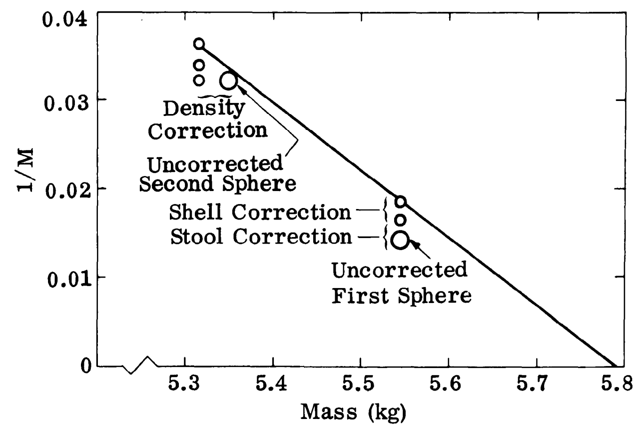

Fig. 6. Plutonium sphere 12-in. water reflector.

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