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AEC RESEARCH AND DEVELOPMENT REPORT

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

PLUTONIUM-METAL CRITICAL ASSEMBLIES

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REACTORS - RESEARCH AND
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LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

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PLUTONIUM-METAL CRITICAL ASSEMBLIES

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ABSTRACT

The two plutonium-metal critical assemblies that have been studied at Pajarito Site are Jezebel, bare plutonium; and Popsy, a plutonium core in a thick normal uranium reflector. These assemblies and their properties are described.

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INTRODUCTION

Two plutonium-metal critical assemblies have been studied at Pajarito Site. Part I of this report describes Jezebel, the bare plutonium assembly, and gives its observed characteristics along with a few comparisons with oralloy assemblies. Part II covers Popsy, a plutonium core in a thick normal uranium reflector. As Popsy was relatively inflexible -- intended only for a preliminary survey -- its experimental program was much less complete than that of Jezebel. Comparison of the experimental data with detailed calculations is a continuing major project, and results are not sufficiently firm to include in this account.

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PART I.

JEZEBEL - THE BARE PLUTONIUM CRITICAL ASSEMBLY

Design

Design features of Jezebel, the bare plutonium critical assembly (Figs. 1, 2, and 3), were dictated by the following requirements. For safety of fabrication, the principal, nearly spherical mass was constructed as four units, and these were mounted to provide three-part subdivision for operational safety. Because of the toxicity of plutonium, and consequent requirement for completely protective nickel coatings, tapped or unnecessarily deep holes in the plutonium were avoided. Demands for the ultimate in reproducibility, adequate flexibility, and minimum tamping fixed the remaining features: 1) light but rigid framework and supports; 2) self-alignment of the three subsections by means of guide wires (under tension) that also support the floating central section, and ball-and-socket support for the upper section; 3) uniform mass adjustment increments to supplement the plutonium control rod; and 4) adjustable air cooling with a recording thermocouple as the indicator.

The pneumatic system for assembly of Jezebel includes

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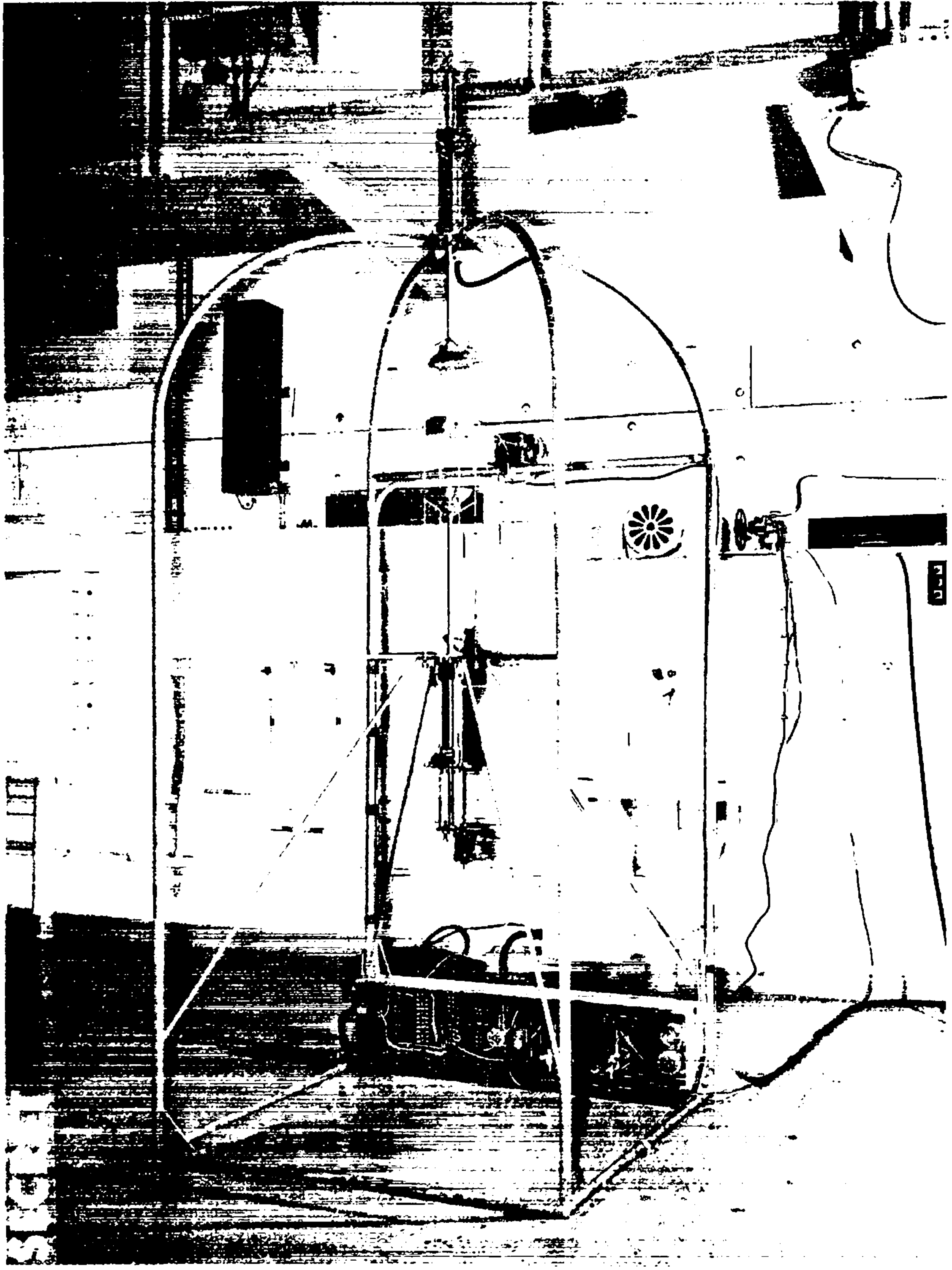

Fig. 1 Jezebel - the bare plutonium assembly.

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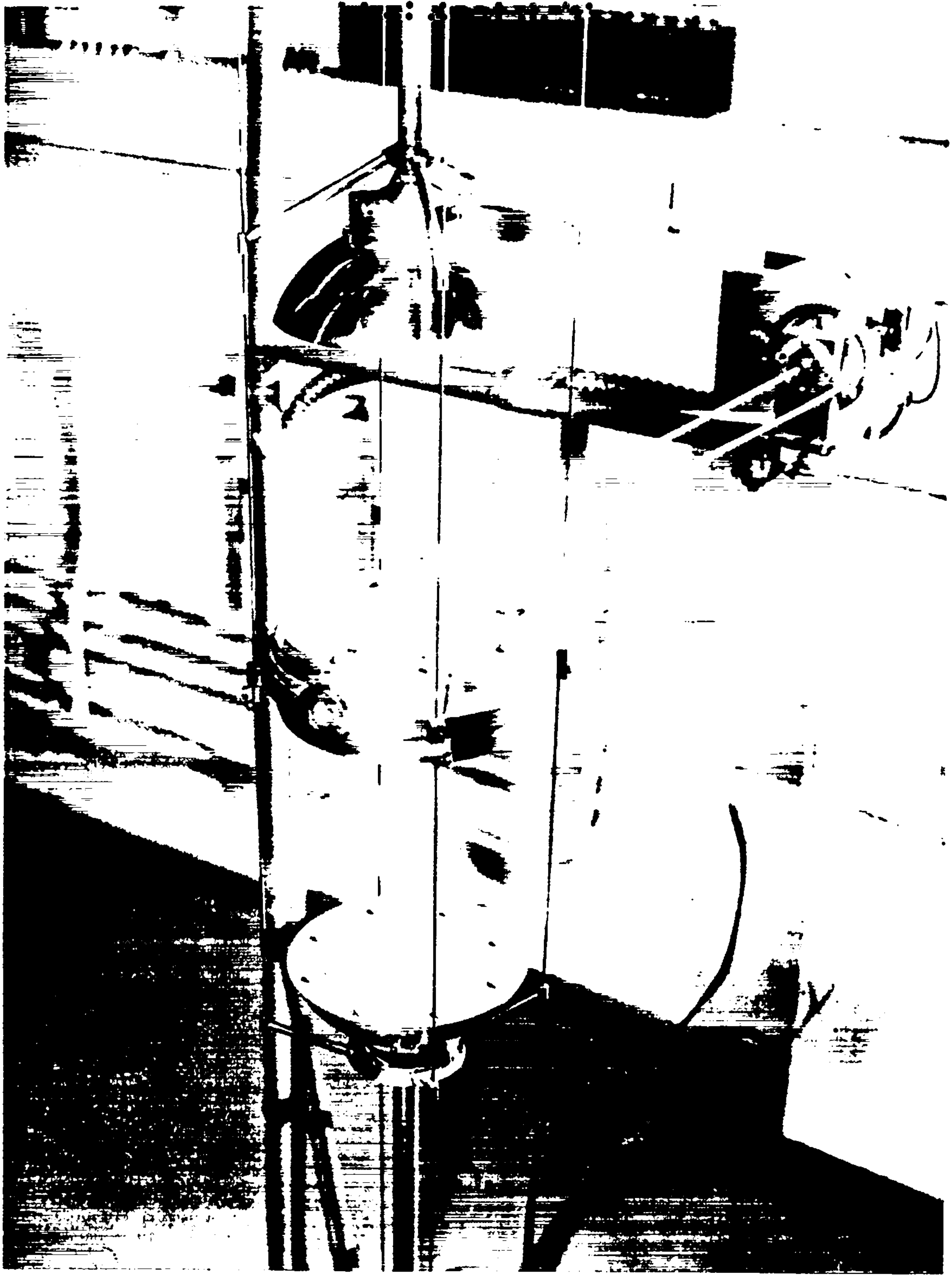

Fig. 2 The Jezebel plutonium components in disassembled, or "safe," condition.

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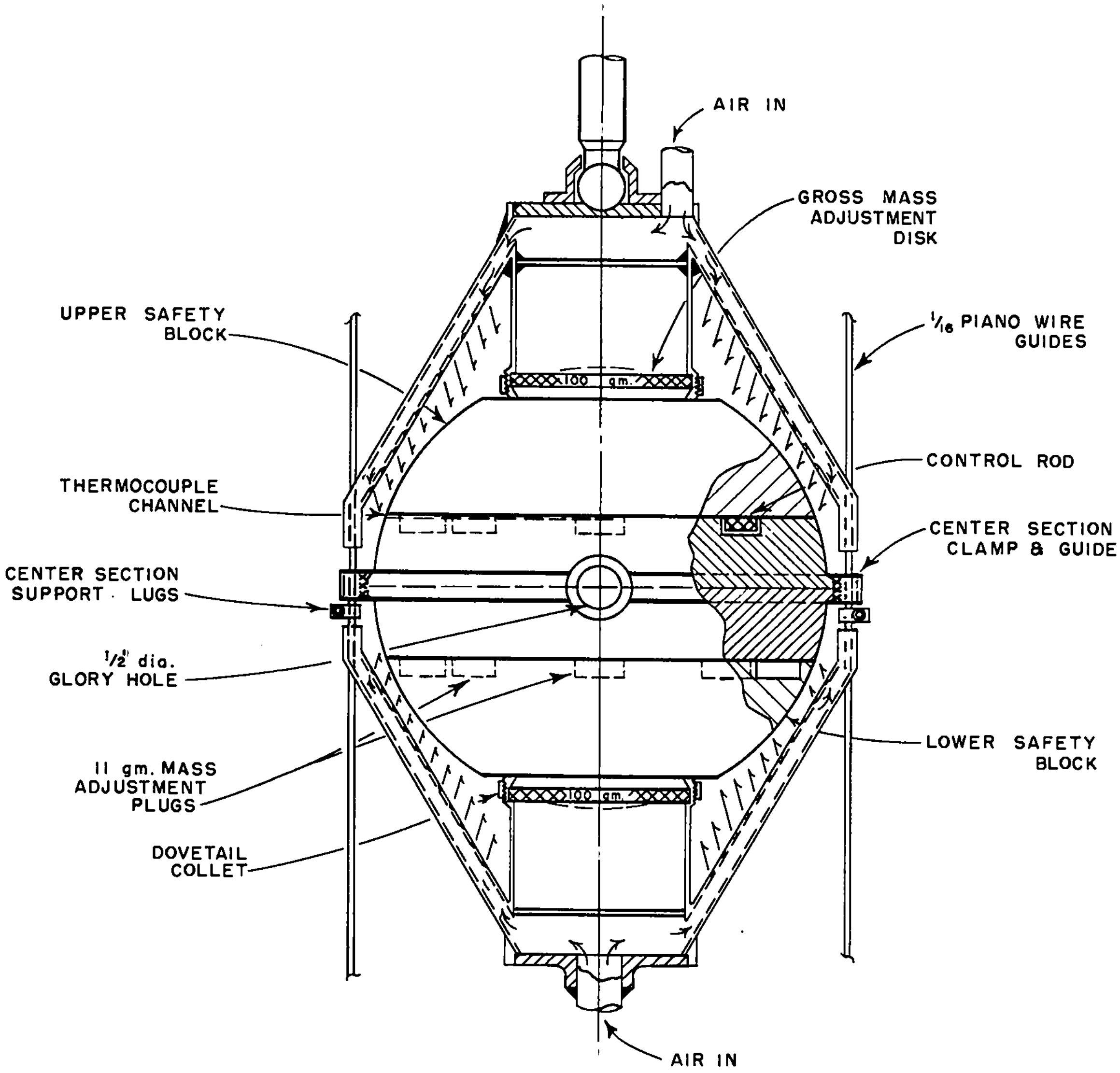

Fig. 3 Design of the active portion of Jezebel.

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an adjustable dashpot to control the speed of final closure. As usual, electrical circuits for remote control are supplemented by scram systems, automatic and manual, and safety interlocks to fix the order of assembly of components.

Glen Newby for sound design and Group CMR-11, particularly John Anderson, for careful plutonium fabrication deserve much of the credit for the eminently satisfactory performance of Jezebel.

Critical Mass

The average density of the delta-phase Pu alloy in Jezebel is 15.82 gm/cm^3, the Ga content averages 1.02 w/o, and the Pu irradiation history is 580 to 600 MWD/T. The actual Pu alloy mass of Jezebel at critical (with major cavities filled, control rod fully inserted, and at 29°C) is 16.745 kg. From reactivity contributions of Pu and Fe (or Ni) at various radii, and of a Ni-filled gap on one of the parting planes, it is possible to correct the Jezebel critical mass in detail for effects of incidental cavities, Ni coating, asphericity, and tamping of supports. Corrections in kilograms of Pu at the surface are:

elimination of cavities (Ni- and air-filled)	-0.398 kg
reduction to sphere	-0.027 kg
elimination of 0.005" Ni tamper	+0.051 kg
elimination of tamping by steel clamps	+0.084 kg
correction from 29°C to 20°C	-0.008 kg

[redacted]

Thus, for a solid, untamped sphere, the critical mass is 16.45 ± 0.05 kg of Jezebel Pu alloy.

Calibration - Rossi Alpha and Positive Periods

Jezebel has effectively two vernier controls of reactivity, the control rod and the temperature adjustment by remote regulation of the cooling air flow. Both reactivity controls have been calibrated in terms of mass adjustment buttons (equal reactivity increments), and in units of cents. The cents scale has been established by measurement of Rossi alpha(1) as a function of number of mass adjustment buttons from delayed critical. As shown by Fig. 4, the value of Rossi alpha at delayed critical is $-0.66 \pm 0.01 \times 10^6$ sec^{-1}. The alpha data are linear with reactivity and indicate that 5.15 ± 0.10 buttons are equivalent to 100 cents. With data on relative effectiveness of Pu as a function of radius, it follows that there is an increment of 135.9 ± 4 gm of surface Pu alloy between delayed and prompt critical (132.5 ± 4 gm for the ideal sphere of Jezebel material). From the value 19.42 cents per button, results of calibration may be summarized:

one linear control rod inch (1 lcri)
= 2.41 buttons (lower) = 46.8 cents,
temperature coefficient of reactivity
= -0.014 lcri/°C = -0.65_5 cents/°C.

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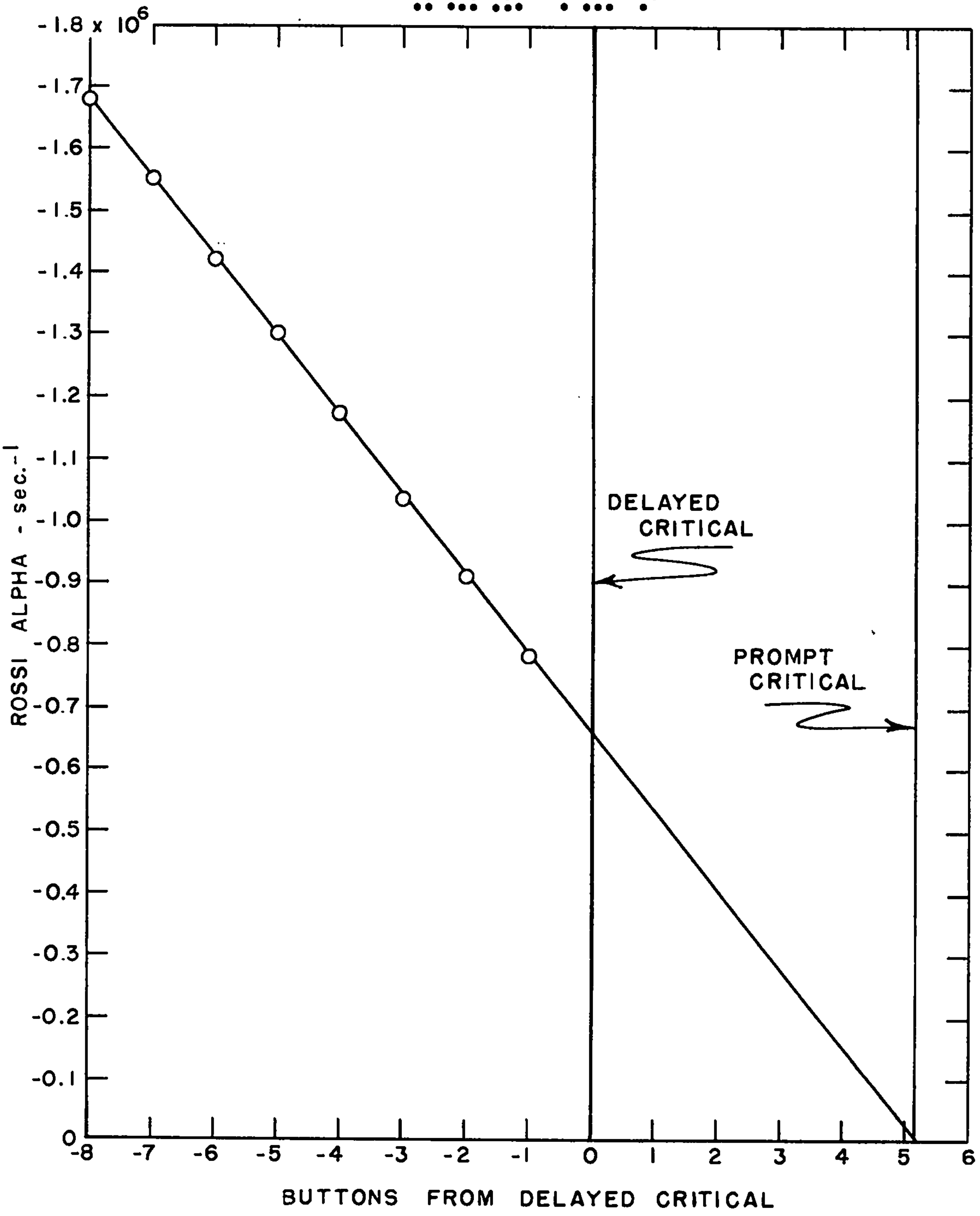

Fig. 4 Rossi alpha vs number of mass adjustment buttons in excess of the delayed critical configuration.

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The ratio of the effective delayed neutron fraction of Jezebel, $(\gamma f)_J$, to that of Godiva, the bare oralloy assembly, $(\gamma f)_G$, may be obtained by means of the following relation from G. E. Hansen (unpublished):

$$\frac{(\gamma f)_J}{(\gamma f)_G} = 1.033 \; \frac{(\Delta m/m_c)_J}{(\Delta m/m_c)_G},$$

where Δm is the surface mass increment between delayed critical and prompt critical, m_c is the critical mass, and, again, J and G refer to Jezebel and Godiva. Using data for idealized spheres$^{(2)}$:

$$\frac{(\gamma f)_J}{(\gamma f)_G} = 1.033 \; \frac{0.1325}{16.45} \; \frac{52.04}{1.27} = 0.34.$$

This leads to $(\gamma f)_J = 0.0023$, if $(\gamma f)_G = 0.0068$ as determined by Hansen in Report LA-1525.$^{(3)}$ Furthermore, from $\alpha_{dc} = -0.66 \pm 0.01 \times 10^6 \text{ sec}^{-1}$ for Jezebel at delayed critical, we have

$$\frac{\Delta\alpha}{\Delta K} = - \frac{\alpha_{dc}}{(\gamma f)_J} = 2.9 \times 10^8 \text{ sec}^{-1}.$$

Positive pile periods are shown in Fig. 5 for various linear control rod increments above delayed critical. From each period, a value of excess reactivity in cents was computed by means of the Pu^{239} delayed neutron data of Keepin

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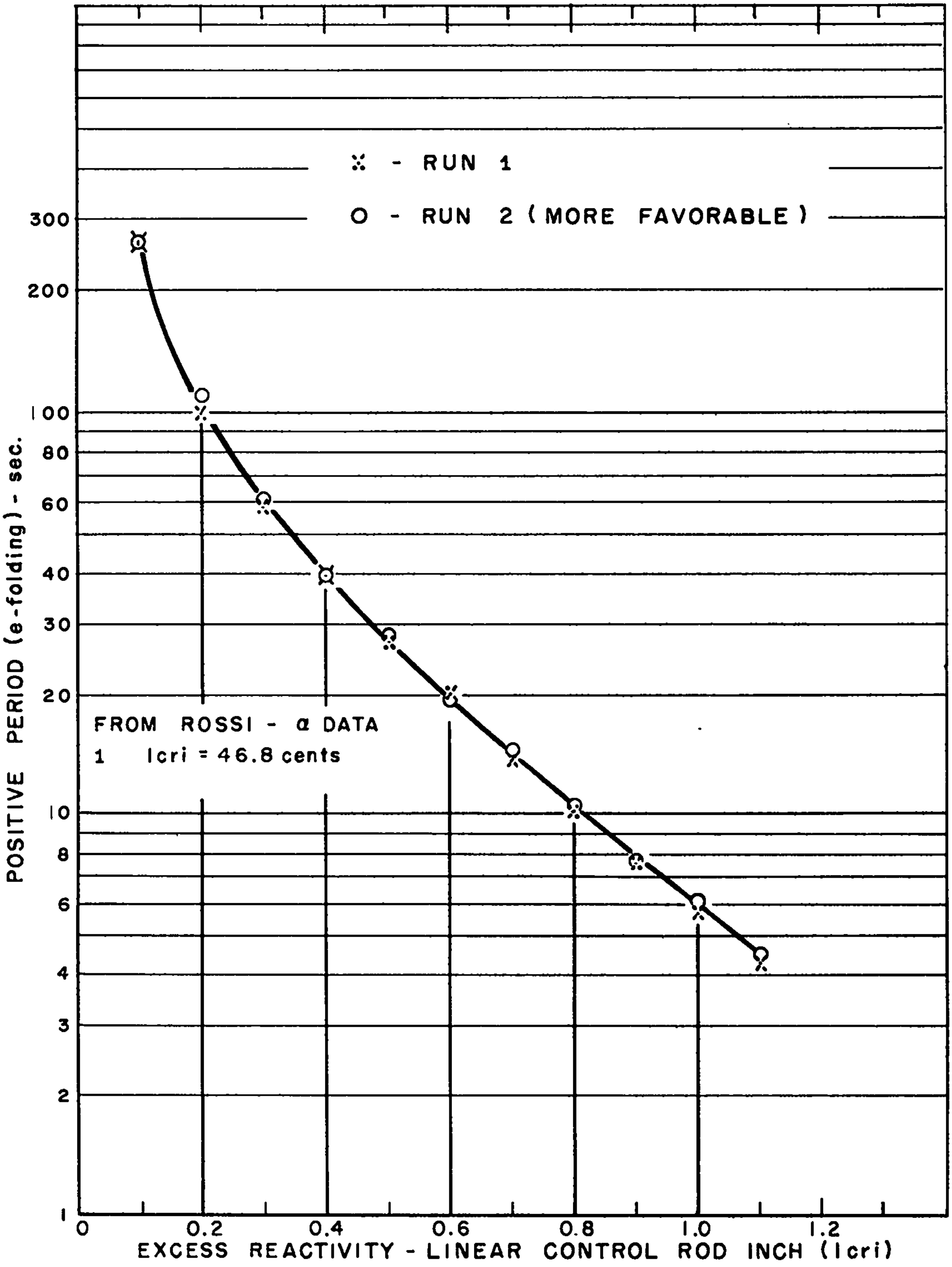

Fig. 5 Positive pile period as a function of excess reactivity in inches of linear control rod.

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and Wimett.$^{(4)}$ Results (Fig. 6) lead to the value 1 lcri = 51 cents. The reason for disagreement between this value and the presumably more precise number from alpha measurements is presently unknown. It may be associated with differences between delayed neutrons from Pu^{240} and Pu^{239}, or differences in effectiveness of various groups of delayed neutrons in the Pu assembly.

Spectral Indices

Response ratios of fissionable elements, which characterize neutron spectra, have been measured at various positions in Jezebel. The measurements were made using small quadruple fission chambers containing foils coated with U^{235}, U^{236}, U^{238}, and Np^{237}, permitting direct comparisons of the fission responses without the need for an additional monitor. Other central values were obtained by J. A. Grundl using good resolution spiral fission chambers.

Results are shown in Table I. The fission cross section ratios are quite flat throughout the interior of the Jezebel sphere, but are depressed near the surface due to the expected hardening of the flux in this region.

The Jezebel central fission cross section ratios are compared in Table II with the corresponding values for Topsy and Godiva.

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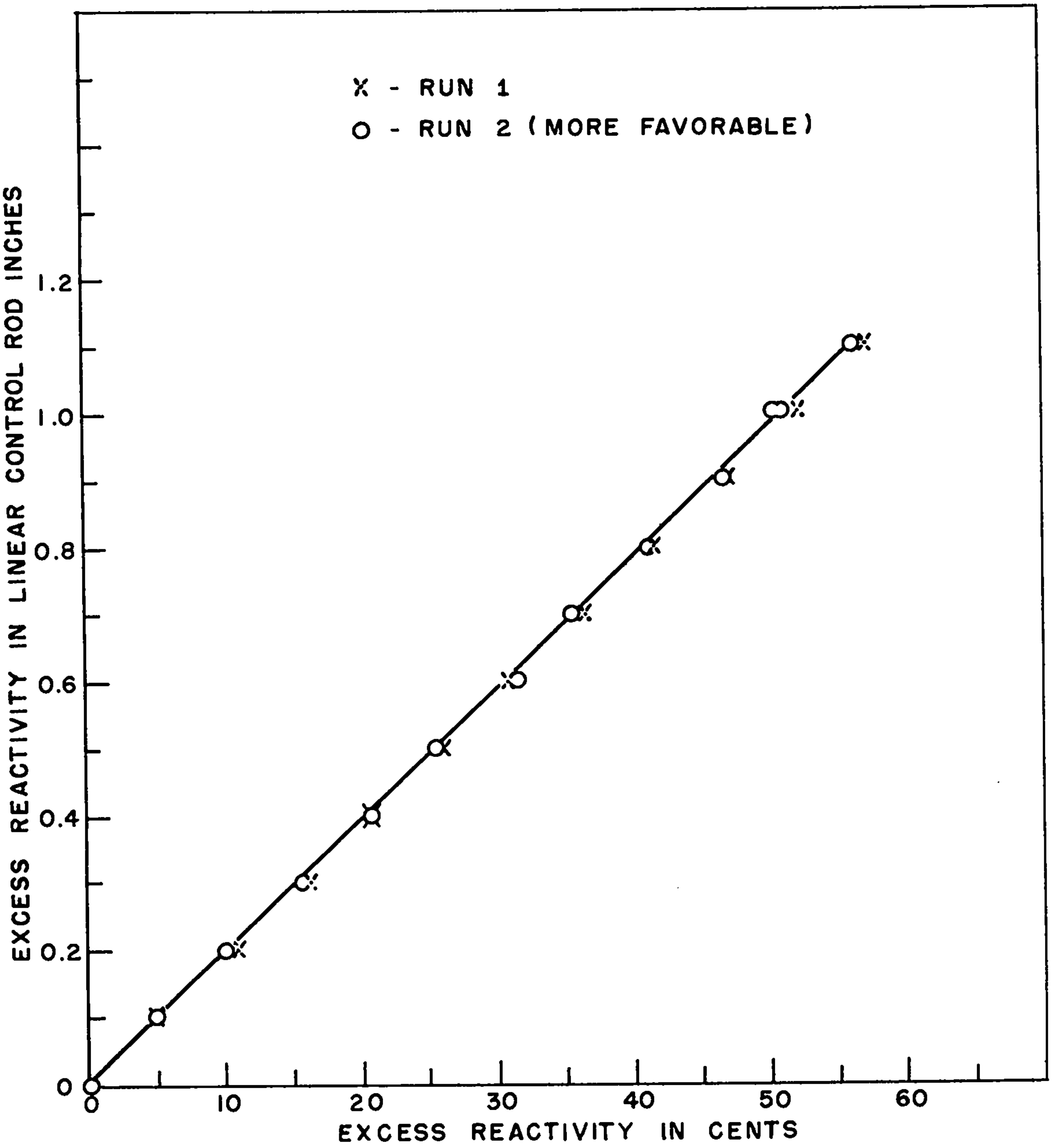

Fig. 6 Excess reactivity in inches of linear control rod vs excess reactivity in cents (from positive periods and Keepin-Wimett delayed neutron data).

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TABLE I.

FISSION CROSS SECTION RATIOS VS JEZEBEL RADIUS

Radius (in.)	Normalized to 7.39 for Topsy Central $\frac{\bar{\sigma}_f(U^{235})}{\bar{\sigma}_f(U^{238})}$	Normalized to 4.56 for Topsy Central $\frac{\bar{\sigma}_f(Np^{237})}{\bar{\sigma}_f(U^{238})}$	$\left[\frac{\bar{\sigma}_f(U^{236})}{\bar{\sigma}_f(Np^{237})}\right]_{rel}$
0	5.13*	4.04*	1.000
0.5	5.12	4.05	0.999
1.0	5.10	4.05	0.996
1.5	5.08	4.05	0.998
2.0	4.94	4.00	1.000

---

*Calibrated spiral chambers gave for these values:

$\bar{\sigma}_f(U^{235})/\bar{\sigma}_f(U^{238}) = 4.56 \pm 4\%$ and $\bar{\sigma}_f(Np^{237})/\bar{\sigma}_f(U^{238}) = 4.76 \pm 5\%$.

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TABLE II.

COMPARISON OF CENTRAL FISSION RATIOS IN VARIOUS ASSEMBLIES

Assemblies Compared	$\frac{\bar{\sigma}_f(U^{235})}{\bar{\sigma}_f(U^{238})}$	$\frac{\bar{\sigma}_f(Np^{237})}{\bar{\sigma}_f(U^{238})}$	$\frac{\bar{\sigma}_f(U^{233})}{\bar{\sigma}_f(U^{235})}$	$\frac{\bar{\sigma}_f(Pu^{239})}{\bar{\sigma}_f(U^{235})}$
Godiva vs Topsy (Quadruple Chamber)	0.894	0.989	0.998	1.017
Jezebel vs Topsy (Quadruple Chamber)	0.694	0.885	0.988	1.065
Godiva vs Topsy (Spiral Chamber)	0.891	0.994		
Jezebel vs Topsy (Spiral Chamber)	0.685	0.908		

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Reactivity Contributions of Various Materials

Determinations have been made of reactivity changes incurred when a void in Jezebel is filled with samples of various elements. Results of central measurements with 1/2" cylindrical samples are listed in Table III, both as reactivity contributions in cents per gram-atom, and as apparent absorption cross sections (σ_a) in barns, which include changes in effectiveness of neutrons in addition to actual absorption. The latter are obtained by normalizing to σ_a(Oy-93.7) = -1.86 barns for a 1/2" sample. For some of the isotopically simple nonfissionable elements, capture cross sections in the Jezebel spectrum (σ_c) have been estimated as 6% greater than Hughes' values for the U^{235} fission spectrum.$^{(5)}$ The difference between capture and effective absorption cross sections then is attributed to the effect of energy degradation of neutrons by scattering; that is, if Z is not small, $\sigma_c - \sigma_a = \Delta\gamma\ \sigma_{in}$, where $\Delta\gamma$ is the change of effectiveness per neutron to which the inelastic scattering cross section σ_{in} is applicable. Table IV compares for Jezebel and Godiva, the bare oralloy assembly,$^{(6)}$ values of σ_a, $\Delta\gamma\ \sigma_{in}$, and $\Delta\gamma$ corresponding to Beyster's values of σ_{in} for scattering out of the fission spectrum to below the U^{238} threshold.$^{(7)}$

The characteristically negative values of $\Delta\gamma\ \sigma_{in}$ for Jezebel as compared with predominantly positive values for

[redacted]

TABLE III.

JEZEBEL CENTRAL REACTIVITY CONTRIBUTION DATA

Material	ΔK (cents/gm-atom)	σ_a (barns)	σ_c* (barns)	$\Delta\gamma\ \sigma_{in}$ (barns)
CH_2	97.3 ± 2.3 (cents/mole)			
Be	12.2 ± 0.3	-0.037		
B^{10} (87%)	-145.2 ± 0.7	0.445		
C	- 5.2 ± 0.7	0.016		
Al	- 11.0 ± 0.6	0.034	0.004	-0.030
Ti	- 10.5 ± 2.4	0.032		
V	- 14.2 ± 0.9	0.043	0.002	-0.041
Fe	- 16.7 ± 0.4	0.051		
Co	- 18.7 ± 0.6	0.057	0.012	-0.045
Ni	- 36.8 ± 0.6	0.113		
Cu	- 25.5 ± 0.7	0.078	0.011	-0.067
Zr	- 22.9 ± 4.4	0.070		
Ag	- 71.1 ± 0.9	0.218	0.137	-0.081
Cd	- 43.0 ± 1.9	0.132		
Dy_2O_3	-161 ± 17 (cents/mole)			
Yb_2O_3	-118 ± 16 (cents/mole)			
Ta	- 75.4 ± 2.9	0.231	0.151	-0.080

[redacted]

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TABLE III. (Continued)

Material	ΔK (cents/gm-atom)	σ_a (barns)	σ_c* (barns)	$\Delta\gamma\ \sigma_{in}$ (barns)
W	- 55.5 ± 0.9	0.170		
Au	- 66.3 ± 0.6	0.203	0.128	-0.075
Bi	- 18.3 ± 2.0	0.056	0.003	-0.053
U (normal)	85.7 ± 0.8	-0.262		
Oy (93.44)	604 ± 3			
Pu (600 MWD/T)	1256 ± 4	-3.56		

---

*Hughes' values for the U^{235} fission spectrum increased 6%.

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TABLE IV.

COMPARISON OF JEZEBEL AND GODIVA CENTRAL CROSS SECTIONS

	σ_a (barns)		$\Delta\gamma\ \sigma_{in}$ (barns)		$\Delta\gamma$*	
Element	Jezebel	Godiva	Jezebel	Godiva	Jezebel	Godiva
H**	-0.141	-0.623				
Be	-0.037	-0.093				
B^{10}	0.512	0.721				
C	0.016	-0.027				
Al	0.034	-0.005	-0.030	0.009	-0.094	0.028
Ti	0.032					
V	0.043	-0.012	-0.041	0.015	-0.071	0.026
Fe	0.051	0.006				
Co	0.057	0.009	-0.045	0.008	-0.075	0.013
Ni	0.113	0.053				
Cu	0.078	0.017	-0.067	-0.005	-0.074	-0.006
Zr	0.070					
Ag	0.218	0.123	-0.081	0.065	-0.049	0.039
Cd	0.132					
Dy***	0.228					
Yb***	0.162					
Ta	0.231	0.112	-0.080	0.061		

[redacted]

TABLE IV. (Continued)

Element	σ_a (barns) Jezebel	σ_a (barns) Godiva	$\Delta\gamma\ \sigma_{in}$ (barns) Jezebel	$\Delta\gamma\ \sigma_{in}$ (barns) Godiva	$\Delta\gamma$* Jezebel	$\Delta\gamma$* Godiva
W	0.170					
Au	0.203	0.085	-0.075	0.052	-0.037	0.025
Bi	0.056	0.014	-0.053	-0.013	-0.073	-0.018
U^{238}	-0.250	-0.299				
Pu^{239}	-3.57	-3.56				

---

*From Beyster's σ_{in} for fission neutrons scattered below the U^{238} threshold (the value for Co comes from E. T. Jurney - unpublished data).

**From CH_2 and C.

***From Dy_2O_3 and Yb_2O_3, assuming $\sigma_a = 0.012$ barn for oxygen.

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Godiva are understandable in terms of fission cross section curves (Fig. 7). The minimum in fission cross section of Pu^{239} below about 2 Mev is sufficiently broad to cover most inelastically scattered neutrons of interest. On the other hand, the effect of the much narrower region of reduced fission cross section for U^{235} would generally be overshadowed by the large rise in cross section below about 0.4 Mev.

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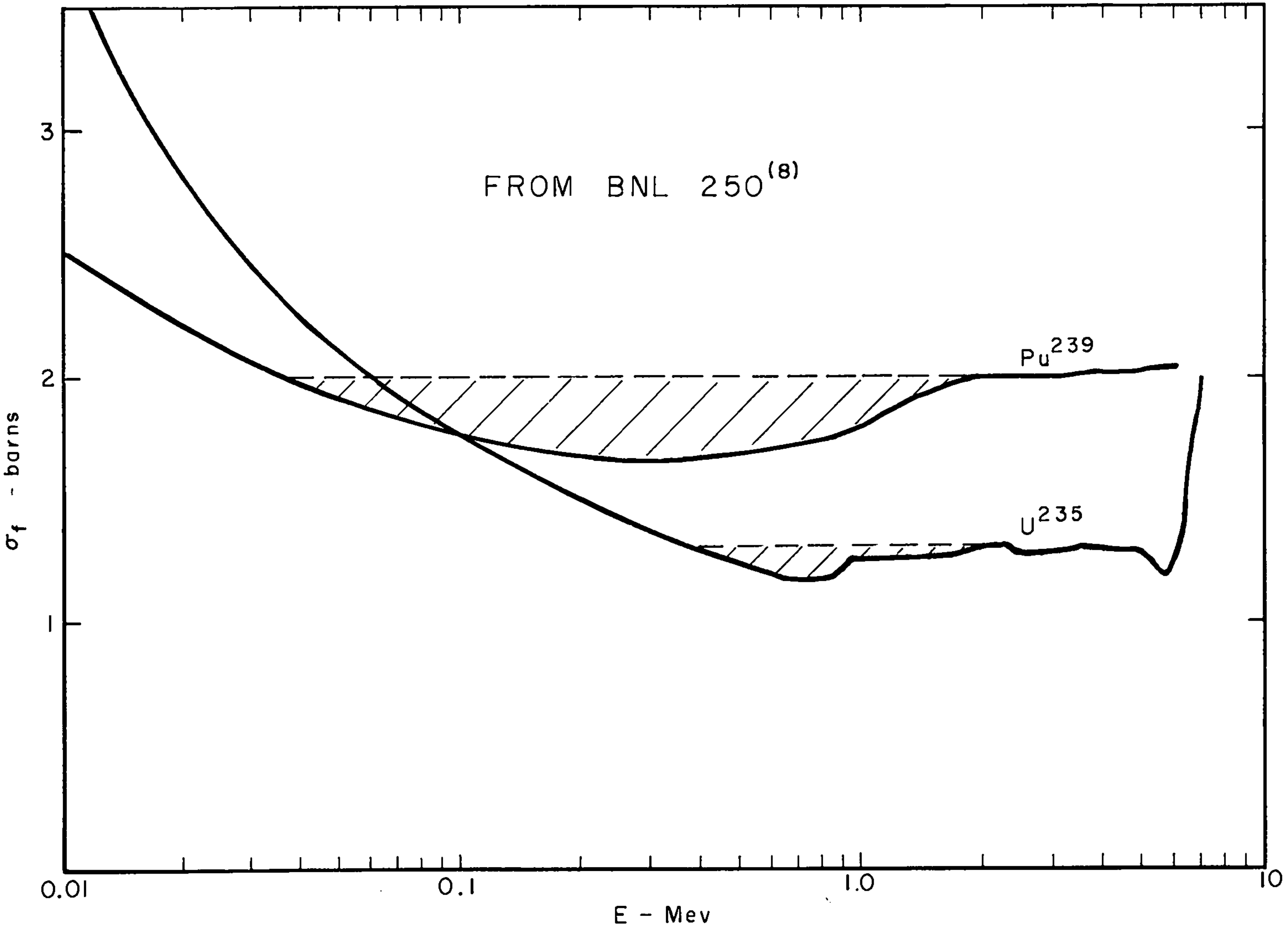

Fig. 7 Fission cross section of U^{235} and of Pu^{239} as functions of energy of neutron producing the fission. Note the difference in regions of reduced cross section below 2 Mev.

[redacted]

PART II.

POPSY - PLUTONIUM CORE IN A THICK NORMAL URANIUM REFLECTOR

Description

The Popsy assembly derived its name from the substitution of a spherical plutonium core for the oralloy core in the Topsy critical assembly machine, and was set up only temporarily for a cursory survey of its more significant parameters. Topsy, described in detail in Report LA-1579,(9) needed only minor reflector modifications to adapt it for the plutonium sphere. Figure 8 presents a schematic drawing of Popsy showing the layout of essential components when assembled for critical operation.

The core consisted of two concentric, nesting, spherical shells (each divided at an equatorial plane), 3.508" O.D. by 0.840" I.D., and 0.810" O.D. by 0.410" I.D. The material was delta-phase Pu alloy having a Ga content of ~1.0 w/o, and an average density of 15.79 gm/cm^3. The Pu had an irradiation history of about 200 MWD/T. All Pu surfaces were coated with Ni averaging 6-1/2 mils in thickness.

As modified to accommodate the Pu ball, Topsy provided

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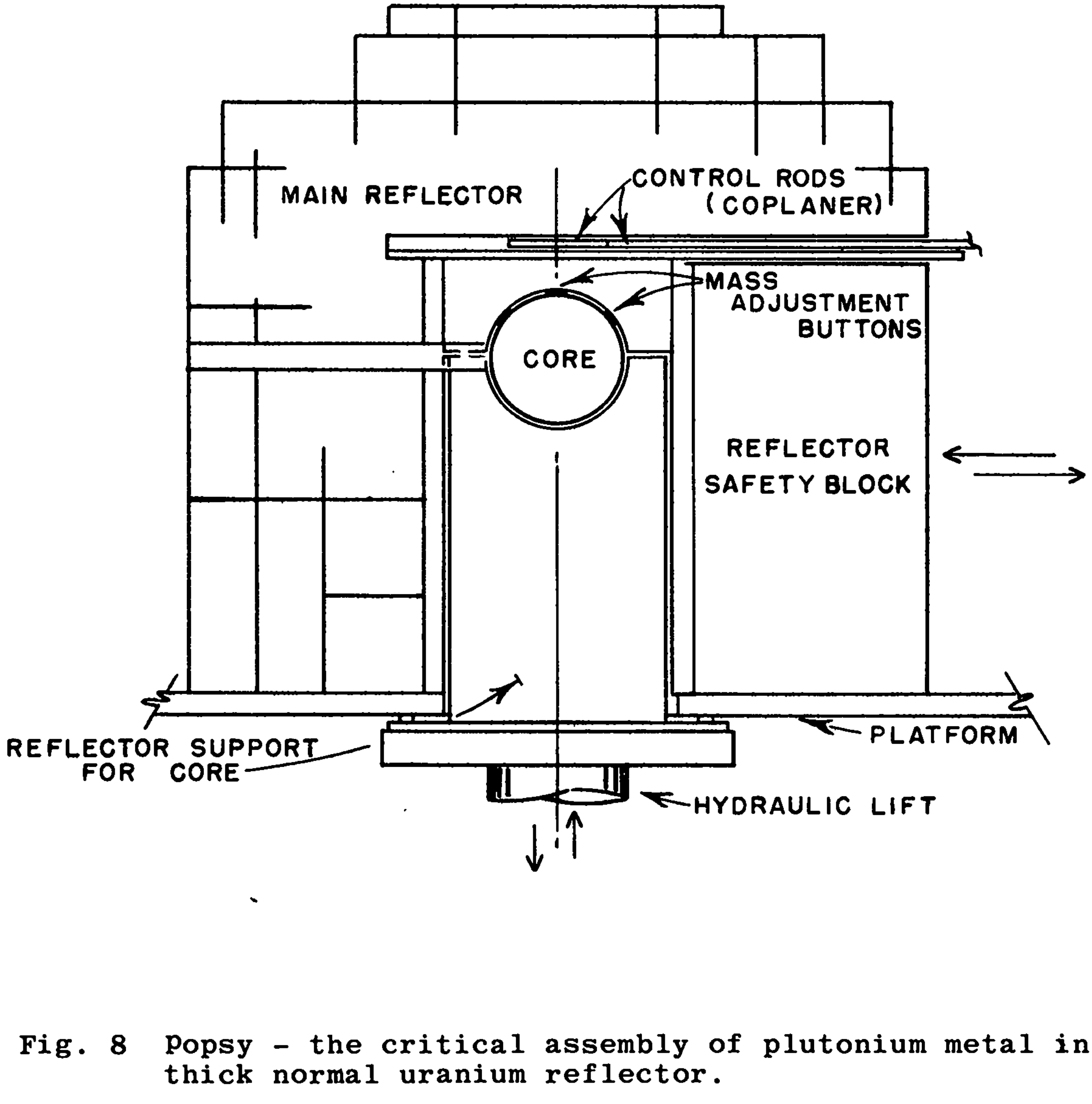

Fig. 8 Popsy - the critical assembly of plutonium metal in thick normal uranium reflector.

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9-1/2" of normal uranium reflector around the core. The innermost part of the reflector immediately adjacent to the Pu consisted of a spherical shell of uranium 1/8" thick that had sixteen 3/4" diameter holes through it. Into these holes could be put matching (spherical radius) buttons of Pu (about 12-1/2 gm each) or uranium (about 15 gm each) for reactivity adjustments greater than that available from the two uranium reflector control rods.

Critical Mass

Without any corrections for the influence of Ni coatings, the critical mass of the two split concentric shells (with 0.410" diameter cavity) in 9-1/2" of uranium (control rods fully inserted) is 5.837 ± 0.020 kg of Pu alloy. Again making no Ni corrections, the critical mass of the larger split spherical shell (with 0.840" diameter cavity) for the same reflector and control rod configurations would be 5.914 ± 0.020 kg of alloy. Finally, the critical mass (m_c) of the outer shell was corrected to give m_c for a solid sphere of alloy as follows:

m_c for outer split shell with Ni	5.914 kg
substitution of Pu for Ni at parting planes	-0.019 kg surface mass
filling 0.840" diameter cavity with alloy	-0.103 kg surface mass
m_c for solid sphere	5.791 ± 0.020 kg

[redacted]

[redacted]

The substitution of 6-1/2 mils of uranium for Ni on the outside reduces m_c by at most 1 gm of surface mass. These corrections were based on 1) observed increments of reciprocal multiplication when one or both inner hemispherical shells were added, and 2) the results of Topsy material replacement measurements(6) scaled to give reactivity contributions of active material and Ni vs radius in Popsy. A crude estimate of the change in reciprocal multiplication when the reflector thickness was increased to about 12" on four sides indicated a decrease in m_c of approximately 12 gm of surface mass, showing that the 9-1/2" reflector was not quite infinitely thick.

Rossi Alpha and Reactivity Calibrations

The value of alpha, the prompt neutron chain decay constant, was measured by the Rossi method(1) at delayed critical, and at reduced reactivities of two and three mass adjustment buttons below delayed critical. Also, positive periods were observed for reactivity increments produced both by adding buttons and also by adding control rod in the linear portion of effectiveness. These data, together with the Pu^{239} delayed neutron data of Keepin and Wimett,(4) permit the calculation of ΔK/button in cents, $\Delta\alpha/\Delta K$ in sec^{-1} $cents^{-1}$, and control rod effectiveness in cents per linear control rod inch (lcri). By taking 100 x $\Delta\alpha/\Delta K$ another value for alpha at delayed critical was obtained. Finally, from ΔK/button

[redacted]

and a correction for the effectiveness of button material vs surface material, the increment of surface mass between delayed and prompt critical was determined. These results are summarized in Table V. The discrepancy between the two values of alpha is thought to be due most likely to the fact that the fission chamber had to be placed in the reflector rather than in the core, and hence was influenced by U^{238}, whose absolute yield of delayed neutrons is some 6-1/2 times that of Pu^{239}.

Spectral Data

A few spectral indices were obtained to permit a crude comparison of Popsy with other assemblies. They were obtained entirely from radiochemical analyses (by J. Sattizahn and co-workers of Group J-11) of samples irradiated at various positions in the assembly. The results are presented in Table VI as cross section ratios, since reactions per atom of isotope were obtained in each case.

TABLE V.

RESULTS OF POPSY CALIBRATION

α (delayed critical) observed	-0.20	$\pm\ 0.01 \times 10^{6}$ sec^{-1}
α' (delayed critical) = 100 x $\Delta\alpha/\Delta K$	-0.16	$\pm\ 0.01 \times 10^{6}$ sec^{-1}
ΔK/button (12-1/2 gm)	24	± 1 cents
$\Delta\alpha/\Delta K$	1.6	$\pm\ 0.1 \times 10^{4}$ sec^{-1} cents^{-1}
Control rod effectiveness	4.0	± 0.2 cents/lcri
\$1.00 of reactivity	46	± 2 gm surface alloy mass

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TABLE VI.

CROSS SECTION RATIOS VS POPSY RADIUS

Radius (in.)	$\frac{\bar{\sigma}_f(U^{235})}{\bar{\sigma}_f(U^{238})}$	$\frac{\bar{\sigma}_f(Pu^{239})}{\bar{\sigma}_f(U^{235})}$	$\frac{\bar{\sigma}_{n,\gamma}(U^{238})}{\bar{\sigma}_f(U^{238})}$	$\frac{\bar{\sigma}_{n,2n}(U^{238})}{\bar{\sigma}_f(U^{238})}$
0.06	5.4_5	1.41	0.44_9	0.055_2
1.83	8.2_8	1.38	0.73_3	0.049_3
3.56	26.7	1.27	2.96	0.044_1
5.67	38.4	1.46	6.0_1	0.037_2

Note: Core reflector interface at 1.76".

[redacted]

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