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**SUMMARY OF EXPERIMENTALLY DETERMINED
PLUTONIUM ARRAY CRITICAL CONFIGURATIONS**

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SUMMARY OF EXPERIMENTALLY DETERMINED PLUTONIUM ARRAY CRITICAL CONFIGURATIONS

Abstract

In this report, we present experimentally determined critical configurations for 28 one-, two-, and three-dimensional plutonium arrays. These arrays include unmoderated, moderated, and externally reflected systems. The basic array part consists of a 3-kg mass of α -phase plutonium in the shape of a right circular

cylinder. The moderator consists of cylindrical mock high-explosive jackets in three thicknesses—1.27, 2.55, and 3.82 cm. Eight different array units were constructed by using one or two of the basic plutonium parts, with or without the moderator jackets. The external reflector material is polyethylene.

Introduction

The Livermore Array Program was initiated in 1965 to provide an experimental and calculational study of plutonium arrays. It was terminated in September 1969 after more than four years of critical and subcritical experiments. The experiments were divided into three phases. Phase I consisted of experiments performed on a small assembly machine originally constructed for another program. When experimental sizes became too large for this machine, a much larger one was constructed specifically for the Array Program, and the immediately succeeding experiments were designated Phase II. When a safety rule was found to be invalid, temporarily suspending the regular experiments, a special set of linear arrays was performed. These experiments, called Phase III, were done

with a single loading unit cut into two halves and turned horizontally on the Phase II machine.

Although many critical configurations were determined, 28 stand out as being individually unique; that is, they were not trivial variations of other arrays. The critical point was generally determined by subcritical extrapolations. Most arrays attained a maximum multiplication greater than 100, and three achieved the critical state, that is, a small positive power-level period. Arrays with lower multiplications naturally had greater uncertainties in their critical spacings.

We have previously published data from 18 of the arrays.¹⁻³ Our earlier publications contained results of certain minor parameter variations and a discussion of our experimental procedures. In this report we will correct a few of

our early results that were reported incorrectly.

The first part of this report presents the material and geometric specifications of the parts used to build array units. These parts include the aluminum support structure components, as well as the plutonium and neutronic mock high-explosive components. Uncertainties in these parameters are given and are to be interpreted as estimates of probable error (that magnitude of deviation whose probability of being exceeded is one half).

The second part of the report presents critical configurations as determined directly and by extrapolation. These results are presented both pictorially and in tabular form. The critical configurations, which are drawn (approx 1/10 scale) in plan and elevation views, are intended to be useful as work sheets (see Figs. 9-36). Unit plutonium center-to-center and

surface-to-surface spacings, along with overall array dimensions, are given in centimeters. For array units having a moderator jacket the moderator surface-to-surface spacing is also given. The tabular summary should be useful for quick reference and includes calculated unit cell volumes for convenience. Uncertainties in critical spacings should be understood as probable errors due to the small variations between individual array units and irregularities in the support structure but not due to table and room return or temperature variations. That is, the uncertainties do not relate to the ideal critical experiment composed of perfect and identical array units at a uniform temperature assembled in free space without supporting structure or any near or distant reflecting materials. Estimates of critical spacings for such ideal experiments have not been made.

Material and Geometric Specifications

PLUTONIUM CYLINDERS

The geometry of the basic plutonium part is a right circular cylinder. Each part was weighed before it was canned, but its dimensions were not recorded. The parts varied between 3.004 and 3.043 kg, with an average of 3.026 ± 0.008 kg.

Table 1. Plutonium cylinder specifications.

Mass, kg	3.026 ± 0.008
Diameter, cm	6.525 ± 0.005
Height, cm	4.633 ± 0.015
Density, g/cm ³	19.53 ± 0.08

Table 1 summarizes our measurements with canned parts and empty cans, which are recommended as working values. One hundred and thirty of these parts were fabricated at the Hanford facility. Table 2 lists the average isotopic

Table 2. Plutonium isotopic composition.

Isotope	Wt%	N, cm ⁻³
239	93.56	4.608×10^{22}
240	5.97	2.925×10^{21}
241	0.46 ^a	2.25×10^{20a}
242	0.01	6.8×10^{18}

^aAs of July 1965; this isotope is decaying with a 13.2-yr half-life.

Table 3. Plutonium impurities.

Element	Amount, ppm	Element	Amount, ppm
Ag	<1	Mn	5
Al	5	Na	1
B	1	Ni	50
Ca	100	Pb	<1
Cr	20	Si	15
Cu	5	Sn	<2
Fe	35	Ti	5
Mg	20	(Total metallic, 265)	
C	180		

distribution of 32 plutonium parts as determined by mass spectrometer measurements. Calculated nuclear number densities are also given. Table 3 lists the averages of spectrographic impurity measurements on all 130 plutonium parts.

CONTAINERS, HEAT SINKS, AND SPACERS

Each plutonium part is sealed in a close-fitting, deep-drawn, seamless aluminum can fitted with a steel lid. The sides of the cans are 0.037 cm thick, and the bottom (which appears at the top of the part in the experimental configuration because the cans are loaded in an inverted position; see Fig. 1) is 0.087 cm thick. The mass of the aluminum can is 19.2 g; its composition appears in Table 4. The steel lid is 0.021 cm thick and has a mass of 8.28 g; its composition is listed in Table 5.

Aluminum heat sinks are used above and below all plutonium parts. When two parts are stacked vertically to form a 6-kg double part, a 16.10-g, 0.356-cm-thick heat sink is placed between the lid of one part and the bottom of the other.

A 26.97-g, 0.479-cm-thick heat sink appears at the top of each part or double part, and a 28.08-g, 0.635-cm-thick sink at the bottom.

Internal spacing between plutonium units is accomplished by suitable combinations of thin aluminum cylinders, 6.208 cm i.d. and 0.222 cm thick. The spacers average 11.25 g/cm of length. Both internal spacers and heat sinks described above are made of 6061 aluminum alloy; its composition is also listed in Table 4.

Minor features such as curves in the plutonium cans and heat sinks exist in the actual apparatus but have not been described above. Furthermore, many air spaces exist that are not detailed. In Figs. 1 and 2 the single and double parts, as well as related components, are shown schematically. Some sections have been homogenized, but there is sufficient detail to prepare calculational input. Of course, further homogenization is always possible.

MODERATOR CELLS

The moderator cells were provided in three thicknesses and were designed to enclose either the 3-kg basic plutonium part or the 6-kg double part. They are comprised of disks inside the support column and rings on the outside. There are always two inner disks per cell (immediately adjacent to the top and bottom heat sinks), and from one to three outer rings. Table 6 lists the physical parameters of the six different-sized moderator cells. The total height of the outer rings does not exactly coincide with the height of the stacked inner parts of

Fig. 1. Schematic drawing of array unit containing single plutonium part (support tube not shown).

the cell. However, the bottom of the lowest ring is always positioned to be even with the bottom of the lowest disk.

It is possible to combine measurements and simplify the description of each cell size. For instance, for working purposes, the moderator density should

be taken as $1.559 \pm 0.018 \text{ g/cm}^3$ for all parts, the outside diameter of the disks a standard 6.795 cm, the inside diameter of the rings a standard 7.628 cm, and the three moderator thicknesses can be called 1.271, 2.549, and 3.816 cm, respectively. Finally, the height of the

Table 4. Aluminum alloy compositions.

Element	Nominal composition, %			
	2024 alloy	2219 alloy	3004 alloy	6061 alloy
Cr	0.10	—	—	0.20
Cu	4.35	6.3	0.25	0.25
Fe	0.50	0.30	0.7	0.7
Mg	1.5	0.02	1.05	1.0
Mn	0.6	0.3	1.25	0.15
Si	0.50	0.20	0.30	0.6
Ti	—	0.06	—	0.15
Zn	0.25	0.10	0.25	0.25
All others	0.15 max	0.15 max	0.15 max	0.15 max
Al (remainder)	~92.05	~92.6	~96.05	~96.55
Uses				
	Column, Phase I shoes, ^a all unspecified structural materials	Phase II table top	Container ^b	Heat sinks, inner spacers

^aShoes are used to fasten column to table (see Fig. 5).

^b9.57 g to be homogenized with upper heat sinks.

Table 5. Steel alloy compositions.

Element	Nominal composition, %			
	Plutonium can lid	Bolts and washers in bottom shoe ^a	Stainless steel clamps in Phase II upper structure ^b	Angle iron under tables ^c
C	0.08	0.38	0.15 max	0.21
Cr	—	4.67	18.00	—
Mn	0.37	0.35	—	0.43
Mo	—	1.21	—	—
Ni	—	—	5.00	—
P	0.015	0.02	—	0.04 max
Pb	—	0.02	—	—
S	0.025	0.04	—	0.05 max
Si	0.01 max	0.85	1.00	—
Sn	0.30 ^d	—	—	—
V	—	0.47	—	—
Fe (remainder)	~99.2	~92.0	~75.9	~99.3

^aShoe fastens bottom end of Phase II column to table (see Fig. 6).

^bClamp fastens top end of Phase II column to table upper structure (see Fig. 6).

^cFull density is approx 7.85 g/cm³.

^dTin plate.

Fig. 2. Schematic drawing of array unit containing two plutonium parts (support tube not shown).

outer rings should be set equal to the distance between the outer faces of the inner disks.

The parts were made of a powdered mock high-explosive formulation that

was cast in an epoxy binder. A chemical analysis of some representative parts is given in Table 7. A listing of moderator impurities is given in Table 8.

Table 6. Physical parameters of moderator parts.

Av cell thickness, cm	Inner disk size, cm ^a	Av inner disk mass, g	3-kg cell parameters		6-kg cell parameters	
			Outer ring size, cm ^b	Av total cell mass, g ^c	Outer ring size, cm ^b	Av total cell mass, g ^c
1.27	6.795 × 1.278	71.51 ± 0.75	6.407 × 7.620 × 1.267	603.8 ± 5.5	14.267 × 7.625 × 1.267	930.8 ± 10.6
2.54	6.795 × 2.555	144.7 ± 1.7	10.932 × 7.635 × 2.543	1662.7 ± 9.5	16.746 × 7.633 × 2.543	2401.2 ± 8.8
3.81	6.795 × 3.813	214.6 ± 2.7	13.480 × 7.638 × 3.818	3354 ± 30	19.334 × 7.628 × 3.818	4614 ± 26

^aOutside diameter × thickness.^bHeight × inside diameter × thickness.^cIncludes two inner disks.

Table 7. Moderator composition.

Element	Composition, wt%	Calculated number densities, 10 ²² /cm ³
C	30.56	2.398
H	3.14	2.89
N	31.57	2.123
O plus impurities	34.73	2.642

SUPPORT STRUCTURE

The columns used to support the plutonium units are shown in Figs. 3 and 4. All arrays containing less than 90 kg of plutonium were performed on a small assembly machine in 18-in. columns.* These were called the Phase I experiments; Fig. 3 schematically shows this support structure. The part of the column surrounding the plutonium is 6.850 cm i.d. × 0.184 cm thick and has a mass per unit length of 11.01 g/cm. The material is 2024 aluminum alloy whose composition is found in Table 4. The "shoes" which fasten the columns to the

* There is one exception—the 2 × 2 × 2, bare 6-kg array (48 kg) was measured with the Phase II apparatus.

Table 8. Moderator impurities.

Element	Amount, ppm	Element	Amount, ppm
Al	3	Mo	0.2
B	1	Na	20
Ba	5	Ni	2
Ca	10	Pb	0.4
Cr	2	Si	2
Cu	0.3	Sn	0.2
Fe	25	Sr	0.2
K	200	Ti	0.5
Mg	3	Zn	0.5
Mn	0.5		

assembly table are also made of 2024 alloy.

Figure 4 shows the Phase II apparatus used in arrays involving more than 90 kg of plutonium.* These columns are taller, have a 6.858-cm i.d., 0.178-cm-thick wall, and a mass per unit length of 10.70 g/cm. The Phase II columns are also 2024 aluminum alloy, but the bottom shoes are made of naval brass, whose composition is 60.00 wt% Cu-39.25 wt% Zn-0.75 wt% Sn. Apart from its size, the support structure for the Phase II arrays is also distinguished by an upper support arrangement involving plugs, clamps, beams, and rails.

Fig. 3. Schematic drawing of Phase I support apparatus.

The Phase III plutonium parts, interior spaces, and moderator cells were the same as those used in Phases I and II. They were loaded horizontally in a modified Phase II outer tube suspended with

its centerline 17.8 cm above the Phase II assembly table.

The assembly tables are also shown schematically in Figs. 3 and 4. Because of the hundreds of bolt holes used for

Fig. 4. Schematic drawing of Phase II support apparatus.

fastening the shoes, the density of the tables is reduced from solid aluminum density by about 12%. The alloy used in the Phase I table top is unknown; the Phase II table top is 2219 aluminum alloy.

Figure 5 is a photograph of the Phase I assembly machine loaded with a $2 \times 2 \times 2$ array mockup. Figure 6 shows the Phase II machine with a large moderated array mockup. The same machine is pictured in Fig. 7, but loaded with Phase III apparatus. The Phase II machine is described in Ref. 4.

Fig. 5. Phase I assembly machine with $2 \times 2 \times 2$ mockup.

REFLECTOR

The reflector used in the Phase I program was fabricated from polyethylene ($\text{CH}_2\text{:CH}_2$)_n slabs and had a density of $0.92 \pm 0.01 \text{ g/cm}^3$. It was 45.08 cm high $\times$ 35.03 cm wide $\times$ 20.64 cm thick. When in place, the bottom was flush with the assembly table top; the reflector was centered horizontally and was touching the surfaces of the outer support columns.

The reflectors used in Phase III were intended to simulate the human body and

Fig. 6. Phase II assembly machine with $4 \times 4 \times 4$ moderated mockup.

Fig. 7. Phase III apparatus on the Phase II assembly machine.

were fabricated from polyethylene (density, $0.92 \pm 0.01 \text{ g/cm}^3$). The large torso simulators were each $152.4 \times 35.6 \times 15.2 \text{ cm}$, and the two arm simulators were $152.4 \times 7.6 \times 7.6 \text{ cm}$.

Moderator dimensions and masses

Moderator thickness A, cm	3-kg unit		6-kg	
	B, cm	Moderator cell mass, kg	B, cm	Moderator cell mass, kg
1.27	8.41	0.604	14.27	0.931
2.55	10.93	1.663	16.75	2.401
3.82	13.48	3.354	19.33	4.614

Material compositions and nuclear number densities

Plutonium			Moderator		
Isotope	Content, wt %	N, cm ⁻³	Element	Content, wt %	N, cm ⁻³
239	93.56	4.608×10^{22}	H	3.1	2.89×10^{22}
240	5.97	2.925×10^{21}	C	30.6	2.398×10^{22}
241	0.46	2.25×10^{20}	N	31.6	2.123×10^{22}
242	0.01	6.8×10^{18}	O	34.7	2.042×10^{22}

Fig. 8. Summary of array unit specifications.

Critical Configurations

Table 9 lists the experimentally determined critical spacings of the one-, two-, and three-dimensional arrays. The arrays have been numbered in chronological order of completion. The Phase I arrays are the 100 series; the Phase II arrays, the 200 series; and the Phase III arrays, the 300 series. Unit cell volumes, the product of the three center-to-center

dimensions in Table 9, are included in the tabulation. The temperatures that appear in Table 9 result from measurements with a thermocouple in contact with one of the plutonium parts on the outer boundary of the array.

Following Table 9 is a summarized specification sheet and a schematic drawing of each critical array (Figs. 9-36).

Table 9. Summary of critical array spacings.

Array No.	Description	Critical center-to-center separation, cm		Unit cell volume, cm ³	Outer can temperature, °C	Fig. No.
		Vertical	Horizontal			
<u>3-kg cells</u>						
304	1 × 1 × 4 bare, four sides reflected ^a	5.56 ± 0.03	—	—	38	9
301	1 × 1 × 5 bare, four sides reflected ^a	6.18 ± 0.03	—	—	30	10
303	1 × 1 × 7 bare, four sides reflected ^a	6.75 ± 0.03	—	—	40	11
302	1 × 1 × 11 bare, four sides reflected ^a	7.25 ± 0.03	—	—	49	12
101	2 × 2 × 2 bare	5.40 ± 0.03	7.30 ± 0.03	287.7	42	13
102	2 × 2 × 2 bare, one side reflected ^b	5.74 ± 0.03	7.64 ± 0.03	334.8	36	14
103	3 × 3 × 3 bare	7.71 ± 0.03	9.60 ± 0.03	710.1	33	15
104	3 × 3 × 3 bare, one side reflected ^b	8.24 ± 0.03	10.15 ± 0.03	848.4	42	16
107	3 × 3 × 3 bare, except 1.27-cm moderator cell around central unit	7.72 ± 0.03	9.61 ± 0.03	712.5	33	17
106	3 × 3 × 3 bare, except 1.27-cm-thick ⁶ LiD slab between two rows	7.73 ± 0.03	9.62 ± 0.03	715.4	33	18

Table 9 (continued)

Array No.	Description	Critical center-to-center separation, cm		Unit cell volume, cm ³	Outer can temperature, °C	Fig. No.
		Vertical	Horizontal			
207	4 × 4 × 4 bare	7.86 ± 0.01	12.51 ± 0.01	1230	31	19
204	4 × 4 × 4, 1.27-cm moderator cells	9.62 ± 0.01	14.19 ± 0.01	1939	34	20
205	4 × 4 × 4, 2.54-cm moderator cells	13.64 ± 0.01	14.55 ± 0.01	2888	32	21
206	4 × 4 × 4, 3.81-cm moderator cells	13.63 ± 0.01	14.62 ± 0.35 ^c	2913	45	22
<u>6-kg cells</u>						
305	1 × 1 × 2 bare, four sides reflected ^a	11.49 ± 0.03	—	—	27	23
306	1 × 1 × 5, 1.27-cm moderator cells, four sides reflected ^a	13.54 ± 0.03	—	—	46	24
105	2 × 2 × 1 bare	—	7.59 ± 0.03	—	35	25
215	2 × 2 × 2 bare	11.98 ± 0.02	9.76 ± 0.03	1141	30	26
214	3 × 3 × 3 bare	13.68 ± 0.02	14.51 ± 0.03	2878	35	27
213	4 × 4 × 1 bare	—	10.91 ± 0.02 ^d	—	31	28
210	4 × 4 × 4 bare	47.12 ± 0.02 ^e	11.93 ± 0.01	6707	32	29
209	4 × 4 × 4 bare	32.12 ± 0.02 ^e	13.09 ± 0.01	5505	31	30
211	4 × 4 × 4 bare	22.12 ± 0.02 ^e	15.23 ± 0.01	5131	33	31
208	4 × 4 × 4 bare	17.12 ± 0.02 ^e	17.28 ± 0.01	5111	34	32
212	4 × 4 × 4 bare	13.12 ± 0.02 ^e	20.19 ± 0.02	5349	41	33
201	4 × 4 × 4, 1.27-cm moderator cells	25.79 ± 0.02	17.50 ± 0.01	7897	38	34
202	4 × 4 × 4, 2.54-cm moderator cells	25.82 ± 0.02	21.24 ± 0.01	11653	39	35

Table 9 (continued)

Array No.	Description	Critical center-to-center separation, cm		Unit cell volume, cm ³	Outer can temperature, °C	Fig. No.
		Vertical	Horizontal			
203	4 × 4 × 4, 3.81-cm moderator cells	25.82 ± 0.02	24.52 ± 0.02	15526	38	36

^aTwo sides were reflected by 152.4 × 35.6 × 15.2-cm polyethylene body simulators, and two sides by 152.4 × 7.6 × 7.6-cm arm simulators.

^bThe polyethylene reflector slab was 45.1 cm high × 35.1 cm wide × 20.5 cm thick.

^cExtrapolated estimate; array was terminated at 15.25-cm horizontal center-to-center spacing when moderator cells touched.

^dWith this planar array located at five heights between 28.3 and 113.4 cm above the assembly table, the critical horizontal center-to-center separation varied between 11.12 ± 0.02 cm and 10.90 ± 0.02 cm. The nominal critical spacing is listed above.

^eThis set of measurements is referred to as the "unit cell series"; i.e., each array was 4 × 4 × 4, but the unit cell configuration was progressively distorted.

Fig. 9. Array no. 304, 1×4 (four faces reflected), 3-kg Pu part.

Fig. 10. Array no. 301, 1×5 (four faces reflected), 3-kg Pu part.

Fig. 11. Array no. 303, 1×7 (four faces reflected), 3-kg Pu part.

Fig. 12. Array no. 302, 1×11 (four faces reflected), 3-kg Pu part.

Fig. 13. Array no. 101, $2 \times 2 \times 2$, 3-kg Pu part, $V_{\text{cell}} = 287.7 \text{ cm}^3$.

Fig. 15. Array no. 103, $3 \times 3 \times 3$, 3-kg Pu part, $V_{\text{cell}} = 710.1 \text{ cm}^3$.

Fig. 14. Array no. 102, $2 \times 2 \times 2$ (one face reflected), 3-kg Pu part, $V_{\text{cell}} = 334.8 \text{ cm}^3$.

Polyethylene reflector, $\rho = 0.92 \text{ g/cm}^3$

Fig. 16. Array no. 104, $3 \times 3 \times 3$ (one face reflected), 3-kg Pu part, $V_{\text{cell}} = 848.4 \text{ cm}^3$.

Elevation

Fig. 17. Array no. 107, $3 \times 3 \times 3$ (central part moderated), 3-kg Pu part (1.27-cm-thick moderator jacket), $V_{\text{cell}} = 712.5 \text{ cm}^3$.

Plan

Plan

Elevation

${}^6\text{LiD}$ slab (93.8 wt% ${}^6\text{Li}$)

$$\rho = 0.79 \text{ g/cm}^3$$

Elevation

Fig. 19. Array no. 207, $4 \times 4 \times 4$, 3-kg Pu part, $V_{\text{cell}} = 1230 \text{ cm}^3$.

Fig. 18. Array no. 106, $3 \times 3 \times 3$ (interstitial slab), 3-kg Pu part, $V_{\text{cell}} = 715.4 \text{ cm}^3$.

Fig. 20. Array no. 204, $4 \times 4 \times 4$, 3-kg Pu part (1.27-cm-thick moderator jacket, $V_{\text{cell}} = 1939 \text{ cm}^3$).

Fig. 21. Array no. 205, $4 \times 4 \times 4$, 3-kg Pu part (2.55-cm-thick moderator jacket, $V_{\text{cell}} = 2888 \text{ cm}^3$).

Fig. 22. Array no. 206, $4 \times 4 \times 4$, 3-kg Pu part (3.32-cm-thick moderator jacket), $V_{\text{cell}} = 2913 \text{ cm}^3$.

Fig. 23. Array no. 305, 1×2 (four faces reflected), 6-kg Pu part.

Fig. 24. Array no. 306, 1×5 (four faces reflected), 6-kg Pu part (1.27-cm-thick moderator jacket).

Fig. 25. Array no. 105, $2 \times 2 \times 1$, 6-kg Pu part.

Fig. 26. Array no. 215, $2 \times 2 \times 2$, 6-kg Pu part, $V_{\text{cell}} = 1141 \text{ cm}^3$.

Fig. 27. Array no. 214, $3 \times 3 \times 3$, 6-kg Pu part, $V_{\text{cell}} = 2878 \text{ cm}^3$.

Fig. 28. Array no. 213, $4 \times 4 \times 1$, 6-kg Pu part.

Plan

Elevation

Fig. 29. Array no. 210, 4 X 4 X 4, 6-kg
Pu part, $V_{\text{cell}} = 6707 \text{ cm}^3$.

Plan

Elevation

Fig. 30. Array no. 209, 4 X 4 X 4, 6-kg
Pu part, $V_{\text{cell}} = 5505 \text{ cm}^3$.

Fig. 31. Array no. 211, $4 \times 4 \times 4$, 6-kg
Pu part, $V_{\text{cell}} = 5131 \text{ cm}^3$.

Fig. 32. Array no. 208, $4 \times 4 \times 4$, 6-kg
Pu part, $V_{\text{cell}} = 5111 \text{ cm}^3$.

Fig. 33. Array no. 212, $4 \times 4 \times 4$, 6-kg Pu part, $V_{\text{cell}} = 5349 \text{ cm}^3$.

Fig. 34. Array no. 201, $4 \times 4 \times 4$, 6-kg Pu part (1.27-cm-thick moderator jacket), $V_{\text{cell}} = 7897 \text{ cm}^3$.

Fig. 35. Array no. 202, $4 \times 4 \times 4$, 6-kg Pu part (2.55-cm-thick moderator jacket), $V_{\text{cell}} = 11,653 \text{ cm}^3$.

Fig. 36. Array no. 203, $4 \times 4 \times 4$, 6-kg Pu part (3.82-cm-thick moderator jacket), $V_{\text{cell}} = 15,526 \text{ cm}^3$.

Acknowledgments

The experimental program that we have described extended over several years (1965-1969). During this period, the program was under the sponsorship and administrative direction of several persons at this laboratory. The original sponsor was A. C. Haussmann, who was succeeded by C. A. McDonald. The program was given administrative direction by H. Reynolds, J. Hadley, and E. Goldberg. We acknowledge a substantial debt to all of these individuals for the guidance provided during the program.

Furthermore, at the outset of the program, the actual experimental operations were directed by J. Morton; some of the earlier experiments described were performed under his direction. During the course of the experiments, L. Gardner, F. Green, and J. Ball performed the necessary setups and measurements competently. G. Pefley gave a variety of professional help. We offer our heartfelt thanks to these, as well as to other, less directly involved personnel.

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