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DESTRUCTIVE AND NONDESTRUCTIVE
ANALYSIS OF PLUTONIUM FUELS
USED IN LATTICE EXPERIMENTS

OCTOBER 1971

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DESTRUCTIVE AND NONDESTRUCTIVE ANALYSIS
OF PLUTONIUM FUELS USED IN LATTICE EXPERIMENTS

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ABSTRACT

Plutonium-enriched fuel rods that have been used in zero-power critical experiments under the Plutonium Utilization Program have been reanalyzed and investigated to check and verify their fuel content and composition. On the basis of this study it appears that average plutonium enrichments reported in the past for these fuels are valid. An important part of this report is the reporting of ^{241}Am contents for the fuels, as well as dates for the original chemical separation of plutonium for each fuel, and dates for each of the critical experiments. This information is needed for accurate calculations of the critical experiments.

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DESTRUCTIVE AND NONDESTRUCTIVE ANALYSIS
OF PLUTONIUM FUELS USED IN LATTICE EXPERIMENTS

I. INTRODUCTION

A series of critical and subcritical experiments⁽¹⁾ have been performed over a number of years to provide neutronic data on plutonium-fueled, light-water-moderated cores. These experimental data, involving lattices of various Al-Pu and $\text{UO}_2\text{-PuO}_2$ rods, have been the base upon which the accuracy of neutronic reactor design methods have been evaluated.⁽²⁾ The results of criticality calculations⁽²⁾ for some of these cores have not compared very favorably with the measured results. As a part of the investigation aimed at uncovering the cause for these discrepancies, some of these fuels have been destructively analyzed to check on the fuel content and composition.

The plutonium-aluminum alloy fuels were examined in detail because these fuels were some of the first plutonium rods fabricated and thus were most suspect. For assessing the uniformity of each Al-Pu fuel type, ten rods of each of the three types (Al - 1.8 wt% Pu, Al - 2 wt% Pu, and Al - 5 wt% Pu) were selected for reactivity worth measurements in the Plutonium Recycle Critical Facility (PRCF). One rod of each Al-Pu fuel type was sacrificed to perform: a chemical and an isotopic analysis for plutonium concentration and composition; alpha energy analysis for ^{241}Am content; and a spectro-chemical analysis for detecting impurities (e.g., B, Cd and Au). Two methods of destructively analyzing the fuel for plutonium content were used. These are the coulometric titration and isotopic dilution methods. Samples which were taken from the mid-part of the fuel rods and from adjacent positions were analyzed.

The possibility of these Al-Pu rods having enrichment variation axially

was investigated in a preliminary manner by gamma-scanning three unirradiated rods of each type.

The results of theory-experiment correlations for the Al-2 wt% Pu systems have been systematically different from those obtained for the other Al-Pu and $\text{UO}_2\text{-PuO}_2$ systems. Therefore, a rod of this type was further analyzed for rare-earth isotopes and for hafnium content in the zircalloy cladding.

In addition to analyzing these Al-Pu fuels, two $\text{UO}_2\text{-PuO}_2$ fuel rods were destructively analyzed for plutonium and americium content to determine how much ^{241}Pu had decayed. Repeat measurements were planned over a specified time period to assist in assessing the reactivity effect of ^{241}Pu decay.

The measured ^{241}Am contents have been used, together with earlier isotopic measurements, to compute the amounts of ^{241}Am and ^{241}Pu present when these rods were used in critical-approach experiments. A list of experiments, dates, and ^{241}Am and ^{241}Pu concentrations is given in an appendix to this report.

II. ROD-TO-ROD UNIFORMITY OF Al-Pu FUELS

For measurements of the uniformity of each Al-Pu fuel type, ten rods from each of the three Al-Pu types of fuel (Figures 1, 2, 3) were selected to represent the total batch of each. These ten rods bracketed the range of Pu content. The reactivity worth of each Al-Pu fuel rod was measured in a central fuel channel in the PRCF. The core was $\text{UO}_2\text{-4 wt% PuO}_2$ (18% ^{240}Pu) fuel rods in a H_2O moderated lattice of 1.06 inch square pitch. All the measurements were made with the fuel in a lucite thimble (1/32 inch wall thickness). The accuracy of the reactivity worth measurements is ± 0.04 mk, which was

determined from the reproducibility of nine measurements. The effect of a lucite thimble on the reactivity worth of a fuel rod (J-73) was measured and found to be less than 0.04 mk, which is the resolution of the measurements.

The results of the reactivity measurements are listed in Table I. Also listed are the average worth of each batch, the standard deviation of the worth of a typical rod, and the standard deviation of the average worth of each batch.

FUEL SPECIFICATIONS: Al-1.8 WT% Pu

FUEL RODS

1. ROD DIMENSIONS:

2. CLADDING: Zircaloy-2 tubing with plugs seal welded at both ends.
Various sizes of end plugs are used.
Averages: Source end - plug + clad beyond fuel = 12.4 gms/rod
Opposite end - Plug + clad beyond fuel = 21.6 gms/rod.

3. TOTAL WEIGHT OF LOADED FUEL RODS: 660.5 gms (Average).

FUEL LOADINGS

1. Al-Pu rods - extruded and sized
2. 389.32 gms Al-Pu alloy per rod
3. Chemical Composition - Pu/Al-Pu = 1.83 wt%.
4. Pu - 7.12 grams per rod (Average)
5. Fuel Density - 0.05049 gms/cm³.
6. Isotopic Composition:

Plutonium - wt%*	Aluminum - wt%
Pu ²³⁹ - 93.97	Al - 97.21
Pu ²⁴⁰ - 5.58	Ni - 1.61
Pu ²⁴¹ - 0.44	Fe - 0.49
Pu ²⁴² - 0.014	Si - 0.69

* Measured ~March 1961 (estimated date of Pu separation is Sept. 1958).

FIGURE 1. Fuel Specifications: Al-1.8 wt% Pu

FUEL SPECIFICATIONS: Al - 2.01 WT% Pu

FUEL RODS

1. ROD DIMENSIONS:

2. CLADDING: Zircaloy-2 tubing with plugs seal welded at both ends.
3. TOTAL WEIGHT OF LOADED FUEL RODS: 526.0 gm (Average)

FUEL LOADINGS

1. Al-Pu rods - extruded and sized
2. 318.19 gms of Al-Pu alloy/rod
3. Chemical composition wt%: Pu/Al-Pu = 2.006 wt%.
4. Pu - 6.383 gms/rod (Average).
5. Fuel Density = 0.0551 gm/cm³.
6. Isotopic Composition:

Plutonium - wt%*	Aluminum - wt%
Pu ²³⁹ - 81.01	Al - 97.57
Pu ²⁴⁰ - 16.46	Ni - 1.63
Pu ²⁴¹ - 2.31	Fe - 0.30
Pu ²⁴² - 0.20	Si 0.10

* Measured October 1961 (Estimated date of Pu separation is Dec. 1960).

FIGURE 2. Fuel Specifications: Al-2.01 wt% Pu

FUEL SPECIFICATIONS: Al - 5.01 WT% Pu

FUEL RODS

1. ROD DIMENSIONS:

2. CLADDING: Zircaloy-2 tubing with plugs seal welded at both ends.
3. TOTAL WEIGHT OF LOADED FUEL RODS: 353.7 gms (Average)

FUEL LOADINGS

1. Al-Pu rods - extruded and sized
2. 219.94 gm of Al-Pu/rod
3. Chemical composition wt%: Pu/Al-Pu = 5.01 11.01 gm Pu/rod
4. Fuel density - 0.1427 gm Pu/cm³
5. Isotopic composition:

Plutonium - wt%*

Pu ²³⁹	- 94.09
Pu ²⁴⁰	- 5.5
Pu ²⁴¹	- 0.38
Pu ²⁴²	- 0.03

Aluminum

Assumed the same as the Al-1.8 wt% Pu fuel.

* Measured ~March 1959 (Estimated date of Pu separation is ~ Aug. 1957).

FIGURE 3. Fuel Specifications: Al-5.01 wt% Pu

TABLE I

REACTIVITY WORTHS OF A1-Pu FUEL RODS

<u>Fuel Rod Number</u>	<u>Reactivity Worth (mk)</u>	<u>Relative Standard Deviation of a Typical Rod</u>	<u>Relative Standard Deviation of the Average</u>
(A) A1-1.8 wt.% Pu			
J-73	1.112		
LW-141	1.233		
A-15 ^T	1.265		
A-15 ^B	1.284		
LW-157	1.334		
LW-139	1.237		
LW-179	1.239		
LW-113	1.302		
C-14 ^T	1.284		
C-14 ^B	1.259		
Average = $1.271 \pm 0.034^*$		2.7%	0.9%
(B) A1-2.0 wt.% Pu			
125	0.814		
236	0.889		
287	0.746		
495	0.830		
518	0.917		
545	0.821		
608	0.846		
750	0.856		
775	0.911		
883	0.879		
Average = 0.851 ± 0.052		6.1%	2.0
(C) A1-5.0 wt.% Pu			
7B1	2.617		
10C2	2.586		
2A4	2.748		
8A1	2.690		
4C4	2.722		
4C7	2.742		
3D3	2.742		
3D1	2.653		
3C8	2.700		
7B4	2.709		
Average = 2.691 ± 0.056		2.1%	0.7%

* Discarding measurement of J-73

From the results given in Table I it is evident that the Al-2 wt% Pu rods showed larger variations than the other two types, the relative standard deviation being 2-3 times as large for the Al-2 wt% Pu fuel than for the other fuels. One must be careful, however, not to attach too much quantitative significance to the comparative standard deviations, because the reproducibility of the reactivity worth measurements (± 0.04 mk) is of the same order as the measured standard deviations (0.034 - 0.056 mk). Thus the larger variation is indicative of the smaller reactivity values and the reproducibility uncertainty.

III. DESTRUCTIVE MEASUREMENTS

A destructive analysis was performed of one rod of each Al-Pu rod type. The analyses performed were: a chemical and an isotopic analysis for plutonium concentration and composition; an alpha-energy analysis for ^{241}Am content; and a spectro-chemical analysis for detecting impurities (B, Cd, Au). Both the coulometric titration and isotopic dilution methods were used. Samples were taken from the mid-part of each rod and from adjacent positions.

The rods that were destructively analyzed are listed in Table II. The bulk of the rods making up the Al-1.8 wt% Pu lot are of the LW designation. Therefore, LW-139 was selected for destructive analysis as a representative rod of this enrichment. This rod best represented the average of the five LW rods measured. Calculated multiplication factors for lattices of Al-2 wt% Pu rods have always been consistently larger than measured values.⁽²⁾ Therefore, this fuel type has been most suspect, as far as enrichment and impurities are concerned. Rod No. 518 was chosen for examination, for its reactivity worth was the largest of the batch; thus it represents an upper limit of

TABLE II
FUEL RODS SELECTED FOR DESTRUCTIVE ANALYSIS

<u>Rod Number</u>	<u>Type</u>
LW-139	A1-1.8 wt.% Pu
518	A1-2.0 wt.% Pu
7B4	A1-5.0 wt.% Pu
411	UO ₂ -2 wt. % PuO ₂ (23.5% Pu ²⁴⁰)
AB-03	UO ₂ -4 wt.% PuO ₂ (18.1% Pu ²⁴⁰)

enrichment in this fuel type. This rod was further analyzed for rare earth isotopes and for hafnium in the cladding. Rod No. 7B4 was chosen from the Al-5 wt% Pu rods because it is representative of the average of the ten rods of this type.

Two mixed oxide rods were also destructively analyzed, to determine the Pu and ^{241}Am contents. Rod No. 411 was chosen as representative of the UO_2 -2 wt% Pu (24% ^{240}Pu) rods (Figure 4), and rod No. AB-03 was chosen as representative of the UO_2 -4 wt% Pu rods (Figure 5).

The results of the plutonium isotopic analysis are given in Table III, along with the values utilized in earlier studies with these rods.^(1,2) Comparing the values for Pu content obtained in these recent analyses (lines C and D) for the Al-Pu rods it is noted that the results obtained using the isotopic dilution technique are consistently smaller than those obtained using the coulometric titration technique. Since the isotopic dilution technique is the more accurate, these values best represent the amount of Pu in these rods as currently measured.

In the fabrication process for the Al-Pu fuels, usually ~6 batches of alloy were taken from a given melt of aluminum and plutonium. From each batch a long rod was swaged and cut into 4 or 5 individual rods 36 inches long. Thus a total of ~ 38 melts were usually used in making a set of experimental fuel.

At least one chemical analysis for plutonium was made for each batch. If the results were outside of the limit of what was expected, additional analyses were made. Experience has shown that averaging all the analytical results obtained for a given set of fuel rods results in the value specified (within

FUEL RODS

1. ROD DIMENSIONS

2. CLADDING: Zircaloy-2 tubing with plugs seal welded at both ends.
3. TOTAL WEIGHT OF LOADED FUEL RODS: 1340 gms (Average).

FUEL LOADINGS

1. PuO₂ mixed in natural UO₂ and vibrationally compacted.
2. 1128 gms of UO₂-PuO₂ mix/rod.
3. PuO₂ is 2 wt% of total mixture.
4. PuO₂ - 22.56 gms/rod.
5. Pu - 19.85 gms/rod (Average).
6. Natural U.
7. Fuel Density - 9.54 gm/cc (~87% theoretical density).
8. UO₂ Powder at the end of fuel column.
9. Isotopic Composition of Plutonium:

Plutonium - atom %*

71.762	²³⁹ Pu
23.503	²⁴⁰ Pu
4.08	²⁴¹ Pu
0.656	²⁴² Pu

The PuO₂ particles are not spherical. They were passed through a 325 mesh screen. Their "mean diameter" is approximately 25 microns.

* Measured May 1965. Half the Pu was separated chemically in April, 1963, the other half in August, 1964. (Effective avg Oct. 1963).

FIGURE 4. Fuel Specifications: UO₂-2 wt% PuO₂

FUEL RODS

1. ROD DIMENSIONS

2. CLADDING: Zircaloy-2 tubing with plugs seal welded at both ends.
3. TOTAL WEIGHT OF LOADED FUEL RODS: 1327 gms (Average).

FUEL LOADINGS

1. PuO₂ mixed in natural UO₂ and vibrationally compacted.
2. 1084.5 gm of mix/rod.
3. Chemical composition wt%: Pu/PuO₂ = 88.1 U/UO₂ = 88.0
Pu/mix = 3.506.
4. PuO₂ is 3.98 wt% of total mixture.
5. Fuel density = 9.46 gm/cc (~86% theoretical density).
6. UO₂ powder at the end of each fuel column.
7. Isotopic composition:

Plutonium - atom %*

0.28	²³⁸ Pu
75.38	²³⁹ Pu
18.10	²⁴⁰ Pu
5.08	²⁴¹ Pu
1.15	²⁴² Pu

The PuO₂ particles are not spherical. They were passed through a 325 mesh screen. Their "mean diameter" is approximately 25 microns.

* These isotopics were measured June, 1967. The Pu was made into a metal May, 1967. (Estimated date of Pu separation is Jan. 1967).

FIGURE 5. Fuel Specifications: UO₂-4 wt% PuO₂

TABLE III
FUEL ROD ANALYSIS RESULTS

				Plutonium						
UO ₂ - PuO ₂ or Al ₂ - Pu (gms)	PuO ₂ gms ²	PuO ₂ wt.%	Weight		Isotopics (wt.%)					
			gms	%	238	239	240	241	242	
LW-139 (Al-1.8 wt.% Pu										
A	389.32		6.83				6.0			
B			7.12	1.83		93.97	5.58	0.44	0.014	
C				2.0	0.013	93.37	6.26	0.328	0.022	
D				1.806	0.0086	93.40	6.26	0.316	0.019	
518 (Al-2.0 wt.% Pu										
A	318.8		6.60	2.07						
B	318.19		6.383	2.01		81.01	16.46	2.31	0.20	
C				2.1	0.016	81.45	16.72	1.608	0.205	
D				2.038	0.0150	81.55	16.66	1.56	0.205	
7B4 (Al-5.0 wt.% Pu										
A	218.3		10.89	4.99						
B	219.94		11.01	5.01		94.09	5.33	0.55	0.03	
C				5.0	0.0075	94.37	5.38	0.226	0.013	
D				4.942	0.008	94.39	5.38	0.220	0.013	
411										
A	1128.0	22.56	2.0	19.85	1.76					
B	1128.0	22.56	2.0			71.76	23.50	4.08	0.66	
C			2.16		1.9					
AB-03										
A	1079.0 ⁽¹⁾	43.20	4.0	38.02	3.52					
B	1084.54 ⁽²⁾	43.20	4.0			0.28	75.38	18.10	5.08	1.15
C			4.25		3.8					

- A The initial analysis supplied with the fuel.
 B Values reported in Reference 1 which are average.
 C Results from this analysis using coulometric method.
 D Results from this analysis using isotopic dilution method.

(1) This rod is less dense than average. The ratio Pu/(UO₂-PuO₂) is same for all rods.

(2) This includes 4.54 gms UO₂ toppings - it does not affect the Pu/(UO₂-PuO₂) ratio.

the standard deviation) when the alloy was mixed even though individual values were much different. Thus it had been concluded that the alloys could be mixed more accurately than an individual melt could be measured. This is corroborated in Table III where the current, more accurate measurements of plutonium content agree with the previously reported values, which were averages, better than with the value reported for the individual rod.

The amount of ^{241}Am found in each rod is given in Table IV. Assuming a 14.5 year half life for ^{241}Pu decay, the amount of ^{241}Am present is consistent with the amount of ^{241}Pu which has disappeared.

These measurements of the ^{241}Am content are the only ones ever made on these fuels. These measurements were made in March 1970. It is important to know this date so that corrections for ^{241}Am content can be calculated for various experiments in which these fuels were utilized over the years. A list of experiments, dates, and ^{241}Am and ^{241}Pu concentrations is given in an appendix to this report.

The analysis for impurities included a search for Cd, Sm, Gd, and Eu down to the limit of detection, which is a concentration of 2 wppm. No impurities were found.

IV. AXIAL UNIFORMITY

The axial uniformity of the fuel rods can be inferred to some extent from the results obtained from gamma scanning the unirradiated rods in three positions, the middle and one inch from each end of the fuel meat. A typical spectrum obtained from the scan is shown in Figure 6. Spectra were obtained from three rods selected from each of the three types of Al-Pu fuel using a Ge-Li detector. The energy per channel is 1/2 keV and the total energy

TABLE IV

 ^{241}Am CONTENT OF FUEL RODS, MEASURED MARCH 1970

<u>Rod Type</u>	<u>Fuel Diam. (inches)</u>	<u>Fuel Length (inches)</u>	<u>UO₂-PuO₂ or Al-Pu (grams/rod)</u>	<u>$^{241}\text{Am}^*$ (grams/rod)</u>
Al-1.83 wt% Pu	0.500	43.83	389.3	0.0152
Al-2.0 wt% Pu	0.500	36.0	318.2	0.0552
Al-5.0 wt% Pu	0.500	24.0	219.9	0.0203
UO ₂ -2.0 wt% Pu (23.5% ^{240}Pu)	0.505	36.0	1128.0	0.229
UO ₂ -4.0 wt% PuO ₂	0.4975	36.0	1084.5	0.279

* The uncertainty on these measurements is $\sim \pm 2\%$.

FIGURE 6. Gamma Spectrum From the Mid Point of Fuel Rod 7B1
(A1-5 wt% Pu)

span studied is 250 KeV. Peak 1 (59.5 keV) is primarily from ^{241}Am and peak 2 (129.3 keV) from ^{239}Pu . The spectra collected were least squares fitted using the GSSLRN-I code⁽³⁾ to obtain the areas under the peaks and derive the intensities. The data presented in Table V are the ratios of activities corrected for background, obtained by dividing the results from each end of the rods by that from the center. The errors on these ratios are determined by the counting statistics as represented by the accumulated count in each channel of the analyzer used to obtain the spectrum of the gamma activity. The largest errors for the ratios of peak 1 and 2 are ± 0.4 and 2.0% respectively.

The results shown in Table V would seem to indicate that variations in enrichment are present, particularly for the ratio of activities, top/middle for one rod of the A1-5 wt% Pu fuel. If these values truly represent variations in Pu, this may contribute to discrepancies between measured and calculated k_{eff} values, because one assumes uniform enrichment in the calculations. Very clearly, this question requires a more extensive analysis. However, these potential variations are not sufficient to cause the total worth to be significantly different from the average to be measurable in the reactivity comparisons.

V. CONCLUSIONS

Results and conclusions obtained in this study are:

- On the basis of this study it appears that the average plutonium enrichments used in the past (e.g., BNWL-801) for these fuels are valid.
- The ^{241}Am content of these fuels was measured in March 1970. The results are listed in Table IV. These measured values can be used for

TABLE V

RATIO OF GAMMA ACTIVITIES OF SELECTED FUEL RODS

<u>Fuel Type</u>	<u>Rod Number</u>	<u>Peak 1⁽¹⁾</u>		<u>Peak 2</u>	
		<u>Bottom⁽²⁾</u> <u>Middle</u>	<u>Top</u> <u>Middle</u>	<u>Bottom</u> <u>Middle</u>	<u>Top</u> <u>Middle</u>
Al-5 wt% Pu	7B1	1.045	0.820	1.040	0.776
	8A1	1.002	1.009	1.003	1.007
	10C2	0.9982	1.001	0.999	0.991
Al-1.8 wt% Pu	LW-179	1.008	0.9841	1.006	0.978
	J-73	1.001	0.9830	0.9906	0.9956
	A-15	0.9981	1.003	0.998	1.000
Al-2 wt% Pu	125	0.978	1.008	1.034	1.038
	287	0.997	0.951	0.993	0.973
	775	1.003	1.004	1.006	1.053

(1) The energies of the major gamma in peak 1 and 2 are 59.6 and 129.3 keV respectively.

(2) The bottom is a position 1 inch from the end of the fuel meat at the end opposite the numbered end. The top is 1 inch from the end of the fuel meat on the opposite end.

determining the ^{241}Am content for experiments conducted with these fuels over the years.

- See Appendix for list of critical experiments, dates, ^{241}Am and ^{241}Pu concentrations.

- The rod-to-rod uniformity of each of the three types of Al-Pu rods is indicated by the results of the reactivity measurements given in Table I. The Al-2 wt% Pu rods showed rather large variations, the standard deviation being 2-3 times as large for this fuel type as for the other fuel types.

- None of the impurities searched for were detected in the Al-Pu rods (down to a detection limit of 2 wppm).

- The axial uniformity measurements indicated some variations in enrichment might be present axially, but no conclusive statements can be made because the study was very limited.

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APPENDIX

APPENDIX

In this Appendix we present a list of the H₂O-moderated lattice experiments measured at PNL over the years. The date (month and year) of the experiment and the ²⁴¹Am and ²⁴¹Pu concentrations are given for each lattice. The ²⁴¹Am and ²⁴¹Pu concentrations were determined on the basis of recent ²⁴¹Am measurements (March 1970) performed for several of the fuel types, and earlier isotopic measurements. A half-life of 14.5 years was assumed for ²⁴¹Pu. For some of the fuel materials no measurements of the ²⁴¹Am content have been made. In these cases the amount of ²⁴¹Pu originally in the plutonium was relatively small. Records were examined for these fuels as far back as practicable and best estimates were made of the original date of chemical separation of the plutonium.

Previous reports on these experiments have ignored the decay of ²⁴¹Pu to ²⁴¹Am. The results reported here can be used for more exact calculations of these experiments.

In addition to the specific experiments listed here, these fuel rods have also been used in other experiments. A series of experiments was performed with the UO₂-2 wt% PuO₂ fuel between June and November, 1966; these experiments were reported by Uotinen and Williams in BNWL-SA-1107 and in Trans. Am. Nucl. Soc., Vol. 10, No. 1, p. 186; they are also mentioned in BNWL-801.

Another extensive series of experiments using UO₂-PuO₂ fuels was the joint BNW-CNEN (Italian) program reported by Loizzo et al. in BNWL-1379; these experiments were performed between November 1967 and June 1968. If anyone desires specific dates for specific experiments conducted under these programs, or for other experiments performed over the years, these can be supplied.

Al-1.8 wt% Pu

^{241}Pu measured ~ March, 1961 to be 5.55×10^{-7} nuclei/bn-cm ($\pm \sim 5\%$)

^{241}Am measured in 3/70 to be 2.69×10^{-7} nuclei/bn-cm ($\pm \sim 2\%$)

Estimated date of Pu separation is ~ 9/58.

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>Nuclei/bn-cm</u>	
		<u>^{241}Pu</u>	<u>^{241}Am</u>
0.75	1/62	5.46×10^{-7}	0.84×10^{-7}
0.80	4/62	5.39×10^{-7}	0.91×10^{-7}
0.85	2/62	5.44×10^{-7}	0.86×10^{-7}
0.90	3/62	5.42×10^{-7}	0.88×10^{-7}
0.95	3/62	5.42×10^{-7}	0.88×10^{-7}

*References: HW-74190 (1962)

BNWL-801 (1968)

A1-2 wt% Pu

^{241}Pu measured 10/61 to be 3.18×10^{-6} nuclei/bn-cm ($\pm \sim 5\%$)

^{241}Am measured 3/70 to be 1.19×10^{-6} nuclei/bn-cm ($\pm \sim 2\%$)

Estimated date of Pu separation is 12/60.

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>^{241}Pu</u>	<u>^{241}Am</u>
0.75	4/63	2.97×10^{-6}	0.35×10^{-6}
0.80	9/63	2.91×10^{-6}	0.41×10^{-6}
0.85	8/63	2.92×10^{-6}	0.40×10^{-6}
0.90	9/63	2.91×10^{-6}	0.41×10^{-6}
0.95	9/63	2.91×10^{-6}	0.41×10^{-6}

*References: HW-79054 (1963)

BNWL-801 (1968)

Al-5 wt% Pu

^{241}Pu measured ~ March 1959 to be 1.35×10^{-6} nuclei/bn-cm ($\pm \sim 5\%$)

^{241}Am measured 3/70 to be 6.57×10^{-7} nuclei/bn-cm ($\pm \sim 2\%$)

Estimated date of Pu separation is ~ August 1957.

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>Nuclei/bn-cm</u>	
		<u>^{241}Pu</u>	<u>^{241}Am</u>
0.85	2/68	0.88×10^{-6}	0.58×10^{-6}
1.05	2/68	0.88×10^{-6}	0.58×10^{-6}
1.30	2/68	0.88×10^{-6}	0.58×10^{-6}
(borated) 1.05 (48 wppm)	2/68	0.88×10^{-6}	0.58×10^{-6}
1.05 (101 wppm)	3/68	0.88×10^{-6}	0.58×10^{-6}
1.05 (164 wppm)	3/68	0.88×10^{-6}	0.58×10^{-6}
1.05 (229 wppm)	3/68	0.88×10^{-6}	0.58×10^{-6}
1.05 (285 wppm)	3/68	0.88×10^{-6}	0.58×10^{-6}

*References: BNWL-907 (1968)

Note: Some earlier experiments were performed with these rods in the latter part of 1959. (HW-70944 (1961)).

UO₂-4 wt% PuO₂

²⁴¹Pu measured 6/67 to be 4.22×10^{-5} nuclei/bn-cm ($\pm \sim 5\%$)

²⁴¹Am measured 3/70 to be 6.08×10^{-6} nuclei/bn-cm ($\pm \sim 2\%$)

Estimated date of Pu separation is 1/67

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>Nuclei/bn-cm</u>	
		<u>²⁴¹Pu</u>	<u>²⁴¹Am</u>
0.80	12/67	4.12×10^{-5}	0.19×10^{-5}
0.85	10/68	3.96×10^{-5}	0.35×10^{-5}
0.93	11/68	3.95×10^{-5}	0.36×10^{-5}
1.05	11/68	3.95×10^{-5}	0.36×10^{-5}
1.143	10/68	3.96×10^{-5}	0.35×10^{-5}
1.386	2/68	4.09×10^{-5}	0.22×10^{-5}
1.60	2/68	4.09×10^{-5}	0.22×10^{-5}
1.70	11/68	3.95×10^{-5}	0.36×10^{-5}

*References: BNWL-739 (1968)

^{241}Pu measured ~ June 1962 to be 2.31×10^{-6} nuclei/bn-cm ($\pm \sim 5\%$)

The estimated average date of separation is also June 1962.

Hexagonal Pitch (in.)	Date of Experiment*	Nuclei/bn-cm	
		^{241}Pu	^{241}Am
0.55	7/64	2.09×10^{-6}	0.22×10^{-6}
0.60	5/64	2.11×10^{-6}	0.20×10^{-6}
0.71	3/64	2.12×10^{-6}	0.19×10^{-6}
0.80	3/64	2.12×10^{-6}	0.19×10^{-6}
0.90	3/64	2.12×10^{-6}	0.19×10^{-6}
0.93	5/64	2.11×10^{-6}	0.20×10^{-6}

*References: Trans. Am. Nucl. Soc., 7, 216 (1964)

BNWL-801 (1968)

²⁴¹Pu measured 5/65 to be 1.72×10^{-5} nuclei/bn-cm ($\pm \sim 5\%$)

²⁴¹Am measured 3/70 to be 4.89×10^{-6} nuclei/bn-cm ($\pm \sim 2\%$)

Pu separation date is 10/63. (This is an effective average date for this plutonium which was from two sources, one separated in 1963, the other in 1964.)

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>Nuclei/bn-cm</u>	
		<u>²⁴¹Pu</u>	<u>²⁴¹Am</u>
0.80	9/65	1.69×10^{-5}	0.16×10^{-5}
0.93	7/65	1.71×10^{-5}	0.14×10^{-5}
1.05	11/65	1.68×10^{-5}	0.17×10^{-5}
1.143	3/66	1.65×10^{-5}	0.20×10^{-5}
1.32	2/66	1.66×10^{-5}	0.19×10^{-5}
1.386	7/65	1.71×10^{-5}	0.14×10^{-5}

*References: Trans. Am. Nucl. Soc., 9, 127 (1966)

BNWL-624 (1968)

BNWL-801 (1968)

²⁴¹Pu measured 12/61 to be 9.05×10^{-6} nuclei/bn-cm (± ~5%)

12/61 is also the estimated date of separation for the plutonium .

<u>Hexagonal Pitch (in.)</u>	<u>Date of Experiment*</u>	<u>Nuclei/bn-cm</u>	
		<u>²⁴¹Pu</u>	<u>²⁴¹Am</u>
0.93	6/65	7.66×10^{-6}	1.39×10^{-6}
1.05	11/65	7.50×10^{-6}	1.55×10^{-6}
1.143	3/66	7.38×10^{-6}	1.67×10^{-6}
1.32	3/66	7.62×10^{-6}	1.43×10^{-6}

*References: Trans. Am. Nucl. Soc., 9, 127 (1966)

BNWL-624 (1968)

BNWL-801 (1968)

^{241}Pu measured 1/65 to be 2.95×10^{-6} nuclei/bn-cm. ($\pm \sim 5\%$)

The plutonium was from several batches with dates of separation from 1/61 to 4/64. More than 80% of the total Pu in these rods was separated between 12/61 and 9/62. An estimated "effective average" time of separation is 4/62.

Hexagonal Pitch (in.)	Date of Experiment*	Nuclei/bn-cm	
		^{241}Pu	^{241}Am
0.80	12/65	2.82×10^{-6}	0.54×10^{-6}
0.93	6/65	2.89×10^{-6}	0.47×10^{-6}
1.05	11/65	2.84×10^{-6}	0.52×10^{-6}
1.143	5/65	2.90×10^{-6}	0.46×10^{-6}
1.32	6/65	2.89×10^{-6}	0.47×10^{-6}
1.386	8/65	2.87×10^{-6}	0.49×10^{-6}
1.6107	9/65	2.86×10^{-6}	0.50×10^{-6}

*References: Trans. Am. Nucl. Soc., 9, 127 (1966)

BNWL-624 (1968)

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