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AEC
RESEARCH
and
DEVELOPMENT
REPORT

PLUTONIUM METALLURGY NOTEBOOK

Compiled by M.E. Hasbrouck

Edited by M.P. Burns

September, 1965

BATTELLE-NORTHWEST

BATTELLE MEMORIAL INSTITUTE / PACIFIC NORTHWEST LABORATORY

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Technical Information Section
Technical and Public Services Department

September, 1965

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

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INTRODUCTION

This report is a compilation of data on the structure and properties of plutonium and its alloys. Included are phase diagrams, crystal structure data, transformation kinetics, physical and mechanical properties, corrosion and corrosive properties, and radiation effects information.

The data were obtained from reports, books, and journals. When results reported by two or more laboratories differed, the most recent data from each laboratory were included. Tentative or uncertain results were included only if later, more positive information was not available. The information is current to September, 1964.

The report is divided into three major sections. The first section presents data for unalloyed plutonium. In the second section, the binary alloys of plutonium are arranged alphabetically by the symbol for the alloying element. The third section consists of information on ternary alloys.

The properties for each material are arranged in a standard order with a number for each property, as shown in the outline on the following pages. In the sections on alloys, the number is preceded by the symbol of the alloying element. For example, the marginal heading 202.1 represents thermal expansion of plutonium, Al 202.1 represents thermal expansion of aluminum-plutonium alloys. The absence of a particular outline topic for a material indicates that no information was found on the subject.

Supplements to this report will be issued periodically. Within two years, a new edition will be issued, together with a volume on the properties of plutonium ceramics. The editor will welcome any suggestions of additions or changes.

GENERAL OUTLINE

PART I. PLUTONIUM

PART II. BINARY ALLOYS

Ag
Al
Au
Be
etc.

PART III. TERNARY ALLOYS

General subject outline for use under PLUTONIUM and each alloy:

100 Structural Properties
200 Physical Properties
300 Mechanical Properties
400 Corrosion
500 Corrosive Properties
600 Radiation Effects

The subdivisions under each of these main headings are given in the detailed outline which follows. This detailed outline will also be used under each alloy, with the chemical symbol of the alloying element and the outline number appearing in the margin. For example, information on the density of aluminum-plutonium alloys will be found under the marginal heading Al 201.

DETAILED OUTLINE

100 Structural Properties

- 101 Phase diagrams
- 102 Transformation kinetics
- 103 Crystal structure
- 104 Stability of the various phases
- 105 Recrystallization and grain growth
- 106 Diffusion

200 Physical Properties

- 201 Density
- 202 Thermal properties (See also Transformation Kinetics)
 - 202.1 Thermal expansion
 - 202.2 Thermal conductivity
 - 202.3 Specific heat and heat capacity
 - 202.4 Entropy
 - 202.5 Temperature of and volume change during transition
 - 202.6 Heats of transition

203 Electrical properties

- 203.1 Electrical conductivity
- 203.2 Superconductivity
- 203.3 Thermoelectric power

204 Magnetic properties

- 204.1 Magnetic susceptibility
- 204.2 Hall effect

205 Optical, thermionic and electronic properties

- 205.1 Emissivity

206 Viscosity

300 Mechanical Properties

- 301 Tensile properties
- 302 Compressive properties
- 303 Torsional and shear properties
- 304 Impact strength
- 305 Creep
- 306 Fatigue
- 307 Hardness

308 Elastic properties

- 308.1 Young's modulus
- 308.2 Shear modulus
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400 Corrosion

401 Reactions with gases

- 401.1 Air
- 401.2 Oxygen
- 401.3 Hydrogen
- 401.4 Inert gases

402 Aqueous corrosion

- 402.1 Water and steam
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- 402.3 Alkaline solutions

403 Organic compounds

404 Reactions with liquid metals

405 Properties of corrosion films

500 Corrosive Properties

600 Radiation Effects

601 Structure

602 Physical properties

603 Mechanical properties

PLUTONIUM METALLURGY NOTEBOOK

PART I PLUTONIUM

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The Phase Diagram of Plutonium. From D. R. Stephens, *J. Phys. Chem. Solids*, vol. 24, p. 1200, 1963.

TRIPLE POINTS AND INITIAL TRANSITION SLOPES

From D. R. Stephens, *J. Phys. Chem. Solids*, vol. 24, p. 1201, 1963.

Triple Point	Experimental Values	Predicted by R. G. Loasby, in <i>Plutonium</i> 1960, p. 97, 1961.
$\gamma - \delta - \epsilon$	$398 \pm 10^\circ\text{C}$ $0.9 \pm 0.2 \text{ kbar}$	374°C 0.69 kbar
$\gamma - \epsilon - \text{liquid}$	$518 \pm 10^\circ\text{C}$ $19.5 \pm 1 \text{ kbar}$	
$\delta - \gamma - \text{liquid}$	$500 \pm 10^\circ\text{C}$ $27.0 \pm 1 \text{ kbar}$	
Transition	Initial Slope of Transition Lines, $^\circ\text{C}/\text{kbar}$	
	Experimental Slope	Predicted by R. G. Loasby
$\alpha - \delta$	11.2	13.1
$\delta - \gamma$	27.3	38
$\gamma - \epsilon$	88	95
$\delta - \epsilon$	-87	-190
$\epsilon - \text{liquid}$	-4.4	-26

Derived Phase Diagram for Plutonium.
From R. G. Loasby, *Plutonium* 1960, p. 102.

PHASE DIAGRAM DATA
From R. G. Loasby, Plutonium 1960, p. 101.

Phase Change	dP/dt , atm/°C	dT/dP , °C/bar 10^2
$\alpha - \beta$	77.5	1.31
$\beta - \gamma$	27.0	3.8
$\gamma - \delta$	10.7	9.5
$\delta - \delta'$	-5.3	-19.0
$\delta' - \epsilon$	-5.8	-17.0
ϵ - liquid	39.6	-2.6
$\gamma - \delta'$	11.1	9.1
$\gamma - \epsilon$	70.5	1.4
$\beta - \epsilon$	44.7	2.3
β - liquid	91.6	1.1

TRIPLE POINTS
From R. G. Loasby, Plutonium 1960, p. 101.

Bounding Phases	Pressure, atm	Temperature, °K
$\gamma - \delta - \delta'$	500	635
$\gamma - \delta - \epsilon$	690	647
$\beta - \gamma - \epsilon$	6750	735
$\beta - \epsilon$ - liquid	6850	737

Limiting Cases for the Effect of Alloying Elements on the $\delta - \delta'$ Transition in Plutonium.
In (a) above the impurity addition does not affect the lower limit of the pure δ region, whereas in (b) the pure δ region is effectively eliminated by the addition.
From R. G. Cope, *Nature*, vol. 186, p. 540. 1960.

PHASE TRANSFORMATION DATA FOR PLUTONIUM METAL (99.95-99.96 WT. % Pu)

Transformation	Temperature, °C				Volume Change		
	Dilatometer (1)	Thermal Analysis (2)	Resistance Measurements		Inch/Inch of Length At Temperature ($\times 10^4$) (1)	% (2)	% (4)
			Specimen 1	Specimen 2 (3)			
$\alpha \rightarrow \beta$	122(+1, -2)	122 ± 2	123.9 ± 0.2	123.3 ± 0.1	288(+25, -36)	8.9	8.9-11.3
$\beta \rightarrow \gamma$	206(-3, -2)	203	205.5-226.1	201.6 ± 0.2	78(+6, -11)	2.4	2.3-2.77
$\gamma \rightarrow \delta$	319(+6, -3)	317	319.6 ± 0.5	317.0 ± 0.5	205(+22, -11)	6.8	6.7-6.8
$\delta \rightarrow \delta'$	451(+4, -2)	453	454.4-458.6	456.1 ± 1.0	-12(+7, -5)	-0.1	-0.1-0.4
$\delta' \rightarrow \epsilon$	476(+3, -5)	478	480.6-486.8	480.1-487.5	-126(+10, -12)	-3.0	-3.0
$\epsilon \rightarrow \text{liquid}$		639.5 ± 2					~ 0.1

(1) From E. M. Cramer et al. in The Metal Plutonium, p. 119.

(2) From E. R. Jette in Nuclear Metallurgy, p. 35.

(3) From T. A. Sandenaw and R. B. Gibney, J. Phys. Chem. Solids, vol. 6, p. 86, 1958.

(4) From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 20.

PHASE-TRANSFORMATION TEMPERATURES FOR ZONE-MELTED PLUTONIUM (ABOUT 99.8 AT. % Pu, 250 PPM TOTAL IMPURITIES)

From M. B. Waldron et al. p/71, Proc. Second Geneva Internat. Conf., vol. 6, p. 162, 1958.

Transformation	Temperature, °C			
	Thermal Analysis		Dilatometry	
	Heating, °C	Cooling, °C	Heating	
	Rate	Rate		
	1°C/min	4°C/min		
Alpha to beta	126 ± 2	142 ± 5	Not determined	133 ± 2
Beta to gamma	209 ± 3	238 ± 5	ca. 150	208 ± 2
Gamma to delta	316 ± 2	325 ± 5	ca. 230	306 ± 2
Delta to delta-prime	456 ± 5	451 ± 5	Not certain	460 ± 2
Delta-prime to epsilon	484 ± 2	481 ± 5	487 ± 2	476 ± 2
Epsilon to liquid	641 ± 2		637 ± 2	≥ 634 ± 5

TRANSITION TEMPERATURES (POSSIBLE ERROR ±5°)

DILATOMETRY, 99.99 WT. % Pu.

From R. Abramson et al. p/327, Proc. Second Geneva Internat. Conf., vol. 6, p. 175, 1958.

Heating		Cooling	
$\alpha \rightarrow \beta$	125°C	$\epsilon \rightarrow \delta'$	493°C
$\beta \rightarrow \gamma$	213°C	$\delta' \rightarrow \delta$	469°C
$\gamma \rightarrow \delta$	314°C	elbow at δ	291°C
$\delta \rightarrow \delta'$	464°C	$\delta \rightarrow \gamma$	beginning 262°C
$\delta' \rightarrow \epsilon$	485°C	$\beta \rightarrow \alpha$	beginning 91°C

TEMPERATURES OF PHASE TRANSITIONS

From S. T. Konobeevsky et al. p/2230, Proc. Second Geneva Internat. Conf., vol. 6, p. 194, 1958.

Transition	Temperature, °C	
Alpha - beta	122	
Beta - gamma	211	
Gamma - delta	315	
Delta - delta-prime	140	
Delta-prime - epsilon	460	
Epsilon - liquid	635	

DELTA/DELTA-PRIME AND DELTA-PRIME/EPSILON TRANSITION

TEMPERATURES OF PLUTONIUM ON HEATING (IN °C)

From R. O. Elliott and A. C. Larson in The Metal Plutonium, p. 277.

Total Impurities (Loss O ₂) In Wt. ppm	Ordinary Purity				High-Purity			
	J-1352-53		J-3015		J-3037		KJ-329	
	<382		<386		<719		<221	
Transformation	Start	End	Start	End	Start	End	Start	End
$\delta \rightarrow \epsilon$	437		437		425		452 ± 2	452 ± 2
$\delta \rightarrow \delta'$	455	460	454	?	455	459	471	480 ± 2
$\delta' \rightarrow \epsilon$		<482		476		479		

A small proportion of epsilon phase formed in the ordinary-purity metals at temperatures 20-30°C below the delta/delta-prime transition temperature. This epsilon coexisted with delta up to the delta/delta-prime transition, after which it coexisted with delta-prime. The amount of epsilon appeared to increase slightly as the temperature was raised, but the main, rapid delta-prime/epsilon transition did not occur much below 480°C.

In high-purity plutonium, delta transformed isothermally to delta-prime at 452 ± 2°C. With continued heating, a small amount of delta-prime was next observed to change to epsilon near 474°C, and this phase mixture remained unchanged to 480 ± 2°C, where the delta-prime/epsilon transition took place rapidly.

Detail of the α - β Transformation in Plutonium. From R. G. Loasby, Plutonium 1960, p. 100

Detail of the ϵ -Liquid Transformation in Plutonium. From R. G. Loasby, Plutonium 1960, p. 101.

$\alpha \rightleftharpoons \beta$ "Maximum Rate" Study. From J. D. Hill, *Nature*, vol. 186, p. 305, 1960.

$\beta \rightleftharpoons \gamma$ "Maximum Rate" Study, including Results by Nelson. From J. D. Hill, *Nature*, vol. 186, p. 305, 1960.

From J. D. Hill, *Less-Common Metals*, vol. 4, p. 381. 1962.
R. D. Nelson, as shown in J. D. Hill, AERE-R-3568.

THE α - δ TRANSFORMATION IN PLUTONIUM. From W. M. Lomer, *Solid State Commun.*, vol. 1, p. 96. 1963.

The α - δ phase transformation in Pu 5% Ce seems to be martensitic. A correspondence matrix is proposed which relates the lattices and accounts for most of the atomic positions.

It has been suggested that the α phase of Pu is in some way particularly closely associated with the δ phase. It is pointed out that the general form of the resistivity-temperature curve is similar in the two phases, and that in the 5% Ce Pu alloy a reversible transformation takes place at temperatures well below room temperature, where presumably atomic mobilities are so small that only a shear (martensitic) transformation seems admissible. There is, however, no direct microscopic evidence for this mechanism.

The details of such a transformation must be discussed in two stages; first a "correspondence" relation between the two lattices must be found. This relationship identifies that block of primitive unit cells of the simpler lattice which is to be deformed slightly to make a single unit cell of the complex lattice. Then secondly the macroscopic deformation required to bring this block to the correct dimensions must be evaluated, and microscopically inhomogeneous deformations discovered to accommodate these strains in a constrained crystal. This stage of the argument is very difficult indeed to carry through even when good metallographic studies are available for guidance. This is not yet the case for Pu.

An apparently satisfactory correspondence matrix has, however, been discovered. The δ lattice is referred to the cube axes, the cube edge ($a_0 = 4.637$ Å) being defined as unity. The monoclinic α lattice is taken with conventional parameters

$$a = 6.182 \text{ Å}; b = 4.826 \text{ Å}; c = 10.956 \text{ Å}; \beta = 101.7^\circ;$$

the unit cell contains 16 atoms, and is therefore constructed from four unit cells of the face-centered cubic lattice. The correspondence proposed is

$$M = \begin{pmatrix} -1 & -1 & 0 \\ 0 & 0 & 1 \\ 3/2 & -5/2 & 0 \end{pmatrix} \quad M^{-1} = \begin{pmatrix} -5/8 & 0 & 1/4 \\ -3/8 & 0 & -1/4 \\ 0 & 1 & 0 \end{pmatrix}$$

The rows of M give the vectors in the δ lattice from which the a , b , and c vectors are derived. The determinant of M is four, as required by the number of atoms per unit cell.

The parameters of the pseudo α cell defined by M in an undistorted δ lattice are

$$a = \sqrt{2}a_0, \quad b = a_0, \quad c = \sqrt{17/2}a_0, \quad \beta = \cos^{-1}(-1/\sqrt{17}).$$

Numerically these values are

$$a = 6.557, \quad b = 4.637, \quad c = 13.52, \quad \beta = 104.1^\circ$$

Conversely the α cell is transformed by the correspondence matrix into a pseudo-cubic cell of dimensions

$$x = 4.259, \quad y = 3.931, \quad z = 4.826, \quad \gamma = 82.06$$

Such a cell would have been produced by a strain matrix ϵ acting on the δ lattice where ϵ is the matrix

$$\epsilon = \begin{pmatrix} -0.084 & 0.061 & 0 \\ 0.061 & -0.154 & 0 \\ 0 & 0 & 0.041 \end{pmatrix}$$

The detailed atomic positions in α Pu of course differ from the ideal ones which would be derived from the homogeneously-distorted f.c.c. lattice. We list below the ideal values and observed values for the 16 atoms in the structure, referred to the center of symmetry as origin. This center is midway between two atoms of the f.c.c. lattice at $(0, 3/4, -1/4)\delta = (-9/32, -1/4, -3/16)\alpha = (-0.281, 0.25, 0.187)\alpha$.

The remaining atoms are at the positions given by reflection in the origin. It will be seen that all the atom movements are small - only the second atom listed is displaced by as much as 1 Å ($= 0.1 c$ or $0.25 a$).

This listing sequence has been chosen to emphasize the well-marked rows of atoms along the (102) direction in the α structure, which are derived from the $(1\bar{1}0)$ δ rows.

Ideal			Ideal Referred to C. o S			Actual		
0	0	0	0.281	0.25	0.187	0.332	0.25	0.152
7/8	0	1/4	0.156	0.25	0.437	0.138	0.25	0.337
3/4	0	1/2	0.031	0.25	0.687	0.013	0.25	0.617
5/8	0	3/4	0.906	0.25	0.937	0.885	0.15	0.897
1/2	0	0	0.781	0.25	0.187	0.767	0.25	0.167
3/8	0	1/4	0.656	0.25	0.437	0.651	0.25	0.456
1/4	0	1/2	0.531	0.25	0.617	0.459	0.25	0.642
1/8	0	3/4	0.406	0.25	0.937	0.335	0.25	0.924

HIGH TEMPERATURE OXIDATION OF PLUTONIUM. From J. T. Waber, *Metallurgy and Fuels*, series V, vol. 4, p. 890.

Plutonium is not very reactive towards nitrogen. For example, plutonium, after being melted in a nitrogen atmosphere and held for several hours at 100°C, contained only a few nitride dendrites near the surface. Thus the high temperature properties in air can be reduced to the behaviour towards pure oxygen at equivalent temperatures.

The oxidation of plutonium in pure oxygen in the range between 315 and 400°C has been studied manometrically. Specimens made from 0.020 in. ribbon were oxidized to completion in about 20 min. at 343°C and in about 6 min. at 400°C. Time dependences greater than one were observed; thus the reaction may be regarded as accelerating in this temperature range. The acceleration is undoubtedly due to the spallation of the oxide during the run. In contrast, the reaction rate decreases with time at 315° to 325°C and possibly at lower temperatures. The reactions went to completion on 0.020 in. sheet in a little over an hour at these temperatures.

A 10 wt.% plutonium alloy in aluminum which consists of the intermetallic compound PuAl_4 dispersed in a matrix of aluminum, was held one week at 400°C in pure oxygen. The pick-up of oxygen was barely detectable by the manometric method employed for the oxidation of pure plutonium. An upper limit on the amount of oxide formed is 8μ . An X-ray diffraction study of the oxidized surface showed only a weak pattern of Al_2O_3 and the patterns of the underlying alloy phases but no PuO_2 . Comparison with the rate of oxidation of pure aluminum suggests that plutonium may slightly reduce the protection afforded aluminum by its oxide.

Isothermal Reaction Curves of the Transformation of Beta Plutonium Showing the Weight Change as a Function of Time. From R. D. Nelson, Trans. Am. Soc. Metals, vol. 51, p. 679. 1959.

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Crystal Structure

CELL DIMENSIONS (Å) AND CALCULATED DENSITIES, (g cm^{-3})

99.9% Pure Plutonium of Isotopic Composition
Corresponding to Atomic Weight 239.05.

From W. H. Zachariasen and F. H. Ellinger,
Acta Cryst., vol. 16, p. 780, 1963.

	21 °C	51 °C	96 °C	104 °C
a	6.183 ± 0.001	6.194	6.211	6.214
b	4.822 ± 0.001	4.831	4.847	4.852
c	10.963 ± 0.001	10.973	10.987	10.989
ρ	101.79 ± 0.01°	101.78°	101.77°	101.75°
ρ	19.86 ± 0.01	19.77	19.62	19.59

The space group is $P2_1/m$. All atoms are in the reflection planes with coordinates $\pm(x, 1/4, z)$. There are 16 atoms per unit cell.

POSITION PARAMETERS FROM LEAST-SQUARE REFINEMENT

From W. H. Zachariasen and F. H. Ellinger,
Acta Cryst., vol. 16, p. 782, 1963.

Atom Type	x	z
I	0.345 ± 0.004	0.162 ± 0.002
II	0.767 ± 0.004	0.168 ± 0.002
III	0.128 ± 0.004	0.340 ± 0.003
IV	0.657 ± 0.005	0.457 ± 0.003
V	0.025 ± 0.005	0.618 ± 0.003
VI	0.473 ± 0.004	0.653 ± 0.002
VII	0.328 ± 0.004	0.926 ± 0.002
VIII	0.869 ± 0.004	0.894 ± 0.002

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol.16, p. 783, 1963.

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol.16, p. 783, 1963.

Atom Type	Short Bonds		Long Bonds		All Bonds	
	Number	Range, Å	Number	Range, Å	Number	Mean Length, Å
I	5	2.57 - 2.76	7	3.21 - 3.71	12	3.10
II	4	2.60 - 2.64	10	3.19 - 3.62	14	3.21
III	4	2.58 - 2.66	10	3.24 - 3.65	14	3.18
IV	4	2.58 - 2.74	10	3.26 - 3.42	14	3.13
V	4	2.58 - 2.72	10	3.24 - 3.51	14	3.19
VI	4	2.64 - 2.74	10	3.21 - 3.65	14	3.22
VII	4	2.57 - 2.78	10	3.30 - 3.51	14	3.15
VIII	3	2.76 - 2.78	13	3.19 - 3.71	16	3.32

The structure as viewed along the *b*-axis is shown below. The atoms are arranged in pseudo-hexagonal layers normal to the *b*-axis and 2.411 Å apart. Each atom forms six bonds with atoms in the same reflection plane and six to ten bonds with atoms of adjacent layers. The distortion from hexagonal configuration in the reflection plane is so great that the bond lengths in this plane range from 2.57 to 3.71 Å. From W. H. Zachariasen and E. H. Ellinger, *Acta Cryst.*, vol. 16, p. 782, 1963.

Projection of the Structure on the (010) Plane. From W. H. Zachariasen and F. H. Ellner, *Acta Cryst.*, vol. 16, p. 782, 1963.

Filled circles represent atoms at $y = 1/4$, open circles atoms at $y = -1/4$. Only the short bonds are indicated in the projection. When corrections are made for the effect of coordination number, these values give 1.58 Å for the metallic radius of plutonium in the α -phase. From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 782, 1963.

COMPARISON OF CRYSTALLOGRAPHIC CONSTANTS OF α -PLUTONIUM
AT 23, 77, AND 294 °K

From R. B. Roof Inc. - A-2912

	23 °K	77 °K	294 °K
a	6.143 ± 0.012 Å	6.113 Å	6.183 ± 0.001 Å
b	4.768 ± 0.011 Å	4.769 Å	4.822 ± 0.001 Å
c	10.987 ± 0.010 Å	10.940 Å	10.963 ± 0.001 Å
β	101.87 ± 0.17 degree	101.80 degree	101.79 ± 0.01 degree
Density	20.17 g/cm ³	20.32 g/cm ³	19.84 g/cm ³
Atoms per Unit Cell	16	16	16
Space Group	P2 ₁ /m	P2 ₁ /m	P2 ₁ /m

Alpha Plutonium, (010) Standard Projection of Directions. From L. T. Lloyd and L. J. Nowicki, J. Nucl Mater., vol. 10, p. 256. 1963.

β -Pu is monoclinic body-centered with 34 atoms per unit cell. At 190°C

a = 9.284, b = 10.463, c = 7.859 Å, β = 92.13

and the density is 17.70 gm⁻³.

The space group is 12_m. One set of two plutonium atoms are in centers of symmetry. Three sets of four plutonium atoms are in reflection planes, one set of four on twofold axes and two sets of eight in general positions. The thirteen parameters in the structure have been determined to an accuracy of about 0.04 Å.

The seven different kinds of plutonium atoms in the structure have coordination number of twelve, thirteen or fourteen. The mean atomic radius is 1.60 Å for coordination number twelve. From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 369, 1963.

UNIT CELL DIMENSIONS*

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371, 1963.

Sample	Temperature, °C	a, Å	b, Å	c, Å	β , degree
Pure Pu	93	9.227	10.449	7.824	92.54
Pure Pu	190	9.284	10.463	7.859	92.13
99 Pu-1 Ce	133	9.251	10.436	7.834	92.35
99 Pu-1 Ce	172	9.260	10.449	7.846	92.24
99 Pu-1 Ce	202	9.286	10.451	7.852	92.06
98 Pu-2 U	83	9.215	10.418	7.815	92.52
98 Pu-2 U	139	9.242	10.433	7.824	92.36
98 Pu-2 U	186	9.264	10.439	7.841	92.22
98 Pu-2 U	252	9.302	10.444	7.859	91.97

*Calculated density for pure plutonium is 17.70 gm⁻³ at 190°C. Precision is ± 0.002 Å for a, b, c, and $\pm 0.02^\circ$ for β .

The structure projected on the Y-plane. Filled circles represent atoms with y = 0; shaded circles, atoms with y = 0.50. The numbers within the open circles give the y-coordinates for atoms at heights z above the projection plane. From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 375, 1963.

PRINCIPAL LINEAR COEFFICIENTS OF THERMAL EXPANSION, ($\times 10^6$)

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371, 1963.

	α_1	α_2	α_3	$\bar{\alpha}$	σ
Pure Pu	94	14	19	42	40 ^o
99 Pu-1 Ce	84	21	7	37	38 ^o
98 Pu-2 U	79	13	15	38	35 ^o

POSITION PARAMETERS

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 372, 1963.

Type	x	y	z
I	0	0	0
II	0.146 $\pm$ 0.004	0	0.387 $\pm$ 0.005
III	0.337 $\pm$ 0.004	0	0.082 $\pm$ 0.005
IV	0.434 $\pm$ 0.004	0	0.672 $\pm$ 0.005
V	0.500	0.220 $\pm$ 0.003	0
VI	0.145 $\pm$ 0.003	0.268 $\pm$ 0.002	0.108 $\pm$ 0.003
VII	0.167 $\pm$ 0.003	0.150 $\pm$ 0.002	0.753 $\pm$ 0.004

METALLIC RADIUS ($\eta = 12$)

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 374, 1963.

Phase	Temperature, °C	Radius, Å	Radius at Room Temperature, Å
α	25	1.58	1.58
β	93	1.60	1.59
γ	235	1.601	1.589
δ	320	1.640	1.644
δ'	465	1.638	1.644
ϵ	490	1.622	1.594

BOND LENGTHS IN OTHER PLUTONIUM PHASES

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 375, 1963.

Phase	Temperature, °C	Bond Number	Bond Length, Å
γ	235	4	3.026
		2	3.159
		4	3.288
δ	320	12	3.279
		8	3.249
δ'	465	4	3.327
		8	3.149

SHORT AND LONG BONDS IN α - AND β -PLUTONIUM

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 375, 1963.

α -Plutonium					β -Plutonium				
Type	Short		Long		Type	Short		Long	
	Number	Range, Å	Number	Range, Å		Number	Range, Å	Number	Range, Å
I	5	2.50 - 2.76	7	3.38 - 3.51	I	4	2.97	8	3.15 - 3.26
II	4	2.62 - 2.66	10	3.36 - 3.64	II	3	3.03 - 3.10	11	3.26 - 3.55
III	4	2.56 - 2.67	10	3.17 - 3.53	III	4	2.79 - 3.03	9	3.15 - 3.43
IV	4	2.55 - 2.67	10	3.17 - 3.52	IV	4	2.79 - 3.01	8	3.16 - 3.48
V	4	2.55 - 2.72	10	3.32 - 3.54	V	4	2.80 - 2.84	10	3.36 - 3.63
VI	4	2.56 - 2.72	10	3.34 - 3.64	VI	4	2.91 - 3.10	10	3.16 - 3.55
VII	4	2.50 - 2.73	10	3.34 - 3.55	VII	5	2.59 - 3.05	7	3.14 - 3.63
VIII	3	2.73 - 2.76	13	3.21 - 3.55					

CRYSTAL STRUCTURE DATA FOR THE PLUTONIUM PHASES

From A. S. Coffinberry and M. B. Waldron in Metallurgy and Fuels, series V, vol. 1, p.373.

Phase	Crystal Lattice	Unit Cell Dimensions, A	Number of Atoms in Unit Cell	Calculated Density, g/cm ³
Alpha	Monoclinic ⁽¹⁾	At 21°C a = 6.1835 ± 0.0005 b = 4.8244 ± 0.0005 c = 10.973 ± 0.001 β = 101.81° ± 0.02°	16	19.816 ± 0.006
Beta	Crystal structure unknown			
Gamma	Face-centered orthorhombic ⁽²⁾	At 235°C: a = 3.1587 ± 0.0004 b = 5.7682 ± 0.0004 c = 10.162 ± 0.002	8	17.14 ± 0.01
Delta	Face-centered cubic ⁽³⁾ ⁽⁴⁾ ⁽⁵⁾	At 320°C a = 4.6371 ± 0.0004	4	15.92
Delta-prime	Body-centered tetragonal ⁽³⁾ ⁽⁴⁾ ⁽⁵⁾	At 465°C: a = 3.327 ± 0.003 c = 4.482 ± 0.007	2	16.00
Epsilon	Body-centered cubic ⁽³⁾ ⁽⁴⁾ ⁽⁵⁾	At 490°C: a = 3.6361 ± 0.0004	2	16.51

(1) From W. H. Zachariasen. Private communication as reported by A. S. Coffinberry and M. B. Waldron.

(2) From W. H. Zachariasen and F. H. Ellinger, Acta Cryst., vol. 8, p. 431. 1955.

(3) E. R. Jette, J. Chem. Phys., vol. 23, p. 367. 1955.

(4) E. R. Jette, Nuclear Metallurgy, Inst. of Metals Div. Report Series No. 1, p. 29. 1955.

(5) F. H. Ellinger, J. of Metals, vol. 8, p. 1256. 1956.

²⁴¹Pu body centered tetragonal unit cell dimensions:

at 465°C a = 3.327 ± 0.003 A, c = 4.482 ± 0.07A,
calculated density 16.0 g/cm³.

UNIT-CELL DIMENSIONS AND VOLUMES OF DELTA-PRIME PLUTONIUM AT 450 °C

From F. H. Ellinger, J. Metals, vol. 8, p. 1256. 1956.

and from R. O. Elliott and A. C. Larson, The Metal Plutonium, pp. 278.

Units	Elliott and Larson (X-Ray Diffractometer)		
	High-Purity; Total Impurities (less O ₂) < 221 ppm (wt)	Ordinary Purity; Total Impurities (less O ₂) < 386 ppm (wt)	Ellinger (X-Ray Powder Method) 99.97% Purity
BCT (a ₀), A	3.3261 ± 0.0008	3.3283 ± 0.0010	3.3119 ± 0.0021
BCT (c ₀), A	4.4630 ± 0.0014	4.4512 ± 0.0016	4.5265 ± 0.0056
Unit-cell volume, A ³	49.374 ± 0.023	49.308 ± 0.027	49.650 ± 0.076

Measured lattice constant values were fitted to straight lines giving the following equations, from which the unit cell dimensions above were calculated:

$$a = 3.3220 \pm 0.0018 + (10.14 \pm 1.16) 10^{-4} (t - 460)$$

$$c = 4.4969 \pm 0.0047 - (29.56 \pm 3.01) 10^{-4} (t - 460)$$

$$a_t = 3.3261 \pm 0.0008 + (14.80 \pm 0.40) \times 10^{-4} (t - 450)$$

$$c_t = 4.4630 \pm 0.0014 - (47.46 \pm 0.81) \times 10^{-4} (t - 450)$$

} for high purity Pu

where t is in °C and the uncertainties are standard deviations. Two atoms/unit cell at 000 and 1/2, 1/2, 1/2. Structure Type I4/mmm. Each Pu atom has eight neighbors at 3.249 A and four at 3.327 A. From F. H. Ellinger, J. Metals, vol. 8, p. 1256. 1956, and from R. O. Elliott and A. C. Larson, The Metal Plutonium, pp. 278-279.

Probability Plot of Data for Couple TC1 Annealed for 192 Hr at 401°C. From R. E. Tate and E. M. Cramer, *Trans. Met. Soc. AIME*, vol. 230, p. 642, 1964.

$$D = \frac{C - c_1}{C_0 - c_1} \frac{1}{2} \left[1 + \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-\lambda^2} d\lambda \right]$$

The values of frequency factors D_0 and activation energy Q for fcc δ plutonium are significantly lower than might be expected from currently accepted theories of diffusion mechanisms, a distinction shared with bcc γ uranium. However, for plutonium the low activation energy may not be surprising when the very low heat of fusion, $L_m = 693$ cal per g-atom, is taken into consideration. The measured activation energy for self-diffusion is higher than that predicted by Nachtrieb's correlation; i.e., $Q = 16.5 L_m$. If the heats of transformation above the δ range are added together (δ to δ' 20 cal per g-atom, δ' to ϵ 444 cal per g-atom, and ϵ to liquid 693 cal per g-atom, a total of 1157 cal per g-atom), Nachtrieb's correlation predicts 19,690 cal per g-atom for the activation energy of δ plutonium compared with the measured value of 23,800 cal per g-atom.

Low D_0 and Q values are usually attributed to short-circuiting diffusion paths. The autoradiographic experiments indicate that grain boundary diffusion is unlikely. Further experiments which might shed additional light on the diffusion behavior of plutonium are being studied. From R. E. Tate and E. M. Cramer, *Trans. Met. Soc. AIME*, vol. 230, p. 642, 1964. DISCUSSION - p. 642, 1st column (first 2 paragraphs)

Arrhenius Plot for Self-Diffusion in δ Plutonium. From R. E. Tate and E. M. Cramer, *Trans. Met. Soc. AIME*, vol. 230, p. 642, 1964.

PHASE DATA
(Probably 99.96 wt% Plutonium)

From E. R. Jette, in *Nuclear Metallurgy*, p. 36. 1955.

Phase	Resistivity, $\rho \times 10^6$	$1/\rho \cdot d\rho/dt \times 10^5$ *
α	145 (25°)	-21
β	108 (150°)	-6
γ	107.5 (235°)	-5
δ	100 (370°)	+7
δ'	103 (475°)	+45
ϵ	111 (510°)	0

* At same temperatures as the resistance values
Note: $t = ^\circ\text{C}$

CALCULATED DENSITY DETERMINED
FROM SELF-HEATING DILATOMETER EXPERIMENTS
WITH 99.95 wt% PLUTONIUM

E. M. Cramer et al. in *The Metal Plutonium*, pp. 112-122.
(Table Compiled by M. E. Hasbrouck)

Phase	Density, g/cm ³	Temperature, °C
α	19.8	25
β	17.8	122
γ	17.2	206
δ	16.0	319
δ'	16.2	451
ε	17.0	476

DENSITY OF PLUTONIUM

From W. D. Wilkinson, in *Extractive and Physical
Metallurgy of Plutonium and Its Alloys*, p. 21.

Allotrope	X-ray	Dilatometric	Fluid Displacement
α	19.737 (25 °C)*		19.5 to 19.62 (30 °C) 19.4 (25 °C, as-cast)
β	17.77 (150 °C)	17.07 - 17.46 (150 °C)	17.8 (150 °C)
γ	17.14 (235 °C)	16.64 - 16.78 (235 °C)	
δ	15.92 (320 °C)	15.52 - 15.69 (320 °C)	
δ'	16.01 (477 °C)	15.82 - 15.87 (477 °C)	
ε	16.48 (510 °C)	16.13 - 16.46 (510 °C)	

* Cooled from 300 °C under high pressure (Pressed at 50,000 psi at 300 °C)

DENSITY OF PLUTONIUM

From C. Z. Serpan, Jr., and L. J. Wittenberg,
Trans. Met. Soc. AIME, vol. 221, p. 1019. 1961.

Temperature, °C	Experimental Density, g/cm ³	Density from Curve, g/cm ³	Deviation, %
664	16.617	16.624	0.04
691	16.602	16.584	0.11
728	16.522	16.527	0.03
746	16.439	16.498	0.36
752	16.499	16.488	0.07
771	16.533	16.460	0.44
788	16.402	16.433	0.19

$$\rho = [17.632 - 1.522 \times 10^{-3} t] \pm 0.038 \text{ g/cc where } t = ^\circ\text{C}$$

The volume expansion coefficient is

$$93 \times 10^{-6} \text{ per } ^\circ\text{C}$$

The density of the liquid at the melting point, 640°C, is calculated to be 16.66 g per cc while an extrapolation of two different measurements of the solid phase give 16.24 (calculated from X-ray data) and 16.26 g per cc as the density of the α phase at 640°C. Since the liquid is, therefore, of 2.4 pct greater density than the solid at the melting point, plutonium metal joins that group of anomalous materials in which the solid floats on the liquid. From C. Z. Serpan, Jr. and L. J. Wittenberg, *Trans. Met. Soc. AIME*, vol. 221, p. 1020, last paragraph. 1961.

Density of Plutonium Vs Temperature for Several Techniques of Measurement. From C. Z. Serpan, Jr. and L. J. Wittenberg, *Trans. Met. Soc. AIME*, vol. 221, p. 1019. 1961.

SPECTROGRAPHIC ANALYSIS OF PLUTONIUM

From C. Z. Serpan, Jr., and L. J. Wittenberg,
Trans. Met. Soc. AIME, vol. 221, p. 1019. 1961.

Element	PPM	Element	PPM
Al*	90	La	<10
B	<0.5	Li	<0.2
Be	<0.2	Mg	25
C	95	Na	<10
Ca	5	Ni	100
Cr	50	O ₂	<500
Cu	10	Pb	2
F	<2	Si**	80
Fe	340		

* Chemical analysis

** Spectrophotometric analysis

LINEAR EXPANSION PER °C

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, pp. 15-20.

α Pu	Standard purity, polycrystalline at -180 to +122°C $\bar{\alpha} \times 10^6 = 48.39 \pm 0.01 + (0.0959 \pm 0.012) t$ High purity, polycrystalline at -186 to +100°C $\bar{\alpha} \times 10^6 = 46.85 \pm 0.05 + (0.559 \pm 0.0004) t$
β Pu	Standard purity, polycrystalline at 82 to 206°C $\bar{\alpha} \times 10^6 = 26.04 \pm 0.01 + (0.0740 \pm 0.0015) t$ Standard purity, polycrystalline at 164°C $\bar{\alpha} \times 10^6 = 38.0$ High purity, polycrystalline, average for 133 to 197°C $\bar{\alpha} \times 10^6 = 34.0$ High purity, X-ray, at 93 to 190°C $a_{\alpha} \times 10^6 = 64$ $a_{\beta} \times 10^6 = 14$ $a_{\gamma} \times 10^6 = 46$
γ Pu	Angular change (per °C) at 93 to 190°C: $\Delta\beta/^{\circ}\text{C} = -74 \times 10^{-6}$ Standard purity, polycrystalline $\bar{\alpha} \times 10^6 = 34.7 \pm 3.0$ High purity, X-ray, 149 to 319°C or 210 to 310 $a_{\alpha} \times 10^6 = -19.7 \pm 1.7$ $a_{\beta} \times 10^6 = 39.5 \pm 0.9$ $a_{\gamma} \times 10^6 = 84.3 \pm 2.3$
δ Pu	Dilatometric, polycrystalline, 320 to 440°C $\bar{\alpha} \times 10^6 = -8.6 \pm 3$ ($\bar{\alpha} \times 10^6 = -8.8$ above 300°C, +73 below 300°C) X-ray (mean) $\bar{\alpha} \times 10^6 = -10$
δ' Pu	High purity, X-ray, 465 to 485°C $a_{\alpha} \times 10^6 = 305 \pm 35$ $a_{\beta} \times 10^6 = -659 \pm 67$ High purity, dilatometric, cooling $\bar{\alpha} \times 10^6 = -53$ High purity, dilatometric, heating $\bar{\alpha} \times 10^6 = -116$
ϵ Pu	$\bar{\alpha} \times 10^6 = 36.5 \pm 1.1$, 490 to 550°C

COEFFICIENTS OF EXPANSION, $10^{-6}/^{\circ}\text{C}$

R. Abramson et al., p/327, Proc. Second Geneva Internat. Conf., vol. 6, p. 177, 1958.

	Sample A (~ 99.9% Pu)	Sample B (99.99% Pu)	Sample C* (Pu From Saclay Fuel)	
		Extreme Values	Average Values	
α phase	59	85 65	76	68
β phase	30	32 21	26	37
γ phase	33	33 23	28	38
δ phase during heating	-8.8	-21 -16	-18	-22
δ' phase during heating		-129 -107	-116	
ϵ phase during cooling	26	35 28	31	30
δ' phase during cooling	-63	-63 -45	-53	-72
δ phase during cooling				
(1) above the elbow		-12.5 -10.5	-11.5	-13
(2) below the elbow		83 61	73	95

* Average of two tests

RESULTS OF SELF-HEATING DILATOMETER EXPERIMENTS
WITH 99.95 wt% PLUTONIUM

E. M. Cramer et al. in The Metal Plutonium, pp. 112-122

Phase	Cylinders 0.500 in. Diameter, 0.500 in. Long Temperature Range, °C	Linear Expansion Coefficient, °C ⁻¹ x 10 ⁻⁶ , Averages
α	58 - 106	58(+3, -3)
β	144 - 201	35(+2, -3)
γ	224 - 300	33(+2, -2)
δ	336 - 447	-16(+2, -2)
δ'	459 - 474	-118(+53, -21)
ϵ	490 - 527	27 (X-ray diffraction = 36.5 ± 1.1)

The limits given are actual maximum variations in values given by seven measurements involving three specimens. Plastic deformation was observed during six of the measurements on ϵ -plutonium.

Tube with 0.017 in. Wall Thickness

α	-180 - 100	46.847 + 0.055881 T
β	133 - 197	33.86

THERMAL EXPANSION COEFFICIENTS

From M. B. Waldron et al., p/71, Proc. Second Geneva Internat. Conf., vol. 6, p. 162, 1958.

Phase	Linear Coefficient of Thermal Expansion, $10^{-6}/^{\circ}\text{C}$
Alpha	67 (80 - 120°C)
Beta	41 (160 - 200°C)
Gamma	35 (220 - 280°C)
Delta	-8.6 (340 - 440°C)
Delta-prime	-596 ³ (470°C)
Epsilon	15 (490 - 550°C)

* Value exaggerated by creep during residual transformation

EXPANSION DURING PHASE TRANSFORMATIONS

R. Abramson et al., p/327,
Proc. Second Geneva Internat. Conf., vol. 6, p. 177, 1958.

	Expansion, %		
	Sample A	Sample B	Sample C
Total	5.6	7.25	7.6
$\alpha \rightarrow \beta$	2	3.2	3.2
$\beta \rightarrow \gamma$	0.8	0.85	0.96
$\gamma \rightarrow \delta$	1.8	2.05	2.1
$\epsilon \rightarrow \delta'$	-0.72	-0.77	-0.66

EXPANSION COEFFICIENTS FOR ALPHA-PLUTONIUM
99.9% PURE, $10^{-6}/^{\circ}\text{C}$

W. H. Zachariasen and F. H. Ellinger,
Acta Cryst., vol. 16, p. 780, 1963.

	21 - 51 °C	21 - 96 °C	21 - 104 °C	Mean, 21 - 100 °C
a_a	59	60	60	60 ± 1
a_b	57	69	75	72 ± 3
a_c	30	29	29	29 ± 1
Δ	-6	-5	-8	-7 ± 2
a_1	-	-	-	62 ± 1
a_2	-	-	-	72 ± 3
a_3	-	-	-	29 ± 1
ϕ	-	-	-	13 ± 2

a_a, a_b, a_c = linear coefficients in the directions of the crystallographic axes. Δ = change in angle β (in radians) per degree rise in temperature. These quantities are related to the principle coefficients a_1, a_2, a_3 and the angle ϕ describing the orientation of the tensor ellipsoid by the equations: (see W. H. Zachariasen and F. H. Ellinger, Acta Cryst., vol. 12, p. 175, 1959.)

$$a_1 - a_3 = -\Delta / \sin \beta \cos (2\phi - \beta),$$

$$\tan (2\phi - \beta) = (a_a - a_c) / \Delta,$$

$$a_2 = a_b.$$

$$a_1 + a_3 = a_a + a_c + \Delta \cotan \beta$$

Thermal Expansion of Normal Purity Plutonium Metal Relative to Fused Quartz. (a) Top dashed line represents curve for relatively rapid cooling and warming. (b) Solid line between $\sim 48^\circ\text{K}$ and 300°K represents results found in 27-1/2 h cooling period. (c) Solid line between 2°K and 60°K represents results from warming trend. [99.9% Pu (combined iron and nickel content 150 ppm).] From T. A. Sandenaw in *Plutonium 1960*, p. 85.

LEAST-SQUARES EQUATION FOR LINEAR EXPANSION OF PLUTONIUM METAL BELOW 273°K

T. A. Sandenaw in *Plutonium 1960*, last paragraph on p. 87.

Because of the offset observed at $\sim 50^\circ\text{K}$ and the region of zero coefficient of linear expansion (between 135° and 160°K), the data were divided into three temperature regions. The equations, uncorrected for expansion behaviour of fused quartz, for these three regions were found to be as follows:

Temperature range: 2° to 55°K

$$\Delta l_T = l_{273}(A + BT + CT^2)$$

$$A = -7.9421680 \times 10^{-3}$$

$$B = -6.4305347 \times 10^{-6}$$

$$C = 4.1447317 \times 10^{-7}$$

$$\sigma = 1.3 \times 10^{-4}$$

Temperature range: 50° to 135°K

$$\Delta l_T = l_{273}(A + BT)$$

$$A = -8.8183670 \times 10^{-3}$$

$$B = 2.5303415 \times 10^{-5}$$

$$\sigma = 6.4 \times 10^{-5}$$

Temperature range: 160° to 273°K

$$\Delta l_T = l_{273}(A + BT)$$

$$A = -1.3240679 \times 10^{-2}$$

$$B = 4.8509769 \times 10^{-5}$$

$$\sigma = 1.6 \times 10^{-4}$$

THERMAL EXPANSION COEFFICIENTS FOR δ -PLUTONIUM, $\times 10^{-6}/^\circ\text{C}$

From W. H. Zachariasen and F. H. Ellinger,

Acta Cryst., vol. 12, p. 176. 1959.

	93 - 190°C
α_a	64
α_b	14
α_c	46
α	-74
1	94
2	14
3	19
α	42
	40

Thermal Expansion of a Plutonium Specimen With 600 PPM Iron Content Relative to Fused Quartz (Solid Line). Dashed curve represents data for the normal purity specimen (combined iron and nickel content 150 ppm). From T. A. Sandenaw in *Plutonium 1960*, p. 86.

THERMAL EXPANSION COEFFICIENTS FOR GAMMA PLUTONIUM

From W. H. Zachariasen and F. H. Ellinger,

Acta Cryst., vol. 8, p. 433. 1955.

Temperature, $^\circ\text{C}$	True $\alpha \times 10^{-6}/^\circ\text{C}$		
	[100]	[010]	[001]
210	-19.68	39.48	84.21
260	-19.70	39.40	83.86
310	-19.72	39.32	83.51
Standard Deviation	5.1%	1.4%	1.9%

Mean linear coefficients for the range 210 - 310°C -19.7 ± 1.0 39.5 ± 0.6 84.3 ± 1.6

Mean linear coefficient for polycrystalline gamma plutonium $= (34.7 \pm 0.7) \times 10^{-6}/^\circ\text{C}$

Mean volume coefficient ($\bar{\alpha}_v = 3\bar{\alpha}$) $= (104 \pm 2) \times 10^{-6}/^\circ\text{C}$

LINEAR THERMAL EXPANSION OF DELTA-PRIME PLUTONIUM, PER $^\circ\text{C}$

From R. O. Elliott and A. C. Larson in *The Metal Plutonium*, p. 279.

Elliott and Larson
(X-Ray Diffractometer)

	High-Purity, KJ-329 <221 ppm Impurities	Ordinary-Purity, J-3015 <386 ppm Impurities	Ellinger (X-Ray Powder Method) 99.97 wt. % Pu	Jette (Dilatometric Method) 99.96 wt. % Pu
Coefficient				
$10^6 \bar{\alpha}_a$	444.8 ± 12.1	329.9 ± 15.1	305 ± 35	305 ± 35
$10^6 \bar{\alpha}_b$	-1063.5 ± 18.2	-828.7 ± 19.1	-659 ± 67	-660 ± 67
$10^6 \bar{\alpha}_c$	-65.6 ± 10.1	-60.8 ± 11.9	-16 ± 28	ca. -20

The mean linear coefficient of thermal expansion, $\bar{\alpha}_p$, for the bulk, randomly oriented polycrystalline material was calculated from the single-crystal coefficients, using the relation $(1 + \bar{\alpha}_p \Delta t)^3 = (1 + \bar{\alpha}_a \Delta t)^2 (1 + \bar{\alpha}_c \Delta t)$.

Thermal Conductivity

Thermal Conductivity

Thermal conductivity of α Pu at room temperature; $k = 0.0105 \text{ cal/cm}^2\text{sec}^\circ\text{C}$

$$= 0.0098 \pm 0.0006 \text{ cal/cm sec } ^\circ\text{C}$$

From W. D. Wilkinson in *Extractive and Physical Metallurgy of Plutonium and Its Alloys*, p. 15.

Thermal Conductivity as a Function of Absolute Temperature. From T. A. Sandenaw and R. B. Gibney, *J. Phys. Chem. Solids*, vol. 6, p. 87. 1958.

Thermal Conductivity of Plutonium. From M. B. Waldron *et al.* p/71, *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 164. 1958.

202.3

Specific Heat and Heat Capacity

Heat Capacity as a Function of Temperature for High-Purity (Predominantly Solid Line) and Normal-Purity (Dashed Line) Plutonium Specimens. From T. A. Sandenaw *et al* in *Plutonium 1960*, p. 72.

Shape of Heat Capacity Peak at the α - β Phase Transition. From T. A. Sandenaw et al in Plutonium 1960, p. 72.

W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, pp. 15-20.

Phase	Heat Capacity, cal/g-atom
α	$C_p = 8.0$
	$C_v = 7.3$
β	$C_p = 9.3$
	$C_v = 8.7$
γ	$C_p = 12$
δ	$C_p = 13$
δ'	$C_p = 15$
ϵ	$C_p = 10$

Variation of Specific Heat with Temperature. From A. E. Kay and R. G. Loasby. Phil. Mag., eighth series, vol. 9, no. 97, p. 42. 1964.

Plutonium containing 160 ppm Ni, 200 ppm Fe, 205 ppm C (4 runs)

Temperature range below 21.25°K

$$C_p = \gamma T + BT^3$$

$$\gamma = 1.1678 \times 10^{-2}$$

$$B = 9.276 \times 10^{-5}$$

$$\sigma(\text{standard deviation}) = 0.066$$

Temperature range 21.25° to 31.81°K

$$C_p = \gamma T + BT^3$$

$$\gamma = 2.2356 \times 10^{-2}$$

$$B = 7.1016 \times 10^{-5}$$

$$\sigma = 0.226$$

Temperature range 40° to 298.15°K

(Peak-free portion of curve for normal-purity specimen No. 1)

$$C_p = A + BT + CT^2 + DT^3$$

$$A = 1.1282876$$

$$B = 8.2517711 \times 10^{-2}$$

$$C = -3.8530037 \times 10^{-4}$$

$$D = 6.4728553 \times 10^{-7}$$

$$\sigma = 0.226$$

The very low temperature data from seven runs with 99.96 and 99.89 wt. % Pu specimens gave the following equation below 21.66°K (7 runs):

Temperature range below 21.66°K

$$C_p = \gamma T + BT^3$$

$$\gamma = 2.0515 \times 10^{-2}$$

$$B = 8.4467 \times 10^{-5}$$

$$\sigma = 0.094$$

From T. A. Sandenaw et al. in Plutonium 1960, pp. 73, 75.

SPECIFIC HEATS

From A. E. Kay and R. G. Loasby, Phil. Mag., eighth series, vol. 9, no. 97, p. 43. 1964

Temperature, °C	Experimental Molar Specific Heat C_p , cal/mole-°C	Calculated Lattice Specific Heat C_v , cal/mole-°C	$[C_p - C_v]_d$, cal/mole-°C	Excess Specific Heat $C_p - C_{p_{\text{calc}}}$
α	-13	8.0	5.79	0.89
	27	8.48	5.83	1.09
	47	8.66	5.85	1.22
	67	8.84	5.86	1.31
β	140	8.20	5.93	0.62
	150	8.24	5.93	0.63
	160	8.28	5.93	0.65
	170	8.34	5.93	0.66
	180	8.41	5.93	0.68
γ	190	8.46	5.93	0.69
	230	8.58	5.93	0.73
	240	8.62	5.93	0.74
	250	8.67	5.93	0.76
	260	8.76	5.93	0.77
δ	270	8.85	5.93	0.78
	327	9.0	5.94	0.026
	377	9.0	5.94	0.024
	427	9.0	5.94	0.022
	500	8.4	5.94	(0.90)
ϵ	600	8.4	5.94	(1.00)
				(1.46)

Specific Heat

α Plutonium	8.0 cal/gram-atom/°C
β Plutonium	8.2 cal/gram-atom/°C

From T. K. Engel et al. USAEC Report TID-7641, pp. 266-272.

THE SPECIFIC HEAT AND HEATS OF TRANSFORMATION OF PLUTONIUM

From A. E. Kay in The Metal Plutonium, p. 133.

Temperature, °C	Specific Heat	Temperature °C	Specific Heat	Temperature, °C	Specific Heat
-62.0	33.4	184	41.6	374	46.4
-58.5	33.4	190	41.9	376	46.9
-50	34.2	192	43.3	379	47.1
-44	35.2	197	43.4	383	46.4
-32	37.5	200	42.3	389	48.3
-25	38.9	204	42.8	397	45.7
-21	38.7	208	43.4	407	45.6
-13	38.8	210	49.7	412	47.8
-1.5	35.7	211	90.3	420	48.6
-1.0	35.5	$\delta \rightarrow \gamma$ transition; latent heat = 140		426	48.6
5.0	32.4	± 15 cal/g-atom		433	45.0
13	35.5	212	66.5	442	47.0
15	33.5	212	59.9	449	49.7
20	33.8	213	42.6	450	50.2
29	34.1	218	40.8	452	51.0
38	34.5	226	42.3	454	53.9
44	34.9	230	44.0	456	56.6
52	36.6	236	43.0	457	64.1
62	36.6	242	44.8	459	86.8
65	35.0	243	44.4	$\delta \rightarrow \delta'$ transition; latent heat = 17	
70	38.7	250	45.0	± 10 cal/g-atom	
79	38.6	254	46.3	461	62.9
81	41.3	260	45.2	464	58.6
85	41.5	267	46.9	468	65.8
90	41.3	272	45.9	470	75.0
96	42.5	279	46.1	473	79.4
104	44.9	284	46.8	473	100.6
111	44.9	288	45.3	477	141.6
113	47.8	291	47.8	480	155.2
118	52.8	297	47.9	481	157.8
121	56.0	303	49.9	483	268.1
122	60.9	305	50.5	$\delta' \rightarrow \epsilon$ transition; latent heat = 470	
124	76.7	307	60.7	± 10 cal/g-atom	
126	101.7	312	89.6	486	55.6
128	129.2	315	128.1	488	43.8
127°: superheat; the true transformation temperature = 121 °C; the latent heat of the $\delta \rightarrow \epsilon$ transition = 958 ± 10 cal/g-atom		$\gamma \rightarrow \delta$ transition; latent heat = 156 ± 5 cal/g-atom		491	43.4
		318	87.3	498	43.1
		320	82.0	505	44.0
127	161.9	322	73.9	513	42.2
130	99.0	324	62.3	518	39.4
132	72.2	326	56.8	527	41.7
133	57.9	327	52.8	533	35.4
135	50.9	332	48.5	538	36.9
140	43.1	334	47.1	546	37.6
145	40.5	343	44.6	$\epsilon \rightarrow$ liquid transition at 639 °C; latent heat = 940 ± 150 cal/g-atom; total heat of plutonium in solid state = 11.7 ± 0.5 Kcal/g-atom	
152	39.9	346	45.5		
158	41.1	350	45.5		
167	41.9	356	48.1		
171	42.0	361	46.5		
176	42.5	368	46.9		

Rate of heat generation, $Q = 2.2125$ mW/g (normal deviation almost 0.1-0.2%)

L. H. Treeman reported a value of $Q = 2.2157$ mW/g (private communication to Sandenaw)

From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 23, p. 825. 1962.

Some C_p values may be obtained using the data of Linford given in Paper 14 (Plutonium 1960, p. 51-8), and these are given below.

Phase	Temperature, °C	C_p , cal/g	C_v , cal/g
α	50	0.036	0.030
β	150	0.034	0.030
	230	0.035	0.032
γ	320	0.043	0.042

From R. G. Loasby in Plutonium 1960, p. 102.

202.4

Entropy

AVERAGED VALUES OF ΔH (cal/mole) AND S (cal/mole-°K) AT VARIOUS TEMPERATURES

From T. A. Sandenaw et al. in Plutonium 1960, p. 74.

Specimen No.	36.0° to 36.5°K		88° to 90°K		154° to 156°K		298.15°K	
	S_T	$H_T - H_0$	S_T	$H_T - H_0$	S_T	$H_T - H_0$	S_T	$H_T - H_0$
HP1 99.96%	2.75(5)	65.0(5)	7.07(5)	328(5)	11.37(5)	834(5)	15.17(3)	1707(3)
NP1 99.90%	1.94(6)	43.6(6)	5.91(6)	283(6)	9.58(5)	728(5)	14.55(5)	1826(5)
HP2 and NP2 (99.96, 99.89%)	2.33(7)	55.3(7)	7.15(6)	338(6)	10.28(1)	764(1)	15.09(1)	1812(1)
Av. of all values	2.32(18)	54.1(18)	6.69(17)	316(17)	10.46(11)	779(11)	14.82(9)	1785(9)

CALCULATED EXTRA ENTROPY IN HEAT CAPACITY PEAKS

From T. A. Sandenaw et al. in Plutonium 1960, p. 74

Temp. at Crest, °K	Extra Entropy, e.u.
31	1.15 $\approx R \ln 2$
47	2.00 $\approx R \ln 3$
123	2.95 $\approx R \ln 4$

The heat capacity curve at the α - β phase transition for a rather impure plutonium specimen was shown in section 202.3. Assuming that the entropy and enthalpy at 298°K were equivalent to the average found for the three specimens, it has been calculated that the entropy and enthalpy at 420°K would be 20.05 ± 0.40 e.u. and 3900 ± 100 cal/mole, respectively.

From T. A. Sandenaw et al. in Plutonium 1960, p. 74.

Temperature of and Volume Change during Transition

See the following tables in section 102 entitled:

- Phase Transformation Data for Plutonium Metal (99.95-99.96 Wt. % Pu)
- Phase Transformation Temperatures for Zone-Melted Plutonium (about 99.8 at. % Pu, 250 ppm total impurities)
- Transition Temperatures (possible error $\pm 5^\circ$)
- Temperatures of Phase Transitions
- Delta/Delta-Prime and Delta-Prime/Epsilon Transition Temperatures of Plutonium on Heating (in $^\circ\text{C}$)

Also see section 602.

Heats of Transition

W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 20.

Transition	ΔH , cal/g-atom
$\alpha - \beta$	925 *
	958 ± 10 (at 121 $^\circ\text{C}$) +
$\beta - \gamma$	140 ± 15 (at 208 $^\circ\text{C}$)
$\gamma - \delta$	156 ± 5 (at 316 $^\circ\text{C}$)
$\delta - \delta'$	17 ± 10 (at 455 $^\circ\text{C}$)
$\delta' - \epsilon$	470 ± 10 (at 479 $^\circ\text{C}$)
ϵ - liquid	790 ± 190

* Normal purity plutonium (99.8% plutonium)
+ The rest of the values are for high-purity plutonium (99.96% plutonium)

T. K. Engel et al. USAEC Report TID-7641, pp. 266-272.

Transformation	Temperature, $^\circ\text{C}$, (on Heating)	Latent Heat, cal/g-atom
$\alpha - \beta$	127	810 ± 5
$\beta - \gamma$	207	124 ± 12
$\gamma - \delta$	320	136 ± 7
$\delta - \delta'$	460	25 ± 8
$\delta' - \epsilon$	481	441 ± 8
ϵ - liquid	640	655 ± 6

LATENT HEATS

From A. E. Kay and R. G. Loasby, Phil. Mag., eighth series, vol. 9, no. 97, p. 43. 1964.

Transition	Temperature, $^\circ\text{C}$	Latent Heat, cal/mole
$\alpha - \beta$	119	803 ± 10
$\beta - \gamma$	204	152 ± 15
$\gamma - \delta$	311	125 ± 5
$\delta - \delta'$	458	20 ± 10
$\delta' - \epsilon$	480	444 ± 10
ϵ - liquid	638	693 ± 10

The unusual behaviour of the δ -phase in having a negative coefficient of expansion and the contraction in volume which occurs on passing from the f.c.c. δ -phase to the b.c.c. ϵ -phase are two other features which might be explained in terms of the thermodynamic data. Varley (1956) has considered the main factors controlling the volume expansion of solids and concluded that a negative coefficient might arise if the density of states at the Fermi surface varies rapidly with energy and if the electronic specific heat is also high. Measurements of the specific heat and a number of other properties from high temperatures down to liquid helium temperatures are being undertaken in an attempt to understand the metallic behaviour of plutonium.

Two problems arise in attempting to measure the low temperature specific heat of plutonium. These are the extremely rapid rate of rise in temperature ($1^\circ/\text{sec}$ below 10 $^\circ\text{K}$) which occurs at low temperatures due to the immutable self-heating capacity of the material and the self-irradiation energy (Sandenaw 1962) which is stored in the lattice if the samples are held at these temperatures for any appreciable time. Low temperature measurements are restricted to the α and δ -phase with possibly the inclusion of the β -phase. The α -phase can be examined in the pure state, whereas the δ and β -phases must be stabilized by the addition of an alloying element. Data on pure metal phases can therefore only be obtained at temperatures where they are normally stable.

From A. E. Kay and R. G. Loasby, Phil. Mag., eighth series, vol. 9, no. 97, p. 37 (beginning with 4th line through the 2nd paragraph). 1964.

S. T. Konobeevsky et al. p/2230, Proc. Second Geneva Internat. Conf., vol. 6, p. 194. 1958.

Transition	Latent Heat of Transformation, cal/g $^{-1}$
$\alpha - \beta$	3.2 ± 0.5
$\beta - \gamma$	0.7 ± 0.1
$\gamma - \delta$	0.8 ± 0.1
$\delta - \delta'$	0
$\delta' - \epsilon$	1.6 ± 0.3
ϵ - liquid	3.3 ± 0.5

Results obtained using a differential vacuum calorimeter.

The thermal arrest due to the $\alpha \rightarrow \beta$ transformation indicated a heat of transition of 938 ± 10 cal/mole.

From T. A. Sandenaw and R. B. Gibney, J. Phys. Chem. Solids, vol. 6, p. 86. 1958.

The latent heat of the $\delta \rightarrow \delta'$ transformation appears to be about 100 cal/g-atom. The latent heat of the $\delta' \rightarrow \epsilon$ transformation is larger, the ratio being 3.5 ± 1 . From J. D. Hill, Less-Common Metals, vol. 4, pp. 376-386. 1962.

Heat of Vaporization = 80.46 ± 0.34 k cal/mole.

From E. R. Jette and A. S. Coffinberry, USAEC Report AECD-3647, p. 237.

Electrical Conductivity

From W. D. Wilkinson, in Extractive and Physical Metallurgy of Plutonium and Its Alloys, pp. 15-20.

Phase	Electrical Resistivity, ρ , $\mu\text{ohm-cm}$	Coefficient of Electrical Resistivity, $\frac{1}{\rho} (d\rho/dT) \times 10^{-5}$
α	145 at 28 $^\circ\text{C}$	-21 to -40
β	110.5 at 132 $^\circ\text{C}$, 117 average	-5 to -11 (average = -6)
γ	110 at 230 $^\circ\text{C}$, 115 average	-4 to -8 (average = -5)
δ	103 at 353 $^\circ\text{C}$	7 to 18
δ'	105 at 462 $^\circ\text{C}$	45
ϵ	114 at 490 $^\circ\text{C}$	-7

J. G. Ball and W. B. H. Lord, J. Inst. Metals, vol. 86, p. 376. 1957-58.

Phase	Resistivity, $\mu\text{ohm-cm}$	Temperature Coefficient of Resistance, $10^{-5}/^\circ\text{C}$
Alpha	150	-22 to -40
Beta	117	-5 to -11
Gamma	115	-4 to 8
Delta	108	+8 to +18
Epsilon	123

Electrical resistivity curves for plutonium metal as a function of temperature between 1.73 °K and 55 °K (Number 1 represents an average of three runs with specimen Number 1, - maximum deviation : 1%, Number 2 shows branching observed with Specimen Number 2.)

From T. A. Sandenaw and C. E. Olsen in Plutonium 1960, p. 61.

Electrical Resistivity of Plutonium Metal Between 50 °K and 295 °K. (Dashed line represents observed limits; solid line represents normal curve.)

From T. A. Sandenaw and C. E. Olsen in Plutonium 1960, p. 63.

Electrical Resistivity of Plutonium Metal Between 130 K and 298°K. Circles represent slow cooling data and triangles data taken on slow warming.

From T. A. Sandenaw and C. E. Olsen in Plutonium 1960, p. 64.

Resistivity Data vs Temperature for Highly Oriented and Randomly Oriented Alpha Plutonium. From R. O. Elliott et al. *Phys. Rev. Letters*, vol. 12, p. 277. 1964.

COMPARISON OF RESISTIVITY DATA FOR HIGHLY ORIENTED AND RANDOMLY ORIENTED ALPHA PLUTONIUM

From R. O. Elliott *et al.* Phys. Rev. Letters, vol. 12, p. 278. 1964.

Orientation of Specimen	Residual Resistivity, $\mu\Omega\text{-cm}$	Temp at ρ_{max} , °K	ρ_{max} , $\mu\Omega\text{-cm}$	$\rho_{\text{max}} - \rho_{300^\circ\text{K}}$, $\mu\Omega\text{-cm}$
(020) planes $\perp$ to direction of current	6.2	125-170*	137	1
Randomly oriented	...	105	163.5	14
(020) planes $\parallel$ to direction of current	7.5	92	171.3	20.7

*Resistivity maximum is flat in this region.

Ideal Resistances Plotted Logarithmically. Specimens: O, Pu 3 run 5; ●, Pu 3 run 7; ▲, Pu 4 run 1a; Δ, Pu 4 run 1b. From G. T. Meaden. Proc. Roy. Soc. (London), Ser. A, vol. 276, p. 565. 1963.

COMPARISON OF THE ELECTRICAL RESISTIVITIES OF TWO PLUTONIUM SPECIMENS

From G. T. Meaden. Proc. Roy. Soc. (London), Ser. A, vol. 276, p. 564. 1963.

	About 200 ppm, Machined, Density = $19.625 \pm 0.02 \text{ g/cm}^3$		About 275 ppm, Cast to Shape, Density = $19.195 \pm 0.02 \text{ g/cm}^3$	
	ρ_T , $\mu\Omega\text{cm}$	$d\rho/dT$	ρ_T , $\mu\Omega\text{cm}$	$d\rho/dT$
1.4°K	20.75	0	49.25	0
10	22.6	+0.75	55.1	+1.21
20	39.3	2.36	72.4	2.21
40	102.6	3.12	117.8	1.81
60	140.1	1.10	142.0	0.72
80	152.5	0.37	152.0	0.28
100	155.5	+0.005	155.6	+0.005
150	153.6	-0.061	154.8	-0.040
200	150.9	-0.041	153.0	-0.034
250	148.9	-0.031	151.4	-0.031
273	148.1	-0.026	150.8	-0.026
300	147.5 ± 0.2		150.5 ± 0.2

Resistivity vs Temperature for Two Specimens of Plutonium in the α -Phase. Experimental points were too numerous to be drawn on the graph. The scatter was such that all the points lay within the thicknesses of the lines. From J. A. Lee *et al.* Cryogenics, vol. 1, p. 52. 1960.

Resistivity of α -Pu. From R. Lallement. Physics Letters, vol. 8, p. 166. 1964.

See section 602.

Electrical resistance, plotted as $100 R/R_{273}$ versus absolute temperature.
From T. A. Sandenaw in The Metal Plutonium, p. 153.

RESISTIVITY VALUES OF PLUTONIUM SPECIMENS (from smoothed curves)

From T. A. Sandenaw and R. B. Gibney,
J. Phys. Chem. Solids, vol. 6, p. 85. 1958.

Temperature, $^{\circ}\text{K}$	Resistivity, $\mu\Omega\text{-cm}$	
	Specimen 1 99.95 wt% Plutonium	Specimen 2 99.96 wt% Plutonium
25.8	-	68.5
27.2	61.1	-
50	128.0	128.0
100	157.0 ± 0.10	156.8 ± 0.06
150	153.5	153.5
273.15	146.3 ± 0.25	146.6 ± 0.04
380	141.0	141.8
420	107.5	109.5
475	107.0	110.0
505	106.2	109.5
590	105.0	109.3
625	97.7	103.0
725	98.5	104.0
735	99.4	104.8
774	107.1	114.0
787	-	114.1

TEMPERATURE COEFFICIENT OF RESISTIVITY OF PLUTONIUM SPECIMENS

From T. A. Sandenaw and R. B. Gibney, J. Phys. Chem. Solids, vol. 6, p. 86. 1958.

Temperature Range, $^{\circ}\text{K}$	Phase	$\frac{1}{\rho_{273}} \cdot \frac{d\rho}{dt} \times 10^{-4}$	
		Specimen 1	Specimen 2
27 - 50	α	$+194.80 \pm 0.30$	$+173.30 \pm 0.30$
126 - 293	α	-4.27 ± 0.04	-4.09 ± 0.04
302 - 381	α	-1.50 ± 0.10	-2.65 ± 0.10
420 - 470	β	-0.74 ± 0.12	-0.51 ± 0.10
503 - 590	γ	-0.62 ± 0.12	-0.39 ± 0.10
625 - 725	δ	$+0.51 \pm 0.10$	$+0.94 \pm 0.10$
736 - 747	δ'	$+3.99 \pm 0.40$	$+4.87 \pm 0.50$
761 - 775	ϵ	0.00 ± 0.20	0.00 ± 0.20

Absolute Thermoelectric Power. From J. A. Lee and R. O. A. Hall, Less-Common Metals, vol. I, p. 358, 1959.

The thermal e.m.f. of a plutonium-platinum thermocouple was measured between 20° and 630°C. The above figure shows the thermoelectric power of the plutonium-platinum couple, calculated from the slope of the e.m.f. temperature curve, and the absolute thermoelectric powers derived from this curve. The scatter in the results for the relative thermoelectric power was within $\pm 5\%$ from run to run, and sample to sample. Values for uranium are included for comparison. The implications of these results in relation to the form of the density of states/energy curve at the Fermi surface and thus in relation to Varley's criterion for a negative volume coefficient of expansion are discussed.

The Absolute Thermoelectric Power of High Purity Pu. From G. T. Meaden. *Proc. Roy. Soc. (London)*, Ser. A, vol. 276, p. 565. 1963.

The Thermoelectric Powers of Uranium and Plutonium as Functions of the Temperature. From G. T. Meaden and J. A. Lee. *Cryogenics*, vol. 2, p. 182. 1962.

Magnetic Susceptibility

From E. R. Jette, *J. Chem. Phys.*, vol. 23, p. 368. 1955. W. D. Wilkinson in *Extractive and Physical Metallurgy of Plutonium and Its Alloys*, pp. 15-20.

Phase	Typical Magnetic Susceptibility, $10^6 \chi_m$
α (at 25 °C)	532
β (middle of stability range)	553
γ (middle of stability range)	531
δ (middle of stability range)	515
δ' (middle of stability range)	515
ϵ (middle of stability range)	522

For the α -phase, susceptibility is practically independent of temperature, for each of the other phases it decreases with increasing temperature, particularly in the β -phase.

THE MAGNETIC SUSCEPTIBILITY OF PLUTONIUM*

From J. K. Dawson, *J. Chem. Soc. (London)*, Part III, p. 3394. 1954

Sample A			Sample B			Sample C		
Weight, 6.74 mg. Length, 5 mm.			Weight, 19.84 mg. Length, 2.8 mm.			Weight, 20.57 mg. Length, 1.6 mm.		
Purity, 99.66% excluding oxygen			Purity, 99.8% excluding oxygen,			Purity, 99.87% excluding oxygen		
(this sample had a rather thick yellow oxide coating).			but no appreciable oxidation visible.			(no appreciable oxidation visible).		
Temperature, °C	t	$10^6 \chi_g$	Temperature, °C	t	$10^6 \chi_g$	Temperature, °C	t	$10^6 \chi_g$
-183	-	4.20	19	-	5.23	20	-	2.52
-72	-	2.75	50.5	0.5	4.90	48	0.5	2.51
+27	1	2.68	79	0.5	4.55	76.5	0.7	2.51
62	1	2.62	103	0.5	4.18	97	1.5	2.50
84	1	2.63	110.5	0.5	4.07	101	0.7	2.50
86	2	2.62	118	1	4.01	115.5	1.5	2.49
110	1	2.62	120	0.5	4.02	117.5	0.5	2.49
114	1	2.62	120	1	4.06	120	2	2.58
116	1	2.65	120	2	4.08	140	1	2.61
118	1.5	2.68	129	1	3.88	140	17	2.61
118	2.5	2.70	143	0.5	3.52	167	1	2.61
125	1	2.69	155	0.5	3.28	186	1	2.59
127	1	2.69	166	0.5	3.02	196	0.5	2.59
133	0.5	2.70	176	0.5	2.80	203	0.7	2.59
135	1	2.70	185	0.5	2.67	216.5	0.7	2.52
156	1	2.68	195	0.5	2.52	239	0.5	2.53
175	1	2.70	196	0.5	2.51	282	0.5	2.52
190	0.5	2.69	200	0.5	2.40			
195	0.5	2.69	200	1	2.40			
201	1	2.71	210	0.5	2.33			
208	1	2.66	220	1	2.30			
234	0.5	2.57	248	0.3	2.26			
283	0.5	2.56	263	0.3	2.25			
294	0.3	2.51	280	0.3	2.24			
304	0.3	2.51	295	0.3	2.23			
327	0.3	2.52	304	0.3	2.19			
			318	0.3	2.19			
			341	0.3	2.19

The Thermomagnetic Behaviour of Plutonium. From J. K. Dawson, *J. Chem. Soc. (London)*, Part III, p. 3395. 1954.

Magnetic Susceptibility as a Function of Temperature for Samples of 99.9% or Purer Pu. From T. A. Sandenaw in *The Metal Plutonium*, p. 154.

Paramagnetic Susceptibilities. From J. A. Lee et al. in *Plutonium 1960*, p. 43.

204.2 Hall Effect

The Hall coefficient of alpha plutonium was found to be $+2.8 \times 10^{-13}$ at $388^{\circ}K$ and -6.5×10^{-13} (V-cm)/(A-G) at $78^{\circ}K$. The variation between these extreme temperatures was found to change gradually with temperature and the value changes sign at $190^{\circ}K$. No field dependence of Hall voltage was found, nor did the application of 11,500 G affect the resistivity maximum at $100^{\circ}K$. From M. B. Brodsky, *Phys. Rev.*, vol. 131, p. 137. 1963.

Hall Coefficient of Alpha Plutonium. From M. B. Brodsky, *Phys.*

Change in Hall Coefficient with Time. From M. B. Brodsky, *Phys.*

Temperature, °K	$R_H, m^3 \text{ Coul}^{-1} \times 10^{-11}$	
	$\lambda\text{-Pu}$	$\gamma\text{-Pu}$
293	+11.1 ± 1.0	+6.9 ± 0.5
77	+16.2 ± 1.5	-9.5 ± 0.6

Note: for comparison with previous data,

$$\frac{\text{volt-cm}}{\text{ampere-gauss}} = 10^2 \frac{m^3}{\text{coulomb}}$$

Viscosity

CALCULATED VISCOSITIES OF PLUTONIUM

From L. V. Jones *et al.*, *Am. Soc. Metals*,
Trans. Quart., vol. 55, p. 822. 1962.

Temperature, °C	Period, sec	Logarithmic Decrement	Density, g/cm ³	Viscosity, centipoise
First Series				
917	11.455	0.0711022	16.235	4.03
824	11.466	0.0733421	16.370	4.43
739	11.480	0.0758731	16.495	4.90
699	11.487	0.0792232	16.548	5.55
650	11.496	0.0812432	16.620	6.00
648	11.497	0.0808763	16.623	5.92
Second Series				
950	11.374	0.0689083	16.185	3.97
902	11.376	0.0697351	16.255	4.11
859	11.386	0.0706259	16.320	4.27
809	11.395	0.0719241	16.392	4.51
765	11.405	0.0727018	16.440	4.66
712	11.414	0.0749486	16.530	5.10
670	11.422	0.0766835	16.592	5.46
645	11.423	0.0792345	16.628	6.02

Viscosity of Plutonium (99.95% pure) as a Function of Absolute Temperature. From L. V. Jones *et al.*, *Am. Soc. Metals, Trans. Quart.*, vol. 55, p. 821. 1962.

The equation of the line in the above Figure is:

$$\log_{10} \eta = 0.672 \frac{1}{T} + 0.037$$

where:

$$\eta = \text{centipoise}$$

$$T = ^\circ\text{K} + 10^{-3}$$

Tensile Properties

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In the above figure, the straight line has a slope of 3200 cal/g-atom, the predicted value for H_η (A. V. Grosse, *J. Inorg. Nucl. Chem.*, Vol. 23, p. 333. 1961) and the points are experimental results obtained at Mound Laboratory. From A. V. Grosse, *J. Inorg. Nucl. Chem.*, vol. 25, p. 138. 1963. The viscosity η of plutonium, in poises, at a temperature T , in °K, is expressed by the equation:

$$\eta = 10.29 \cdot 10^{-3} \exp(3200/RT).$$

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CHEMICAL ANALYSIS OF PLUTONIUM STUDIED

	Al	Ca	Cr	Cu	Fe	Mg	Mn	Ni	Si	C	O ₂	H ₂	N ₂	Total	Number of Samples
Minimum	<2	2	5	<2	152	5	5	10	2	40	<10	2	1	-	-
Maximum	200	200	250	100	1625	100	100	500	200	550	160	37	92	-	-

TENSILE PROPERTIES OF PURE PLUTONIUM

From H. R. Gardner et al, p. 1081, Second Geneva Internat. Conf., vol. 6, p. 688, 1958.

	Ultimate Strength, psi	Yield Strength 0.02% Offset, psi	Modulus of Elasticity, 10^6 psi	Modulus of Resilience, in.-lb./in. ³	Diamond Pyramid Hardness (10 kg Load)	Density, g/cm ³	Testing Temperature, °C	Total Impurity Content, ppm	Number of Specimens Tested
0.250 in. Diameter - As Cast and Cold Treated									
Minimum	43,800	30,600	11.5	9.1	250	19.29	29	420	-
Maximum	77,200	45,800	14.6	41.2	283	19.58	35	1129	-
Average	62,800	39,300	13.6	23.5	262	19.51	31	975	15
0.250 in. Diameter - As Cast, Delta Annealed and Cold Treated									
Minimum	43,700	33,800	11.4	18.8	250	19.41	28	500	-
Maximum	74,300	42,000	14.5	45.0	277	19.58	34	1882	-
Average	61,000	38,700	12.8	28.6	259	19.51	31	1091	10
0.500 in. Diameter - As Cast and Cold Treated									
Minimum	47,500	32,700	13.6	11.6	260	19.41	31	525	-
Maximum	63,700	40,300	14.9	21.8	276	19.56	37	2510	-
Average	59,100	35,300	14.1	16.3	269	19.49	34	1514	8
0.500 in. Diameter - As Cast, Delta Annealed and Cold Treated									
Minimum	60,500	36,200	12.9	11.7	266	19.05	30	704	-
Maximum	65,300	43,200	14.2	22.9	275	19.47	37	1610	-
Average	63,100	38,900	13.6	18.2	270	19.33	34	1254	3

Stress Strain Relationship for Plutonium (99.4% Pu) at 32°C Cold Treated at -23°C after Casting.

From H. R. Gardner et al, p. 1081, Second Geneva Internat. Conf., vol. 6, p. 687, 1958.

Ultimate tensile strength: 50,000 to 51,800 psi (as-cast, unmachined, α Pu)

Yield strength: 45,000 psi (α Pu)

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 15.

Effect of Temperature on Stress-Strain Curves for Alpha-Plutonium in Tension. From H. R. Gardner. Unpublished Data.

DIRECT HEATING CURVES

From C. T. Horton and B. J. Ward in Plutonium 1960, p. 507.

Testing Temperature, °C	Heat Treatment	U. T. S., ton/in. ²	Elongation, %
25	None	21.6	<1
25	None	26.9 [†]	<1
25	None	14.7	<1
100	Held for 20 min	14.98	<1
130	Held for 2 h	11.68	3
130	Held for 30 min	13.54	4
140	Held for 20 min	8.9	3
160	Held for 25 min	4.94	150
175	Held for 1 h, 30 min	2.05	212
175	Held for 25 min	2.2	256
175	Held for 1 h, 30 min	2.62	224
175	Held for 25 min	2.61	240
175	Held for 30 min	2.64	(55) [‡]
175	Held for 30 min	2.17	350
200	Held for 30 min	1.49	344

TESTS AFTER β - PHASE ANNEAL

(held at 175 °C for 45 min)

175	Tested	2.62	224
150	Cooled to 150 °C. Tested	4.32	168
140	Cooled to 140 °C. Tested	6.12	154
130	Cooled to 130 °C. Tested	6.83	180
120	Cooled to 120 °C. Tested	7.08	78
100	Cooled to 100 °C. Tested	9.53	80
90	Cooled to 90 °C. Tested	13.95	60

TESTS IN γ - AND α -PHASES

260	Held for 30 min	3.5	36
400	Held for 30 min	0.25	30

[†] Strain rate 0.006/min (0.02/min in all other tests).

[‡] Surface defect in specimen.

EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF α -PHASE PLUTONIUM*

From H. R. Gardner and L. B. Mann in Plutonium 1960, p. 522.

	Test Temperature, °C	Ultimate Strength, lb/in. ²	0.01% Yield Strength, lb/in. ²	Modulus of Elasticity, 10 ⁶ lb/in. ²	Elongation, ⁺ %	Reduction in Area, %	Number of Samples Tested
Min	-30	52500	46700	14.0	0.016	----	4
Max		63300	56800	15.2	0.020	----	
Avg		57300	50300	14.7 (12.7) ⁺⁺	0.018	----	
Min	30	47800	28200	13.5	0.054	----	5
Max		56800	35600	14.8	0.077	----	
Avg		50900	32100	14.3	0.068	----	
Min	70	42900	14900	12.6	0.41	----	2
Max		44600	15600	12.7	0.45	----	
Avg		43800	15200	12.6	0.43	----	
Min	100	29100	11800	8.5	0.91	----	3
Max		38700	14100	9.4	1.08	----	
Avg		35100	13300	9.0 (9.2) ⁺⁺	1.00	----	
Min	110	-----	11600	9.0	-----	----	2
Max		-----	13000	10.9	-----	----	
Avg		33100	12300	10.0	-----	----	

* Testing speed: 0.015 in./min.

⁺ Based on 1-in. gauge length.

⁺⁺ Determined with Martens Extensometer.

EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF β -, γ - AND δ -PHASES*From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 523.

	Test Temperature, °C	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Modulus of Elasticity, 10 ⁶ lb/in. ²	Elongation, + %	Reduction in Area, %	Number of Samples Tested	Phase
Min		11700	10240	2.0	272.0	100.0		
Max	130	12500	10570	3.9	316.0	100.0	2	β
Avg		12100	10400	3.0	294.0	100.0		
Min		5500	3720	---	519.0	100.0		
Max	160	5830	4380	---	621.8	100.0	3	β
Avg		5620	3950	---	570.4	100.0		
Min		3550	2540	---	481.3	100.0		
Max	180	3600	2600	---	525.0	100.0	2	β
Avg		3580	2620	---	503.2	100.0		
Min		2950	1730	1.4	271.5	93.5		
Max	190	3590	2630	1.7	406.2	100.0	6	β
Avg		3280	2210	1.6	325.9	97.8		
Min		2730	1950	---	93.8	60.2		
Max	200	3390	2630	---	151.0	97.1	6	β
Avg		2940	2210	---	121.0	82.1		
Min		3330	3250	1.8	37.5	61.0		
Max	230	4990	4210	1.8	65.8	92.5	7	γ
Avg		4420	3860	1.8	50.0	75.0		
Min		2500	2340	---	33.0	64.0		
Max	265	4750	3660	---	84.4	84.7	7	γ
Avg		3470	2900	---	57.2	77.0		
Min		1540	1360	0.9	37.5	57.9		
Max	300	2630	2100	1.2	68.8	98.6	8	γ
Avg		2020	1650	1.0	50.1	82.8		
Min		837	731	0.35	65.8	97.5		
Max	325	953	848	0.40	68.8	98.4	2	δ
Avg		895	790	0.38	67.3	98.0		

* Testing speed: 0.015 in./min.

+ Based on 1 in. gauge length.

Effect of Test Temperature on Alpha Phase Elongation (Test speed 0.015 in./min). From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 522.

Effect of Temperature on Tensile Strength. * Taken at point of departure from linearity on load-displacement curve, approximates a 0.2% offset yield strength. From: (1) P. M. French. Personal Communication;

Horton-Ward Tensile Data on Beta Phase Rolled Sheet. From C. T. Horton and B. J. Ward in *Plutonium* 1960, pp. 499-512.

From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 524.

(1) From P. M. French. Personal Communication.

EFFECT OF TESTING SPEED ON α -PHASE STRENGTH

From H. R. Gardner and I. B. Mann, in *Plutonium* 1960, p. 530.

Testing Speed, in./min.	Sample Number	30°C				Sample Number	110°C			
		Density, g/cm ³	Total Impurity, ppm	Ultimate Strength, lb/in. ²	0.01% Yield Strength, lb/in. ²		Density, g/cm ³	Total Impurity, ppm	Ultimate Strength, lb/in. ²	0.01% Yield Strength, lb/in. ²
0.002	19-9-1A	19.56	439	42600	23000	19-4-11	19.53	384	21500	-
	19-9-1B	19.56	439	44800	24600	19-4-10	19.53	384	23200	7800
	19-11-2G	19.47	1476	51300	35300					
0.015	19-5-8N	19.60	377	56800	35600					
	19-4-2P	19.43	780	50500	-	19-3-4G	19.51	328	33100	13000
	19-3-4E	19.51	328	47800	-					
	19-9-1C	19.56	439	-	29300	19-3-4H	19.51	328	-	11700
	19-3-4F	19.51	328	48100	28200	-	-	-	-	-
0.060	19-9-2E	19.49	380	54800	31800	19-5-3A	19.48	504	33400	12800
	19-9-4L	19.53	468	49200	29700	19-5-3B	19.48	504	37400	-
	19-9-6U	19.52	616	50700	25700	19-4-1M	19.53	384	32600	13400
0.250	19-9-3K	19.56	295	47000	-	19-5-3C	19.48	504	39500	-
	19-9-5Q	19.55	616	56500	28100	19-5-3D	19.58	504	38600	-
	19-9-6V	19.52	616	54000	36600	19-4-1L	19.53	384	33300	-
1.0	19-9-6X	19.52	616	51700	-	19-5-6G	19.57	486	31500	-
	19-9-6Z	19.52	616	46800	-	19-5-5E	19.60	295	29800	-

*Unlike the specimens tested at faster speeds at this temperature, the load dropped off gradually just before failure indicating that some necking may have taken place. However, the degree of necking was so small that it could not be measured with a micrometer caliper.

EFFECT OF TESTING SPEED ON β - AND γ - PHASE TENSILE PROPERTIES

From H. R. Gardner and I. B. Mann, in *Plutonium* 1960, p. 533.

Specimen Number	Test Speed, in./min	Density, g/cm ³	Total Impurity Content, ppm	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Elongation,* %	Reduction in Area, %
19-9-5L	0.002	19.54	326	3400	2550	-	-
β-phase - 160 °C							
19-9-3H	0.015	19.56	295	5500	3760	-	-
19-9-7C	0.015	19.56	347	5520	4380	621.8	100
19-5-7J	0.015	19.52	321	5830	3720	519.0	100
19-10-2C	0.060	19.52	570	8840	6480	406.2	100
19-10-5M	0.060	19.54	326	8170	5920	315.6	100
19-10-2D	0.250	19.52	570	12900	10200	308.2	98.9
19-10-1A	0.250	19.54	438	11900	9600	196.9	98.3
19-10-2E	1.0	19.52	570	18800	14800	78.1	61.1
19-10-1B	1.0	19.54	438	18600	15700	143.7	79.0
γ-phase - 265 °C							
19-11-1C	0.002	19.60	412	3250	2280	75.0	90.9
18-10-1S	0.015	19.46	219	3610	2960	37.5	-
18-10-3B	0.015	19.53	935	4750	-	37.5	82.7
18-10-4G	0.015	19.56	388	4160	3650	33.0	83.2
19-5-5F	0.015	19.60	295	2800	2340	82.8	84.7
19-9-8E	0.015	19.56	553	2580	2440	84.4	71.2
19-9-8H	0.015	19.56	553	2500	2340	84.4	76.0
19-9-4M	0.060	19.53	468	3280	3100	44.0	49.4
19-10-5N	0.060	19.54	326	4240	3540	40.7	57.4
19-11-3J	0.060	19.55	1277	4200	3270	64.1	99.0
19-9-4N	0.250	19.53	468	3710	3520	50.0	52.3
19-10-5D	0.250	19.54	326	4590	3980	46.9	69.6
19-11-3H	0.250	19.55	1277	5200	4600	31.3	85.6
19-9-4O	1.0	19.53	468	4160	4050	37.5	38.0
19-11-1B	1.0	19.60	412	5300	5070	53.2	76.7
19-11-3K	1.0	19.55	1277	5350	5030	43.7	93.2

* Based on 1-in. gauge length

Effect of Testing Speed on α -Phase Tensile Strength. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 531.

Effect of Testing Speed on Beta Phase Properties at 130, 160, and 190°C. From H. R. Gardner and I. B. Mann. HW-65019. A portion of this figure appears in H. R. Gardner and I. B. Mann in *Plutonium* 1960, Fig. 10.36, p. 532.

The Effect of Strain Rate on the Compression Stress-Strain Curves for Alpha Plutonium at Room Temperature. (Fine grained polycrystalline cylinders, 500 ppm total impurities.)

Stress-strain compression tests were run in an oil bath at temperatures from 24°C to 100°C and at head speeds from 0.005 to 0.5 cm/min. Yield stress varies inversely with temperature. Total deformation in compression ranged from 20% at 24°C to 80% at 100°C.

From S. E. Bronisz and A. E. Gorum, *J. Nucl. Mater.*, vol. 2, p. 353, 1960.

Strain Aging Yield Points Observed in Alpha Plutonium Tested in Compression at 100°C at a Head Speed of 2.0 in/min. From S. E. Bronisz, *J. Nucl. Mater.*, vol. 9, p. 104, 1963.

The Effect of Strain Aging on the Nominal Stress-Strain Curves of Alpha Plutonium Tested in Compression at 24°C at a Head Speed of 0.02 in/min. From S. E. Bronisz, *J. Nucl. Mater.*, vol. 9, p. 104, 1963.

The Effect of Testing Temperature on the Compression Yield Strength of Alpha Plutonium at Various Testing Speeds. From S. E. Bronisz, *J. Nucl. Mater.*, vol. 9, p. 104, 1963.

The Effect of Testing Speed on the Yield Strength of Alpha Plutonium at Various Temperatures. From S. E. Bronisz, *J. Nucl. Mater.*, vol. 9, p. 104. 1963.

CHEMICAL ANALYSES OF PLUTONIUM USED FOR COMPRESSION TESTING

From S. E. Bronisz, *J. Nucl. Mater.*, vol. 9, p. 102. 1963.

	Calcium Reduced Plutonium	Electrorefined Plutonium, As Deposited	Electrorefined Plutonium, Once Remelted	Electrorefined Plutonium, Thrice Remelted
Total Impurities	480	115	185	227

YIELD STRENGTH AND MODULUS OF ELASTICITY IN COMPRESSION* AT 30°C

From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 538.

Specimen Number	0.01% Yield Strength, lb/in. ²	Modulus of Elasticity, 10 ⁶ lb/in. ²	Density, g/cm ³	Diamond Pyramid Hardness, 10 kg Load
18-8-1C	47300	13.9	19.49	261
18-8-1D	39600	14.5	19.55	-
18-8-4O	34200	14.7	19.56	-
18-8-4P	32100	14.2	19.56	259
18-8-5R	37500	14.0	19.55	258
Average	38200	14.3	19.54	259

* Testing speed: 0.015 in./min; h/d: 5:5.

COMPRESSION PROPERTIES OF PLUTONIUM* AT 30 °C

From H. R. Gardner and I. B. Mann in *Plutonium* 1960, pp. 537-538.

Specimen Number	Density, g/cm ³	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Diamond Pyramid Hardness, 10 kg Load	Plastic Decrease in Length Prior to Failure†, %	Metal Group
Density Less Than 19.50 g/cm ³						
17-12-1G1	19.42	178600	-	272	-	1
17-12-1G2	19.42	175200	-	272	-	
18-1-1A	19.34	163900	-	255	-	2
18-1-1B	19.47	175600	-	255	-	3
18-1-4G1	19.43	177000	-	267	-	4
18-1-4G2	19.43	177800	-	267	-	
18-1-6L1	19.47	156600	-	265	-	5
18-1-6L2	19.47	149000	-	265	-	
18-1-7M1	19.43	163200	-	256	-	6
18-1-7M2	19.43	172000	-	256	-	
18-1-7N1	19.46	165600	-	275	-	7
18-1-7N2	19.46	164400	-	275	-	
Average ††	19.43	168500	-	260	-	-
Density Equal to or Greater than 19.50 g/cm ³						
18-1-3F1	19.55	177600	-	265	-	8
18-1-3F2	19.55	175600	-	265	-	
18-1-6K1	19.56	166800	-	256	-	9
18-1-6K2	19.56	169000	-	256	-	
18-8-1D1	19.55	168200	102400	-	21.3	10
18-8-1D2	19.55	164000	109100	-	18.6	
18-8-4P1	19.56	184000	103200	259	24.0	11
18-8-4P2	19.56	178000	109800	259	22.6	
18-8-5Q1	19.55	183000	99800	-	23.4	12
18-8-5Q2	19.55	181000	112700	-	23.4	
18-8-5Q3	19.55	189000	107600	-	25.0	
18-8-5R1	19.55	169200	109900	258	20.6	13
18-8-5R2	19.55	189100	101700	258	25.6	
19-7-3-G2	19.53	167500	113200	-	26.4	14
19-8-2-C5	19.55	178000	106300	-	20.3	15
Average ††	19.55	175000	107400	263	22.8	-

* Testing speed: 0.015 in./min.

† Determined from load-platen displacement curve at point of failure.

†† All average values were obtained by first finding the average within each metal group and then averaging these values for an overall average. This was done because the material tested in each metal group came from the same casting heat. It was felt that a more

COMPRESSIVE STRENGTH AND RELATED DATA FOR HIGH-DENSITY PLUTONIUM

From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 540.

Specimen Number	Test Temperature, °C	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Increase in Area, %	Plastic Decrease in Length, %	Density, g/cm ³	Total Impurity Content, ppm
19-7-3-E4	-30	194200	161600	-	4.7**	19.53	745
19-7-3-E5	-30	190300	160600	-	4.5**	19.53	745
††	30	175000	107400	-	22.7**	19.55	-
19-7-2-D5	73	-	74200	-	26.5**	19.54	324
19-7-3-E1	70	118400	80200	-	-	19.53	745
19-7-3-E2	110	78300	65400	-	18.3**	19.53	745
19-7-3-E3	110	77200	64800	-	-	19.53	745
19-5-4-B4	128	-	-	392	79.8†	19.59	266
19-5-4-A3	130	-	20900	409	79.9†	19.59	266
19-5-4-A4	130	-	24100	498	82.2†	19.59	266
19-6-4-H4	131	-	24600	497	83.3†	19.56	412
19-6-4-G1	130	-	17700	436	81.6†	19.56	412
19-5-4-B3	149	-	11650	557	84.8†	19.59	266
19-5-4-A2	149	-	12000	557	84.5†	19.59	266
19-5-4-C3	151	-	11970	592	85.2†	19.59	266
19-5-4-C1	176	-	8170	625	86.0†	19.59	266
19-5-4-C2	176	-	8770	625	85.5†	19.59	266
19-5-4-A1	189	-	6820	658	86.6†	19.59	266
19-5-4-D4	190	-	7130	658	86.3†	19.59	266
19-6-4-H3	191	-	6910	661	86.5†	19.56	412
19-4-3-C1	230	-	4930	945	89.1†	19.55	310
19-4-3-B1	231	-	5110	841	87.7†	19.55	310
19-5-4-B5	232	-	4530	800	88.5†	19.59	266
19-5-4-B2	266	-	3970	957	90.3†	19.59	266
19-6-4-H2	266	-	4340	942	90.3†	19.56	412
19-7-1-A3	300	-	3430	1145	91.4†	19.56	343
19-5-4B	300	-	3380	1353	92.6†	19.59	266
19-4-3-B2	300	-	3500	1196	92.2†	19.55	310
19-4-3A	330	-	816	1593	93.8†	19.55	310
19-7-1-A1	331	-	1265	1610	92.8†	19.56	343

* Testing speed: 0.015 in./min.

** Total plastic decrease in length was determined from load-platen displacement curve at point of failure.

† After exceeding the yield strength the load was increased at a rapid rate to 100,000 lb. The increase in area and decrease in length data were taken after unloading and cooling to room temperature.

†† A total of 15 specimens were tested at this temperature. The average values are reported.

Effect of Temperature on Average Compressive Strength for High Density Plutonium. Testing speed: 0.015 in./min. From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 539.

COMPRESSIVE STRENGTH AND RELATED DATA FOR LOW-DENSITY PLUTONIUM

From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 545

Specimen Number	Test Temperature, °C	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Increase in Area †, %	Plastic Decrease in Length, %	Density, g/cm ³	Total Impurity Content, ppm
††	30	168500	-	-	-	19.43	-
19-2-2-7	100	97500	68000	-	-	19.41	1467
19-2-2-10	100	90000	67000	-	-	19.41	1467
19-2-2-3	150	-	10880	-	-	19.41	1467
19-2-2-9	150	-	14120	-	-	19.41	1467
19-2-2-11	150	-	12500	-	-	19.41	1467
19-2-2-12	150	-	15300	599	-	19.41	1467
19-2-2-19	150	-	15300	613	86.1	19.41	1467
19-2-2-1	175	-	8750	-	-	19.41	1467
19-2-2-4	175	-	8160	683	86.8	19.41	1467
19-2-2-2	190	-	5870	-	-	19.41	1467
19-2-2-17	190	-	5900	725	87.7	19.41	1467
19-2-2-5	230	-	6120	958	89.3	19.41	1467
19-2-2-14	230	-	6830	907	89.2	19.41	1467
19-2-2-16	230	-	7490	853	89.2	19.41	1467
19-2-2-15	265	-	5400	1069	91.7	19.41	1467
19-2-2-18	265	-	4700	1110	91.7	19.41	1467
19-2-1-4A	300	-	2600	-	-	19.45	2300
19-2-1-3A	300	-	-	1072	92.7	19.45	2300
19-2-2-25	330	-	2350	1473	94.2	19.41	1467
19-2-1-1A	330	-	2575	-	-	19.45	2300

* Testing speed: 0.015 in./min.

† After exceeding the yield strength the load was increased at a rapid rate to 100,000 lb. The increase in area and decrease in length data were taken after unloading and cooling to room temperature.

†† A total of 12 specimens were tested at this temperature. The average values are reported.

EFFECT OF METAL QUALITY ON YIELD STRENGTH OVER A RANGE OF TESTING SPEEDS (Test Temperature, 175 °C)

From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 554.

Low-Quality Metal				
Testing Speed, in./min	Specimen Number	Yield Strength, lb/in. ²	Density, g/cm ³	Total Impurity Content, ppm
0.003	19-2-2-22	6650	19.41	1467
0.007	19-2-2-24	7650	19.41	1467
0.015	19-2-2-4	8700	19.41	1467
0.015	19-2-2-1	8960	19.41	1467
0.060	19-2-2-20	14480	19.41	1467
0.125	19-2-2-21	17190	19.41	1467
0.250	19-2-2-23	20400	19.41	1467
High-Quality Metal				
0.002	19-7-1-A-4	3900	19.56	343
0.002	19-7-1-A-5	3870	19.56	343
0.015	19-5-4-C-1	8170	19.59	266
0.015	19-5-4-C-2	8770	19.59	266
0.060	19-7-1-A-6	8930	19.56	343
0.060	19-7-1-B-1	8910	19.56	343
0.250	19-7-1-B-3	15600	19.56	343
0.250	19-7-1-B-4	14700	19.56	343
1.00	19-7-1-B-5	16900	19.56	343
1.00	19-7-1-B-6	20200	19.56	343

TOTAL PLASTIC DEFORMATION IN α-PHASE

From H. R. Gardner and I. B. Mann
in Plutonium 1960, p. 554.

Testing Speed, in./min	Total Plastic Decrease in Length, %			
	-30 °C	30 °C	70 °C	110 °C
0.002	7.3	27.7	23.3	15.7
0.015	4.7	26.4	26.5	18.3
	4.3	20.3	-	-
0.060	2.7	15.5	28.3	20.0
	2.3	18.8	-	18.3
0.250	3.0	21.0	24.7	12.0
	2.3	17.7	26.0	18.3
1.00	3.0	9.0	11.0	7.7
	2.3	9.0	-	7.7

* Testing speed: 0.015 in./min.

† Total plastic decrease in length determined from load-platen displacement.

Effect of Temperature on Total Plastic Deformation Prior to Fracture. From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 553.

Effect of Testing Speed on Total Plastic Deformation Prior to Fracture. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 553.

EFFECT OF TESTING SPEED IN α -, β - AND γ -PHASES ON COMPRESSIVE STRENGTH

From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 55L.

Testing Speed, in./min.	α -Phase								β -Phase	γ -Phase
	-30°C		29°C		70°C		110°C		175°C	265°C
	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Ultimate Strength, lb/in. ²	Yield Strength, lb/in. ²	Yield Strength, lb/in. ²	Yield Strength, lb/in. ²
0.002	190700	145200	142000	95300	95700	69000	63500	48100	3900	2620
	-	-	149000	95900	96000	69000	68600	46900	3870	-
0.015	190300	161600	178000	106300	118400	80200	77200	64800	8170	3970
	194200	160600	167500	113200	-	-	78300	65400	8770	4340
0.060	179800	158600	156750	123000	123200	85400	85000	64800	8930	3630
	186400	161000	165500	117200	125800	79000	85000	69500	8910	-
0.250	183200	158500	136500	112100	117800	83700	75400	68300	14700	4040
	184000	166000	147600	112800	114100	86000	75900	70400	15600	-
1.00	176800	140000	140100	111500	107000	-	77500	63500	16900	4420
	175200	139000	141300	107300	103400	76300	75250	61200	20200	4500

Effect of Testing Speed on Ultimate Strength in Compression. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 550.

Effect of Testing Speed on Yield Strength in Compression. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 552.

Effect of Temperature on Formability in Compression. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 546.

Effect of Metal Quality on Yield Strength in the β -, γ - and δ -Phases. Testing speed: 0.015 in/min. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 544.

Effect of Metal Quality on Yield Strength Test Temperature, 175°C. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 552.

Effect of Temperature on Average Compressive Strength for High Density Plutonium. *Yield Strength Determined as in Previous Figure. From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 539.

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Torsional and Shear Properties

Room temperature shear strength of α Pu:

from compression tests: 80,000 psi

from tensile tests of threaded joints: 35,000-45,000 psi

From A. S. Coffinberry et al. *Reactor Handbook*, 2nd ed., vol. 1, p. 266.

Tubular torsion specimens were cast, cold treated, and machined, then tested in a torsion testing machine at a speed of 0.01 RPM. A typical helicoidal fracture was obtained in each test bar.

The ultimate shear strength data and helicoidal fracture obtained indicate that Pu's ultimate tensile strength is less than its ultimate shear strength. Thus, failure under torsional loading occurs by tensile separation along a plane making a 45 degree angle with the plane of maximum shear.

It has been reported that the ratio of the true shear strength to true tensile strength is in the range of 1.1 to 1.3 for brittle metals such as cast iron. Using a ratio of 1.2 and a value of 50,900 psi for the true ultimate tensile strength of Pu, an estimate of 61,100 psi can be obtained for the true ultimate shear strength of Pu.

Specimen Number	Ultimate Shear Strength, psi	Density, g/cc	Total Impurity Content, ppm
19-6-4B	46,400	19.56	382
19-10-8A	54,700	19.55	694
19-10-8B	53,700	19.55	694
19-10-8C	57,800	19.55	694
Average	53,200	-	-
Average Ultimate Tensile Strength	50,900	19.53	520

* Test temperature, 30 °C. From H. R. Gardner, HW-66009

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Impact Strength

TENSION IMPACT DATA AT 30 °C

From H. R. Gardner and I. B. Mann in *Plutonium* 1960, p. 558.

Tension Impact Value, ft-lb	Density	Total Impurity Content, ppm
1.4	19.48	446
1.6	19.48	475
3.5	19.41	1755
4.2	19.41	1638
2.3	19.51	-
4.8	19.51	-
2.1	19.53	773
1.3	19.53	773
Average:		
2.6	19.48	976

Specimens were fabricated to 0.250 in. gage diameter and 1.5 in.

IMPACT TEST RESULTS

From H. R. Gardner, HW-70607.

Test Temperature, °C	Unnotched Charpy Specimens			V-Notched Charpy Specimens		
	Impact Energy, ft-lb		Number Tested	Impact Energy, ft-lb		Number Tested
	Average	Range		Average	Range	
-43	4.6	4.2 - 5.0	5	1.8	1.7 - 1.8	2
30	6.5	4.5 - 8.8	9	1.9	-	2
70	5.6	5.5 - 5.7	2	-	-	-
100	6.9	5.1 - 10.0	10	3.1	2.7 - 3.5	3
130	9.9	8.2 - 12.9	3	1.9	1.8 - 2.0	2
175	7.7	6.5 - 9.0	3	1.8	1.7 - 2.0	4
230	*	-	1	11.1	9.9 - 13.5	5
300	-	-	-	11.0	9.0 - 13.8	4
330	-	-	-	*	-	1

* Specimen bent in U-shape and did not break

UNNOTCHED CHARPY IMPACT TEST DATA SEGREGATED ON BASIS OF IRON CONTENT

From H. R. Gardner, HW-70607

Test Temperature, °C	High Iron: 1200 ppm Eutectic Present			Low Iron: 100 ppm Eutectic Absent		
	Impact Energy, ft-lb		Number Tested	Impact Energy, ft-lb		Number Tested
	Average	Range		Average	Range	
30	7.5	5.3 - 8.8	4	5.7	4.5 - 7.8	5
100	7.7	5.7 - 10.0	6	5.8	5.1 - 6.2	4

From H. R. Gardner, Trans. Met. Soc. AIME,
vol. 224, p. 201. 1962.

Iron	Impurities	Total	Density, g/cc	Iron Class.
268		431	19.67	Low
L50		288	19.64	Low
1142		1377	19.54	High
80		303	-	Low
1200		1560	19.52	High

Effect of Temperature on Unnotched and Notched Impact Properties of Plutonium. From H. R. Gardner, Trans. Met. Soc. AIME, vol. 224, p. 201. 1962.

Creep

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CREEP DATA

From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 557.

Specimen Number	Test Temperature, °C	Applied Stress, lb/in. ²	Secondary Creep Rate, %	Total Strain (10 ⁻⁴)	Duration of Test, hr	Density, g/cm ³	Total Impurity Content, ppm
18-10-12A	31.0	10000	15.0	4.2	1370	19.43	520
19-3-2A	26.0	8000	15.2	4.3	1850	19.49	486
19-3-2A	42.3	8000	28.2 †	-	870	19.49	486
18-10-12B	100.0	10000	330.0	41.0	570	19.43	425

* 10⁻⁴ 10000 hr.

† Obtained during 870 hr testing period after raising temperature to 42.3 °C from 26.0 °C

α -Plutonium Creep Curve. From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 557.

α -Plutonium Creep Curves. From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 557.

Creep rate (under a 6 psi load)

Delta Pu (450°C) No creep occurs in 2 hr

Epsilon Pu ($600 \pm 5^{\circ}\text{C}$) $1.3 \times 10^{-3}/\text{hr}$

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, pp. 1-24.

CHEMICAL ANALYSES AND DENSITY DATA

From H. R. Gardner, J. Nucl. Mater., vol. 10, p. 259. 1963.

	Al	Cr	Cu	Fe	Mg	Mn	Ni	Si	C	Density, g/cm^3
Minimum	<2	15	<5	138	2	10	5	<2	120	19.40
Maximum	20	40	20	1040	25	40	200	<5	500	19.64
Average	10	30	11	629	11	24	83	<5	310	19.53

Reported in parts per million.

The fatigue results which fall on or near the curve were obtained with good quality specimens in which microcracking had been eliminated by the addition of 600-1000 ppm iron. Those specimens failing below 20,000 psi and from 10^4 to 3.5×10^4 cycles contained moderate microcracking. All specimens failing below 20,000 psi and 10^4 cycles contained extensive microcracking, particularly those failing on the first cycle shown at the left hand side of the figure.

The fatigue limit appears to be approximately 14,000 psi which is of the order of 20% of the ultimate tensile strength.

From H. R. Gardner, J. Nucl. Mater., vol. 10, p. 259. 1963.

Compiled by H. R. Gardner, Hanford Atomic Products Operation, General Electric Co., 1964.

Microhardness of α Pu = 223-250 kg/mm²
 From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 15.

Elastic Properties

ELASTIC CONSTANTS AT VARIOUS TEMPERATURES

P. F. T. Linford and A. E. Kay, Personal Communication.

Temperature, °C	Phase	Modulus of Elasticity, 10 ⁶ psi	Shear Modulus, 10 ⁶ psi	Poisson's Ratio	Bulk Modulus, 10 ⁶ psi
-170	Alpha	17.35	7.26	0.20	9.63
- 80	Alpha	16.00	6.69	0.20	8.90
0	Alpha	14.65	6.17	0.20	8.18
20	Alpha	14.00	6.08	0.16	6.88
60	Alpha	13.30	5.80	0.15	6.33
100	Alpha	12.40	5.45	0.14	5.76
140	Beta	5.90	2.29	0.29	4.68
170	Beta	5.58	2.20	0.27	4.05
200	Beta	5.37	2.12	0.27	3.89
220	Gamma	5.28	2.13	0.24	3.38
260	Gamma	4.94	1.97	0.25	3.29
300	Gamma	4.58	1.52	0.25	3.06
330	Delta	2.49	0.87	0.43	5.9
380	Delta	2.45	0.84	0.45	8.1
430	Delta	2.39	0.81	0.42	4.9

ROOM TEMPERATURE (20 °C) ELASTIC CONSTANTS

P. F. T. Linford and A. E. Kay, Personal Communication.

Specimen	Remarks	Density, g/cm ³	Modulus of Elasticity, 10 ⁶ psi	Shear Modulus, 10 ⁶ psi	Poisson's Ratio	Bulk Modulus, 10 ⁶ psi
E1	As-Cast	19.50	14.15	6.02	0.175	7.26
E3	As-Cast	19.50	14.17	6.02	0.177	7.32
E4	As-Cast	19.48	14.26	6.03	0.182	7.47
F2	As-Cast	19.45	14.00	6.00	0.171	7.08
F3	As-Cast	19.50	-	6.08	-	-
E5	High Density	19.71	14.60	6.12	0.186	7.74
E6	High Density	19.74	14.73	-	-	-

Pu 99.5% pure or better, density 19.35 g/cm³

Velocity of longitudinal waves= 2370 ± 7 m/sec

Velocity of transverse waves = 1453 ± 4 m/sec

Young's modulus = (9.825 ± 0.075) × 10¹¹ dynes/cm²

Modulus of transverse rigidity = (4.080 ± 0.040) × 10¹¹ dynes/cm²

Poisson's ratio = 0.199 ± 0.002

Compressive strength = (5.44 ± 0.06) × 10¹¹ dynes

- from J. J. DeCadenet in Plutonium

1960, p. 107.

SUMMARY OF RESULTS AND EXTRAPOLATION TO X-RAY DENSITY AT 30 °C

From H. L. Laquer in The Metal Plutonium, p. 174.

Quantity	Symbol	Range of Observed Values	Extrapolation to X-Ray Density	Units
Density	ρ	(18.8) 19.0 - 19.72	19.79 ₀	gm/cm ₃
Rod velocity	v_O	2.17 - 2.26	2.25 ₅ ± 0.01 ₅	x10 ⁵ cm/sec
Inf. med. velocity	v_L	2.27 - 2.30	2.31 ₃ ± 0.01	x10 ⁵ cm/sec
Shear velocity	v_T	(1.37) 1.40 - 1.49	1.49 ₀ ± 0.007	x10 ⁵ cm/sec
Poisson's ratio	ν	0.14 - 0.20	0.14 ₅ ± 0.01	.
Young's modulus	E	{ 8.9 - 10.1	10.0 ₂ ± 0.1 ₃	x10 ¹¹ dynes/cm ²
		{ 12.9 - 14.6	14.5 ₄ ± 0.2	x10 ⁶ psi
Shear modulus	μ	{ (3.5) 3.8 - 4.3	4.37 ₆ ± 0.04 ₁	x10 ¹¹ dynes/cm ²
		{ (5.1) 5.5 - 6.2	6.34 ₆ ± 0.06 ₁	x10 ⁶ psi
Adiabatic compressibility	χ_s	{ 1.8 - 2.2	2.1 ₅ ± 0.1 ₄	x10 ⁻¹² cm ² /dyne
Isothermal compressibility	χ_T	{ 1.8 - 2.2	2.1 ₅ ± 0.1 ₄	x10 ⁻⁶ (atm) ⁻¹
		2.1 - 2.5	2.4 ₁ ± 0.2	x10 ⁻¹² cm ² /dyne

APPROXIMATE TEMPERATURE COEFFICIENTS AT 30 °C
Reciprocal °C x 10⁵

From H. L. Laquer in The Metal Plutonium, p. 178.

Quantity	Low Purity	High Purity	Source
L	+5.127	+5.127	Measured (10)
ε	-15.381	-15.381	Derived from above
v _O	-56 ± 4	-93 ± 7	Measured
v _T	-65 ± 5	-99 ± 5	Measured
v _L	-48 ± 6	-88 ± 11	Derived
σ	+138 ± 70	+90 ± 130	Derived
E	-127 ± 8	-201 ± 14	Derived
μ	-145 ± 10	-213 ± 10	Derived
χ _S	+68 ± 30	+166 ± 70	Derived

PRESSURE COEFFICIENTS, 0 - 2000 BARS, ° AT 30 °C
Reciprocal Bars x 10⁶

From H. L. Laquer in The Metal Plutonium, p. 179.

L	-0.72 ₉ ± 0.01 ₄	Derived
ε	+2.18 ₈ ± 0.04 ₂	Derived
v _O	+7.7 ₇ ± 0.5 ₅	Derived
v _T	+6.1 ₂ ± 0.6 ₅	Measured
v _L	+9.2 ₁ ± 0.4 ₂	Measured
σ	+26. ₆ ± 6. ₆	Derived
E	+17. ₇ ± 1. ₁	Derived
μ	+14. ₄ ± 1. ₃	Derived
χ _S	-28. ₄ ± 2. ₉	Derived

* 1 bar = 10⁶ dynes/cm² = 0.98692 atm = 14.504 psi.

ELASTIC PROPERTIES AND SOUND VELOCITIES OF ALPHA PLUTONIUM AT 30 °C

From H. L. Laquer in Metallurgy and Fuels, Progress in Nuclear Energy, series V, vol. 1, p. 383.

Property	Value *	Pressure Coefficient †, x 10 ⁻⁶ /bar	Temperature Coefficient ††, x 10 ⁻⁵ /°C
1. Young's modulus	(9.93 ± 0.03) x 10 ¹¹ dynes/cm ² (14.40 ± 0.04) x 10 ⁶ lb/in. ²	+18 ± 1	-127 ± 8
2. Shear modulus	(4.34 ± 0.01) x 10 ¹¹ dynes/cm ² (6.29 ± 0.01) x 10 ⁶ lb/in. ²	+14 ± 1	-145 ± 10
3. Poisson's ratio	0.15 ± 0.01	+27 ± 7	+138 ± 71
4. Compressibility	(2.14 ± 0.02) x 10 ⁻⁶ /bar	-28.5 ± 3	+68 ± 32
5. Rod velocity (v _O)	(2.244 ± 0.004) x 10 ⁵ cm/sec	+7.8 ± 0.6	-56 ± 4
6. Shear velocity (v _T)	(1.483 ± 0.002) x 10 ⁵ cm/sec	+6.1 ± 0.7	-65 ± 5
7. Infinite medium velocity (v _L)	(2.301 ± 0.003) x 10 ⁵ cm/sec	+9.2 ± 0.4	-48 ± 6

* Measurements by pulse technique on sample having ρ = 19.722 ± 0.005 at 30 °C.

† Measurements by pulse technique on sample having ρ = 19.62 at 30 °C.

†† Measurements by resonance technique on two different samples (ρ = 19.5 and 19.6).

ROOM TEMPERATURE ELASTIC CONSTANT DATA FROM VARIOUS SOURCES

P. F. T. Linford and A. E. Kay, Personal Communication

Source	Density, g/cm ³	Modulus of Elasticity, 10 ⁶ psi	Shear Modulus, 10 ⁶ psi	Poisson's Ratio	Bulk Modulus, 10 ⁶ psi	Adiabatic Compressibility, 10 ⁻⁷ in. ² /lb	Isothermal Compressibility, 10 ⁻⁷ in. ² /lb	Method
Linford (1) (mean as-cast)	19.49	14.15	6.01	0.176	7.29	1.36	1.51	Resonance
Linford (high density)	19.71	14.60	6.13	0.186	7.75	1.30	1.44	Resonance
Laquer (2) (high density)	19.72	14.40	6.30	0.15	6.77	1.48	1.62	Pulse
DeCadenet (3) (as-cast)	19.35	14.25	5.93	0.199	7.90	1.27	1.41	Pulse
Bridgman (4)	-	-	-	-	-	-	1.38	Compressibility
Robinson (5)	19.6	-	-	-	-	-	1.32	Compressibility
Gardner (6)	19.53	14.32	-	-	-	-	-	Tensile Test

(1) P. F. T. Linford, Personal Communication.

(2) H. L. Laquer, quoted in Metallurgy and Fuels, Progress in Nuclear Energy, series V, vol. 1, p. 383. 1956.

(3) J. J. DeCadenet, in Plutonium 1960, p. 107.

(4) P. W. Bridgman, J. Appl. Phys., vol. 30, p. 214. 1959.

(5) A. C. Robinson, Personal Communication.

(6) H. R. Gardner, in Plutonium 1960, pp. 513-570.

CHANGE OF MODULUS WITH TEMPERATURE

P. F. T. Linford and A. E. Kay. Personal Communication

Specimen	Δ Modulus		Alpha Phase, - 170 $\rightarrow$ 20 $^{\circ}$ C	Alpha Phase, 20 $\rightarrow$ 110 $^{\circ}$ C	Beta Phase, 140 $\rightarrow$ 210 $^{\circ}$ C	Gamma Phase, 230 $\rightarrow$ 310 $^{\circ}$ C	Delta Phase, 330 $\rightarrow$ 440 $^{\circ}$ C
	ΔT , psi/ $^{\circ}$ C						
F2	ΔE	-	-	$- 2.03 \times 10^4$	$- 0.75 \times 10^4$	$- 0.88 \times 10^4$	$- 0.108 \times 10^4$
	ΔT						
F3	ΔG	-	-	0.858×10^4	0.290×10^4	0.38×10^4	-
	ΔT						
E2	ΔE	$- 1.68 \times 10^4$	-	-	-	-	-
	ΔT						
E2	ΔG	$- 0.65 \times 10^4$	-	-	-	-	-
	ΔT						

ELASTIC CONSTANT DATA CORRECTED FOR POROSITY

P. F. T. Linford and A. E. Kay. Personal Communication

Specimen	Density, g/cm ³	Modulus of Elasticity, 10 ⁶ psi	Shear Modulus, 10 ⁶ psi	Bulk Modulus, 10 ⁶ psi	Isothermal Compressibility, 10 ⁻⁷ in. ² /lb
E3	19.50	14.63	6.22	7.62	1.45
E5	19.71	14.73	6.22	7.80	1.42

ROOM TEMPERATURE (20 $^{\circ}$ C) DATA

From A. E. Kay and P. F. T. Linford in Plutonium 1960, p. 56.

Specimen	Remarks	Density, g/cm ³	Length, cm	Diameter, cm	Young's Modulus	Rigidity Modulus	Poisson's Ratio	Bulk Modulus
					E, dyn/cm ² $\times 10^{-11}$	G, dyn/cm ² $\times 10^{-11}$	σ	K, dyn/cm ² $\times 10^{-11}$
E1	As-cast	19.50 $\pm$ 0.02	2.541	0.30	9.76 $\pm$ 0.01	4.15 $\pm$ 0.005	0.175 $\pm$ 0.005	5.00 $\pm$ 0.03
E3	As-cast	19.50	2.542	0.30	9.77	4.15	0.177	5.04
E4	As-cast	19.48	2.250	0.30	9.84	4.17	0.181	5.14
E5	High density	19.71	2.021	0.31	10.04	4.23	0.186	5.33
E6	High density	19.74	1.502	0.30	10.17	-	-	-
E6	After 1 cycle	19.5 *	1.53	-	9.55	-	-	-
E6	After 2 cycles	19.3 *	1.57	-	8.75	-	-	-
E6	After 3 cycles	19.1 *	1.57	-	-	3.45	-	-

* Estimated

Variation of E and G with Temperature. From A. E. Kay and P. F. T. Linford in Plutonium 1960, p. 57.

ELASTIC CONSTANTS AT VARIOUS TEMPERATURES

From A. E. Kay and P. F. T. Linford in Plutonium 1960, p. 58.

Temperature, °C	Phase	E, dyn/cm ² x 10 ⁻¹¹ 3rd Cycle	G, dyn/cm ² x 10 ⁻¹¹ 4th Cycle
21.5	α	8.75	3.45
60	α	8.34	3.32
100	α	7.91	3.14
150	β	3.97	1.42
190	β	3.76	1.35
230	γ	3.57	1.33
270	γ	3.18	1.24
310	γ	2.86	1.21

TEMPERATURE COEFFICIENTS

From A. E. Kay and P. F. T. Linford in Plutonium 1960, p. 58.

Specimen	Remarks	Modulus	α -phase	β -phase	γ -phase
E6	3rd Cycle	Young's	- 126 x 10 ⁻⁵ /°C	- 165 x 10 ⁻⁵ /°C	- 251 x 10 ⁻⁵ /°C
E6	4th Cycle	Rigidity	- 150 x 10 ⁻⁵ /°C	- 167 x 10 ⁻⁵ /°C	- 183 x 10 ⁻⁵ /°C

ELASTIC CONSTANTS AND DEBYE TEMPERATURES

From A. E. Kay and R. G. Loasby,

Phil. Mag., eighth series, vol. 9, no. 97, p. 44. 1964.

Phase	Young's Modulus, x 10 ⁻¹¹ dyne/cm ²	Poisson's Ratio	Bulk Modulus x 10 ⁻¹¹ dyne/cm ²	Debye Temperature, °K
α	12.6	0.20	7.0	192
β	6.1	0.28	4.62	133
γ	6.1	0.25	4.06	136
δ	5.1	0.33	5.1	120

308.1

Young's Modulus

- Gardner 14.7×10^6 psi
From H. R. Gardner and I. B. Mann in Plutonium 1960, p. 522.
- Laquer $(12.9 \text{ to } 14.6) \times 10^6$ psi
 $(8.9 \text{ to } 10.1) \times 10^{11}$ dyne/cm²
From H. L. Laquer in The Metal Plutonium, p. 174.
- Konobeevsky 9.1×10^3 kg/cm²
From S. T. Konobeevsky et al. p/2230, Proc. Second Geneva Internat. Conf., vol. 6, p. 194. 1958.
- Kay and Loasby 12.6×10^{11} dyne/cm²
From A. E. Kay and R. G. Loasby. Phil. Mag., eighth series, vol. 9, no. 97, p. 44. 1964.

ELASTIC MODULUS OF ALPHA PLUTONIUM

From A. S. Coffinberry et al. Reactor Handbook, 2nd ed., vol. I, p. 258.

Derived from tensile stress-strain curves 8.2×10^{11} dyne/cm² (11.9×10^6 psi)

A dynamic method 8.6×10^{11} dyne/cm² (12.5×10^6 psi)

Tensile tests $(14.0 \text{ to } 15.5) \times 10^6$ psi

Young's Modulus for Alpha Plutonium. From R. Lallement. Physics Letters, vol. 5, p. 182. 1963.

Young's modulus — room temperature, cast Pu

Tensile measurements 8.2×10^{11} dyne/cm²

Compression measurements 9.9×10^{11} dyne/cm²

Poisson's ratio 0.13

From A. E. Kay in The Metal Plutonium, p. 189.

308.2

Shear Modulus

Shear modulus of elasticity: $G = 5.4 \times 10^6$ psi

(α Pu)

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 15.

A value for the shear modulus G of 3.8×10^3 kg/mm² was obtained by the resonance method at room temperature for alpha Pu extruded at 230°C. From S. T. Konobeevsky et al. p/2230, Proc. Second Geneva Internat. Conf., vol. 6, p. 194. 1958.

308.4

Poisson's Ratio

for α Pu: $\nu = 0.15 \pm 0.01$

for α Pu extruded at 230°C: $\nu = 0.21$

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 15.

$\mu = 0.21$ (calculated from Young's modulus and shear modulus obtained by the resonance method at room temperature for alpha Pu extruded at 230°C). From S. T. Konobeevsky et al. p/2230, Proc. Second Geneva Internat. Conf., vol. 6, p. 194. 1958.

See end of section 308.1.

308.5

Compressibility (Reciprocal of Bulk Modulus)

Compressibility of α Pu at atmospheric pressure: 2.0×10^{-6} /bar

From W. D. Wilkinson in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 15.

401.1

Reactions with Gases — Air

EFFECT OF TEMPERATURE AND HUMIDITY ON THE OXIDATION OF ALPHA PLUTONIUM

From A. S. Coffinberry et al. Reactor Handbook, 2nd ed., vol. I, p. 263.

Temperature, °C	Relative Humidity, %	Duration, hr	Weight Gain, mg/cm ²
25	40	900	0.01 - 0.07
	100	900	6.5
50	7	900	4.3
	7	200	0.6

EFFECT OF MOISTURE AND TEMPERATURE ON THE AIR CORROSION OF HIGH-PURITY PLUTONIUM

From A. S. Coffinberry et al. *Reactor Handbook*, 2nd ed., vol. 1, p. 263.

Temperature, °C	Relative Humidity, %	Weight gain, mg/cm ² , at indicated time, hr	
		1000	10,000
35	20	1.2	30
50	0 (MgClO ₄)	0.11	-
	50	8	120
75	0 (MgClO ₄)	0.13	0.41
	50	100	400

The pickup of 1 mg/cm² of oxygen corresponds to the consumption or penetration of 3.77 μ of alpha plutonium. The corresponding figure for the delta phase is 4.86 μ . One-mil penetration of alpha corresponds to 6.74 mg/cm² oxygen gained per square centimeter.

Oxidation of Plutonium in Air. (Curves A, B, and C - 100% Relative Humidity; Curve D - 0% Relative Humidity). From E. Dempsey and A. E. Kay, *J. Inst. Metals*, vol. 86, p. 383, 1957-1958.

Oxidation of Plutonium in Air at High Temperatures. (Relative Humidity Between 50 and 55%). From E. Dempsey and A. E. Kay, *J. Inst. Metals*, vol.

The Effect of Humidity on the Oxidation of α -Pu at 90°C. From J. F. Sackman in *Plutonium 1960*, p. 224.

The Oxidation of α -Pu Under Mild Conditions Showing the Unusual Behavior at 30°C and 90 percent RH. From J. F. Sackman in *Plutonium 1960*, p. 225.

Uptake of Oxygen by Plutonium in Moist Air and in Moist Argon (95% Relative Humidity) at 25°C. From J. B. Raynor and J. F. Sackman, *Nature*, vol. 197, p. 588, 1963.

OXIDATION-RATE OF PLUTONIUM AT 25°C

From J. B. Raynor and J. F. Sackman. *Nature*, vol. 197, p. 588. 1963.

Cast	Rate of Oxidation in *		$\frac{k_{Ar}}{k_{Air}}$	Humidity, %
	Argon k_{Ar} †	Air k_{Air} †		
92	0.0071	0.00028	25.4	95
106	0.0040	0.00096	4.2	95
108	0.0062	0.00029	21.4	95
119	0.0043	0.00079	5.5	95
119 A ‡	0.0087	0.00065	13.4	95
All	0 §	0 §	--	0

* Derived from slope of line after initial deviations from linearity.

† $Mg/cm^2/h$.

‡ As 119, but electropolished surface.

§ Not detectable.

Abraded specimens of Pu, both cast disks and rolled sheet, were oxidized for 1,800 hours in air and in argon. Results suggest that the reaction is anodically controlled.

Comparison of the Corrosion Weight Gains in Dry and Moist Air at 55°C. The approximately 50% relative humidity was maintained with a saturated solution of NaBr. The dried air was continuously in contact with $MgClO_4$. From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 199.

Corrosion Weight Gains of High-Purity Plutonium in 35°C Air Maintained at Approximately 20% Relative Humidity by a Saturated Solution of $LiNO_3$. From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 198.

Comparison of the Corrosion Weight Gains of Pure Plutonium in Dry and Moist Air at 75°C. The Approximately 50% Relative Humidity was Maintained with a Saturated Solution of NaBr. The Dried Air was Continuously in Contact with $MgClO_4$. From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 200.

Approximate Determination of the Temperature Dependence of the Reaction Rate Constant for Plutonium Exposed to Moist Air. From J. T. Waber and E. S. Wright in The Metal Plutonium, p. 201.

COMPARISON OF OBSERVED CORROSION WEIGHT GAINS FOR ALPHA PLUTONIUM WITH CALCULATED WEIGHT GAINS FOR TWO COMPOSITIONS OF THE PRODUCTS (75°C, 50% RH)

From J. T. Waber et al. J. Nucl. Mater., vol. 3, p. 210. 1961.

Initial Wt. Metal, g	Exposure Time, hr	Final Weight, g	Wt. PuO ₂ Calc., g	Percent Excess	x in Formula*
1.548 748	3,360	1.779 133	1.756 114	1.310	0.188
1.716 152	2,832	1.969 484	1.945 929	1.210	0.173
1.063 517	2,832	1.220 691	1.205 912	1.226	0.175
2.213 135	2,712	2.541 928	2.509 454	1.294	0.186
2.022 589	2,352	2.309 693	2.293 955	0.710	0.101

*Value of x in the composition PuO₂·xH₂O.

Oxidation of Electropolished Plutonium in Dry Air. From D. M. Poole et al. in Plutonium 1960, p. 631.

Oxidation of Mechanically Polished Plutonium in Air Dried Over Magnesium Perchlorate. The Temperature Measured is that of the Gas Stream. From D. M. Poole et al. in Plutonium 1960, p. 632.

High-Temperature Oxidation of High-Purity Plutonium in Purified Oxygen. The Slopes in Excess of Unity Characterize the Reaction as Accelerating with Time.

The rate data are represented quite well by the following equation:

$$W = k_n t^n,$$

with the rate constant $k_n = 320$ and exponent of time $n = 2.2$ for the test at 343°C , and $k_n = 480$, $n = 1.4$ for the test at 400°C .

From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 201.

For the three runs shown to the left, the rate data can be represented by the logarithmic growth law:

$$W = k_L \log_{10}(bt + c),$$

with k_L and b appropriate kinetic constants:

Specimen No.	Test Temp., $^\circ\text{C}$	k_L mg/cm^2	b_0 hr^{-1}
1144	315	24.6	4.81
1145	315	20.2	6.49
1142	325	20.6	12.96

It was found that c could be neglected.

From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 202.

Semilogarithmic Plots of the Gas-Consumption Data for Pure Plutonium and Oxygen. The gas and metal were preheated in a molten salt bath before they were brought into contact. The sigmoid shape of the curves results from an increase in surface temperature at the beginning of the reaction, followed by depletion of metal at its end. From J. T. Waber and E. S. Wright in *The Metal Plutonium*, p. 202.

Plutonium metal at room temperature will take up hydrogen or deuterium with the evolution of heat. The lump of metal disintegrates during reaction and particles of hydride are thrown off the metal piece. At room temperature the formation of the hydride or deuteride may show an induction period of some minutes or may be almost instantaneous.
From MUC-JCW-223 (Book 1). p. 121.

REACTIVITY OF PLUTONIUM METAL WITH VARIOUS SOLUTIONS
From A. S. Coffinberry et al. *Reactor Handbook*, 2nd ed., vol. I, p. 262.

Reagent Solution	Remarks
Ammonium fluoride (conc. aqueous)	Slow attack with darkening of the surface
Ammonium fluoride (sat. alcoholic)	No attack at room temperature or on heating
Nitric acid	No visible attack in any concentration range over a period of several hours; some preferential dissolution expected from the experience with uranium.
Hydrochloric acid	Vigorous attack in all concentrations, becoming violent at high concentrations
Sulfuric acid	Slow initial evolution of hydrogen in concentrated acid which eventually stops; moderate attack in dilute acid
Acetic acid	No visible attack by glacial acetic acid even at elevated temperatures; very slow dissolution in dilute acid
Trichloroacetic acid	Vigorous attack in concentrated acid; rate of solution decreases upon dilution
Perchloric acid	Fairly rapid gas evolution in 72% acid
Phosphoric acid	Fairly rapid attack in 85% acid

Plot of $\log N_{Ta}$ vs $1/T$. (N_{Ta} = solubility of Ta expressed as the mole fraction). From D. F. Bowersox. LAMS-2952.

THE SOLUBILITY OF Ta in Pu AS A FUNCTION OF TIME AT 850°C

From D. F. Bowersox. LAMS-2952.

Total Time at 850°, hours	Solubility, ppm Ta
1.0	<50
3.0	<35
6.0	<35
16.0	<35
22.0	<50
44.0	220
66.0	210
88.0	215
112.0	195
158.0	205
187.0	215

THE SOLUBILITY OF Ta IN Pu AS A FUNCTION OF TEMPERATURE

From D. F. Bowersox. LAMS-2952.

Temperature, °C	Hours at Temperature	Solubility, ppm Ta *	Mole Fraction Ta, $N_{Ta} \times 10^4$
700	97.0	<35	----
750	24.0	45	0.59
800	15.5	85	1.12
	18.0	85	1.12
	65.5	80	1.06
		Avg. 83	1.10
850	44.0	220	2.90
	66.0	210	2.77
	88.0	215	2.84
	112.0	195	2.57
	158.0	205	2.70
	215.0	215	2.84
		Avg. 210	2.77
900	16.0	375	4.95
	40.0	385	5.08
	45.0	385	5.08
	88.0	380	5.01
		Avg. 381	5.03
950	16.0	520	6.86
	40.0	620	8.19
	72.0	520	6.86
		Avg. 550	7.26
1000	68.0	1070	14.11

* Parts per million parts Pu, by weight.

(Pu — 99.91 wt. % pure, Ta — all impurities <100 ppm)

VALUES OF S AND ΔH AT DIFFERENT TEMPERATURES

From T. A. Sandenaw. J. Phys. Chem. Solids, vol. 23, p. 1245. 1962.

Run	50°K		100°K		298°K (Calculated)	
	S_T (cal/g atom/°K)	H_T-H_0 (cal/g atom)	S_T	H_T-H_0	S_T	H_T-H_0
Liq He	2.67(3)*	88(3)	5.91	320	12.30 ± 0.12	1543 ± 25
Liq H ₂ (1 day)	2.65	89	----	309		
Liq H ₂ (1 week)	2.65	87	----	258		
Liq N ₂ (quench)	----	--	5.83(3)	319(3)		
Liq N ₂ (3 days holding)	----	--	5.81	314		

* Number in parentheses signifies number of values averaged.

Spectrographic analysis and chemical analysis showed the following impurities present in the button from which the specimen was cast (in parts per million): carbon, 10; oxygen, 40 to 70; aluminum, 15; iron, 30; hydrogen, 10. No other elements were detectable. The rate of heat generation was 2.167 mW/g. This was determined just before starting the heat capacity measurements. Specimen dimensions were: diameter, 0.335 in.; length, 1.727 in.

The value of $(H_{298}-H_0)$ is calculated to be 1543 ± 25 cal/g atom, and S_{298} to be equivalent to 12.30 ± 0.12 cal/g atom/°K. These values are averages from the results of liquid nitrogen runs to 300°K.

Heat Capacity Curves for an Electro-Refined Plutonium Specimen Showing Effects of Various Holding Times in Boiling Liquid Helium and Boiling Liquid Hydrogen. From T. A. Sandenaw. J. Phys. Chem. Solids, vol. 23, p. 1244. 1962.

Heat Capacity Curves Below 100°K for Three Liquid Helium Coolings of an Electro-Refined High Purity Plutonium Specimen. From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 23, p. 1243. 1962.

Heat capacity equations:

$$C_p = \gamma T + BT^3 \quad (11^\circ\text{K to } 31^\circ\text{K})$$

where γ (electronic contribution coefficient) $= 1.9621 \times 10^{-2}$

$$B = 5.8815 \times 10^{-5}$$

σ (standard deviation) $= 0.13$

$$C_p = A + BT + CT^2 \quad (98^\circ\text{K to } 300^\circ\text{K})$$

where

$$A = 2.3186$$

$$B = 2.4651 \times 10^{-2}$$

$$C = -2.2813 \times 10^{-5}$$

Limitations in the data, from the equation as given, were estimated to be (in cal/g atom/°K): ± 0.05 at 100°K , ± 0.13 at 200°K and ± 0.17 at 300°K .

From T. A. Sandenaw, *J. Phys. Chem. Solids*, vol. 23, p. 1244, 1962.

MOLAL HEAT CAPACITY OF PLUTONIUM METAL AT ROUNDED TEMPERATURES

From T. A. Sandenaw, *J. Phys. Chem. Solids*, vol. 23,
p. 1245, 1962

T, °K	C_p , cal/°K	T, °K	C_p , cal/°K	T, °K	C_p , cal/°K
100	4.56	170	5.85	240	6.92
110	4.75	180	6.02	250	7.06
120	4.95	190	6.18	260	7.19
130	5.14	200	6.34	270	7.31
140	5.32	210	6.49	280	7.43
150	5.50	220	6.64	290	7.55
160	5.68	230	6.78	300	7.66

COMPARISON OF HEAT CAPACITY, C_p , AND ENTHALPY, $H_T - H_0$, OF α -PHASE PLUTONIUM AND A δ -ALLOY CONTAINING 3.4 at. % ALUMINUM "SELF-DAMAGED" STATES

From C. E. Olsen et al. in *Radiation Damage in Reactor
Materials*, p. 55.

Temperature, °K	C_p , cal mole ⁻¹ deg K ⁻¹		$H_T - H_0$, cal/mole*	
	α -Phase, 163 h	δ -Phase, 184 h	α -Phase, 163 h	δ -Phase, 184 h
25	1.20	2.68	12.7	23.0
50	4.24	4.52	87	100
75	2.68	5.46	183	236
100	4.52	5.78	258	379
150	5.54	6.70	513	693
200	6.35	7.20	816	1030
273.15	7.40	7.75	1327	1570
298.15	7.70	7.97	1519	1768

*After storage of self-irradiation damage by holding at $\sim 19.6^\circ\text{K}$
for the specified times.

Heat Capacity as a Function of Absolute Temperature for High-Purity Electro-
Refined α -Plutonium and for a 96.6 at. % Plutonium — 3.4 at. % Aluminum
 δ -Phase Alloy. (Data were taken after holding for about 1 week at $\sim 19.6^\circ\text{K}$.)
From C. E. Olsen et al. in *Radiation Damage in Reactor Materials*, p. 53.

Resistivity of α -Plutonium as Function of (a) Damage and Temperature, and
(b) Damage and Time. (c) Additional Resistivity as Function of Time. From
J. A. Lee et al., *Physics Letters*, vol. 1, p. 326, 1962.

Variation of Additional Resistivity After Annealing for 30 Minute Periods with Temperature. From J. A. Lee et al., *Physics Letters*, vol. 1, p. 326. 1962.

The specimen which for most of the time was kept in liquid helium ($\sim 5^\circ\text{K}$) was on several occasions temporarily transferred into a bath of liquid hydrogen ($\sim 20^\circ\text{K}$) and the resulting changes in resistivity are plotted in dependence on temperature and time in (a) and (b). The following features were noted:

1. After warming the damaged specimen for a short while from $\sim 5^\circ\text{K}$ to $\sim 20^\circ\text{K}$, the original resistivity was again recorded at $\sim 5^\circ\text{K}$, showing that no annealing had taken place in this temperature interval.
2. The rate of resistivity-rise at both temperatures changes with time, the resistivities approaching almost the same saturation values ρ_s of about $141 \mu\Omega\text{cm}$, as shown in (c).
3. The rate of the resistivity-change with time can in first approximation be expressed as $d\rho/dt \propto (\rho_s - \rho)$.
4. In accordance with 2, it is found that the rise in resistivity $\Delta\rho$ due to the same amount of accumulated damage is smaller at 20°K than at 4°K , as is best seen in a plot of $\Delta\rho$ against time. (C) This means that the additional resistivity does not obey Matthiessen's rule, and that the scattering cross section of this radiation damage appears temperature dependent.
5. Annealing out of the radiation damage becomes noticeable at $\sim 50^\circ\text{K}$ and is rapid $\sim 80^\circ\text{K}$. A specimen of α -plutonium which had accumulated an additional resistivity $\Delta\rho$ of $41.5 \mu\Omega\text{cm}$ at $\sim 5^\circ\text{K}$ was raised to 40°K for a period of 30 min and then cooled again to $\sim 5^\circ\text{K}$ where its resistivity was recorded. This procedure was repeated at successively higher temperatures up to 290°K and the resulting graph is shown in (d). From J. A. Lee et al., *Physics Letters*, vol. 1, p. 325. 1962.

Resistivity of α -Plutonium. (a) Undamaged; (b) After 5,000 Hr of Self-Damage Below 20°K ; (c) Partially Annealed at $\sim 90^\circ\text{K}$; (d) Fully Annealed at $\sim 90^\circ\text{K}$; and (e) After Warming up to $\sim 300^\circ\text{K}$. From J. A. Lee et al., *Cryogenics*, vol. 3, p. 47. 1963.

The rise of resistivity ρ with holding time t follows approximately $d\rho/dt \propto (\rho_s - \rho)$, where ρ_s is the saturation value.

Isothermal Anneal of Pu-2 at $\sim 90^\circ\text{K}$ After 5,000 Hr at or Below $\sim 20^\circ\text{K}$.

The initial rise was, within 3-1/2%, the same for all specimens in the α -phase amounting at $\sim 5^\circ\text{K}$ to $0.0515 \mu(\Omega)\text{cm/hr}$ and being slightly smaller at $\sim 20^\circ\text{K}$. From J. A. Lee et al., *Cryogenics*, vol. 3, p. 47. 1963. Similar curves appear in *J. Phys. Soc. Japan*, vol. 18, supplement III, pp. 312-313. 1963.

RATE OF INCREASE IN RESISTANCE AT $\sim 5^\circ\text{K}$ FOR TIMES UP TO 7000 HOURS (SLOPE OF THE CURVE OF RESISTANCE VS TIME)

From E. King et al., *Acta Met.*, vol. 12, p. 112. 1964

Time, hr	α Plutonium		4% Al δ -Stabilized Plutonium	
	Slope, $10^{-3} \mu\Omega\text{cm/hr}$	Normalised Slope	*Slope, $10^{-3} \mu\Omega\text{cm/hr}$	Normalised Slope
0	52.50	1.000	11.45	1.000
1000	33.05	.629	10.025	(.876)
2000	17.35	.330	9.725	.849
3000	8.20	.156	8.46	.739
4000	3.71	.0706	6.78	.592
5000	1.675	.0319	5.628	.491
6000	0.715	.0136	4.395	.384
7000	0.412	.00785	3.044	.266

*Slope corrected for change in absolute magnitude due to a change in form factor of specimen.

Resistivity-Temperature Values for Pure Plutonium, β -Phase. From E. King and J. A. Lee. *Cryogenics*, vol. 3, p. 177, 1963.

Resistivity-Temperature Values for High Purity Plutonium, β -Phase. From E. King and J. A. Lee. *Cryogenics*, vol. 3, p. 178, 1963.

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PART II
BINARY ALLOYS

PuAg_3 is hexagonal, with
 $a = 12.730 \pm 0.003 \text{ \AA}$
 $c = 9.402 \pm 0.005$
 $Z = 16$, $D_x = 11.33$
 Space group. $\text{---} \text{P6}_3$ (Int. Tab. 173), $\text{P6}_3/\text{m}$ (Int. Tab. 176), or P6_322 (Int. Tab. 182).

The atomic positions have not been determined.
 From O. J. C. Runnalls quoted in *The Metal Plutonium*, p. 302.

Phase Diagrams

Al 101

The Plutonium-Aluminum Phase Diagram.
 From F. H. Ellinger et al., *J. Nucl. Mater.*, vol. 5, p. 167. 1962.

(Al approx. 99.97 wt. % pure, Pu approx. 99.9 wt. % pure.)

The Plutonium-Rich End of the Plutonium-Aluminum System.
 From M. B. Waldron *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6,
 p. 165. 1958.

The Plutonium-Aluminum System.
From F. W. Schonfeld, in The Metal Plutonium, p. 259.

PLUTONIUM-ALUMINUM

Pu_2Al
Tetragonal, partially ordered SrPb_3 type (tetragonally deformed AuCu_3 type)

$a = 4.499 \pm 0.002$, $c = 4.538 \pm 0.002$ Å
 $a = 4.530$, $c = 4.475$ Å From A. S. Coffinberry and M. B. Waldron,
Metallurgy and Fuels, series V, vol. 1, p. 390.

$Z = 1$, $D_x = 13.45$

Space group. — $P4/mmm$ (?) (Int. Tab. 123).

Atomic positions

1Al in (a): 0, 0, 0
1Pu in (c): $1/2, 1/2, 0$
2Pu in (e): $0, 1/2, 1/2; 1/2, 0, 1/2$

Interatomic distances

Pu-8Pu = 3.195 Al-8Pu = 3.195
Pu-4Al = 3.181 Al-4Pu = 3.181

PuAl
Body centered cubic F. H. Ellinger et al., *J. Nucl. Mater.*, vol. 5, p. 165, 1962.

$a = 10.769 \pm 0.001$ Å
 $Z = 29.01$ (58 atoms)

PuAl_2
Cubic face-centered, Cu_3Mg type

Pu-rich: $a = 7.838 \pm 0.001$ Å
Al-rich: $a = 7.848 \pm 0.001$ Å
 $a = 7.831 \pm 0.005$ O. J. C. Runnalls, *Can. J. Chem.*, vol. 34, p. 133, 1956.
 $a = 7.832$ (Coffinberry and Waldron)
 $Z = 8$, $D_x = 8.06$

$X = 8.10$ (Runnalls)

Space group. — $Fd3m$ (Int. Tab. 227).

Atomic positions

(0, 0, 0; $0, 1/2, 1/2; 1/2, 0, 1/2; 1/2, 1/2, 0$) +
8Pu in (a): $0, 0, 0; 1/4, 1/4, 1/4$
16Al in (d): $5/8, 5/8, 5/8; 5/8, 7/8, 7/8; 7/8, 5/8, 7/8; 7/8, 7/8, 5/8$

Interatomic distances (based on $a = 7.848$ Å)

Pu-4Pu = 3.398 Al-6Al = 2.775
-12Al = 3.254 -6Pu = 3.254

Isotypes. — LaAl_2 , CeAl_2 , UAl_2 , NpAl_2 .

PuAl_3
Hexagonal, PuAl_3 type (new structure type)

$a = 6.10 \pm 0.02$ Å (Larson et al., *Acta Cryst.*, vol. 10, p. 443, 1957.)
 $c = 14.47 \pm 0.02$
 $a = 6.08 \pm 0.01$ (Runnalls)
 $c = 14.40 \pm 0.03$
 $Z = 6$, $D_x = 6.67$
 $X = 6.92$ (Runnalls)

Space group. — $P6_3/mmc$ (Int. Tab. 194).

Atomic positions

2Pu_I in (b): $\pm(0, 0, 1/4)$
4Pu_{II} in (f): $\pm(1/3, 2/3, z; 1/3, 2/3, 1/2 - z)$ with $z = 0.0892 \pm 0.0001$
6Al_I in (h): $\pm(x, 2x, 1/4; 2\bar{x}, \bar{x}, 1/4)$ with $x = 0.5160 \pm 0.0030$
12Al_{II} in (k): $\pm(x, 2x, z; 2\bar{x}, \bar{x}, z; x, \bar{x}, z; \bar{x}, 2\bar{x}, 1/2 + z; 2x, x, 1/2 + z; x, x, 1/2 + z)$ with $x = 0.8337 \pm 0.0040$
 $z = 0.0815 \pm 0.0007$

Interatomic distances

Pu_I-6Al = 3.01 Al_I-2Pu = 3.02
-6Al = 3.06 -2Pu = 3.06
Pu_{II}-3Al = 3.02 -2Al = 2.76
-3Al = 3.03 -4Al = 2.96
-6Al = 3.05 -2Al = 3.34
Al_{II}-2Pu = 3.01
-2Pu = 3.05
-2Al = 2.94
-2Al = 2.96
-4Al = 3.05

Mean Pu-12Al = 3.04

Atomic positions or space group. — $P6m2$ (Runnalls)

1Pu in (a) 0, 0, 0
1Pu in (b) 0, 0, $1/2$
2Pu in (h) $1/3, 2/3, z; 1/3, 2/3, \bar{z}; z = 1/6$
2Pu in (i) $2/3, 1/3, z; 2/3, 1/3, \bar{z}; z = 1/3$
3Al in (j) $x, \bar{x}, 0; x, 2x, 0; 2\bar{x}, \bar{x}, 0; x = -1/2$
3Al in (k) $x, \bar{x}, 1/2; x, 2x, 1/2; 2\bar{x}, \bar{x}, 1/2; x = -1/2$
6Al in (n) $x, \bar{x}, z; x, 2x, z; 2\bar{x}, \bar{x}, z; x, \bar{x}, \bar{z}; x, 2x, \bar{z}; 2\bar{x}, \bar{x}, \bar{z}; x = -1/6, z = 1/6$
6Al in (n) $x = 1/6, z = 1/3$

PuAl_4
Orthorhombic body-centered, UAl_4 type

$a = 4.41$ Å (Singer, unpublished)
 $b = 6.29$
 $c = 13.79$
 $a = 4.42 \pm 0.02$ (Runnalls)
 $b = 6.26 \pm 0.02$
 $c = 13.66 \pm 0.03$
 $Z = 4$, $D_x = 6.02$

Space group. — $Imma$ (Int. Tab. 74).

Atomic positions

(0, 0, 0; $1/2, 1/2, 1/2$) +
4Pu in (e): $\pm(0, 1/4, z)$ with $z = 0.113$
4Al_I in (e): $\pm(0, 1/4, z)$ with $z = -0.113$
4Al_{II} in (b): $0, 0, 1/2; 0, 1/2, 1/2$
8Al_{III} in (h): $\pm(0, y, z); \pm(0, 1/2 - y, z)$ with $y = 0.033, z = 0.314$

Interatomic distances (based on $a = 4.41, b = 6.29, c = 13.79$)

Pu-4Al = 3.01 -4Al = 3.12
-5Al = 3.12 -2Al = 3.15
-2Al = 3.15 Al_{III}-2Pu = 3.01
-2Al = 3.29 -1Pu = 3.29
Al_I-1Pu = 3.12 -1Al = 2.57
-2Pu = 3.15 -1Al = 2.73
-4Al = 2.78 -2Al = 2.78
-2Al = 3.09 -2Al = 2.82
-4Al = 3.12 -1Al = 3.09
Al_{II}-4Pu = 3.12 -1Al = 3.56
-2Al = 2.57

Isotypes. — $\text{UAl}_4, \text{NpAl}_4$.

Remarks. — The atomic parameters are those of Borie, but Singer modified the z parameter for the plutonium atoms from 0.111 to 0.113.

From F. H. Ellinger, in *The Metal Plutonium*, pp. 281-308.

 δ -PHASE LATTICE CONSTANT/COMPOSITION DATA

($23 \pm 2^\circ\text{C}$)

From F. H. Ellinger et al., *J. Nucl. Mater.*, vol. 5, p. 170, 1962.

Composition at % Al		Lattice constant, Å *	No. of Samples
Nominal	Analyzed		
0.5		4.6359 ± 0.0003	1
0.7		4.6333 ± 0.0003	1
0.9		4.6326 ± 0.0003	1
2.0		4.6249 ± 0.0001	2
3.5	3.35	4.6143 ± 0.0004	4
5.0		4.6023 ± 0.0007	5
6.5	6.44	4.5927 ± 0.0003	3
8.0		4.5818 ± 0.0004	5
9.5	9.12	4.5710 ± 0.0011	3
11.0	11.11	4.5590 ± 0.0006	2

* Uncertainty is the mean deviation.

The Lattice Constant/Composition Curve of the δ Plutonium Solid Solution. From F. H. Ellinger et al., *J. Nucl. Mater.*, vol. 5, p. 170, 1962.

ROOM TEMPERATURE DENSITIES, g/cm³

From A. E. Martin and G. D. Selmanoff, LA-501, (Classified)

Nominal Composition at, % Al.	As-Cast	After 400°C Anneal	After Holding in Ice Water
0.5	17.58	17.25	17.45
1.0	16.92	16.76	16.90
1.5	16.55	16.05	16.30
1.5	16.72	-----	
1.5	16.74	15.74	
2.0	16.01	15.80	15.98
2.0	16.47	15.60	
3.0	16.18	15.57	
4.0	15.93	15.59	

DENSITIES OF Pu-Al ALLOYS HOMOGENIZED AT 450°C FOR 500 HOURS, AIR COOLED TO ROOM TEMPERATURE

From R. O. Elliott et al., J. Phys. Chem. Solids, vol. 23, p. 1036, 1962.

Al, at. %	Density at 24°C, g/cm ³
1.2	15.80
2.5	15.67
3.4	15.56
4	15.60
5	15.41
7	15.34
10	15.01

Density of as-cast 8 at. % Al-Pu alloy at room temperature = 15.235 g/cm³.
From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 16, p. 330, 1960.

From H. R. Gardner, in Proc. Second Geneva Internat. Conf., vol. 6, p. 689, 1958

Density of Al-Pu Alloys. (1) From T. I. Jones, in Plutonium 1960, p. 726.
(2) From O. J. C. Runnalls, Can. J. Chem., vol. 34, pp. 133-145, 1956.For alloys containing PuAl₄ and aluminum, the following relationship between x, the weight fraction of plutonium, and ρ, the density, has been derived:

$$x = 1.24924 - 3.37296 \frac{1}{\rho}$$

From R. E. Tate, in The Metal Plutonium, p. 359.

Thermal Expansion

Al 202.1

Al, at. %	$\bar{\alpha} \times 10^6 / ^\circ\text{C}$	Temp. range for $\bar{\alpha}$, °C	$\bar{\alpha}_i \times 10^6 / ^\circ\text{C}$ $t_0 = 300^\circ\text{C}$	$\bar{\alpha}_i \times 10^6 / ^\circ\text{C}$ 440°C
0.6	- 8.0	300-440	- 6.4	- 9.5
1.2	- 4.8	300-440	- 3.2	- 6.5
1.8	- 0.7	300-440	0.3	- 1.8
2.5	- 1.8	300-440	- 0.4	- 3.1
5.0	7.7	300-440	7.7	7.6
7.0	11.6	300-440	10.9	12.3
10.0	13.4	300-440	13.0	13.8

From R. O. Elliott et al., in Plutonium 1960, p. 150.

Average Linear Coefficients of Thermal Expansion vs at. % Aluminum
From R. O. Elliott et al., in Plutonium 1960, p. 152.

THERMAL EXPANSION OF Al-Pu ALLOYS

From J. M. Taylor, Private Communication, reported by I. D. Thomas and O. J. Wick in Plutonium 1960, p. 768.

Alloy	Al at. %	Temperature Range, °C	Thermal Expansion Coefficient, °C
Al (Commercial)	100	26-600	28.7×10^{-6}
Al-2 wt. % Pu	99.77	40-600	28.1×10^{-6}
Al-5 wt. % Pu	99.41	22-600	27.68×10^{-6}
Al-10 wt. % Pu	98.76	26-600	26.4×10^{-6}
Al-15 wt. % Pu	98.05	26-600	26.3×10^{-6}

Thermal Expansion of Al-Pu and Al-12 Wt. % Si-Pu (1-in. specimen). From J. M. Taylor, Private Communication, reported by I. D. Thomas and O. J. Wick in Plutonium 1960, p. 769.

Effect of Plutonium Concentration on the Linear Expansion of Al-Pu and Al-Si-Pu. From J. M. Taylor, Private Communication, reported by I. D. Thomas and O. J. Wick in Plutonium 1960, p. 769.

Lattice Parameter vs Temperature for Pu-Al δ -Phase Solid Solutions. From J. A. Lee et al., in Plutonium 1960, p. 41.

Thermal Expansion Curve for an 8 At. % Al-Pu Alloy (Stabilized Delta Phase at Room Temperature) Relative to Fused Quartz. The dashed line represents behavior on first cooling. From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 16, p. 331, 1960.

Curve of Coefficient of Thermal Expansion for an 8 At. % Al-Pu Alloy. Dashed line at 150°K and above represents data of dashed line in preceding figure in the same temperature range. From T. A. Sandenaw, *J. Phys. Chem. Solids*, vol. 16, p. 334. 1960.

Least squares equations for linear expansion of 8 at. % Al-Pu alloy

The thermal expansion data for the plutonium alloy were submitted to least squares analysis. Because of the abrupt changes of slope of the curve, the data

were divided into four temperature ranges. Equations for these temperature ranges were:

Temperature Range: 1.86-30°K

$$\Delta l_T = l_{273} (A + BT + CT^2 + DT^3 + ET^4 + FT^5)$$

$$A = -6.0281 \times 10^{-3}$$

$$B = -7.4790 \times 10^{-4}$$

$$C = 6.6822 \times 10^{-5}$$

$$D = -2.9584 \times 10^{-6}$$

$$E = 6.3943 \times 10^{-8}$$

$$F = -5.3308 \times 10^{-10}$$

$$\sigma = 1.6 \times 10^{-4}$$

Temperature Range: 30-42°K

$$\Delta l_T = l_{273} (A + BT + CT^2)$$

$$A = -1.1283 \times 10^{-2}$$

$$B = 1.2230 \times 10^{-4}$$

$$C = -1.8558 \times 10^{-6}$$

$$\sigma = 1.1 \times 10^{-5}$$

Temperature Range 44-76°K

$$\Delta l_T = l_{273} (A + BT + CT^2 + DT^3)$$

$$A = -1.6472 \times 10^{-2}$$

$$B = 3.8990 \times 10^{-4}$$

$$C = -7.5351 \times 10^{-6}$$

$$D = 5.3651 \times 10^{-8}$$

$$\sigma = 3.4 \times 10^{-4}$$

Temperature Range 78-273°K

$$\Delta l_T = l_{273} (A + BT + CT^2 + DT^3 + ET^4)$$

$$A = -7.3254 \times 10^{-3}$$

$$B = -3.9405 \times 10^{-5}$$

$$C = 9.8614 \times 10^{-7}$$

$$D = -4.8175 \times 10^{-9}$$

$$E = 7.6700 \times 10^{-12}$$

$$\sigma = 8.6 \times 10^{-4}$$

From T. A. Sandenaw, *J. Phys. Chem. Solids*, vol. 16, p. 333. 1960.

Thermal Conductivity

Aluminum Avg. at. % Measured	K(cal/cm °C Sec)
0	0.58
1.39	0.53
5.18	0.47
10.26	0.28
11.92	0.21

The ratio of thermal to electric conductivity is approximately constant over the range of compositions studied.

$$K = 5.02\sigma T \times 10^{-9} + 0.05$$

K = thermal conductivity (cal/cm °C Sec)
 σ = electrical conductivity (ohm⁻¹cm⁻¹)
 T = absolute temperature

From R. B. Gibney. LAMS-1080.

Al 202.2

Thermal Conductivity as a Function of Atomic Percent Pu in Pu-Al Alloys. Temperature Range = 0 to 25-30°C. From R. B. Gibney. LAMS-1080.

Al 202.3 Specific Heat and Heat Capacity

From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 16, p. 330. 1960.

The equations for heat capacity (C_p), as a function of temperature for regions where spikes were absent, were found to be as follows:

Temperature Range below 25.74°K

$$C_p = \gamma T + BT^3$$

$$\gamma = 139.3 \times 10^{-4}$$

$$B = 2.0994 \times 10^{-4}$$

$$\sigma = \text{standard deviation} = 0.358$$

Temperature Range: 76-193°K

$$C_p = A + BT + CT^2 + DT^3$$

$$A = 2.2804$$

$$B = 4.4898 \times 10^{-2}$$

$$C = 1.7175 \times 10^{-4}$$

$$D = -1.5012 \times 10^{-6}$$

$$\sigma = 0.323$$

Temperature Range: 208-300°K

$$C_p = A + BT + CT^2$$

$$A = -3.8356$$

$$B = 8.5039 \times 10^{-2}$$

$$C = -1.5484 \times 10^{-4}$$

$$\sigma = 0.450$$

From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 16, p. 333. 1960.

ESTIMATED HEAT CAPACITY OF ALUMINUM-STABILIZED DELTA-PHASE PLUTONIUM

From F. W. Schonfeld. Unpublished Data, 1961.

Temperature, °K	C_p (cal/°C)/mole
300	7.8
400	8.3
500	8.6
600	8.8

Al 202.4 Entropy

AVERAGED VALUES OF S AND ΔH AT SEVERAL TEMPERATURES

From T. A. Sandenaw, J. Phys. Chem. Solids, vol. 16, p. 334. 1960.

Temperature, °K	S_T	$H_T - H_0$
77.5	7.66 ± 0.24	324 ± 8
138	11.70 ± 0.17	754 ± 10
203	14.60 ± 0.14	1240 ± 14
262	16.54 ± 0.11	1675 ± 10
298	17.52 ± 0.11	1950 ± 14

Al 202.6 Heats of Transition

ALUMINUM-PLUTONIUM ALLOYS

From R. Abramson et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 180. 1958.

Pu Concentration, wt. %	Heat of Fusion, cal	Temperature of Eutectic Fusion, °C
0	94.5	-----
4	81.5	645.3
8	71.2	642.9
11.3	76.5	643.5
12.75	79.4	642.4
14.9	66.2*	640.5
20	56.3*	642.9
23.9	49.8*	640.5
27.9	49.2*	640.5
55	26.6*	646

* Heat of fusion of the eutectic mass present in the alloy.

Heats of Fusion for Al-U and Al-Pu Alloys. From R. Abramson et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 180. 1958.

ELECTRICAL CONDUCTIVITY OF Al-Pu ALLOYS

From R. B. Gibney, LAMS-1080.

Specimen	$\sigma \times 10^{-5}$ $\text{ohm}^{-1} \text{cm}^{-1}$
Aluminum	3.60
1.39 at. % Pu	3.22
5.18 at. % Pu	2.77
10.26 at. % Pu	1.48
11.92 at. % Pu	1.16

Electrical Conductivity as a Function of Thermal Conductivity for Pu-Al Alloys. From R. B. Gibney, LAMS-1080.

Resistivity of Three Plutonium-Aluminum Alloys. From J. A. Lee et al., *Cryogenics*, vol. 1, p. 52, 1960. Resistivities of Pu-Al β -Phase Solid Solutions. From J. A. Lee et al. in *Plutonium 1960*, p. 44. Electrical Resistivity of Two Al-Pu β -Phase Alloys. From J. A. Lee et al. in *Plutonium 1960*, p. 45.

The Resistivities of Three δ -Pu + Al Alloys Below 300°K. Specimens: A, 3 at. % Al; B, 5 at. % Al; C, 10 at. % Al. From G. T. Meaden, *Proc. Roy. Soc. (London)*, Ser. A, vol. 276, p. 566, 1963.

The resistivity rise in δ plutonium (4 at. % Al) held below 20°K was about 0.012 $\mu\Omega\text{cm/hr}$.
From J. A. Lee et al., *J. Phys. Soc. Japan*, vol. 18, supplement III, p. 312, 1963.

Electrical Resistivity Curve for an 8 at. % Al-Pu Alloy (Stabilized Delta Phase at Room Temperature). From T. A. Sandenaw, *J. Phys. Chem. Solids*, vol. 16, p. 332, 1960.

Thermoelectric Power. From J. A. Lee et al. in *Plutonium 1960*, p. 43. Paramagnetic Susceptibilities. From J. A. Lee et al. in *Plutonium 1960*, p. 43.

Hall effect in 3.4 at. % Aluminum Delta Stabilized Plutonium

$$\text{at } 293^\circ K \quad R_H = +11.1 \pm 1.0 \times 10^{-11} \text{ m}^3 \text{c}^{-1}$$

$$\text{at } 77^\circ K \quad R_H = +16.2 \pm 1.5 \times 10^{-11} \text{ m}^3 \text{c}^{-1}$$

From B. G. Loasby and J. C. Taylor, *Proc. Phys. Soc. (London)*, vol. 78, p. 777 1961.

The Effect of Composition on Ultimate Strength in Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on the 0.1% Yield Stress in Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

Elongation Ranges From 3 to 12% for Alloys Studied. From H. R. Gardner et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 689. 1958.

Effect of Temperature on Tensile and Compressive Properties of Plutonium -4.5 at. % Aluminum Delta-Stabilized Alloy. Testing Speed, 0.015 in./min.

▲, □, ○ Less than 250 ppm iron
 △ 910 ppm iron
 ● 1300 ppm iron

From H. R. Gardner in HW-77182 and HW-78158. (Classified)

Effect of Testing Speed and Temperature on the Strength of a Plutonium-4.5 at. % Aluminum Delta-Stabilized Alloy. From H. R. Gardner in HW-77182 and HW-78158. (Classified)

Stress-Strain Curves for Rolled, and Rolled and Annealed, Pu-8.3 at. % Al Alloy.
 From P. J. Bacca, LAB-CMB-11-3904, p. 51. (Classified) Reported by H. R. Gardner.

TENSILE PROPERTIES OF Pu-11.1 at. % Al DELTA-STABILIZED ALLOY ROLLED TO 94% REDUCTION

From H. R. Gardner in HW-78158. (Classified)

Treatment	Ultimate Strength, psi	0.2% Yield Strength, psi
As-rolled*	50,800	46,300
Annealed for 6 hrs at 650°C before rolling.**	50,100	44,300
Anneal as above, roll, anneal at 450°C for 24 hrs, furnace cool.*	28,500	16,900

* Average of two tests.

** Average of four tests.

Effect of Temperature on Ductility of Plutonium-4.5 at. % Aluminum Delta-Stabilized Alloy. Testing Speed, 0.015 in./min.

- Less than 250 ppm iron
- △ 910 ppm iron
- 1300 ppm iron

From H. R. Gardner in HW-77182 and HW-78158. (Classified)

The Effect of Composition on Elongation in Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on Reduction in Area in Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

Effect of Testing Speed and Temperature on Ductility in a Plutonium-4.5 at. % Aluminum Delta-Stabilized Alloy. From H. R. Gardner in HW-77182 and HW-78158. (Classified)

Effect of Testing Speed and Temperature on the Compression Properties of a Plutonium-4.5 At. % Delta-Stabilized Alloy. From H. R. Gardner in HW-77182 and HW-78158. (Classified)

Shear strength of cold-rolled, delta-phase, Pu-6.0 at. % Al and Pu-8.0 at. % Al at room temperature is approximately 16,000-18,000 psi. From F. W. Schonfeld, as reported by H. R. Gardner in Chap. 4, The Plutonium Handbook, 1966.

The Effect of Composition on Hardness in Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Concentration of Aluminum and Pressure up to About 10,000 Atm on the Hardness of Delta-Stabilized Aluminum-Plutonium Alloys. From R. O. Elliott and K. A. Gschneidner, Jr., in Extractive and

Aluminum-Plutonium Alloys (0-14 At. % Pu). From H. R. Gardner *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 689. 1958.

HARDNESS OF ALUMINUM-PLUTONIUM ALLOYS IN VICKERS UNITS BEFORE AND AFTER ANNEALING AT 600°C

From R. Abramson *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6, pp. 181-182. 1958.

Composition, (wt. % Pu)	Test Load	As Cast	Annealing Time, (hr)					
			1/2	1	2	4	8	24
10	5 kg	37						
20	5 kg	44	48	45	43	42		27
32	10 kg	57						52
40	10 kg	75						73

Average microhardness of PuAl_3 and PuAl_4 . Under loads of 30 and 40 g:

PuAl_4 380 kg/mm²

PuAl_3 500 kg/mm²

Effect of Composition on the Hardness of Cast and Annealed Al-Pu Alloys. From T. I. Jones in *Plutonium 1960*, p. 725.

Effect of Anneal Time and Temperature on Hardness of a Plutonium-11.1 At. % Aluminum Delta-Stabilized Alloy Rolled to 94% Reduction at Room Temperature. From H. R. Gardner in HW-78185. (Classified)

Young's Modulus

The Variation of Young's Modulus with Composition for Pu-Al. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner in Chap. 1, *The Plutonium Handbook*, 1966.

Al 308.1

The Effect of Composition on the Elastic Modulus of As-Cast Plutonium-Aluminum Alloys. From P. F. T. Linford, Private Communication, reported by H. R. Gardner. In Chap. 4, *The Plutonium Handbook*, 1966.

The Effect of Temperature on the Elastic Modulus of As-Cast Plutonium-Aluminum Alloys. From P. F. T. Linford, Private Communication, reported by H. R. Gardner.

ELASTIC MODULUS OF PLUTONIUM-11.1 AT. % ALUMINUM, DELTA-STABILIZED ALLOY ROLLED TO 91% REDUCTION

From H. R. Gardner, Unpublished Data.

Treatment	Elastic Modulus, 10^6 psi
As-rolled*	11.9
Annealed for 6 hrs at 650°C before rolling.**	11.6
Anneal as above, roll, anneal at 450°C for 24 hrs, furnace cool.*	6.0

* Average of two tests.

** Average of four tests.

Corrosion Data for 8 At. % Al-Pu Alloys, Rolled and Annealed: Exposed to Air Containing 20% Relative Humidity at 35°C. From J. T. Waber in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 211. 1958.

WEIGHT GAINS IN mg/cm² FOR Pu-3 At. % Al AT 50% RELATIVE HUMIDITY

From J. T. Waber in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 212. 1958.

	55°C	75°C
1750 hr	0.16	0.91
10,800 hr	0.29	3.0 (10,750 hr)
High purity Pu, 9000 hr	5.08	52.3

Comparison of the Corrosion Behaviors of Plutonium-Aluminum Alloys and

The Effect of Humidity on the Oxidation of 3.5 At. % Al-Stabilized Plutonium at 90°C. From J. F. Sackman in *Plutonium 1960*, p. 225.

The Oxidation of 3.5 At. % Al-Stabilized Plutonium Under Mild Conditions Showing the Termination of Oxidation at 30°C and 90% RH. From J. F. Sackman in *Plutonium 1960*, p. 226.

MERIT RATIOS FOR 3.5 At. % Al-STABILIZED Pu

From J. F. Sackman in *Plutonium 1960*, p. 229.

°C	% RH	Merit Ratio Observed at Time, (hr)					
		12	24	50	250	500	1000
90	95		130				
90	55	50	100	120			
30	95				13	13	8
100	0				20	12	6

$$\text{Merit Ratio} = \frac{\text{Weight increase for } \alpha\text{-plutonium in a given time}}{\text{Weight increase for } \beta\text{-stabilized plutonium in the same time}}$$

An aluminum alloy containing 10 wt. % plutonium, which consists of the intermetallic compound PuAl_3 dispersed in a matrix of aluminum, was held 1 week at 400°C in pure oxygen. The pickup of oxygen was barely detectable by the manometric method that has been employed in the oxidation of pure plutonium. An upper limit on the amount of oxide formed is 8μ . An X-ray diffraction study of the oxidized surface showed only a weak pattern of Al_2O_3 and the patterns of the underlying alloy phases, but no Pu_2O_3 . Comparison with the rate of oxidation of pure aluminum suggests that plutonium may slightly reduce the protection afforded aluminum by its oxide.

From J. T. Weber and E. S. Wright in *The Metal Plutonium*, pp. 202, 203.

Corrosion of Al-Pu Alloys in Static Water at 340°C and pH 7.1 (in AISI 316 Stainless-Steel Autoclave). From T. I. Jones in *Plutonium 1960*, p. 733.

A Two-hour corrosion test was carried out on the four alloys at 360°C . The 5 wt. % alloy was completely destroyed and the corrosive attack penetrated 0.076 cm (0.030 in.), 0.071 cm (0.028 in.) and 0.0005 cm (0.0002 in.) into the 10, 15 and 20 wt. % alloys, respectively.

Corrosion product varied in colour from a light greyish-green for the 5 wt. % alloy to a very dark greyish-green for the 20 wt. % alloy. The corrosion product from the 5 wt. % alloy was soft and powdery and became increasingly dense with greater plutonium concentrations.

An X-ray diffraction pattern of the corrosion product showed that it consisted of $\alpha\text{-Al}_2\text{O}_3 \cdot 11\text{H}_2\text{O}$ (Bohmite) and Pu_2O_3 .

Since the alloys were all cast at 999°C , resulting in varying differentials between the pouring and liquidus temperatures, it would be misleading to plot extent of corrosion against alloy composition.

From T. I. Jones in *Plutonium 1960*, p. 733.

DESCRIPTION OF ALLOY PREPARATION

From H. C. Bowen. Corrosion, vol. 17, no. 7, p. 12.

Alloy, wt. %	Max. Melt, °C	Soak Time, hrs	Casting, °C
<u>Al-Si-Pu</u>			
2 Pu	925	2	700
5 Pu	900	2	725
10 Pu	900	1-1/2	775
15 Pu	950	4	850
<u>Al-Pu</u>			
To 15 Pu	900	4	730

RAPID HIGH TEMPERATURE ATTACK OF Al-Pu AND
Al-Si-Pu ALLOYS IN 360°C WATERFrom H. C. Bowen. Corrosion, vol. 17, no. 7, p. 12.

Wt. % Pu	Time, hr	Sample Treat- ment*	Results
13	24	1	Etched cut end attacked.
13	24	2	Both ends attacked and 3/4 of sample destroyed.
10	24	1	Etched cut end attacked, 2 small spots on side attacked.
10	24	2	Cut end and one side of sample attacked and 1/2 of sample destroyed.
6	12	1	Etched cut end attacked and 1/2 of sample destroyed.
6	12	2	Destroyed
1.8	12	1	
1.8	12	2	
15**	24	1	Not attacked.
15**	24	2	
10**	24	1	
10**	24	2	
5**	24	1	
5**	24	2	
1.8**	24	1	
1.8**	24	2	

** In Al-12% Si

RAPID HIGH TEMPERATURE ATTACK BY Al-Pu
ALLOYS IN 350°C WATERFrom H. C. Bowen. Corrosion, vol. 17, no. 7, p. 12

Wt. % Pu	Time, hr	Sample Treat- ment*	Results
13	24	1	1/4" D spot attacked on etched cut end.
13	24	2	1/4" D spot attacked on both ends.
10	24	1	Not attacked.
10	24	2	Both ends and one side attacked.
6	24	1	Not attacked.
6	24	2	Badly attacked on cut end and one side
1.8	24	1	Destroyed.
1.8	24	2	
10	3	3	Approximately 1/2 of diameter lost
10	3	3	
1.9	3	3	Destroyed.
1.9	3	3	

*Sample Treatments:

1. A 2-inch long end section was cut from a 6-inch long cast rod. The cut end was etched in a 78 percent commercial H_3PO_4 , 11 percent commercial HNO_3 , 11 percent commercial H_2SO_4 , and 0.8 g/l $FeSO_4 \cdot 7H_2O$ chemical polishing bath. This was done to remove the cold work due to cutting. This left an as-cast and etched cut end on the sample.

2. A 2-inch long section was cut from the center of a 6-inch long cast rod. One end was treated in a polishing bath as above. This left a cut end and an etched cut end on the sample.

3. Two-inch long sections were cut from 1/2-inch diameter extruded rod and tested without further treatment.

The following conclusions may be drawn from these tests:

1. Low percentage (<6 percent) aluminum-plutonium as-cast alloys have little resistance to rapid high temperature attack but resistance increases with increasing plutonium content up to at least 13 percent Pu.

2. Any working of the material drastically decreases its resistance to attack as compared to as-cast material of the same Pu content.

3. Addition of 12 percent silicon to aluminum-plutonium alloy makes the alloys up to at least 15 percent Pu resistant to attack for at least 24 hours and makes them less sensitive to working.

From H. C. Bowen. Corrosion, vol. 17, no. 7, p. 12.

Reactions with Liquid Metals

CORROSION OF 4 AT. % Al-Pu* IN NaK

From H. H. Hyman and J. J. Katz, ANL-5090.

Treatment	Wt. After Treatment, g	Wt. Change, mg	Apparent Corrosion Rate, mg cm ⁻² hr ⁻¹
Coating removed	0.1167		
160 hr, 400°C in NaK large container pickled in HCl	0.1144 0.0785	- 2.3 -35.9	-0.06
720 hr, 400°C in NaK Rinsed and air dried	0.0845	(+ 6.0)	
Rinsed and mech- anically dried	0.0794	+ 0.9	+0.005

* The sample piece was a nickel-coated cylinder 1/16" in dia. x 3/16" long.

Interaction of etched Al-Pu alloys with etched Zircaloy-2 sheaths;
No sheath/core interaction was observed after 2 weeks at 310°C.

Sheath/Core Interaction After 26 Hr at 636°C. From T. I. Jones in Plutonium 1960, p. 727.

Effect of Core Alloy Composition on Sheath Dissolution After 1 Hr at 660°C. From T. I. Jones in Plutonium 1960, p. 728.

Diffusion Band Thickness Between Zircaloy-2 and Al-10 Wt. % Pu Alloy as a Function of Time and Temperature. From T. I. Jones in Plutonium 1960, p. 729.

Hardness of Diffusion Band Relative to Zircaloy-2 Sheath and Al-10 Wt. % Pu Alloy Core. The specimen had been heated for 5 hr at 638-642°C, producing a diffusion band 0.02 cm (0.008 in.) wide. From T. I. Jones in Plutonium 1960, p. 731.

Hardness Changes After Irradiation and Postirradiation Annealing with Aluminum-Plutonium Alloys.

- Specimens machined for operation with no sheath/core diametral clearance, irradiation temperature, 350-400°C.
- ×—× Specimens machined for operation with sheath/core diametral clearance, initial irradiation temperature, 550-625°C.
- Unirradiated alloys.

Annealing treatments were carried out for one hour at each temperature. Each point is an average of five hardness determinations.

From T. I. Jones, CRRM-1097.

Effect of Plutonium Fissioning on the Hardness of Aluminum-Plutonium Alloys.

- Irradiation temperature, 350-400°C.
- × Initial irradiation temperature, 550-625°C
final irradiation temperature ~ 400°C
- B₅ Irradiation throughout at ~ 625°C

From T. I. Jones, CRRM-1097.

Effect of Plutonium Fissioning, Irradiation Temperature and Postirradiation Heat-Treatment at 640-650°C on the Volumes of Aluminum-Plutonium Alloys.

- Specimens irradiated under restraint at 350-400°C.
- × Specimens irradiated under no restraint; initial irradiation temperatures, 550-625°C.
- Specimens irradiated initially under no restraint at 600-625°C and later under restraint at ~ 400°C.
- Specimens postirradiation annealed at 640-650°C, after desheathing.

DATA FOR THE ALUMINUM-CLAD Al-5 WT. % Pu ALLOY IRRADIATED TO
 11.97×10^{21} nvt (89.3% Pu ATOMS FISSIONED) AND THEN ANNEALED
 15 MIN AT VARIOUS TEMPERATURES From B. A. Loomis, ANL-6651.

Annealing Temperature, °C	Weight, g	Volume, cm ³	Density, g/cm ³	Change in Density, %	Hardness, R _H
Preirradiation	20.354	7.480	2.721		
Postirradiation	19.708 †	7.281	2.707		61 ‡
125	19.710	7.281	2.707	0	62
150	19.708	7.278	2.708	-0.04	59
200	19.708	7.272	2.710	+0.11	
250	19.707	7.275	2.709	-0.07	68
300	19.706	7.274	2.709	+0.07	57
325	19.705	7.274	2.709	+0.07	
360	19.706	7.271	2.710	+0.11	10
420	19.706	7.265	2.712	+0.19	
465	19.708	7.265	2.713	-0.22	15
496	19.704	7.260	2.714	-0.26	1
550	19.710	7.630	2.583	-4.58	15
575	19.702	7.628	2.583	-4.58	15
598	19.706	7.625	2.584	-4.54	16

* The percent change in density is expressed as the ratio of the change in density on annealing to the density of the specimen after irradiation.

† This weight change is partially due to removal of an oxide film.

‡ This value is the average of three or more determinations.

DATA FOR THE ALUMINUM-CLAD Al-10 WT. % Pu ALLOY IRRADIATED TO
 2.14×10^{21} nvt (75.6% Pu ATOMS FISSIONED) AND THEN ANNEALED
 15 MIN AT VARIOUS TEMPERATURES From B. A. Loomis, ANL-6651.

Annealing Temperature, °C	Weight, g	Volume, cm ³	Density, g/cm ³	Change in Density, %	Hardness, R _H
Preirradiation	20.670	7.569	2.731		
Postirradiation	20.599 †	7.572	2.720		52 ‡
125	20.599	7.571	2.721	+0.04	
150	20.592	7.570	2.720	0	59
200	20.592	7.567	2.721	+0.04	
250	20.590	7.568	2.721	-0.04	53
275	20.588	7.567	2.721	+0.04	15
325	20.588	7.568	2.721	-0.04	
375	20.586	7.562	2.722	+0.07	15
410	20.586	7.561	2.723	-0.11	15
453	20.586	7.560	2.723	-0.11	
487	20.586	7.561	2.723	-0.11	
499	20.588	7.544	2.729	+0.33	15
521	20.590	7.554	2.726	+0.22	
550	20.587	7.566	2.721	-0.04	
574	20.588	7.572	2.719	-0.04	
605	20.589	7.607	2.707	-0.48	15

* The percent change in density is expressed as the ratio of the change in density on annealing to the density of the specimen after irradiation.

† This weight change is partially due to removal of an oxide film.

‡ This value is the average of three or more determinations.

PLUTONIUM-GOLD

Plutonium-gold intermetallic phases are known to exist, but they have not yet been identified.

From F. H. Ellinger in *The Metal Plutonium*, p. 291.

Phase Diagrams

Be 101

Constitutional Diagram for the System Plutonium-Beryllium.
From F. W. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2, p. 580.

The Plutonium-Beryllium System
From F. W. Schonfeld in *The Metal Plutonium*, p. 256.

Crystal Structure

Be 103

PuBe₁₃

Cubic face-centered, NaZn₁₃ type

Be-rich: $a = 10.282 \pm 0.001$ Å

Be-rich: $a = 10.284 \pm 0.001$ (Runnalls)

Pu-rich: $a = 10.278 \pm 0.001$ (Runnalls)

$Z = 8$, $D_x = 4.35$ (Runnalls)

Space group. — Fm3c (Int. Tab. 226).

Atomic positions

(0, 0, 0; 1/2, 1/2, 1/2; 1/2, 1/2, 0) +

8 Pu in (a): $\pm(1/4, 1/4, 1/4)$

8 Be in (b): 0, 0, 0; 1/2, 1/2, 1/2

96 Be in (i): $\pm(0, y, z)$, $\pm(1/2, z, y)$, $\pm(0, \bar{y}, z)$, $\pm(1/2, \bar{z}, y)$

with $y = 0.1806 \pm 0.0003$, $z = 0.1192 \pm 0.0003$

Interatomic distances (based on $a = 10.283$ Å)

Pu-24Be = 2.988

Be_I-12Be = 2.225

Be_{II}-2Be = 2.153

-1Be = 2.225

-2Be = 2.245

-4Be = 2.313

-1Be = 2.451

-2Pu = 2.988

Isotypes. — CeBe₁₃, ThBe₁₃, UBe₁₃, NpBe₁₃.

Remarks. — The atomic parameters used for calculating the interatomic distances are those of NaZn₁₃ taken from the work of D. P. Shoemaker,

R. E. Marsh, F. J. Ewing, and L. Pauling. (*Acta Cryst.*, vol. 5, p. 637. 1952.)

Be 204.1

Magnetic Susceptibility

Mass susceptibility at 20°C, $X_g \times 10^6 = 2.4$ emu/g

Temperature dependence of susceptibility: $X_g \times 10^6 = \frac{900}{T - 80}$

Magnetic moment, $\mu_B = 1.7$

From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195.

Be 307

Hardness

Microhardness of $\text{PuBe}_{13} = 947 \text{ kg/mm}^2$

From S. T. Konobeevsky, AEC-tr-2345 Pt. 2, p. 207.

Bi 101

Phase Diagrams

Constitutional Diagram for the System Plutonium-Bismuth.
From F. W. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2, p. 581.

From A. A. Bochvar et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 189. 1958.

Bi 103

Crystal Structure

Cubic face-centered, NaCl type

$a = 6.350 \pm 0.001 \text{ \AA}$

$z = 4, D_x = 11.62$

Space group. — $Fm\bar{3}m$ (Int. Tab. 225).

Atomic positions. — See PuC.

Interatomic distances

$\text{Pu-Bi} = 3.18$

$\text{Bi-Bi} = 3.18$

Isotypes. — LaBi, CeBi, PrBi, UBi (?).

Remarks. — Although PuBi is pyrophoric, it was prepared successfully by melting a mixture of plutonium and bismuth filings in an evacuated clear silica capillary which was then used for the X-ray specimen.

PuBi_2 is pyrophoric and a satisfactory diffraction pattern of it has not been obtained. Its composition is based upon metallographic and thermal-analysis observations.
From F. H. Ellinger in *The Metal Plutonium*, p. 287.

Constitutional Diagram for the System Plutonium-Calcium.
From F. W. Schonfeld et al. in *Metallurgy and Fuels*, Series V, vol. 2, p. 582.

Plutonium-Cerium Phase Diagram.
From L. J. Wittenberg and G. R. Grove, MLM-1184.

The Plutonium-Cerium System.
From F. H. Ellinger et al. in *Extractive and Physical Metallurgy of Plutonium and Its Alloys*, p. 152.

Ce 102

Transformation Kinetics

The $\delta \rightleftharpoons \gamma$ Transformation Pressure at 296 K as a Function of Pu Concentration.
From K. A. Gschneidner, Jr., et al., *J. Phys. Chem. Solids*, vol. 23, p. 1153, 1962.

UNIT CELL DIMENSIONS*

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371.

Sample	Temperature	a, Å	b, Å	c, Å	β , °
Pure Pu	93°C.	9.227	10.449	7.824	92.54
Pure Pu	190	9.284	10.463	7.859	92.13
99 Pu-1 Ce	133	9.251	10.436	7.834	92.35
99 Pu-1 Ce	172	9.260	10.449	7.846	92.24
99 Pu-1 Ce	202	9.286	10.451	7.852	92.06

*Calculated density for pure Pu is 17.70 g.cm.^{-3} at 190°C. Precision is $\pm 0.002 \text{ Å}$ for a, b, c, and $\pm 0.02^\circ$ for β .

Thermal Expansion

Ce 202.1

PRINCIPAL LINEAR COEFFICIENTS OF
THERMAL EXPANSION ($\times 10^6$)

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371.

	α_1	α_2	α_3	$\bar{\alpha}$	β
Pure Pu	94	14	19	42	40°
99 Pu-1 Ce	84	21	7	37	38°

Cerium Alloys

Linear expansion (per °C) for β Pu-1 at. % Ce at 133–202°C:

$$\alpha_a \times 10^6 = 55$$

$$\alpha_b \times 10^6 = 21$$

$$\alpha_c \times 10^6 = 33$$

Angular change (per °C) at 133–202°C: $\Delta \beta / ^\circ\text{C} = -73 \times 10^{-6}$

From W. D. Wilkinson in *Extractive and Physical Metallurgy of Plutonium and Its Alloys*, p. 16. Also, W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 12, p. 176, Table 3.

Average Linear Coefficients of Thermal Expansion vs at. % Solute For Binary Pu-Ce β -phase Solid Solution Alloys. From R. O. Elliott *et al.* in *Plutonium 1960*, p. 152.

Electron-to-atom ratios and concentrations at which the thermal expansion of cerium-plutonium alloys are zero:

$$e/a \text{ Ratio} = 4.74$$

$$\text{at. \% Ce} = 6.3$$

$$\text{at. \% Ce for constant } e/a = 6.2 \pm 1.7$$

$$4.74 \pm 0.02$$

Ce 202.5

Temperature of and Volume Change during Transition

The $\alpha \rightarrow \gamma$ Transformation Temperature as a Function of Pu Concentration at 1 atm. From K. A. Gschneidner, Jr., et al., *J. Phys. Chem. Solids*, vol. 23, p. 1195, 1962.

The Volume of Transformation as a Function of Pu Concentration on Cooling at 1 atm. From K. A. Gschneidner, Jr., et al., *J. Phys. Chem. Solids*, vol. 23, p. 1195, 1962.

The Volume of Transformation as a Function of the Pu Concentration, Measured During Compression at 296°K. From K. A. Gschneidner, Jr., et al., *J. Phys. Chem. Solids*, vol. 23, p. 1193, 1962.

Ce 202.6

Heats of Transition

The Heat of Transition Per Mole of Cerium Versus the Pu Concentration at 296°K. From K. A. Gschneidner, Jr., et al., *J. Phys.*

Specific Resistivity in $\mu\Omega\text{-cm}$ as a Function of Absolute Temperature: (a) for Metastable δ -phase, Solid-Solution Alloys Containing 4, 5 and 5.9 at.% Cerium and (b) for Stable δ -phase, Solid-Solution Alloys Containing 7, 8, 9 and 10 at.% Cerium. From R. O. Elliott et al., J. Phys. Chem. Solids, vol. 23, p. 1033.

Specific Resistivity in $\mu\Omega\text{-cm}$ as a Function of Absolute Temperature for Stable β -phase, Solid-Solution Alloys Containing 12, 14, 16 and 18 at.% Cerium.
From R. O. Elliott et al., J. Phys. Chem. Solids, vol. 23, p. 1034, 1962.

Isothermal Plots of Specific Resistivity in $\mu\Omega\text{-cm}$ as a Function of Atomic Per Cent Cerium for β -phase, Solid-Solution Alloys at Temperatures Between 300 and 10 $^{\circ}\text{K}$. (Solid Lines Indicate Direct Measurements on Stable β Alloys and Dashed Lines Indicate Corrected Values on Metastable β Alloys that Transformed When Cooled to Low Temperatures.)
From R. O. Elliott et al., J. Phys. Chem. Solids, vol. 23, p. 1034, 1962.

The Effect of Composition on Ultimate Strength in Plutonium-Cerium Alloys. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on the 0.1% Yield Stress in Plutonium-Cerium Alloys. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on Elongation in Plutonium-Cerium Alloys. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on Reduction in Area in Plutonium-Cerium Alloys. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Composition on Hardness in Pu-Ce. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner.

The Effect of Concentration of Cerium and Pressure up to About 10,000 atm on the Hardness of Delta-Stabilized Plutonium Alloys. From R. O. Elliott and K. A. Gschneidner, Jr., in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 259.

The Variation of Young's Modulus with Composition for Plutonium-Cerium Alloys. Tested at Room Temperature. From D. C. Miller and J. S. White, Private Communication, reported by H. R. Gardner in Chap. 4, The Plutonium Handbook, 1966.

The Effect of Composition on the Modulus of Elasticity and Modulus of Rigidity of as-cast Plutonium-Cerium Alloys at Room Temperature. From P. F. T. Linford, Private Communication, reported by H. R. Gardner in Chap. 4, The Plutonium Handbook, 1966.

The Effect of Temperature on the Elastic Modulus of an as-cast Plutonium-21.4 at. % Cerium Alloy. From P. F. T. Linford, Private Communication, reported by H. R. Gardner in Chap. 4, The Plutonium Handbook, 1966.

Comparison of the Corrosion Behaviors of Plutonium-Cerium Alloys and Unalloyed Plutonium Exposed to Air at 75 $^{\circ}$ C and 50% Relative Humidity. From J. T. Waber et al., J. Nucl. Mater., vol. 3, p. 205. 1961.

The Plutonium-Cobalt System
 From F. W. Schonfeld in The Metal Plutonium, p. 242.

Pu-Co Phase Diagram.
From D. M. Poole *et al.* in *Plutonium* 1960, p. 274.

Crystal Structure

Pu₆Co

Tetragonal body-centered, U₆Mn type

$a = 10.46 \pm 0.02$ Å
 $c = 5.33 \pm 0.01$ Å
 $a = 10.475 \pm 0.005$ From D. M. Poole *et al.* in *Plutonium* 1960, p. 276.
 $c = 5.340 \pm 0.005$ Å
 $Z = 4, D_x = 17.00$

Space group. — I4/mcm (Int. Tab. 140).
 Atomic positions. — See Pu₆Fe.

Interatomic distances (based on $a = 10.46$, $c = 5.33$ Å)

Pu_I — Pu_I = 2.75

— Pu_{II} = 2.86

— Pu_I = 3.30

— Pu_{II} = 3.34

— Pu_{II} = 3.43

Pu_{II} — Pu_{II} = 2.73

— Pu_I = 2.86

— Pu_{II} = 3.14

— Pu_I = 3.34

— Pu_{II} = 3.41

— Pu_I = 3.44

— Pu_{II} = 3.51

— 2Co = 2.81
 Co — 2Co = 2.66
 — 8Pu_{II} = 2.81

Average Pu-Pu distance = 3.24
 Isotypes. — U₆Co.

Pu₃Co

Orthorhombic

$a = 3.470$ Å (Elliott and Larsen)
 $b = 10.939$ Å
 $c = 9.196$ Å
 $Z = 4, D_x = 14.76$

Space group. — Probably Cmcm (Int. Tab. 63).

$a = 3.501 \pm 0.003$ Å
 $b = 11.03 \pm 0.03$ Å
 $c = 9.23 \pm 0.015$ Å } Pu-rich

$a = 3.477 \pm 0.003$ Å
 $b = 10.99 \pm 0.03$ Å
 $c = 9.20 \pm 0.015$ Å } Co-rich

A Pu-Co alloy ingot of nominal composition 25.5 at. % Co was prepared by arc melting and then was heat treated at 440°C for one week.

a = 3.475 ± 0.004 Å (λMo Kα₁ = 0.70926 Å)
b = 10.976 ± 0.010
c = 9.220 ± 0.008
d_o = 14.82 g.cm⁻³
d_c = 14.65 g.cm⁻³

Interatomic distances in Pu₃Co.

The standard deviation of Pu-Pu distances is 0.02 Å and for Pu-Co distances 0.06 Å

Pu(1)-2Pu(1)	3.48 Å	Pu(2)-2Pu(1)	3.36 Å
Pu(1)-4Pu(2)	3.36	Pu(2)-2Pu(1)	3.40
Pu(1)-4Pu(2)	3.40	Pu(2)-1Pu(1)	3.65
Pu(1)-2Pu(2)	3.65	Pu(2)-1Pu(2)	3.08
Pu(1)-2Co	2.80	Pu(2)-2Pu(2)	3.28
Pu(1)-1Co	3.29	Pu(2)-2Pu(2)	3.48
		Pu(2)-1Pu(2)	3.59
Co-2Pu(1)	2.80	Pu(2)-2Co	2.69
Co-1Pu(1)	3.29	Pu(2)-1Co	3.24
Co-4Pu(2)	2.69		
Co-2Pu(2)	3.24		
Co-2Co	3.475		

From A. C. Larson *et al.*, *Acta Cryst.*, vol. 16, pp. 835, 836.

Pu₂Co

Hexagonal, Fe₂P type

Co-rich: a = 7.763 ± 0.002 Å c/a = 0.470
c = 3.648 ± 0.003 c/a = 0.449 From A. S.
Pu-rich: a = 7.902 ± 0.004 Coffinberry and F. H. Ellinger
c = 3.549 ± 0.002 in *Proc. First Geneva Internat. Conf.*, vol. 9, p. 139, 1958.

Co-rich: a = 7.732 ± 0.008 Å From D. M. Poole *et al.* in
Plutonium 1960, p. 276.
c = 3.654 ± 0.005

Pu-rich: a = 7.803 ± 0.008
c = 3.606 ± 0.005

Z = 3, D_x = 14.0

Space group. — P321 (Int. Tab. 150).

Atomic positions

1Co_I in (b): 0, 0, 1/2

2Co_{II} in (d): 1/3, 2/3, z; 2/3, 1/2, $\bar{z}$ with z = 1/8

3Pu_I in (e): x, 0, 0; 0, x, 0; $\bar{x}$, $\bar{x}$, 0 with x = -0.26

3Pu_{II} in (f): x, 0, 1/2; 0, x, 1/2; $\bar{x}$, $\bar{x}$, 1/2 with x = 0.40

Interatomic distances (based on a = 7.763, c = 3.648 Å)

Pu_I-2Pu_{II} = 3.21
4Pu_{II} = 3.28
-2Pu_I = 3.50
-2Co_I = 2.72
-2Co_{II} = 2.95
Pu_{II}-2Pu_I = 3.21
-4Pu_I = 3.28
-1Co_I = 3.11
-2Co_{II} = 2.74
Co_I-6Pu_I = 2.72
-3Pu_I = 3.11
Co_{II}-3Pu_I = 2.95
-3Pu_{II} = 2.74

PuCo₂

Cubic face-centered, Cu₂Mg type

Pu-rich: a = 7.081 ± 0.001 From A. S. Coffinberry and F. H. Ellinger in *Proc. First Geneva Internat. Conf.*, Vol. 9, p. 139, 1958.

a = 7.075 ± 0.005 (Runnalls)

a = 7.095 ± 7.023
± 0.005

Z = 8, D_x = 13.35

D_x = 13.39 From O. J. C. Runnalls, *Can. J. Chem.*, vol. 34, p. 140.

Space group. — Fd3m (Int. Tab. 227).

Atomic positions. — See PuAl₂.

Interatomic distances

Pu-4Pu = 3.066 Co-6Co = 2.503
-12Co = 2.936 -6Pu = 2.936

Isotypes. — UCo₂, CeCo₂.

PuCo₃

Rhombohedral, PuNi₃ type

a = 8.635 ± 0.010 Å From D. M. Poole *et al.* in *Plutonium* 1960, p. 276.

α = 33° 40' ± 4'

or Hexagonal

a = 5.003 ± 0.007 Å

c = 24.42 ± 0.06

Pu₂Co₁₇

Hexagonal, Th₂Ni₁₇ type

a = 8.325 ± 0.002 Å

c = 8.104 ± 0.003

a = 8.327 ± 0.005 From D. M. Poole *et al.* in *Plutonium* 1960, p. 276.

c = 8.107 ± 0.005

Z = 2, D_x = 10.10

Space group. — P6₃/mmc (Int. Tab. 194).

Atomic positions

2Pu_I in (b): ± (0, 0, 1/4)

2Pu_{II} in (d): ± (1/3, 2/3, 3/4)

6Co_I in (g): 1/2, 0, 0; 0, 1/2, 0; 1/2, 1/2, 0; 1/2, 0, 1/2;
0, 1/2, 1/2; 1/2, 1/2, 1/2

12Co_{II} in (j): ± (x, 0, 1/4); ± (0, x, 1/4); ± (x, $\bar{x}$, 1/4); ± ($\bar{x}$, 0, 1/4);
± (0, $\bar{x}$, 1/4); ± ($\bar{x}$, $\bar{x}$, 1/4) with $\bar{x}$ = 1/3

12Co_{III} in (k): ± (x, 2x, 0); ± ($\bar{x}$, x, 0); ± (2x, x, 0); ± (x, 2x, 1/2);
± ($\bar{x}$, x, 1/2); ± (x, 2x, 1/2) with x = 1/6

4Co_{IV} in (f): ± (1/3, 2/3, z); ± (1/3, 2/3, 1/2-z) with z = 0.11

Remarks. — The atomic parameters are those of Th₂Ni₁₇ as determined by Florio *et al.*

Where no other reference is indicated, data are from F. H. Ellinger in *The Metal Plutonium*, pp. 288, 289.

PARAMAGNETIC SUSCEPTIBILITIES OF PLUTONIUM-COBALT COMPOUNDS

From S. T. Konobeevsky *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195. 1958.

Compound	Structure	Paramagnetic Susceptibility at 20°C	
		Mass	Atomic*
		$\chi_g \times 10^6$ emu g ⁻¹	$\chi_a \times 10^6$ emu g-at. ⁻¹
Pu (a)	Orthorhombic	2.4	570
Pu ₆ Co	bc, tetragonal, type U ₆ Mn	2.3	490
Pu ₃ Co	---	2.5	480
Pu ₂ Co	Hexagonal, type Fe ₂ P	2.4	430
PuCo ₂	fcc, type MgCu ₂	10.5	1250

*The average susceptibility per gram atom is calculated according to the formula $\chi_a = \chi_g(A + B)$ where the expression in brackets stands for the mean atomic weight.

Paramagnetic Susceptibility of Plutonium Alloys with Cobalt at Room Temperature. From S. T. Konobeevsky *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195. 1958.

Temperature dependence of paramagnetic susceptibility of Certain Plutonium Compounds; 1, Pu₃Co; 2, Pu₂Co.

From S. T. Konobeevsky *et al.* in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195. 1958.

Cr 101

Phase Diagrams

Constitutional Diagram for the Systems Plutonium-Vanadium, Plutonium-Chromium, Plutonium-Niobium, Plutonium-Molybdenum, Plutonium-Tantalum, and Plutonium-Tungsten. From A. S. Coffinberry et al. in *Reactor Handbook*, 2nd ed., vol. 1, p. 273.

The Plutonium-Chromium System. From F. W. Schonfeld in *The Metal Plutonium*, p. 260.

Cu 101

Phase Diagrams

Proposed Pu-Cu Binary Phase Diagram (by Differential Thermal Analysis). From T. B. Rhinehammer et al. in *Plutonium 1960*, p. 295.

Solid Solution Section of Pu-Cu System. From T. B. Rhinehammer et al. in *Plutonium 1960*, p. 296.

INVARIANT EQUILIBRIA IN THE SYSTEM Pu-Cu

From T. B. Rhinehammer et al. in *Plutonium 1960*, p. 296.

Composition, at. %		Temperatures*, °C	Type of Invariant Point
Pu	Cu		
94.0	6.0	626	Eutectic Pu + PuCu ₂
33.3	66.7	865	Congruent m.p. of PuCu ₂
29.5	70.5	849	Eutectic PuCu ₂ + PuCu ₄
25.0	75.0	906	Peritectic point
20.0	80.0	906	Incongruent m.p. of PuCu ₄
19.2	80.8	954	Congruent m.p. of Pu ₄ Cu ₁₇
15.4	84.6	926	Incongruent m.p. of Pu ₂ Cu ₁₁
14.5	85.5	926	Peritectic point
9.0	91.0	881	Eutectic Pu ₂ Cu ₁₁ + Cu

*Accuracy ±3°C.

DIFFERENTIAL THERMAL ANALYSIS OF Pu-Cu SYSTEM

From T. B. Rhinehammer et al. in *Plutonium* 1960, p. 297.

Composition, at. %		Transitions, °C			
Pu	Cu	Eutectic	Peritectic	Liquidus	Solidus
99.0	1.0	---	---	640	636
98.0	2.0	---	---	639	630
97.0	3.0	---	---	635	627
96.0	4.0	626	---	633	---
94.0	6.0	625	---	626	---
92.5	7.5	626	---	660	---
91.0	9.0	625	---	687	---
85.0	15.0	626	---	708	---
80.0	20.0	625	---	716	---
75.0	25.0	626	---	722	---
70.0	30.0	626	---	734	---
65.0	35.0	626	---	742	---
60.0	40.0	626	---	756	---
55.0	45.0	627	---	769	---
50.0	50.0	624	---	787	---
45.0	55.0	625	---	819	---
40.0	60.0	626	---	841	---
37.0	63.0	620	---	855	---
34.0	66.0	---	---	865	---
33.0	67.0	847	---	864	---
31.5	68.5	849	---	862	---
29.0	71.0	849	---	854	---
27.5	72.5	849	---	891	---
25.0	75.0	849	---	906	---
24.0	76.0	849	908	926	---
22.0	78.0	854	906	948	---
21.0	79.0	850	907	951	---
20.0	80.0	854	906	952	---
19.2	80.8	---	---	954	---
18.2	81.8	---	928	954	---
16.7	83.3	---	926	952	---
16.0	84.0	---	928	951	---
15.39	84.61	---	926	941	---
14.5	85.5	881	---	926	---
12.0	88.0	881	---	916	---
8.0	92.0	880	---	916	---
5.0	95.0	881	---	1002	---

SOLID PHASE TRANSITIONS

From T. B. Rhinehammer et al. in *Plutonium* 1960, p. 298.

Composition, at. %		Transitions, °C							
Pu	Cu	Other	$\alpha-\beta$	$\beta-\gamma$	$\gamma-\delta$	Other	$\delta-\delta'$	$\delta'-\epsilon$	
99.0	1.0	118	134	218	317	358	439	453	
98.0	2.0	121	129	229	321	350	447	454	
97.0	3.0	124	132	216	319	360	445	457	
96.0	4.0	124	134	222	321	365	450	457	
94.0	6.0	124	130	227	322	346	447	453	
92.5	7.5	122	132	222	319	358	448	452	
91.0	9.0	122	132	226	336	353	450	457	
85.0	15.0	120	128	230	327	351	448	457	
80.0	20.0	122	128	232	325	350	447	454	
75.0	25.0	110	122	234	324	355	448	457	
70.0	30.0	116	124	220	322	338	450	458	
65.0	35.0	122	128	222	331	346	452	462	
60.0	40.0	122	128	222	329	353	450	462	
55.0	45.0	118	126	222	324	348	448	459	
50.0	50.0	116	122	212	324	---	448	457	
45.0	55.0	---	122	222	326	---	445	457	
40.0	60.0	---	122	---	324	---	---	455	
37.0	63.0	---	122	---	---	---	---	455

The Plutonium-Copper System. From F. W. Schonfeld in The Metal Plutonium, p. 261.

The Plutonium-Iron System
From F. W. Schönfeld in *The Metal Plutonium*, p. 243.

The Plutonium-Iron System
 From F. W. Schonfeld in The Metal Plutonium, p. 256.

Pu_6Fe Tetragonal body-centered, U_6Mn type

$$\begin{aligned} a &= 10.404 \pm 0.004 \text{ \AA} \\ c &= 5.355 \pm 0.002 \\ a &= 10.40 \pm 0.02 \\ c &= 5.345 \pm 0.005 \end{aligned}$$

$$\begin{aligned} a &= 10.403 \\ c &= 5.347 \\ Z &= 4, D_x = 17.07 \end{aligned}$$

Space group. — $I4/mcm$ (Int. Tab. 140).

Atomic positions

$$\begin{aligned} (0, 0, 0; 1/2, 1/2, 1/2) + \\ 4\text{Fe in (a): } \pm (0, 0, 1/4) \\ 8\text{Pu}_I \text{ in (b): } \pm (x, 1/2 + x, 0); \pm (1/2 - x, x, 0) \text{ with } x = 0.407 \\ 16\text{Pu}_{II} \text{ in (k): } \pm (x, y, 0); \pm (y, \bar{x}, 0); \pm (x, \bar{y}, 1/2); \pm (y, x, 1/2) \\ \text{with } x = 0.214, y = 0.102 \end{aligned}$$

Interatomic distances (based on $a = 10.404$, $c = 5.355$)

$$\begin{aligned} \text{Pu}_I\text{-Pu}_I &= 2.74 \\ -2\text{Pu}_{II} &= 2.85 \\ -4\text{Pu}_I &= 3.30 \\ -4\text{Pu}_{II} &= 3.35 \\ -2\text{Pu}_{II} &= 3.41 \\ \text{Pu}_{II}\text{-Pu}_{II} &= 2.71 \\ -1\text{Pu}_I &= 2.85 \\ -2\text{Pu}_{II} &= 3.14 \\ -2\text{Pu}_I &= 3.35 \\ -1\text{Pu}_I &= 3.41 \\ -2\text{Pu}_{II} &= 3.42 \\ -2\text{Pu}_{II} &= 3.49 \\ 2\text{Fe} &= 2.81 \\ \text{Fe-2Fe} &= 2.68 \\ -8\text{Pu}_{II} &= 2.81 \end{aligned}$$

Average Pu-Pu distance = 3.23

Isotypes. — U_6Fe .Remarks. — The atomic parameters given for Pu_6Fe are those determined by Baenziger et al. for U_6Mn .Thermal expansion. — The average coefficients of linear expansion of Pu_6Fe parallel to the axes of the unit cell between room temperature and 400°C have been found to be

$$\bar{\alpha}_a = (7.3 \pm 2) \times 10^{-6}/^\circ\text{C}$$

$$\bar{\alpha}_c = (-10 \pm 1) \times 10^{-6}/^\circ\text{C}$$

 $\text{Pu}_6\text{Fe-U}_6\text{Fe}$ SOLID SOLUTIONS Pu_6Fe and U_6Fe were found to be miscible in all proportions.Although it is difficult to prepare single-phase alloys of the ternary composition $(\text{Pu}, \text{U})_6\text{Fe}$, the powder photographs do show essentially a single phase, and there is a uniform change in the unit-cell dimensions between Pu_6Fe and U_6Fe .From F. H. Ellinger in *The Metal Plutonium*, pp. 292, 293. PuFe_2 Cubic face-centered, Cu_3Mg type

$$\begin{aligned} \text{Pu-rich: } a &= 7.191 \pm 0.001 \text{ \AA} \\ a &= 7.150 \pm 0.005 \text{ (Runnalls)} \\ a &= 7.190 \pm 0.005 \text{ (Runnalls)} \end{aligned}$$

$$\begin{aligned} \text{Pu-rich: } a &= 7.18 \pm 0.01 \\ a &= 7.178 \\ Z &= 4, D_x = 12.53 \end{aligned}$$

Space group. — $\text{Fd}\bar{3}m$ (Int. Tab. 227).Atomic positions. — See PuAl_2 .Interatomic distances (based on $a = 7.191$)

$$\begin{aligned} \text{Pu-4Pu} &= 3.114 \\ -12\text{Fe} &= 2.981 \\ \text{Fe-6Fe} &= 2.542 \\ -6\text{Pu} &= 2.981 \end{aligned}$$

Isotypes. — CeFe_2 , GdFe_2 , UFe_2 . $\text{PuFe}_2\text{-UFe}_2$ Solid Solutions

PuFe_2 and UFe_2 are mutually soluble in any proportion. The variation in the unit-cell dimension from PuFe_2 to UFe_2 is shown in Figure 2. From F. H. Ellinger in *The Metal Plutonium*, p. 294.

Unit-Cell Dimensions Versus Composition of $\text{Pu}_6\text{Fe-U}_6\text{Fe}$ Solid Solution. From F. H. Ellinger in *The Metal Plutonium*, p. 294.

Unit-Cell Dimensions Versus Composition of $\text{PuFe}_2\text{-UFe}_2$ Solid Solution. From F. H. Ellinger in *The Metal Plutonium*, p. 294.

PuFe_2 is face centered cubic with $a_0 = 7.164 \text{ \AA}$ (7.178 Å)

It is isostructural with MgCu_2 .

It has 8 formula weights/unit cell.

Calculated density = 12.59 g/cm^3 , 31.8 wt. % Fe

Pu_6Fe is tetragonal with $a_0 = 10.382 \text{ \AA}$ (10.403 Å) and $c = 5.336 \text{ \AA}$ (5.347 Å)

It contains 4 formula weights/unit cell.

Calculated density = 17.1 g/cm^3 , 3.75 wt. % Fe

From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 211.

face centered cubic, isostructural with UFe_2

a range of composition:

lattice constants:

- (a) $7.150 \pm 0.005 \text{ \AA}$
(b) $7.190 \pm 0.005 \text{ \AA}$

calculated density:

- 12.74 g/cm^3
 12.53 g/cm^3

MgCu_2 structure, space group $\text{Fd}3\text{m}$

8 formula weights/unit cell

From O. J. C. Runnals, *Can. J. Chem.*, vol. 34, p. 140. (Selected parts of table VI).

INTERATOMIC DISTANCES IN THE COMPOUNDS PuFe_2

Atom	Neighbor	Number of Neighbors	Distance A	
			(a)	(b)
Pu	Pu	4	3.10	3.12
	Fe	12	2.96	2.98
Fe	Fe	6	2.53	2.54
	Pu	6	2.96	2.98

From O. J. C. Runnals, *Can. J. Chem.*, vol. 34, p. 140. (Selected parts of table VI).

CRYSTALLOGRAPHY OF PLUTONIUM-IRON SYSTEM

From F. W. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2, p. 586.

Compound	Type	Crystal Lattice	Unit Cell Dimensions, A	Number of Molecules	Space Group	Calculated Density, g/cm ³
Pu_6Fe	U_6Mn	Body-centered tetragonal	$a = 10.41$ $c = 5.359$	4	I4/mcm	17.04
PuFe_2	Cu_2Mg	Face-centered cubic	7.19	8	Fd3m	12.53

Fe 201 Density

The density of a Pu-7.93 at.% Fe alloy was determined to be:

$$\rho = [16.88 - (1.369T)] \pm 0.012 \text{ g/cm}^3$$

The apparatus and procedure used are described in: LA-2358, "The Density of Liquid Plutonium Metal", C. E. Olsen, T. A. Sandenaw, and C. C. Herrick, May 1959.
From C. E. Olsen et al. LA-2358.

Phase (+Pu ₆ Fe)	Run #	Temperature at Data Points, °C		Density, g/cm ³		Coeff. of Cubic Expansion From Low to High Temp. in Phase (x 10 ⁻⁶)		Temperature* at Phase Change, °C	Expansion, Vol. %	
		(1)	(2)	(1)	(2)	(1)	(2)		(1)	(2)
■		25	23.5	16.857	16.770		112. ₉			
			109.75		16.61					
■ - β								122 ± 2		0.4 ₇
β		138	136.5	16.50	16.49	133. ₈	89. ₂			
		150	197.25	16.47	16.40					
		193		16.38						
β - γ								206 ± 3	0.3 ₁	0.2 ₆
γ		225	221.5	16.26	16.32	137. ₅	76. ₃			
		308	296	16.08	16.23					
γ - δ								319 ± 5	0.9 ₃	1.4 ₀
δ		328	329	15.90	15.96	65. ₉	138. ₄			
		412	400	15.81	15.80					
δ - liquid								411 ± 7	-1.9 ₆	-2.1 ₇
Liquid (Only)		470	460	16.01	16.04	124. ₄	113. ₃			
		535	621	15.88	15.76					
			664		15.68					

(1) Run #1 = 2/36 wt. % Fe, (2) Run #2 = 2.35 wt. % Fe. From F. W. Knight in Plutonium 1960, p. 693.
 * From A. S. Coffinberry and M. B. Waldron in Metallurgy and Fuels, series V, vol. 1, p. 372.

Thermal Conductivity

Fe 202.2

Thermal Conductivity of Pu-Fe Eutectic. The Temperature Coefficient of Conductivity for the Solid State is $13 \times 10^{-4}/^{\circ}\text{C}$, for the Liquid State, $7.0 \times 10^{-4}/^{\circ}\text{C}$. From J. E. Deverall, LA-2269.

Fe 202.5

Temperature of and Volume Change during Transition

Comparison of Plutonium-Iron Liquids With Ideal Solution Behavior.
From L. J. Wittenberg and G. R. Grove, MLM-1184.

Fe 204.1

Magnetic Susceptibility

Temperature Dependence of Magnetization of PuFe₂.
From S. T. Konobeevsky et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 197, 1958.

Hysteresis Curve for PuFe₂.
From S. T. Konobeevsky et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 197, 1958.

DEPENDENCE OF VISCOSITY UPON TEMPERATURE FOR Pu-Fe ALLOY

From L. J. Wittenberg et al. in *Plutonium 1960*, p. 682.

Run No.	Temperature, °C	Logarithmic Decrement, $\delta_l - \delta_e$	Period, sec	Density, g/cm ³	Viscosity, cP
1	707	0.084301	11.244	15.63	7.36
1	654	0.087085	11.254	15.72	8.84
1	603	0.090385	11.273	15.80	10.2
1	553	0.093535	11.298	15.88	11.4
2	808	0.069602	11.304	15.37	6.14
2	759	0.071501	11.308	15.53	6.57
2	706	0.074228	11.310	15.63	7.51
2	656	0.076533	11.320	15.72	8.71
2	604	0.078925	11.332	15.80	9.64
3	597	0.052195	2.720	15.80	10.3
3	555	0.055281	2.724	15.88	11.9
3	532	0.058358	2.725	15.92	13.4
3	511	0.059846	2.731	15.96	14.7
3	494	0.062538	2.739	16.00	16.5
3	474	0.064760	2.747	16.02	18.5
3	451	0.067860	2.755	16.06	20.8
3	433	0.069834	2.757	16.10	22.4

Viscosity of Plutonium-Iron Alloys as a Function of Reciprocal Absolute Temperature.

From L. J. Wittenberg and G. R. Grove, MLM-1184.

Viscosity of Plutonium Iron Eutectic Alloy as a Function of Absolute Temperature.

From L. J. Wittenberg et al. in *Plutonium 1960*, p. 683.

EQUATIONS FOR VISCOSITY DATA*

From L. J. Wittenberg and G. R. Grove, MLM-1184.

Composition	m	b	Standard Deviation, poise	Activation Energy, cal/g-atom
Pu	1.1270	0.4191	±0.0035	5157
99 at.% Pu-1 at.% Fe	1.1226	0.3898	±0.0012	5137
95 at.% Pu-5 at.% Fe	1.4013	0.5480	±0.0013	6411
90.5 at.% Pu-9.5 at.% Fe	1.5565	0.7096	±0.0044	7351
87 at.% Pu-13 at.% Fe	1.4166	0.5478	±0.0032	6482

$$\text{*General Equation: } \log \left(\frac{\eta}{T} \times 10^5 \right) = m \left(\frac{1000}{T} \right) - b$$

Viscosities of Plutonium-Iron Molten Alloys as a Function of Iron Concentration and Super-Heating Temperature.
From L. J. Wittenberg and G. R. Grove, MLM-1184.

TENSILE AND HARDNESS PROPERTIES OF PLUTONIUM-IRON ALLOYS*

From H. R. Gardner in HW-66985 (Classified)

Iron, at. %	Ultimate Strength, psi	Yield Strength 0.01% Offset, psi	Modulus of Elasticity, 10 ⁶ psi	Elonga- tion †, %	Reduction In Area, %	Test Temp., °C	Density, g/cm ³	Diamond Pyramid Hardness, 10-Kg Load
7.0	54,500	26,700	7.1	0.23	0	30	17.54	218
7.0	29,700	-	-	-	-	125	17.54	-
7.0	24,500	8,720	3.8	0.59	0	127	17.54	-
8.7	35,900	25,700	6.7	0.044	0	30	17.07	202
8.7	34,100	10,750	5.0	0.43	0	127	17.07	-
8.7	14,150	-	-	< 1.0	0	220	17.07	-
8.7	4,260	-	-	12.5	5.9	318	17.07	-

*All tensile specimens 0.250-in. diameter. Testing Speed: 0.015 in./min

†Gage length 1 in.

Compressive Properties

Ultimate compression strength of two specimens of 8.7 at. % Fe = 112,000 and 115,000 psi. Total deformation at failure = 6.7% and 7.3%.

Hardness

ROOM TEMPERATURE HARDNESS FIGURES FOR PLUTONIUM ALLOYS

From D. M. Poole et al. in *Plutonium* 1960, p. 640.

Alloy Composition, at. %	Heat Treatment	Vickers Hardness Number, VHN
Fe-2.5Pu	Arc cast	106
Fe-5Pu	Arc cast	184
Fe-7.5Pu	Arc cast	223
Fe-10Pu	Arc cast	268
Fe-12.5Pu	Arc cast	286
Fe-15Pu	Arc cast	318
Fe-20Pu	Arc cast	423
Fe-10Pu	1000°C 2 days	222
Fe-15Pu	1000°C 2 days	293
Fe-20Pu	1000°C 2 days	365

Alloy

Diamond Pyramid
Hardness, kg/mm²

• Pu	223-250
Compound Pu ₆ Fe (14.3 at. %)	260
Compound PuFe ₂ (166.4 at. %)	636
Eutectic (2.5 wt. % Fe) (10 at. %)	230
Eutectic (50 wt. % Fe) (81.1 at. %)	473

From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 211.

Air

Oxidation of Plutonium-Iron Alloys in Dry CO₂ at 600°C.
From M. J. F. Notley *et al.*, AERE-R-4070.

Oxidation of Plutonium-Iron Alloys in Dry CO₂ at 700°C.
From M. J. F. Notley *et al.*, AERE-R-1070.

Oxidation of Plutonium-Iron Alloys in Dry CO₂ at 800°C
From M. J. F. Notley *et al.*, AERE-R-4070.

OXIDATION RATES, PHYSICAL APPEARANCE AND STRUCTURE OF OXIDES OBTAINED FROM
PLUTONIUM-IRON ALLOYS OXIDIZED IN DRY CO₂ AT 600, 700 AND 800°C

From M. J. F. Notley *et al.*, AERE-R-4070.

Alloy, at.% Pu In Fe	Temperature, °C	Linear Rate, mg/cm ² /hr	Constituents Identified By X-ray Analysis	Micrograph Figure	Appearance
2	600	0.072		19	Dull grey adherent oxide layer
5	600	0.126			Dull grey adherent oxide layer
10	600	0.148			Dull grey adherent oxide layer
15	600	0.220			Dull grey adherent oxide layer
2	700	0.432	Pu ₂ O ₃ , FeO	21	Dull grey oxide.
5	700	0.792	PuO ₂ , Pu ₂ O ₃ , FeO	17, 20	darker than at 600°C and more easily detached
10	700	1.836	PuO ₂ , FeO, $\blacksquare$ Fe, Fe ₃ O ₄		2/3 surface bright and metallic, remainder dark grey
15	700	3.060	PuO ₂ , FeO, $\blacksquare$ Fe, Fe ₃ O ₄		
2	800	1.476	PuO ₂ , FeO, trace Fe ₃ O ₄		Bright surface covered in dark friable oxide
5	800	2.718	-		
10	800	9.360	PuO ₂ , FeO, some $\blacksquare$ Fe		Hard scale, some cracking
15	800	14.76	PuO ₂ , $\blacksquare$ Fe	18, 22	Very hard scale, extensive

Arrhenius Plot of Oxidation of Plutonium-Iron Alloys in Dry CO_2 .
From M. J. F. Notley et al., AERE-R-4070.

Corrosive Properties

Ta MASS TRANSFER RATES IN CONCENTRATED Pu FUELS

From C. C. Burwell et al., *Nucl. Sci. Eng.*, vol. 14, p. 130.

Fuel	Additive	No. Tests	Average Attack Rate, Mils Per Year		
			Temp. 700°C.	Temp. 750°C.	Temp. 800°C.
PuFe (cast iron)	None	16	0	0	0-11
PuFe (pure iron)	None	8	0-58	24-44	-
PuFe (pure iron)	500 to 2000 ppm C	5	0	0	-
PuFe (pure iron)	500 to 5000 ppm Si	3	0-10	3-23	-
PuFe (pure iron)	5000 ppm Mn	1	11	-	-

INTERGRANULAR PENETRATION OF Ta VS. THE ADDITION OF C TO THE Pu-Fe FUEL (200 HR AT 750°C)

From C. C. Burwell et al., *Nucl. Sci. Eng.*, vol. 14, p. 131.

Fuel	Additive	No. Tests	Average no. of 180° bends to failure	Results of radioautography
Pu-Fe (cast iron)	PuC to give 1000 ppm C	1	15 1/2	Negative
Pu-Fe (cast iron)	None	2	1	-
Pu-Fe (pure iron)	None	3	2	Positive
Pu-Fe (pure iron)	Graphite rod to give 1000 ppm C	3	13 1/2	Negative
Pu-Fe (pure iron)	PuC to give 1000 ppm C	1	7 1/2	-
Pu-Fe (pure iron)	Premixed with PuC to give 500 ppm C	1	13	Negative

A positive result for radioautography means that Pu penetrated the capsule wall during test. In bend testing a result over 11 indicates little or no intergranular attack of the metal.

INTERGRANULAR PENETRATION OF Ta AT 625°C VS. ADDITIONS OF C AND Si TO Pu-Fe FUEL

From C. C. Burwell et al., *Nucl. Sci. Eng.*, vol. 14, p. 132.

Additive	No. Tests	Time, Hr.	Results Of Radioautograph	No. 180° Bends To Failure
None	2	1026	Positive	1/2
PuC (300 ppm C)	2	1026	Positive	1/2
PuC premixed to give 300 ppm C	1	1026	Positive	1/2
0.7 wt.-% Si added	1	1026	Positive	3 1/2
0.7 wt.-% Si added	1	1026	Negative (test continued)	-
0.7 wt.-% Si prealloyed	1	1026	Negative (test continued)	-
0.7 wt.-% Si added	1	1526	Positive	5 1/2
0.7 wt.-% Si prealloyed	1	1526	Positive	7 1/2

INTERGRANULAR PENETRATION OF Ta AT 625° AND 750°C VS. ADDITIONS OF Si AND Al TO Pu-Fe EUTECTIC

From C. C. Burwell et al., *Nucl. Sci. Eng.*, vol. 14, p. 132.

Additive	Radioautograph	1000 hr at 625°C		200 hr at 750°C	
		Number Of 180° Bends To Failure	Radioautograph	Number Of 180° Bends To Failure	Radioautograph
0.4 wt.-% Si	Positive	10	Positive	-	-
0.7 wt.-% Si	Negative	14 1/2	Negative	13 1/2	-
1.5 wt.-% Si	Positive	3	Positive	11	-
0.7 wt.-% Si + 0.7 wt.-% Al	Negative	12	Negative	5	-
0.7 wt.-% Al	Negative	11 1/2	Negative	-	-
0.3 wt.-% Al	Negative	11 1/2	Positive	12	117

INTERGRANULAR PENETRATION OF THE CAPSULE
GAS PHASE vs. ADDITIONS OF Ca OR Mg TO
THE Pu-Fe FUEL (200 hr AT 750°C)

From C. C. Burwell et al., *Nucl. Sci. Eng.*, vol. 14, p. 132.

Fuel System	Composition	No. Of 180° Bend To Failure In The Gas Zone	Results Of Radioautograph
Pu-Fe prealloyed with Mg and PuC	700 ppm C, 350 ppm Mg	1	Positive
Pu-Fe plus a layer of Na-Ca	3 at. % Ca in Na layer	1/2	Positive
Mg without Pu-Fe		10	Not applicable
Pu-Fe plus a Ca- Mg layer	73 at. % Ca eutectic	1/2	Positive

CUMULATIVE PERCENTAGE OF CAPSULES OF Ta + 0.1% W LEAKING
AS A FUNCTION OF THE PRESENCE OR ABSENCE
OF ADDED CALCIUM AND MAGNESIUM IN THE FUEL
(The capsules had been annealed in a vacuum at 1300°C for 1 h.
The basic fuel was Pu-Fe alloy of high purity.
The limits of detection were 10 ppm for Ca and 5 ppm for Mg.)

From B. J. Thamer in *Corrosion of Reactor Materials*, vol. II, p. 299.

Additive Treatment		Cumulative Time at 625°C			
		700 h	1400 h	2100 h	2800 h
Added:	15-160 ppm Mg <10-150 ppm Ca	67%	100	Discontinued----	
Same, then removal, <5 ppm Mg, <10 ppm Ca		33	33	67	100
Basic fuel:	20-30 ppm Mg, <10 ppm Ca	0	0	0	33

TANTALUM MASS TRANSFER RATES OF FUELS
CONSIDERED FOR USE IN LAMPRE

From C. C. Burwell et al., *Trans. Am. Nucl. Soc.*, vol. 4, p. 347.

Eutectic Fuels	No. Tests	Total Test Time, Hr.	Ave. Mass Transfer Rate, Mills/yr	Temp., °C
Pu-Fe (made with cast iron)	9	6722	0.5	700
Pu-Fe (made with cast iron)	11	2832	13	800
Pu-Fe (made with pure iron)	8	1901	24	700

TANTALUM MASS TRANSFER RATES OF
Pu-Fe EUTECTIC FUELS WITH ADDITIONS
OF C, Mn, AND Si

From C. C. Burwell et al., *Trans. Am. Nucl. Soc.*, vol. 4, p. 347.

Fuel	No. Tests	Total Test Time, Hr.	Ave. Mass Transfer Rate, Mills/yr	Temp., °C
Pu-Fe (cast iron)	5	1142	0	700
	4	1230	0.4	750
Pu-Fe (pure iron)	8	1901	24	700
	3	601	> 31	750
Pu-Fe (pure iron) +500-2000 ppm C	5	1137	0	700
	5	1227	0	750
Pu-Fe (pure iron) +500-5000 ppm Si	3	648	3	700
	2	500	14	750
Pu-Fe (pure iron) +5000 ppm Mn	1	149	11	700

Control of intergranular attack of tantalum by modifications to the Pu-Fe eutectic fuel is promising but still in the experimental stage. The major effects of fuel modifications observed so far are:

1. The addition of 500 ppm carbon to the Pu-Fe fuel reduces intergranular attack of tantalum at 750°C but is ineffective or even detrimental at 625°C.
2. The addition of 0.4-1.5 wt. % silicon to the Pu-Fe fuel eliminated intergranular attack of tantalum in 200 hour tests at 750°C. At 625°C the addition of 0.7 wt. % silicon to the fuel reduced the rate of intergranular attack (by approximately a factor of 2), but did not eliminate it.
3. The addition of 0.3-0.7 wt. % aluminum to the fuel appears to reduce the rate of intergranular attack at 750°C.
4. The addition of 500 ppm oxygen to the fuel does not significantly affect the fuel properties with respect to intergranular attack.
5. Small amounts (<10 ppm) of calcium and magnesium in the fuel are detrimental in that they facilitate fuel-capsule wetting and thus aid exposure of the tantalum above the fuel level to plutonium. From C. C. Burwell et al., *Trans. Am. Nucl. Soc.*, vol. 4, p. 348.

COMPARATIVE RATES OF MASS TRANSFER OF TANTALUM
FOR VARIOUS FUELS AND FUEL ADDITIVES

Units: mil/yr. Sensitivity: 0.2 mil/yr.*

From B. J. Thamer in *Corrosion of Reactor Materials*, vol. II, p. 298.

Fuel	Hot Zone at 700°C	Hot Zone at 750°C
Pu-Fe (pure iron)	24.	>31
Pu-Fe (cast iron)	0.3	0.4
Pu-Fe (pure iron) +500-2000 ppm C	0.	0.
Pu-Fe (pure iron) +500-5000 ppm Si	3.	14.
Pu-Fe (pure iron) +5000 ppm Mn	11.	----

*1 mil = 0.001 inch.

EFFECTS OF TANTALUM STRUCTURE ON CORROSION

Excellent corrosion resistance was observed in some early "pure" tantalum capsules from Metallwerk Plansee A.G., in which the fine, heavily worked structure had the form of platelets oriented parallel to the surfaces (Fig. 10), and is characteristic of ironed material. It is postulated that this structure presented a minimum of grain boundary area to the fuel and created a tortuous path of penetration through the wall (Fig. 11). In deep-drawn tantalum capsules the platelets were oriented radially, and the rapid penetration by plutonium was ascribed to the direct paths existing through the material (Fig. 12). The ratio between penetrations in the radial and longitudinal directions, respectively, was actually observed to be proportional to the number of grain boundaries of those orientations originally present in the tantalum. These conclusions led to the early specification of impact extrusion and ironing instead of deep drawing.

Ironed capsules, however, still exhibited a point of weakness at the juncture between the worked structure and the heat-affected zone associated with the weld at the cap. Fuel alloys showed a tendency to penetrate at this point, then to creep downward through the worked structure. The advancing plutonium caused recrystallization of the tantalum, presumably through dissolution of strained crystals and precipitation of unstrained tantalum. This recrystallization in the presence of fuel is complete within a few hours at 700°C, which is hundreds of times faster than recrystallization of intact metal at the same temperature. Figure 13 shows a specimen penetrated by fuel alloy and recrystallized, while a small area still unaffected shows the unaltered heavily ironed tantalum structure.

There is evidence that penetration at the heat-affected zone may result either from internal energy differences between the general worked structure and the annealed structure near the weld, or from diffusion of copper from the chill block in which the capsule is clamped during welding. Diffusion of some such deleterious substance as thorium from the welding electrode into the heat-affected zone has also been suggested. The results of independent studies of the effects of carbon and nitrogen, and the practice of purging and thorough blanketing with helium and argon of selected purities before welding, seem to have eliminated the possibility of interstitial elements as primary causes of this attack.

The hypothesis of an internal energy difference as the cause of attack at the heat-affected zone is strengthened by the fact that capsules annealed before loading and welding have better corrosion resistance than those with any worked structure. Treatment at the minimum annealing conditions of one hour at 1050°C doubled the time required for plutonium penetration.

Annealing at higher temperatures leads naturally to the growth of larger and more symmetrical crystals. It would seem reasonable that this further growth past a visually complete anneal should involve minor changes in internal energy, probably having no effect on corrosion. The experimental fact is, however, that at least up to 1450°C, higher annealing temperatures result in progressively improved corrosion resistance, as shown in Table VI. From R. M. Bidwell "Effects of Tantalum Structure on Corrosion" et al., *Nucl. Sci. Eng.*, vol. 14, pp. 115-188.

PERCENT OF Ta-0.1% W TEST CAPSULES FAILING AS A
FUNCTION OF ANNEALING TEMPERATURE AND
EXPOSURE TIME AT 625°C

From R. M. Bidwell "Effects of Tantalum Structure on Corrosion" et al., *Nucl. Sci. Eng.*, vol. 14, p. 120.

Annealing Temperature °C	Cumulative Percent Failing in Given Time			
	700 hr	1400 hr	2100 hr	2800 hr
1050	100	---	---	---
1200	50	100	---	---
1350	0	25	75	---
1450	0	0	0	0

The Plutonium-Gallium Equilibrium Diagram.
From F. H. Ellinger et al., *J. Nucl. Mater.*, vol. 12, p. 228. 1964.

Ga 103

Crystal Structure

PLUTONIUM-GALLIUM INTERMEDIATE PHASES - CRYSTAL STRUCTURE AND HARDNESS DATA

From F. H. Ellinger et al., J. Nucl. Mater., vol. 12, p. 229, 1964.

Phase	Structure Type	Space Lattice And Space Group	Unit Cell Dimensions, Å	Formula Units Per Unit Cell	Calculated Density, g/cm ³	Microhardness, DPHN, kg/mm ²
Pu ₃ Ga (Γ)	AuCu ₃	Cubic Pm3m	a = 4.507 ± 0.002	1	14.27	135-149
Pu ₃ Ga (Γ')	SrPb ₃	Tetragonal P4/mmm	a = 4.469 ± 0.001 c = 4.527 ± 0.002	1	14.45	
Pu ₅ Ga ₃ (Θ)	W ₅ Si ₃ (?)	Tetragonal I4/mcm	a = 11.735 ± 0.003 c = 5.511 ± 0.002	1	12.29	250-381
PuGa (ι)		Tetragonal I.....	a = 6.640 ± 0.001 c = 8.066 ± 0.004	8	11.53	125-216
(Pu ₂ Ga ₃ ?) X						357-578
PuGa ₂ (λ)	AlB ₂	Hexagonal P6/mmm	a = 4.248 ± 0.001 c = 4.120 ± 0.001	1	9.76	250-471
PuGa ₃ (μ)						266-464
PuGa ₃ (μ')	Ni ₃ Sn	Hexagonal P6 ₃ /mmc	a = 6.300 ± 0.001 c = 4.514 ± 0.001	2	9.59	

Ga 201

Density

Densities (g/cm³) for some cast Pu-Ga alloys

Gallium, at. %	
3	15.983
6	15.66
9	15.56
12	15.392

WASH-915 (Classified).

Ga 301

Tensile Properties

Stress-Strain Curve for Plutonium-3.0 at. % Gallium Delta Stabilized
Plutonium, 0.250 in. Diameter Specimen
From H. R. Gardner, HW-72991, (Classified)

Effect of Temperature on Tensile Properties of Plutonium-3.0 and -4.0 at. % Gallium Delta-Stabilized Plutonium Alloys. Testing Speed, 0.015 in./min. *Yield Strength Determined as in Figure 4.1, compiled by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

○, ●, □, ■ <250 ppm iron
 ▲ 390 ppm iron
 ▲ 725 ppm iron
 ◇ 930 ppm iron

Effect of Testing Speed and Temperature on Tensile Strength in a Plutonium-4.0 at.% Gallium Delta-Stabilized Alloy.
From O. J. Wick, HW-77182. (Classified)

Effect of Testing Speed and Temperature on Ductility in a Plutonium-4.0 at.% Gallium Delta-Stabilized Alloy.
From O. J. Wick, HW-77182. (Classified)

Ga 302 Compressive Properties

Effect of Temperature on Compression Properties of Alloys. Testing Speed, 0.015 in./min.
From H. R. Gardner, HW-77642. (Classified)

Effect of Testing Speed on Compressive Yield Strength of Alloys.
From H. R. Gardner, HW-77642. (Classified)

Pu_3Ge and Pu_3Ge_2

These two plutonium-rich phases have been observed by means of X-ray and metallographic methods, but their crystal structures are not known. The composition Pu_3Ge is fairly certain, but the composition Pu_3Ge_2 has not been proved.

The other Pu-Ge intermetallics are as follows:

 Pu_2Ge_3

Hexagonal, pseudo- AlB_2 type

$$a = 3.975 \pm 0.002 \text{ \AA}$$

$$c = 4.198 \pm 0.002$$

$$Z = 1/2, D_x = 10.06$$

Space group. — $P6/mmm$ (Int. Tab. 191).

Atomic positions

$$1\text{Pu in (a): } 0, 0, 0$$

$$1.5\text{Ge in (d): } 1/3, 2/3, 1/2; 2/3, 1/3, 1/2$$

Interatomic distances

$$\text{Pu-12Ge} = 3.11$$

$$-6\text{Pu} = 3.98$$

$$\text{Ge-3Ge} = 2.29$$

$$-6\text{Pu} = 3.11$$

Remarks. — See Pu_2Si_3 .

 PuGe_2

Tetragonal body-centered, ThSi_2 type

$$\text{Ge-rich: } a = 4.102 \pm 0.002 \text{ \AA}$$

$$c = 13.81 \pm 0.01$$

$$Z = 4, D_x = 10.98$$

Space group. — $I4/amd$ (Int. Tab. 141).

Atomic positions. — See PuSi_2 .

Interatomic distances

$$\text{Pu-12Ge} = 3.12$$

$$\text{Ge-3Ge} = 2.36$$

$$-6\text{Pu} = 3.12$$

 PuGe_3

Cubic primitive, AuCu_3 type

$$a = 4.223 \pm 0.001 \text{ \AA}$$

$$Z = 1, D_x = 10.07$$

Space group. — $\text{Pm}\bar{3}\text{m}$ (Int. Tab. 221).

Atomic positions

$$1\text{Pu in (a): } 0, 0, 0$$

$$3\text{Ge in (c): } 0, 1/2, 1/2; 1/2, 0, 1/2; 1/2, 1/2, 0$$

Interatomic distances

$$\text{Pu-12Ge} = 2.99$$

$$\text{Ge-8Ge} = 2.99$$

$$-4\text{Pu} = 2.99$$

Isotypes. — UGe_3 .

From F. H. Ellinger in *The Metal Plutonium*, pp. 290, 291. Also from *Proc. First Geneva Internat. Conf.*, vol. 9, pp. 139, 140, 1956.

Density

Density

$$2 \text{ at. } \% \text{ Ge, as cast: } 17.87 \text{ g/cm}^3 \text{ (average)}$$

From A. E. Martin and G. D. Selmanoff, LA-501. (Classified)

Reactions with Gases — Air

Comparison of the Corrosion Behaviors of Plutonium-Hafnium Alloys and Unalloyed Plutonium Exposed to Air at 75°C and 50% Relative Humidity.

From J. T. Waber et al., *J. Nucl. Mater.*, vol. 3, p. 205.

The High-Mercury End of the Plutonium-Mercury System. From F. W. Schonfeld in The Metal Plutonium, p. 248.

PuHg_3

Apparently this intermetallic is isostructural with hexagonal UHg_3 , but a satisfactory diffraction pattern of PuHg_3 has never been obtained.

PuHg_4

This intermetallic is isostructural with UHg_4 . The dimension of the pseudocube is $a = 3.61 \pm 0.01 \text{ \AA}$.

From F. H. Ellinger in The Metal Plutonium, p. 296

Pu_3In

Cubic primitive, AuCu_3 type

$$a = 4.703 \pm 0.002 \text{ \AA}$$

$$Z = 1, D_x = 13.3$$

Space group. — $\text{Pm}\bar{3}\text{m}$ (Int. Tab. 221).

Atomic positions. — See PuGe_3 .

Interatomic distances

$$\text{Pu}-8\text{Pu} = 3.32$$

$$-4\text{In} = 3.32$$

$$\text{In}-12\text{Pu} = 3.32$$

Remarks. — Although Pu_3In is described above as having the AuCu_3 type of structure, i.e., fully ordered, it has not been observed with complete ordering of the atoms. The powder patterns of the alloys that were examined showed weaker super-lattice lines than would be required by complete ordering. It is believed, however, that proper thermal treatment of Pu_3In would result in a fully ordered structure.

From F. H. Ellinger in The Metal Plutonium, p. 292.

Density of as cast 3 at. % In = 16.80 g/cm^3 .

From A. E. Martin and G. D. Selmanoff, LA-501. (Classified)

Tentative Phase Diagram of the Pu-La System.
From D. M. Poole et al. in *Plutonium* 1960, p. 279.

Constitutional Diagram for the System Plutonium-Lithium.
From F. M. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2, p. 587.

The Plutonium-Magnesium System.
From F. W. Schönfeld in *The Metal Plutonium*, p. 244.

PuMg_2

Cubic face-centered, CaF_2 type

$$a = 7.34 \pm 0.01 \text{ \AA}$$

$$z = 4, D_x = 4.83$$

Space group. — $\text{Fm}\bar{3}\text{m}$ (Int. Tab. 225).

Atomic positions. — See PuHf_2 .

Interatomic distances

$$\text{Pu}-8\text{Mg} = 3.18 \quad \text{Mg}-4\text{Pu} = 3.18$$

Remarks. — PuMg_2 is formed by a reaction in the solid state, and its diffraction pattern has never been obtained free from the superimposed patterns of other phases. Earlier it was reported (1) as possibly being Pu_3Mg , but re-evaluation of the data indicates that the composition PuMg_2 is more probably correct.

PuMg_x (Where x is Approximately 2)

Hexagonal

$$a = 13.8 \pm 0.1 \text{ \AA}$$

$$c = 9.7 \pm 0.1$$

Like PuMg_2 , this intermetallic is formed by a peritectoid reaction, and its approximate composition was determined by microstructural studies.

From F. H. Ellinger in *The Metal Plutonium*, p. 295.

Mn 103

Crystal Structure

PuMn₂

Cubic face-centered, Cu₂Mg type

Pu-rich: a = 7.292 ± 0.001 Å From A. S. Coffinberry and F. H. Ellinger in Proc. First Geneva Internat. Conf., vol. 9, p. 139, 1956.

a = 7.290 ± 0.005 From O. J. C. Runnals, Can. J. Chem., vol. 34, pp. 140, 144.

Pu-rich: a = 7.29 From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 210.

Mn-rich: a = 7.26 (Konobeevsky)

Z = 8, D_x = 11.95

11.96 (Runnals)
12.0 (Konobeevsky)

Space group. — Fd3m (int. Tab. 227).

Atomic positions. — See PuAl₂.

Interatomic distances (based on a = 7.292 Å) From O. J. C. Runnals, Can. J. Chem., vol. 34, pp. 140, 144.

Pu-Pu = 3.157

Mn-Mn = 2.578

-12Mn = 3.023

-6Pu = 3.023

Isotypes. — GdMn₂, UMn₂.

From F. H. Ellinger in The Metal Plutonium, pp. 295, 296.

Mn 201

Density

Density

1 at. % Mn

as - cast 18.46 g/cm³

after 400°C anneal 18.69 g/cm³

From A. E. Martin and G. D. Selmanoff, LA-501. (Classified)

Mn 204.1

Magnetic Susceptibility

Paramagnetic susceptibility of PuMn₂ at 20°C

Mass
χ × 10⁶,
g emu⁻¹

7.8

Atomic
χ_a × 10⁶
emu g-at.⁻¹

930

χ_a = χ_g(A + B) where the expression in brackets stands for the mean atomic weight.

From S. T. Konobeevsky et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 195.

Temperature Dependence of Paramagnetic Susceptibility of PuMn₂. From S. T. Konobeevsky et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 195.

Mo 101

Phase Diagrams

Constitutional Diagram for the Systems Plutonium-Vanadium, -Chromium, -Niobium, -Molybdenum, -Tantalum, -Tungsten.

From F. W. Schonfeld et al. in Metallurgy and Fuels, series V, vol. 2, p. 583.

The Plutonium-Molybdenum System.
From F. W. Schonfeld in The Metal Plutonium, p. 261.

Phase Diagrams

Ni 101

The Plutonium-Nickel System.
From F. W. Schonfeld in The Metal Plutonium, p. 245.

The Plutonium-Nickel System.
From F. W. Schonfeld in The Metal Plutonium, p. 258.

Ni 103 Crystal Structure

CRYSTALLOGRAPHY OF PLUTONIUM-NICKEL SYSTEM

From F. W. Schonfeld et al. in Metallurgy and Fuels, series V, vol. 2, p. 591.

Compound	Type	Crystal Lattice	Unit Cell Dimensions, Å	Number of Molecules	Space Group	Calculated Density, g/cm ³		
PuNi PuNi ₂	Cu ₂ Mg	Face-centered cubic	Pu-rich Ni-rich	7.141 7.115	8 Fd3m	13.1		
PuNi ₃ PuNi ₄ PuNi ₅			CaZn ₅	Hexagonal			Pu-rich Ni-rich	a = 4.872 c = 3.980 a = 4.861 c = 3.982
Pu ₂ Ni ₁₇ Th ₂ Ni ₁₇	Hexagonal	a = 8.29 c = 8.01			2 P6 ₃ mmc	10.3		

PuNi

orthorhombic T11 type

a = 3.59 ± 0.01, b = 10.21 ± 0.02, c = 4.22 ± 0.01 Å.

From D. T. Cromer and R. B. Roof, Jr., Acta Cryst., vol. 12, p. 943.

1959.

130

Z = 4, D_x = 12.9

Space group Cmc2

Each atom has seven neighbors of the opposite kind, 4 at 2.85, two at 2.88 and one at 2.86 Å. In addition, the Ni atom has two Ni neighbors at 2.64 Å and the Pu has eight Pu neighbors, two at 3.54 and six at 3.59 Å. The estimated standard deviations are 0.02 Å for Pu-Pu, 0.04 Å for Pu-Ni and 0.05 Å for Ni-Ni distances.

PuNi₂

Cubic face-centered, Cu₂Mg type

Pu-rich: a = 7.141 ± 0.001 Å

Ni-rich: a = 7.115 ± 0.001

a = 7.16 ± 0.01 (Runnalls)

a = 7.14 (Konobeevsky)

Z = 8, D_x = 13.1

Space group, $\overline{F}d3m$ (Int. Tab. 227).

Atomic positions. — See PuAl₂.

Interatomic distances (based on a = 7.115 Å)

Pu-4Pu = 3.081 Ni-6Ni = 2.516

-12Ni = 2.950 -6 Pu = 2.950

Isotypes. — LaNi₂, CeNi₂, PrNi₂.

From F. H. Ellinger in The Metal Plutonium, p. 296.

PuNi₃

This compound has been found to have a rhombohedral unit cell. Its structure is being determined by D. T. Cromer.

PuNi₄

The crystal structure of PuNi₄ is not known, but its diffraction pattern suggests a close relationship to the PuNi₅ structure.

PuNi₅

Hexagonal, CaZn₅ type

Pu-rich: $a = 4.872 \pm 0.002$ Å
 $c = 3.980 \pm 0.001$ Å
 Ni-rich: $a = 4.861 \pm 0.002$ Å
 $c = 3.982 \pm 0.001$ Å
 $a = 4.875 \pm 0.005$ (Runnalls)
 $c = 3.970 \pm 0.005$ Å

$Z = 1$, $D_x = 10.8$

Space group, $\overline{X}$ P6/mmm (Int. Tab. 191).

Atomic positions

1Pu in (a): 0,0,0

2Ni_I in (c): 1/3, 2/3, 0; 2/3, 1/3, 0

3Ni_{II} in (g): 1/2, 0, 1/2; 0, 1/2, 1/2; 1/2, 1/2, 1/2

Interatomic distances (based on $a = 4.861$, $c = 3.982$ Å)

Pu-6Ni_I = 2.81 Ni_I-3Pu = 2.81

-12Ni_{II} = 3.14 -6Ni_{II} = 2.44

-3Ni_I = 2.81

Ni_{II}-4Pu = 3.14

-4Ni_I = 2.44

-4Ni_{II} = 2.44

Isotypes. — LaNi₅, CeNi₅, PrNi₅, GdNi₅, ThNi₅.

Pu₂Ni₁₇

Hexagonal, Th₂Ni₁₇ type

$a = 8.29 \pm 0.02$ Å

$c = 8.01 \pm 0.02$ Å

$Z = 2$, $D_x = 10.3$

Space group, $\overline{X}$ P6₃/mmc (Int. Tab. 194).

Atomic positions. — See Pu₂Co₁₇.

From F. H. Ellinger in The Metal Plutonium, pp. 296, 297.

In the Th₂ structure there are four formula units per unit cell with the larger atom (Pu in this case) in the set 4c with $y \approx 0.14$, and the smaller atom in the same set with $y \approx 0.42$. The calculated density of PuNi is thus 12.9 g cm⁻³.

From D. T. Cromer and R. B. Roof, Jr., Acta Cryst., vol. 12, p. 942, 1959.

PuNi₂ is face-centered cubic with $a = 7.13$ kx.

It is of the MgCu₂ type structure, with

8 formula weights/unit cell.

From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 212.

PuNi₂

Face-centered cubic, isostructural with UFe₂

Lattice constant 7.16 ± 0.01 Å

Calculated density 12.90 g/cm³

MgCu₂ lattice structure, space group Fd3m

8 formula weights/unit cell

From O. J. C. Runnalls, Can. J. Chem., vol. 34, p. 144, 1956.

INTERATOMIC DISTANCES IN THE COMPOUNDS PuNi₂

From O. J. C. Runnalls, Can. J. Chem., vol. 34, p. 140, 1956.

Atom	Neighbor	Number of Neighbors	Distance, Å
			PuNi ₂
Pu	Pu	4	3.10
	X	12	2.96
X	X	6	2.53
	Pu	6	2.96

PuNi₅

A powder photograph of a Pu-Ni alloy near the composition PuNi_{2.45} wt. % Pu, showed a single phase which was indexed on a hexagonal lattice with dimensions

$a_0 = 4.875 \pm 0.005$ Å,

$c_0 = 3.970 \pm 0.005$ Å.

The X-ray data resembled closely those for the compound ThNi₅, which has the CaZn₅ structure (6).

Thus, PuNi₅ may be described by the CaZn₅ structure with the following atomic positions in space group P6/mmm:

1 Pu in 0, 0, 0
 2 Ni_I in 1/3, 2/3, 0; 2/3, 1/3, 0
 3 Ni_{II} in 1/2, 0, 1/2; 0, 1/2, 1/2; 1/2, 1/2, 1/2.

The calculated density is 10.82 gm. cm.⁻³.

Interatomic distances are listed

From O. J. C. Runnalls, Can. J. Chem., vol. 34, p. 140, 1956.

INTERATOMIC DISTANCES IN PuNi₅

From O. J. C. Runnalls, Can. J. Chem., vol. 34, p. 142, 1956.

Atom	Neighbor	Number of Neighbors	Distance Å
Pu	Ni _I	6	2.82
	Ni _{II}	12	3.14
Ni _I	Pu	3	2.82
	Ni _I	3	2.82
Ni _{II}	Ni _{II}	6	2.44
	Pu	4	3.14
	Ni _I	4	2.44
	Ni _{II}	4	2.44

Cromer and Olsen[†] then published a rhombohedral cell for PuNi₃ with $a = 6.22$ and $\alpha = 33^\circ 44'$ but this did not fit our pattern of PuCo₃; the non-primitive hexagonal cell ($a = 5.00$, $c = 24.35$ Å) mentioned in the text of reference[†] did fit our pattern, however. These two cells are not equivalent and it appeared that the rhombohedral cell of PuNi₃ should have been reported as $a = 8.615$, $\alpha = 33^\circ 44'$, in which case agreement with our patterns was obtained[‡]. The first 21 observed lines of the pattern of PuCo₃ agreed very well with the first 28 calculated lines (including 6 overlaps) for a cell 8.635 Å, $\alpha = 33^\circ 40'$, but the higher angle lines showed less satisfactory agreement.

[†] Cromer D. T. and Olsen C. E. "The Crystal Structures of PuNi₃ and CeNi₃." Acta Cryst. 12 689-94 (1959).

[‡] Cromer and Olsen are aware of the error and state that the a parameter of the rhombohedral cell should in fact be reported as 8.615 Å in their paper. From D. M. Poole et al. in Plutonium 1960, p. 277.

PuNi₃

The structure of PuNi₃ and the structure and composition of CeNi₃ have

been determined by single crystal X-ray methods. PuNi₃ has three formula units in a rhombohedral unit cell with $a = 6.22$ Å and $\alpha = 33^\circ 44'$, probable space group R3m. Calculated density = 11.8 g cm⁻³ (measured density = 11.8)

with 1 Pu in 1a (0,0,0), 2Pu in 2c(x,x,x) with $x \approx 1/7$;
 1 Ni in 1b (1/2,1/2,1/2), 2Ni in 2c(x,x,x) with $x \approx 1/3$;
 and 6 Ni in 6h (x,x,z) with $x \approx 7/12$ and $z \approx 1/12$

From D. T. Cromer and C. E. Olsen, Acta Cryst., vol. 12, pp. 689, 690.

RESULTS OF THE LEAST-SQUARES REFINEMENT

OF PuNi₃ WITH $\Delta_{\text{Pu}} = -20$ ELECTRONS

From D. T. Cromer and C. E. Olsen, Acta Cryst., vol. 12, p. 691.

Atom	x	y	z	B (Å ²)
Pu ₁	0	0	0	0.37 ± 0.11
Pu ₂	0	0	0.1414 ± 0.0002	0.59 ± 0.08
Ni ₁	0	0	1/2	0.58 ± 0.30
Ni ₂	0	0	0.3336 ± 0.0005	0.45 ± 0.20
Ni ₃	0.5002 ± 0.0013	-x	0.0829 ± 0.0002	1.10 ± 0.11

INTERATOMIC DISTANCES IN PuNi₃

From D. T. Cromer and C. E. Olsen, Acta Cryst., vol. 12, p. 694.

Atom	Neighbor	Number	Distance
Pu ₁	Pu ₂	2	3.44 Å
	Ni ₂	6	2.89
	Ni ₃	12	3.21
Pu ₂	Pu ₁	1	3.44
	Pu ₂	3	3.14
	Ni ₂	3	2.95
	Ni ₁	3	3.02
	Ni ₃	6	2.88
Ni ₁	Pu ₂	6	2.95
	Ni ₃	6	2.50
Ni ₂	Pu ₁	3	2.89
	Ni ₁	3	2.89
	Ni ₃	6	2.50
Ni ₃	Pu ₁	2	3.21
	Pu ₂	1	3.02
	Pu ₂	2	2.88
	Ni ₁	1	2.50
	Ni ₁	2	2.50
	Ni ₃	4	2.50

These structures are both derived from stacking single layers of the MNi₃ structure (CaCu₅-type) and double layers of the MNi₂ structure (Cu₂Mg-type).

(a) Several Unit Cells of PuNi_3 . The Large Circles are Pu Atoms and the Small Circles are Ni Atoms. (b) The PuNi_4 Structure in Projection Down $[100]$. The x Coordinates of the Atoms are Given Inside the Circles. From D. T. Cromer and A. C. Larson, *Acta Cryst.*, vol. 13, p. 911, 1960.

PuNi₄

The structure of PuNi₄ has been determined by single crystal X-ray methods. The unit cell is mono-clinic, space group C2/m with

$$a = 4.87, b = 8.46, c = 10.27 \text{ \AA}, \beta = 100^\circ.$$

There are six formula units per unit cell. Two of the six Pu atoms have a coordination essentially identical to that of the Pu in PuNi₅. The other Pu atoms have a coordination somewhat similar to the Pu in PuNi₅. The PuNi₄ structure can be obtained by removing the Ni atoms at $z = 1/2$ from every third unit cell of PuNi₅ and by slightly shifting the remaining atoms. Calculated density is therefore 11.3 g cm^{-3} .

From D. T. Cromer and A. C. Larson, *Acta Cryst.*, vol. 13, p. 909. 1960.

FINAL LEAST-SQUARES PARAMETERS FOR PuNi₄

From D. T. Cromer and A. C. Larson, *Acta Cryst.*, vol. 13, p. 910. 1960.

Atom	x	y	z	B (Å ²)
Pu ₁	0	0	0	1.59 ± 0.13
Pu ₂	0.1263 ± 0.0010	0	0.3552 ± 0.0004	1.67 ± 0.10
Ni ₁	0	0.3331 ± 0.0011	0	1.99 ± 0.31
Ni ₂	0.5712 ± 0.0028	0	0.1987 ± 0.0013	1.50 ± 0.28
Ni ₃	0.3199 ± 0.0019	0.2507 ± 0.0009	0.1993 ± 0.0007	1.70 ± 0.18
Ni ₄	0.1422 ± 0.0020	0.3300 ± 0.0007	0.4066 ± 0.0009	2.11 ± 0.23

INTERATOMIC DISTANCES IN PuNi₄

The number of neighbors of a given kind is in parentheses

From D. T. Cromer and A. C. Larson, *Acta Cryst.*, vol. 13, p. 909. 1960.

Pu ₁ -Pu ₂	3.59(2) Å	Pu ₂ -Pu ₁	3.59 (1) Å
-Ni ₁	3.15(2)	-Pu ₁	3.41(1)
-Ni ₁	3.16(2)	-Ni ₂	2.89(1)
-Ni ₁	2.81(4)	-Ni ₁	2.91(1)
-Ni ₂	2.82(2)	-Ni ₁	2.90(1)
-Ni ₂	3.16(4)	-Ni ₃	2.91(1)
-Ni ₃	3.17(4)	-Ni ₃	2.84(2)
		-Ni ₄	2.86(2)
		-Ni ₄	2.89(2)
		-Ni ₄	2.89(2)

Ni ₁ -Pu ₁	3.15(1) Å	Ni ₂ -Pu ₁	2.81(2) Å
-Pu ₁	3.16(1)	-Pu ₁	2.82(1)
-Pu ₁	2.89(1)	-Ni ₁	2.45(2)
-Pu ₂	2.91(1)	-Ni ₂	2.81(2)
-Ni ₂	2.45(2)	-Ni ₂	2.82(1)
-Ni ₂	2.43(2)	-Ni ₃	2.45(2)
-Ni ₃	2.45(2)	-Ni ₃	2.46(2)
-Ni ₄	2.55(2)		

Ni ₃ -Pu ₁	3.16(1) Å	Ni ₄ -Pu ₂	2.84(1) Å
-Pu ₁	3.17(1)	-Pu ₂	2.86(1)
-Pu ₁	2.90(1)	-Pu ₂	2.89(1)
-Pu ₂	2.91(1)	-Pu ₂	2.89(1)
-Ni ₁	2.43(1)	-Ni ₁	2.55(1)
-Ni ₁	2.45(1)	-Ni ₃	2.51(1)
-Ni ₂	2.45(1)	-Ni ₃	2.52(1)
-Ni ₂	2.46(1)	-Ni ₃	2.43(1)
-Ni ₂	2.43(2)	-Ni ₄	2.55(1)
-Ni ₃	2.51(1)	-Ni ₄	2.79(2)
-Ni ₄	2.52(1)	-Ni ₄	2.88(1)

Pu₂Ni₁₇

Since PuNi₅ proved to be isostructural with ThNi₅, a search was made for a Pu-Ni compound isomorphous with Th₂Ni₁₇. A phase with an X-ray pattern similar to, but more complex than, PuNi₅ was observed in alloys containing 30-35 wt. % Pu. This pattern was solved using a hexagonal lattice of dimensions

$$a_o = 8.30 \pm 0.01 \text{ \AA}, \\ c_o = 8.00 \pm 0.01 \text{ \AA}.$$

The isomorphous phase Th₂Ni₁₇ has $a_o = 8.37 \text{ \AA}$ and $c_o = 8.14 \text{ \AA}$ (6). Since the intensities in the powder patterns of Th₂Ni₁₇ and Pu₂Ni₁₇ are closely related it seems reasonable to assign the Th₂Ni₁₇ structure to Pu₂Ni₁₇. The following approximate atomic positions apply in space group P6₃/mmc, for two molecules per unit cell:

2 Pu_I in (b), 2 Pu_{II} in (d), 6 Ni_I in (g), 12 Ni_{II} in (j) with $x = 1/3$ and $y = 0$, 12 Ni_{III} in (k) with $x = 1/6$ and $z = 0$, and 4 Ni_{IV} in (f) with $z = 0.11$.

From O. J. C. Runnalls, *Can. J. Chem.*, vol. 34, pp. 140, 142. 1956.

Magnetic Susceptibility

PARAMAGNETIC SUSCEPTIBILITIES OF PLUTONIUM-NICKEL COMPOUNDS

From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195. 1958.

Compound	Structure	Paramagnetic Susceptibility at 20°C	
		Mass $\chi_g \times 10^6$, emu g ⁻²	Atomic* $\chi_a \times 10^6$, -2 emu g-at.
PuNi	—	2.4	490
PuNi ₂	fcc, type MgCu ₂	1.9	220
PuNi ₃	—	2.7	280
PuNi ₄	—	3.6	350
PuNi ₅	hexagonal	4.8	430
Pu ₂ Ni ₁₇	hexagonal, type Th ₂ Ni ₁₇	15.4 †	1200
Ni (500°)	fcc	45	2620

*The average susceptibility per gram atom is calculated according to the formula $\chi_a = \chi_g (A + \beta B)$ where the expression in brackets stands for the mean atomic weight.

† Determined from the susceptibility of the PuNi₅ + Pu₂Ni₁₇ alloy.

Ni 204.1

Paramagnetic Susceptibility of Plutonium Nickel Alloys at Room Temperature. From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195. 1958.

Temperature Dependence of Paramagnetic Susceptibility of Certain Plutonium Compounds. 1) PuNi₁; 2) PuNi₂; 3) PuNi₄. From S. T. Konohevsky *et al.*, in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 195, 1958.

Ni 301

Tensile Properties

Alloys containing up to 25 at. % Ni were hot extruded. The compounds were brittle, but zeta Ni appeared to be ductile.

Phase	Ductility
Alpha Pu	Slight
PuNi	Slight
PuNi ₂	Brittle
PuNi ₃	Brittle
PuNi ₄	Probably brittle
PuNi ₅	Brittle
PuNi ₉	Brittle
Zeta Ni	Ductile
Pure Ni	Ductile
Zeta Ni - about 1.6 at. % Pu	Pu

From G. W. Wensch and D. D. Whyte, LA-1304.

Ni 307

Hardness

Phase	DPH (25-g load)	Remarks
Alpha Pu	285	Slight ductility
Pu Ni	250	Slight ductility
Pu Ni ₂	505 - 631	Brittle
Pu Ni ₃	388 - 550 (as cast)	Brittle
	499 - 575 (heat treated)	
Pu Ni ₄	196 - 292	Probably brittle
Pu Ni ₅	442 - 580 (as cast)	Brittle
	516 - 641 (heat treated)	
Pu Ni ₉	416 - 560 (as cast)	Brittle
	199 - 616 (heat treated)	
Zeta Ni	138 - 221	Ductile
Pure Ni	97	Ductile

From G. W. Wensch and D. D. Whyte, LA-1304.

The Neptunium-Plutonium Constitution Diagram. From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, *Less-Common Metals*, vol. 3, p. 282. 1961.

X-Ray Data, Neptunium-Rich Alloys. From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, *Less-Common Metals*, vol. 3, p. 283. 1961.

X-Ray Data, Plutonium-Rich Alloys. From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, *Less-Common Metals*, vol. 3, p. 284. 1961.

The Pu-Np Phase Diagram (From Dilatometric Results). From R. G. Cope et al. in *Plutonium* 1960, p. 288.

Np 103 Crystal Structure

Lattice Parameter - Composition Curves, $\bullet$ - Plutonium Field (20°C). From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, *Less-Common Metals*, vol. 3, p. 284. 1961.

Lattice Parameter - Composition Curves, $\bullet$ - Plutonium Field (290°C). From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, *Less-Common Metals*, vol. 3, p. 285. 1961.

Lattice Parameter - Composition Curves, ϵ -Pu $\equiv$ γ -Np Field (550°C).
From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, Less-Common Metals, vol. 3, p. 287. 1961.

Since γ -neptunium is not a stable phase at 550°C, the extrapolated value for pure Np has been adjusted to 600°C, assuming a value of $36.5 \cdot 10^{-6}$ °C for the coefficient of linear expansion, the resultant lattice parameter is 3.548 Å. At the Pu-rich end of the system the ϵ phase containing 4 wt.% neptunium decomposes by a eutectoid reaction ϵ -Pu $\rightleftharpoons$ γ + δ -Pu at 140°C.

An intermediate phase exists at high temperatures at the Pu-rich end of the Ni-Pu system. Its crystal structure is complex. An orthorhombic cell has been assigned to it with $a = 10.86$ Å, $b = 10.67$ Å, $c = 10.43$ Å for a 19 wt.% Np alloy at 375°C. Density at 450°C was 17.56 g/cm^3 which corresponds to 54 atoms per unit cell.

From P. J. Mardon, J. H. Pearce, and J. A. C. Marples, Less-Common Metals, vol. 3, p. 287. 1961.

Electrical Conductivity

Np 203.1

Resistivities of Pu-Np ϵ -Phase Solid Solutions. From J. A. Lee et al. in Plutonium 1969, p. 48.

From F. W. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2, p. 591. 1959.

According to Konobeevsky there are five Pu-Os intermetallic phases. The crystal structures of Pu₁₉Os and high- and low-temperature modifications of Pu₃Os₃ and Pu₅Os₃ were not determined. Crystal data given for PuOs₂ are as follows:

PuOs₂
Hexagonal, MgZn₂ type
a = 5.337 Å
c = 8.683
Z = 4, D_x = 19.2

Space group. — P6₃/mmc (Int. Tab. 194).

From F. H. Ellinger in *The Metal Plutonium*, pp. 297, 298.

Density of 3 wt. % Os alloy = 18.3 g/cm^3
 Calculated density of PuOs_2 = 19.2 g/cm^3
 (61.4 wt. % Os)

From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 214.

Mechanical Properties

Os 300

Pu-Os alloys in the range 2.7-6 wt. % Os have good plastic and mechanical properties.

From S. T. Konobeevsky, AEC-tr-2435 Pt. 2, p. 214.

Phase Diagrams

Pb 101

Constitutional Diagram for the System Plutonium-Lead.
 From F. W. Schonfeld et al. in *Metallurgy and Fuels*, series V, vol. 2,
 p. 586, 1959.

The Plutonium-Lead System. From F. W. Schonfeld in *The Metal Plutonium*,
 p. 257.

Crystal Structure

Pb 103

PuPb_3

Cubic, probably ordered AuCu_3 type

$a = 4.808 \pm 0.001 \text{ \AA}$

$a = 4.81$ From S. T. Konobeevsky, AEC-tr-2435 pt. 2, p. 209.

$Z = 1, D_x = 12.86$

Space group. — $\text{Pm}\bar{3}\text{m}$ (Int. Tab. 221).

Atomic positions. — See PuGe_3 .

Interatomic distances

$\text{Pu}-12\text{Pb} = 3.40$ $\text{Pb}-8\text{Pb} = 3.40$

$-4\text{Pu} = 3.40$

Isotypes. — 1aPb_3 , CePb_3 , PrPb_3 , UPb_3 . A plutonium-rich,

plutonium-lead compound is known to exist, but its composition is uncertain.
 From F. H. Ellinger in *The Metal Plutonium*, p. 295.

PuRe₂
Hexagonal, MgZn₂ type
a = 5.396 ± 0.001 Å
c = 8.729 ± 0.001
Z = 4, D_{8h} 18.45
Space group, — P6₃/mmc (Int. Tab. 194).
Atomic positions
4Pu in (f): ± (1/3, 2/3, z); ± (1/3, 2/3, 1/2 — z) with z = 0.062
2Re_I in (a): 0,0,0; 0,0,1/2
6Re_{II} in (h): ± (x, 2x, 1/4); ± (2x̄, x̄, 1/4); ± (x̄, x̄, 1/4) with x = -1/6
Interatomic distances
Pu—3Re_{II} = 3.14 Re_I—6Re_{II} = 2.68
—6Re_{II} = 3.16 —2Re_I = 4.36
—3Re_I = 3.16 —6Pu = 3.16
—1Pu = 3.28 Re_{II}—2Re_I = 2.68
—3Pu = 3.30 —4Re_I = 2.70
— —2Pu = 3.14
— —4Pu = 3.16

From F. H. Ellinger in The Metal Plutonium, pp. 299, 300.

Ru 101 Structural Properties

The Plutonium-Ruthenium System. From F. W. Schonfeld et al. in Metallurgy and Fuels, series V, vol. 2, p. 593. (Same as Fig. 12 from F. W. Schonfeld in The Metal Plutonium, p. 246.)

Pu-Ru Phase Diagram From Dilatometric and Thermal Analysis Results. From R. G. Cope *et al.* in *Plutonium* 1960, p. 283.

(a) Showing the Limit of Pure Plutonium; (b) The Variation in Magnitude of the Transformation $\delta \rightarrow \gamma$ With Ruthenium Content; (c) The Variation of Eutectoid Contraction with Ruthenium Content. From R. G. Cope *et al.* in *Plutonium* 1960, p. 284.

Crystal Structure

Pu_{19}Ru , Pu_3Ru , and Pu_5Ru_3

The identities of these three plutonium-rich intermetallic phases have been well established by metallography and X-ray diffraction, but their crystal structures are not yet known. The other two plutonium-ruthenium intermetallics are as follows:

PuRu

Cubic primitive, CsCl type

$a = 3.363 \pm 0.001 \text{ \AA}$

$Z = 1, D_x = 14.87$

Space group. — $\text{Pm}\bar{3}\text{m}$ (Int. Tab. 221).

Atomic positions

1 Pu in (a): 0,0,0

1 Ru in (b): $1/2, 1/2, 1/2$

Interatomic distances

Pu-Ru 2.91

Ru-SiPu 2.91

PuRu_2

Cubic face-centered, Cu_2Mg type

Pu-rich: $a = 7.476 \pm 0.001 \text{ \AA}$

$Z = 8, D_x = 14.06$

Space group. — $\text{Fd}\bar{3}\text{m}$ (Int. Tab. 227).

Atomic positions. — See PuAl_2 .

Interatomic distances

Pu-4Pu = 3.24

-12Ru = 3.10

Ru-6Ru = 2.64

-6Pu = 3.10

From F. H. Ellinger in *The Metal Plutonium*, p. 300.

Ru 103

Phase Diagrams

The System Plutonium-Silicon

It is believed that there are five intermetallic compounds in this system. There are two eutectic reactions, one between epsilon plutonium and what may be Pu_3Si_3 at 570°C and 4 at. % silicon, and one between PuSi_2 and silicon at about 82 at. % silicon (temperature unknown). About 1 at. % of silicon is soluble in the delta phase of plutonium.

From A. S. Coffinberry *et al.* in *Reactor Handbook*, 2nd ed., vol. 1, p. 287.

Si 101

Si 103

Crystal Structure

The existence of two plutonium-rich intermetallics in this system has been established by X-ray and metallographic observations, but the crystal structures are not known. Their compositions fall in the range of 30-40 at. % silicon. Other plutonium-silicon intermetallics are as follows:

PuSi

Orthorhombic, FeB type

$$a = 5.727 \pm 0.005 \text{ \AA}$$

$$b = 7.933 \pm 0.003$$

$$c = 3.847 \pm 0.001$$

$$Z = 4, D_x = 10.15$$

Space group. — Pbnm (Int. Tab. 62).

Atomic positions

$$4\text{Pu in (c): } \pm (x_1, y_1, 1/4); \pm (1/2 - x_1, y_1, + 1/2, 1/4)$$

$$\text{with } x_1 = 0.125, y_1 = 0.180$$

$$4\text{Si in (c): } \pm (x_2, y_2, 1/4); \pm (1/2 - x_2, y_2, + 1/2, 1/4)$$

$$\text{with } x_2 = 0.611, y_2 = 0.028$$

Interatomic distances

$$\text{Pu}-2\text{Si} = 2.95$$

$$\text{Si}-2\text{Si} = 2.35$$

$$-2\text{Si} = 3.01$$

$$-2\text{Pu} = 2.95$$

$$-1\text{Si} = 3.03$$

$$-2\text{Pu} = 3.01$$

$$-1\text{Si} = 3.07$$

$$-1\text{Pu} = 3.03$$

$$-1\text{Si} = 3.18$$

$$-1\text{Pu} = 3.07$$

$$-4\text{Pu} = 3.62$$

$$-1\text{Pu} = 3.18$$

$$-2\text{Pu} = 3.73$$

Isotypes. — ThSi, USi.

Remarks. — The atomic parameters are those of USi, taken from Zachariasen.

Pu₂Si₃

Hexagonal, pseudo-A1B₂ type

$$a = 3.876 \pm 0.002$$

$$c = 4.090 \pm 0.002$$

$$Z = 1/2, D_x = 8.77$$

Space group. — P6₃/mmm (Int. Tab. 191).

Atomic positions

$$1\text{Pu in (a): } 0, 0, 0$$

$$1.5\text{Si in (d): } 1/3, 2/3, 1/2; 2/3, 1/3, 1/2$$

Interatomic distances

$$\text{Pu}-12\text{Si} = 3.03$$

$$\text{Si}-6\text{Pu} = 3.03$$

$$-6\text{Pu} = 3.88$$

$$-3\text{Si} = 2.24$$

$$-2\text{Pu} = 4.09$$

Isotypes. — β -USi₂, Th₂Si₃.

PuSi₂

Tetragonal body-centered, ThSi₂ type

$$\text{Si-rich: } a = 3.967 \pm 0.001$$

$$c = 13.72 \pm 0.03$$

$$a = 3.98 \pm 0.01 \text{ (Zachariasen)}$$

$$c = 13.58 \pm 0.05$$

$$Z = 4, D_x = 9.08$$

Space group. — I₄/amd (Int. Tab. 141).

Atomic positions

$$(0, 0, 0; 1/2, 1/2, 1/2) +$$

$$4\text{Pu in (a): } 0, 0, 0; 0, 1/2, 1/4$$

$$8\text{Si in (e): } 0, 0, z; 0, 0, \bar{z}; 0, 1/2, 1/4 + z; 0, 1/2, 1/4 - z$$

$$\text{with } z = 0.417$$

Interatomic distances

$$\text{Pu}-12\text{Si} = 3.03$$

$$\text{Si}-6\text{Pu} = 3.03$$

$$-8\text{Pu} = 3.96$$

$$-3\text{Si} = 2.29$$

Isotypes. — LaSi₂, CeSi₂, PrSi₂, NdSi₂, SmSi₂, ThSi₂, USi₂, NpSi₂.

From F. H. Ellinger in The Metal Plutonium, pp. 300-302.

Sn 101

Phase Diagrams

A eutectic occurs between Pu and Pu₄Sn(?) at about 13 at. % Sn.
From A. S. Coffinberry et al. in Reactor Handbook, 2nd ed., vol. 1, p. 287.

Sn 103

Crystal Structure

PuSn₃

Cubic primitive, AuCu₃ type

$$a = 4.630 \pm 0.001 \text{ \AA}$$

$$Z = 1, D_x = 9.96$$

Space group. — Pm3m (Int. Tab. 221).

Atomic positions. — See PuGe₃.

Interatomic distances

$$\text{Pu}-12\text{Sn} = 3.27$$

$$\text{Sn}-4\text{Sn} = 3.27$$

$$-8\text{Pu} = 3.27$$

Isotypes. — LaSn₃, CeSn₃, PrSn₃, USn₃.

From F. H. Ellinger in The Metal Plutonium, p. 303.

Th 101

Phase Diagrams

The Plutonium-Thorium System. From F. W. Schonfeld et al. in Metallurgy and Fuels, series V, vol. 2, p. 594. (Same as Fig. 13 in Compendium of the Metal Plutonium, p. 216.)

Th 103

From F. H. Ellinger in *The Metal Plutonium*, p. 303.

From M. B. Waldron in The Metal Plutonium, p. 233.

Th 201 Density

DENSITY AND SPECIFIC VOLUME OF CRYSTAL BAR THORIUM AND THORIUM-PLUTONIUM ALLOYS

From B. Blumenthal, ANL-6671. 1963.

Number	Alloy Nominal Wt. % Th Pu	Density at 25°C, g/cm ³	Mean Value at 25°C, g/cm ³	Spec. Volume at 25°C, cm ³ /g
B772	100 0	11.713 11.717	11.715	0.08536
B766	90 10	11.913 11.916	11.914	0.08393
B767	80 20	12.134 12.127	12.131	0.08244
B768	70 30	12.367 12.374	12.371	0.08084
B769	60 40	12.741 12.746	12.744	0.07847
B770	50 50	13.139 13.139	13.139	0.07611
B773	40 60	13.660 13.670	13.665	0.07318

Specific Volume of Arc-Melted High-Purity Thorium-Plutonium Alloys.
From B. Blumenthal, ANL-6671. 1963.
The intersection of the curves indicates the limit of solid solubility.

DENSITY OF Th-Pu ALLOYS

From Baumrucker and Kelman as reported by L. T. Lloyd in WASH-703. 1957.

Nominal Composition Wt. % Th	Density g/cm ³
95	11.64
90	11.86
80	12.02
75	12.05
70	12.25
60	12.51

Density Values of As-Cast Plutonium-Thorium Alloys Plotted Against Composition. From D. M. Poole, G. K. Williamson, and J. A. C. Marples, *J. Inst. Metals*, vol. 86, p. 176. 1957-1958. (Same as Fig. 14 in *The Metal Plutonium*, p. 233.)

Th 202.1 Thermal Expansion

AVERAGE LINEAR THERMAL EXPANSION COEFFICIENTS

25 - 391°C

From L. T. Lloyd in WASH-703. 1957.

Composition, Wt. % Th	Expansion Coefficient, $\alpha \times 10^{-6}/^{\circ}\text{C}$
75	9.33
80	9.75
90	12.08
95	10.16

Th 307 Hardness

ROOM TEMPERATURE HARDNESS OF ARC CAST Th-Pu ALLOYS

From P. M. French as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Composition, at. % Pu	Vickers Hardness Number, VHN
10	105
20	130
30	148
40	133

HARDNESS OF Th-Pu ALLOYS

From Baumrucker and Kelman as reported by L. T. Lloyd in WASH-703. 1957.

Nominal Composition, Wt. % Pu	Hardness Rockwell F
5	71 - 79
10	82 - 86
20	91 - 97
25	93 - 99
30	96 - 102
40	99 - 102

Pu-Th Oxidation in Air Dried Over Magnesium Perchlorate. From D. M. Poole et al. in *Plutonium* 1960, p. 629.

EFFECTIVENESS OF SMALL Al AND Th ADDITIONS TO Pu IN AIR AT 50% RELATIVE HUMIDITY (WEIGHT GAINS IN mg/cm²)

From J. T. Waber in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 212, 1958.

Alloy	Test Temperature, 55°C		Test Temperature, 75°C	
	1750 Hr	10,800 Hr	1750 Hr	10,750 Hr
3.5 at.% Al	0.16	0.29	0.91	3.0
3.5 at.% Th	2.06	3.91	10.1	16.7
High-purity control	—	5.08*	—	52.3

*Control samples after 9000 hr in the same test.

Phase Diagrams

The Pu-Ti System. From D. M. Poole et al. in *Plutonium* 1960, p. 278.

TTT Curve for the $\beta \rightarrow \alpha$ Transformation in a Pu-0.23 at. % Ti Alloy. From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, p. 223, 1964.

TTT Curve for the $\beta \rightarrow \alpha$ Transformation in a Pu-0.82 at. % Ti Alloy. From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, p. 223, 1964.

TTT curve for the $\beta \rightarrow \alpha$ Transformation in a Pu-1.05 at. % Ti Alloy. From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, p. 224, 1964.

Arrhenius Plot of the Reaction Data for the Three Pu-Ti Alloys Investigated. From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, p. 224, 1964.

The results suggest that, depending upon the temperature, the $\beta \rightarrow \alpha$ change proceeds by one of two distinct mechanisms. The low value of the activation energy at low temperatures indicates a martensitic transformation. It is tentatively proposed that the other reaction mechanism is massive transformation.

From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, p. 221, 1964.

THE COMPOSITIONAL DEPENDENCE OF THE ACTIVATION ENERGY FOR THE $\beta \rightarrow \alpha$ TRANSFORMATION AT LOW TEMPERATURES

From L. G. T. Davy and J. S. White, *J. Nucl. Mater.*, vol. 12, 224, 1964.

Composition, at. % Ti	Activation Energy, kcal/mole (lower 'C')
0.23	2.2
0.82	1.25
1.05	2.4

The Plutonium-Uranium System. From F. H. Ellinger, R. O. Elliott, and E. M. Cramer, *J. Nucl. Mater.*, vol. 1, p. 235, 1959. (Same as Fig. 14 in *The Metal Plutonium*, p. 247.)

U 103

Crystal Structure

UNIT CELL DIMENSIONS*

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371. 1963.

Sample	Temperature	a, Å	b, Å	c, Å	β , °
Pure Pu	93°C.	9.227	10.449	7.824	92.54
Pure Pu	190	9.284	10.463	7.859	92.13
98 Pu-2U	83	9.215	10.418	7.815	92.52
98 Pu-2U	139	9.242	10.433	7.824	92.36
98 Pu-2U	186	9.264	10.439	7.841	92.22
98 Pu-2U	252	9.302	10.444	7.859	91.97

*Precision is ± 0.002 Å for a, b, c, and $\pm 0.02^\circ$ for β .

eta (η)*

composition limits 2-70 at. % U
not stable at room temperature
Tentative unit cell:
Pu₃U (25 at. % U) tetragonal
a = 10.57 ± 0.05, c = 10.76 ± 0.05 Å
52 atoms/unit cell
calculated density ‡ 17.3 g/cm³

zeta (ζ)

Maximum composition limits 25-74 at. % U +
25-80 wt. % U +
Room temperature composition limits ‡ 33-65 at. % U ±
Tentative unit cells:
(1) simple cubic* - or tetragonal with axial ratio of unit at
room temperature ‡.

PuU contains 58 atoms/unit cell
Calculated density 18.95 g/cm³ +
(2) tetragonal +
20 wt. % U lattice constants: a = 10.73, b = 10.44 Å
56 atoms/unit cell
calculated density 18.5 g/cm³ +

*From A. S. Coffinberry and M. B. Waldron in Metallurgy and Fuels,
series V, vol. 1, pp. 396, 403. 1956.

+ From A. A. Bochvar et al. in Proc. Second Geneva Internat. Conf., vol. 6,
p. 192. 1958.

± From F. H. Ellinger in The Metal Plutonium, p. 304.

‡ From F. H. Ellinger et al., J. Nucl. Mater., vol. 1, p. 239. 1959.

Lattice Constant Vs. Composition of the Zeta Phase.
From F. H. Ellinger et al., J. Nucl. Mater., vol. 1, p. 239. 1959.

LATTICE CONSTANTS FOR ALPHA URANIUM-PLUTONIUM ALLOYS

From A. F. Berndt, J. Nucl. Mater., vol. 9, p. 55. 1963.

Pu, Wt. %*	Lattice Constants, Å			Probable Error x 10 ⁵ , Å		
	a ₀	b ₀	c ₀	a ₀	b ₀	c ₀
0	2.8536	5.8688	4.9558	2	3	2
2.06	2.8547	5.8657	4.9558	3	4	3
3.84	2.8550	5.8641	4.9563	2	4	3
6.06	2.8571	5.8625	4.9578	2	3	2
8.80 ±	2.8593	5.8610	4.9577	2	4	3
11.30	2.8603	5.8579	4.9611	2	3	3
13.11 ±	2.8615	5.8574	4.9618	2	2	2
15.22	2.8624	5.8561	4.9627	3	3	4
17.48	2.8637	5.8560	4.9635	12	7	11
19.66	2.8630	5.8561	4.9632	8	8	7
21.70	2.8612	5.8566	4.9626	35	13	34
13.11 ± ±	2.8605	5.8581	4.9627	3	3	3
15.22 ±	2.8623	5.8569	4.9631	3	11	1

Wavelengths used: CuK_{α1} 1.54051 Å; CuK_{α2} 1.54433 Å.

Each reflection weighted as 1/sin² 2θ.

Correction term = sin² 2θ (1/sin θ + 1/θ).

For each case the proper correction term was chosen as the one which
minimized the systematic errors as evidenced on a sin² θ_{calc} - sin² θ_{obs}
vs. θ plot and which minimized the calculated probable errors.

*Average of analyzed and weighed-out values.

+ Correction term = sin² 2θ.

± Specimens annealed for 116 hr.

Lattice Constants vs. Composition Curves for Alpha Uranium-Plutonium Alloys. From A. F. Berndt, *J. Nucl. Mater.*, vol. 9, p. 55. 1963.

ALPHA U-15 Wt. % Pu	
a_0	2.862 Å
b_0	5.856 Å
c_0	4.963 Å
γ	0.104°
ϕ	127° 45' ±

± Estimated values.

From A. F. Berndt, *J. Nucl. Mater.*, vol. 9, p. 57. 1963.

Temperature Dependence of Axial Lattice Parameters of the α Phase of Uranium Alloy Containing 15 at. % of Plutonium. From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 198. 1958.

$$a = 2.861 (1 + 26.2 \times 10^{-6}t + 1.4 \times 10^{-8}t^2) \text{ Å}$$

$$b = 5.859 (1 + 1.9 \times 10^{-6}t - 3.0 \times 10^{-8}t^2)$$

$$c = 4.956 (1 + 25.2 \times 10^{-6}t + 1.6 \times 10^{-8}t^2)$$

$a, b,$ and c = lattice parameters of α phase in Å, t = temperature, °C at 25°C, $a = 2.863$
 $b = 5.860$
 $c = 4.958$

From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 197. 1958.

U 201 Density

DENSITIES OF ALLOYS

A. E. Martin and G. D. Selmanoff, LA-501. 1945 (Classified)

Nominal Composition in at. %	DENSITIES	
	As Cast	After 400°C Anneal
1% Uranium	18.65	18.46
4% Uranium	19.37	-----
4% Uranium	19.35	-----
8% Uranium	19.10	-----
8% Uranium	19.06	-----
15% Uranium	18.0	-----
15% Uranium	17.95	17.99
25% Uranium	18.07	-----
25% Uranium	18.07	-----

As-Cast Density vs. Composition for Uranium-Plutonium Alloys. From A. F. Berndt, *J. Nucl. Mater.*, vol. 9, p. 54. 1963.

The dip in the curve at the plutonium-rich compositions is attributed to the retention of beta plutonium, as indicated by the observation that a plutonium-10 at. % uranium alloy quenched from 300°C was composed of the alpha-plutonium and zeta phases, and had a density of 18.55 g/cm³, whereas the same composition quenched from 250°C was composed of the beta-plutonium and zeta phases, and had a density of 17.94 g/cm³. From F. H. Ellinger, R. O. Elliott, and E. M. Cramer, *J. Nucl. Mater.*, vol. 1, p. 242. 1959.

Alpha extruded U-20 wt. % Pu had a density of 18.8g/cm³. From A. S. Coffinberry et al., *Reactor Handbook*, 2nd ed., vol. 1, p. 281. 1960.

The Density of Plutonium-Uranium Alloys in the As-Cast Condition. From F. H. Ellinger, R. O. Elliott, and E. M. Cramer, *J. Nucl. Mater.*, vol. 1, p. 242. 1959.

Thermal Expansion

PRINCIPAL LINEAR COEFFICIENTS OF THERMAL EXPANSION ($\times 10^6$)

From W. H. Zachariasen and F. H. Ellinger, *Acta Cryst.*, vol. 16, p. 371. 1963.

	α_1	α_2	α_3	$\bar{\alpha}$	ϕ
98 Pu-2 U	79	13	15	38	35°

THERMAL EXPANSION COEFFICIENTS - EFFECT OF ALLOYING

From S. T. Konobeevsky et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 197. 1958.

Alpha Phase Uranium - 15 at. % Plutonium Alloy

Temperature Range, °C	$\alpha_a \times 10^6$	$\alpha_b \times 10^6$	$\alpha_c \times 10^6$
20-300	30 ± 4	-8 ± 4	29 ± 4
20-400	32 ± 4	-12 ± 4	32 ± 4

THERMAL EXPANSION COEFFICIENTS FOR URANIUM-PLUTONIUM ALLOYS (ROOM TEMPERATURE TO 300°C)

From W. D. Wilkinson and L. R. Kelman in ANL-5439. 1955.

Alloy Composition		Average Linear Thermal Expansion Coefficient $\bar{\alpha} \times 10^{-6}/^{\circ}\text{C}$	
Wt. % Plutonium	Condition	Longitudinal	Radial
10	Extruded	11	25
15	Extruded	16.6	6
15	Cast	10.4 - 13.3	--
20	Extruded	21	8

The addition of up to 20 wt. % plutonium causes an increase in the longitudinal expansion coefficient and thus decreases the degree of anisotropy exhibited by the unalloyed uranium.

From A. S. Coffinberry et al. in *Reactor Handbook*, 2nd ed., vol. 1, p. 280. 1960.

Thermal Conductivity

U-10 wt. % Pu

The room temperature thermal conductivity appears to be lower than that of pure U, and the temperature coefficient of conductivity is positive.

From A. S. Coffinberry et al. in *Reactor Handbook*, 2nd ed., vol. 1, pp. 280-281. 1960.

U 202.1

U 202.2

U 301

Tensile Properties

Room temperature tensile properties of as-cast Pu-3 at. % U (testing speed: 0.015 in./min.)
Ultimate strength = 55,000 psi
0.01% Yield strength = 41,200 psi
From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

TENSILE PROPERTIES OF INJECTION CAST Pu - 90 Wt. % U AS A FUNCTION OF TEMPERATURE
TESTING SPEED, 0.065 IN./MIN.

From H. E. Savage and E. R. Gilbert, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

Temp., °C	Ultimate Strength, psi	0.29, Yield Strength, psi	Reduction in Area, %	Elongation in 1 in., %	Elastic Modulus, 10 ⁶ psi
23.5	37,500 ± 1%	---	< 1	0.625 ± 5%*	19.0 ± 1%
305	32,700 ± 1%	---	< 1	< 1	---
454	23,200 ± 1%	21,000 ± 1%	< 1	0.900 ± 5%*	15.5 ± 8%
502	18,900 ± 1%	16,900 ± 1%	< 1	0.725 ± 5%*	13.0 ± 8%
548 +	11,600 ± 1%	10,500 ± 1%	~ 1	6.3 ± 5%	9.20 ± 8%
550	13,300 ± 1%	13,300 ± 1%	< 1	0.700 ± 5%*	14.4 ± 8%
589	14,800 ± 1%	---	< 1	0.300 ± 5%*	22.3 ± 8%
651	9,600 ± 1%	---	< 1	0.275 ± 5%*	7.31 ± 8%
700	8,290 ± 1%	8,100 ± 1%	< 1	0.687 ± 5%*	1.00 ± 8%

* Fracture strain includes elastic-plastic components.
+ High Purity.

U 302

Compressive Properties

Room temperature ultimate strength in compression of Pu-7 at. % U = 185,000 psi. Testing speed was 0.015 in/min. The specimen had been heat treated at 270°C for 2.5 hours, then quenched to room temperature.
From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

U 305

Creep

SECOND STAGE CREEP RESULTS FOR INJECTION-CAST U-10 At. % Pu ALLOY, AS-CAST

From H. E. Savage and E. R. Gilbert, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

Temp., °C	Strain Rate in Terms of Stress (σ), Sec ⁻¹	Testing Conditions		Fracture Strain, %
		Stress, σ, psi	Strain Rate, Sec ⁻¹	
409	1.67 x 10 ⁻⁸ e ^{0.498σ}	8 to 17	1 x 10 ⁻⁸ to 8 x 10 ⁻⁷	2.88
448	1.15 x 10 ⁻¹⁰ e ^{0.565σ}	7 to 12	7 x 10 ⁻⁹ to 1 x 10 ⁻⁷	2.50
551	3.67 x 10 ⁻⁹ e ^{1.20σ}	2.5 to 5	7 x 10 ⁻⁸ to 3 x 10 ⁻⁶	1.85
300	4.67 x 10 ⁻¹² e ^{5.04σ}	6 to 10	7 x 10 ⁻⁸ to 5 x 10 ⁻⁷	*
550	5.22 x 10 ⁻⁸ e ^{3.68σ}	2.5 to 5	1 x 10 ⁻⁶ to 3 x 10 ⁻⁵	1.5

* Specimen failed prematurely at a defect.

U 307

Hardness

In general the hardness of the binary alloys increases with increasing plutonium content. From 5 to 15 wt. % plutonium, the binary alloys increase in hardness from about 59 to 67 Rockwell A (210 to 250 DPHN). The extruded 20 wt. % plutonium alloy has a hardness of about 77 Rockwell A (280 DPHN).
From A. S. Coffinberry et al, in The Reactor Handbook, 2nd ed., vol. 1, p. 281. 1960.

MICROHARDNESSES OF PLUTONIUM-URANIUM PHASES

From F. H. Ellinger, R. O. Elliott, and E. M. Cramer, J. Nucl. Mater., vol. 1, p. 242. 1959.

Phase	Alloy Composition (at. % U)	Diamond Pyramid Hardness Number, (25-g Load)
Alpha plutonium	0 - 5	200 - 240
Beta plutonium	10 - 25	140 - 165
Zeta, as-cast	40 - 75	275 - 450
Zeta, heat treated	30 - 85	200 - 300
Beta uranium	75 - 90	195 - 300
Alpha uranium	82 - 100	160 - 210

Alloy	Specimen History	Diamond Pyramid Hardness 10-kg. Load	ROOM TEMPERATURE HARDNESS FIGURES		
Pu-3 at. % U	As-Cast	270	From D. M. Poole et al., in <u>Plutonium</u> 1960, p. 640.		
	Heat treated at 315°C for 2.5 hr. Quenched to room temp.	250	Alloy Composition	Treatment	Vickers Hardness Number VHN
	Heat treated at 270°C for 2.5 hr. Quenched to room temp.	240			
Pu-7 at. % U	As-Cast	215	U-5 at. % Pu	Roller	261
	Heat treated at 315°C for 2.5 hr. Quenched to room temp.	220	U-10 at. % Pu	Roller	300
	Heat treated at 270°C for 2.5 hr. Quenched to room temp.	180	U-15 at. % Pu	Roller	400
Pu-14 at. % U	As-Cast	200			
From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, <u>The Plutonium Handbook</u> , 1966.					

Elastic Properties

U 308

AVERAGE VALUES FOR ELASTIC MODULUS AND EXTREME FIBER STRESS
AT FRACTURE FOR URANIUM - 10 at. % PLUTONIUM

From E. R. Gilbert, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

Specimen Condition	Uranium-10 at. % Plutonium	
	Elastic Modulus, 10 ⁶ psi	Extreme Fiber Stress, 10 ³ psi
As-Cast	24.0	133.0
Heat-treated at 900°C (65 hr) and 150°C (24 hr).	24.1	144.0

See end of section U301.

Reactions with Gases — Air

U 401.1

Oxidation of U-Pu and U-Mo-Pu Alloys in Air Dried Over Magnesium Perchlorate. From D. M. Poole et al., in Plutonium 1960, p. 630.

OXIDATION RATES, LATTICE PARAMETER
MEASUREMENTS AND STOICHIOMETRY OF OXIDES
OBTAINED FROM PLUTONIUM URANIUM ALLOYS
OXIDIZED IN DRY CO₂

From M. J. F. Notley, E. N. Hodkin, and J. A. C. Davidson, AERE-R-4070, 1962.

Composition	Temperature	Rate, mg/cm ² -hr	Lattice Parameter of Oxide, Å	Stoichiometry (X in UO _X)
5 at.% Pu-U	500	1.0	5.4567	
	600	4.7	-	
	700	15.8	5.4617	2.105
	800	43.0	5.4382	
10 at.% Pu-U	500	1.05	-	
	600	16.2-21.6	5.4425	2.049
	700	52.5	5.4346	2.053
	800	61.3	5.4598

Oxidation of U-Pu Alloys in Dry CO₂.
From D. M. Poole *et al.* in *Plutonium 1960*, p. 634.

Arrhenius Plot of Oxidation of U-Pu Alloys in CO₂ Dried Over Magnesium Perchlorate.
From D. M. Poole *et al.* in *Plutonium 1960*, p. 634.

CAST PLUTONIUM-URANIUM ALLOYS
PREIRRADIATION AND POSTIRRADIATION DATA

From A. S. Coffinberry *et al.* in *The Reactor Handbook*, 2nd ed., vol. 1, p. 282, 284. 1960.

Specimen	Plutonium Content, Wt. %		Density, g/cm ³	Indicated Burnup ^a , Per Cent	Calculated Maximum Temp ^b , °C	Wt. Change, mg	Fission Gas		Length Increase, %	Growth Rate, in./in./ppm Burnup
	Nominal	Analyzed					Amount Released, cm ³	% of Theoretical Amt.		
2A	0		18.89	0.11	88	-4.1	0	0	0	0
2B	0		18.89	0.12	91	-2.3	--	--	0	0
2C	0		18.86	0.10	83	-2.6	0.037	57	4.9	48
4A	5	{ Top 3.6; bottom 3.8	18.84	0.75	340	0.8	--	--	4.9	6.4
4B	5		18.81	1.1	480	3.1	0	0	6.1	5.4
4C	5		18.88	0.60	270	3.8	--	--	5.4	8.8
6A	10	{ Top 7.5; bottom 5.6	18.92	1.6	720	--	0.60	55	--	--
6B	10		17.94	1.9	820	532.3	1.3	105	18	8.7 ^c
6C	10		18.70	0.81	360	-242.9	0.34	65	7.7	9.2 ^d
7A	15	10.6	18.75	1.5	740	-15.1	0.86	88	11	6.9
7B	15	15.4	18.72	1.9	920	-588.9	0.41	35	26	12 ^c
7C	15		18.78	0.75	370	3.1	0.075	24	17	21

a From results previously obtained on similarly sized enriched specimens, the following flux depressions were assumed respectively for 5, 10, and 15 per cent alloys: 5, 15, and 25 per cent.

b At beginning of irradiation, using the above flux depressions and thermal conductivities 95, 80, and 75 per cent that of unalloyed uranium.

c Probably too low a value because part of specimen was missing.

d Found in two pieces.

EXTRUDED PLUTONIUM-URANIUM ALLOYS

PREIRRADIATION AND POSTIRRADIATION DATA

From A. A. Collierberry et al. in *The Reactor Handbook*, 2nd ed., vol. 1, p. 284, 1960.

Specimen	Plutonium Content, Wt. %		Condi- tion ^b	Density, g./cm. ³	Hardness, Rockwell A	Calculated Burnup, at. %	Calculated Temp., °C		Length Change, %	Growth Rate, in./in./ ppm Burnup	Dia. Change, %	Wt. Change, %
	Nominal	Average Analyzed					Center	Surface				
BG-1	0		AE	18.822	58.0-61.4AC	0.045	85	80	-1.1	-91	3.2	0.1
BG-2	0		AE	18.901	59.2-65.2AC	0.048	90	85	-5.1	-110	3.2	0.1
BG-3	10	9.4	AE	18.810	51.2-70.3AC	0.70	780	590	b,c			
BG-4	10		AE	18.707		0.35	410	310	c			
BG-5	10		HT	18.877		0.45	520	400	c			
BG-6	10		HT	18.855		0.25	300	230	1.5	6	b	e
BG-7	15	11.2	AE	18.832	62.1-68.8AC	0.32	330	290	47	150	b	e
BG-8	15		AE	18.871		0.80	890	670	97	85	-46	15.7
BG-9	15		HT	18.797		0.70	780	590	39	47	b	e
BG-10	15		HT	18.776		0.14	190	150	49	285	130	-8.8
BG-11	20	18.5	AE	18.778	76.4-78.4AE	0.60	630	510	5.2	9	0 to 23	e
BG-12	20		AE	18.798		0.40	460	350	5.7	14	-0.8	e
BG-13	20		HT	18.804		0.52	590	450	5.2	10	0.8	e
BG-14	20		HT	18.801		0.25	300	230	10	40	15	-7.6

a AE as extruded, and HT heat-treated—heated to 645°C, cooled to and held at 500°C for 1 hr, cooled to room temperature.

b Poor condition of specimen did not permit measurements.

c Stuck in irradiation capsule.

d Ignited and burned before measurements could be taken. e Could not be measured because balance was out of order.

Phase Diagrams

Va 101

Constitutional Diagram for the Systems Plutonium-Vanadium.
From F. W. Schönfeld et al. in *Metallurgy and Fuels*, series V, vol. 2,
p. 583, 1959.

The Plutonium-Vanadium System
From F. W. Schönfeld in *The Metal Plutonium*, p. 259.

The Plutonium-Zinc Phase Diagram Including Revisions From This Investigation. The Symbols Represent: ● Metallographic Data Indicating the Number of Phases by the Number of Quadrants Filled in; ○ Visual Thermal Analysis Data; ● Thermal Analysis Data After Cramer *et al.* From E. D. Albrecht, *J. Nucl. Mater.*, vol. 12, p. 127. 1964.

The Plutonium-Rich Portion of the Phase Diagram. (○) Data From High-Temperature X-Ray Diffractometry, (●) X-Ray Parametric Data, (●) Metallographic Data Indicating the Number of Phases Present by the Number of Quadrants Filled in. From E. M. Cramer, F. H. Ellinger, and C. C. Land in *Extractive and Physical Metallurgy of Plutonium and Its Alloys*, p. 175. 1960.

X-RAY DIFFRACTION STUDIES

From E. M. Cramer, F. H. Ellinger, and C. C. Land in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 173. 1960.

Com- pound	Structure Type	Crystal Lattice	Unit Cell Dimensions, Å	Formula Units in Unit Cell	Space Group	Cale Density g/cm ³
PuZn ₂	Cu ₂ Mg	Cubic, face- centered	Pu-rich: a = 7.760 ± 0.001 Zn-rich: a = 7.747 ± 0.001	8	Fd3m	10.5
Pu ₂ Zn ₉	Unknown					9.05*
PuZn ₈	Unknown					8.6*
Pu ₂ Zn ₁₇	U ₂ Zn ₁₇	Hexagonal	a = 8.994 ± 0.004 c = 26.60 ± 0.08	6	P6m2	8.50

*From A. C. Larson, as reported by E. D. Albrecht, J. Nucl. Mater., vol. 12, p. 126. 1964.

Density

DENSITY OF Pu-Zn ALLOYS AT 24°C

From R. O. Elliott, C. E. Olsen, and J. Louie, J. Phys. Chem. Solids, vol. 23, p. 1036. 1962.

Composition at. % Zn	Heat Treatment	Density g/cm ³
1.51	1	15.87 ± 0.03
1.79	1	15.74 ± 0.03
2.16	1	15.77 ± 0.03
2.92	1	15.69 ± 0.03
3.35	2	15.64 ± 0.03
3.89	2	15.55 ± 0.03

1. Heat treated at 450°C for 500 hr.
2. Heat treated at 480°C for 500 hr.

DENSITIES OF INTERMETALLIC COMPOUNDS (g/cm³)

From E. D. Albrecht, J. Nucl. Mater., vol. 12, p. 126. 1964.

Compound	X-Ray Density	Measured Density
PuZn ₂	10.5*	10.8 +
Pu ₂ Zn ₉	9.05**	9.05
PuZn ₈	8.6**	8.43
Pu ₂ Zn ₁₇	8.5*	7.79 ++

- * Cramer et al.
** Private Communication A. C. Larson, August 10, 1960.
+ Sample contained a small amount of alpha plutonium.
++ Sample contained a considerable proportion of voids.

Electrical Conductivity

ELECTRICAL RESISTIVITY OF Pu-Zn ALLOYS

From R. O. Elliott, C. E. Olsen, and J. Louie, J. Phys. Chem. Solids, vol. 23, p. 1036. 1962

Composition Zn, At. %	Specific Resistivity μΩ-cm			
	10°K	50°K	100°K	300°K
3.35	81.4	99.6	113.6	113.0
3.89	88.1	100.8	111.7	110.3

Zn 307 Hardness

From R. O. Elliott and K. A. Gschneidner, Jr., in Extractive and Physical Metallurgy of Plutonium and Its Alloys, p. 259. 1960.

MICROHARDNESSES OF INTERMETALLIC COMPOUNDS

From E. D. Albrecht, J. Nucl. Mater., vol. 12, p. 126. 1964.

Compound	D. P. H. No. * (Range)	D. P. H. No. (Average)
PuZn ₂	340-370	350
Pu ₂ Zn ₉	360-480	420
PuZn ₈	340-470	390
Pu ₂ Zn ₁₇	200-320	280

* Diamond Pyramid Hardness Numbers obtained at a load of 25g.

Zn 401.1 Reactions with Gases - Air

MERIT RATIOS FOR PLUTONIUM-ZINC ALLOYS EXPOSED TO AIR CONTAINING 50% RELATIVE HUMIDITY 75°C

From J. T. Waber et al., J. Nucl. Mater., vol. 3, p. 206. 1961.

Composition, at. %	Merit Ratio*		
	At 500 hr	At 1000 hr	
6	34.0	44.1	122
9	19.7	26.1	80
12	31.1	36.8	62.5t

* Merit Ratio = $\frac{\text{Weight gain of unalloyed Pu}}{\text{Weight gain of alloy}}$

Partial Phase Diagram For Pu-Zr System. From F. H. Ellinger in Plutonium 1960, p. 319.

Solid lines from D. M. Poole et al, in PLUTONIUM 1960, p. 269.
Broken lines conform to X-ray diffraction studies at Los Alamos.

Plutonium-Zirconium Equilibrium Diagram 0-35 at. % Zirconium. From J. A. C. Marples, Less-Common Metals, vol. 2, p. 333. 1960.

Zr 102

Transformation Kinetics

Isothermal Reaction Curves For Pu-0.65 at. % Zr Alloy. From J. M. Taylor, HW-SA-2560.

Zr 103

Crystal Structure

Two intermetallic phases have been observed in plutonium-zirconium alloys.

Los Alamos reports that the plutonium-rich phase is believed to correspond stoichiometrically to Pu_{19}Zr .^{*} Harwell reports that all observed lines on diffraction patterns are explicable in terms of Pu_4Zr and retained phases of pure plutonium.[†] Russia[‡] reports a phase in the composition range 12.1 to 20.6 at. % corresponding to the composition Pu_6Zr . Pu_6Zr is orthorhombic with $a = 10.39$, $b = 10.44$, and $c = 11.18$ Å. It has 8 formula units per unit cell and a calculated density of 16.7 g/cm^3 .

PuZr_2 is hexagonal, isostructural with UZr_2

$$a = 5.055 \pm 0.005, c = 3.123 \pm 0.005 \text{ Å}^+$$

$$a = 5.060 \pm 0.002, c = 3.119 \pm 0.002 \text{ Å}^{\dagger}$$

Space group P6m2

3 atoms per unit cell

Pu and Zr atoms share positions $2/3, 1/3, 1/2; 1/3, 2/3, 1/2$

Zr atoms occupy $0,0,0$

(The pattern closely resembles that of a cubic cell having a 4.390 Å and several forbidden reflections)[†]

^{*}From F. H. Ellinger in *The Metal Plutonium*, p. 304.

[†]From M. B. Waldron in *The Metal Plutonium*, p. 234.

[‡]From A. A. Bochvar et al. in *Proc. Second Geneva Internat. Conf.*, vol. 6, p. 187.

Composition Zr at. %	Average Density at Room Temperature g/cm ³
2.4	17.41
1.7	17.55
0.65	19.21
0.24	19.45
Unalloyed Pu	19.59

From J. M. Taylor, HW-SA-2560.

The Densities of Plutonium-Zirconium Alloys as a Function of Their Composition. From M. B. Waldron in *The Metal Plutonium*, p. 236.

Composition at. % Zr	Temp. Range, °C	$\alpha \times 10^6 / ^\circ\text{C}$
8.0	349-470	10.3
10.0	360-450	10.7
12.0	370-454	15.8

From R. O. Elliott et al. in *Plutonium 1960*, p. 151.

Zr 203.1 Electrical Conductivity

Resistivities of Pu-Zr δ -Phase Solid Solutions. From J. A. Lee et al. in Plutonium 1960, p. 43.

Zr 204.1 Magnetic Susceptibility

Paramagnetic Susceptibility of Plutonium-Zirconium Alloys.
O—Alloys of the δ -Plutonium Structure;
●—Compound Pu₆Zr
From S. T. Konobeevsky et al. in Proc. Second Geneva Internat. Conf., vol. 6, p. 195.

Zr 301 Tensile Properties

COMPARISON OF MECHANICAL PROPERTIES* OF VARIOUS COMPOSITIONS OF PLUTONIUM-ZIRCONIUM ALLOY AND UNALLOYED PLUTONIUM AT ELEVATED TEMPERATURES

From J. M. Taylor, HW-SA-2560.

Composition at.% Zr	Test Temperature, $^{\circ}$ C	Ultimate Strength, psi	Elongation, %	Reduction In Area, %	Average Density at Room Temperature, g/cm ³	Heat Treatment
2.4	180	18,000	---	---	17.41	†
2.4	130	28,940	---	---		§
1.7	180	16,105	---	---	17.55	†
1.7	130	26,000	---	---		§
0.65	180	12,000	100	100	19.21	†
0.65	130	24,224	---	---		§
0.24	180	6,448	450	75	19.45	†
0.24	130	13,308	160	30		§
Unalloyed Pu	180	3,580	503.2	100	19.59	Beta Phase Plutonium
Unalloyed Pu	130	12,100	294	100		Beta Phase Plutonium

*All tensile specimens 0.250-in. diameter. Testing speed: 0.015 in./min.

† Gage length 1 in.

‡ Held at 180 $^{\circ}$ C for 20 min., then tested.

EFFECT OF TEMPERATURE ON TENSILE PROPERTIES OF A BETA STABILIZED Pu-2.4 at. % Zr ALLOY*

From J. M. Taylor, HW-SA-2560.

Test Temp., °C	Ultimate Strength, psi	Yield Strength, psi	Elongation, %	Reduction In Area, %	Heat Treatment And Remarks
30	51,000	28,400 [‡]	0.076	--	Specimen held at 220°C for 24 hrs, quenched to room temperature, tested 7 hrs after quench.
70	45,546	38,500	--	--	Held at 220°C for 5 hrs. Cooled to 70°C, and held for 20 min. and tested.
130	36,800	33,400	--	--	Held at 220°C for 5 hrs. Cooled to 130°C, and held for 20 min. and tested.
160	28,700	23,300	--	--	Held at 220°C for 5 hrs. Cooled to 160°C, and held for 20 min. and tested.
180	23,835	20,000	--	--	Held at 220°C for 5 hrs. Cooled to 180°C, and held for 20 min. and tested.
200	18,367	14,300	--	--	Held at 220°C for 24 hrs, quenched to room temperature. Heated to 200°C, and held for 20 min. then tested.
210	13,700	11,600	--	--	Held at 220°C for 24 hrs, quenched to room temperature. Heated to 210°C, and held for 20 min. then tested.
230	12,240	8,300	--	2	Held at 220°C for 24 hrs, quenched and heated to 230°C and held for 20 min. then tested.
250	10,290	7,300	5.0	28	Held at 220°C for 24 hrs, quenched and heated to 250°C for 20 min. then tested.
260	7,800	6,900	6.3	40	Held at 220°C for 24 hrs, quenched and heated to 260°C for 20 min. then tested.

* Testing Speed: 0.015 in./min. [‡]Based on one in. gage length [‡]A 0.01% offset yield strength.

STUDY OF THE EFFECT OF AGING TIME ON THE TENSILE PROPERTIES* OF A BETA STABILIZED Pu-2.4 at. % Zr ALLOY

From J. M. Taylor, HW-SA-2560.

Aging Time After Quench [†]	Ultimate Strength, psi	0.01% Yield Strength, psi	Elongation, %	Reduction In Area, %	Modulus of Elasticity x 10 ⁻⁶	Temperature Of Test, °C
40 min	40,000	22,100	0.076	--	6.43	30
7 hr	51,000	28,400	0.28	--	5.73	30
24 hr	42,700	24,800	0.081	--	6.09	30
48 hr	43,000	16,200	0.102	--	6.59	30

*Testing speed: 0.015 in./min.

[†]All tensile specimens were heat treated at 220°C for 24 hr and then quenched in oil at room temperature.

Effect of Zirconium Concentration and Test Temperatures on the Tensile Properties of Plutonium-Zirconium Alloys. From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Effect of Temperature on Tensile Properties of Beta-Stabilized Plutonium-2.4 at 7% Zirconium Alloy. From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Zr 302 Compressive Properties

EFFECT OF TEMPERATURE ON THE COMPRESSION PROPERTIES* OF BETA STABILIZED Pu-2.4 at. % Zr ALLOY

From J. M. Taylor, HW-SA-2560.

Test Temperature, °C	Ultimate Strength, psi	Yield Strength, psi	Plastic Decrease in Length, %	Heat Treatment, 30 min °C
60	67,000	59,800	4.6	60
80	61,600	57,900	5.3	80
130	53,500	48,700	5.3	130
160	45,600	41,000	6.0	160
180	46,800	43,000	5.0	180
200	32,800	27,700	5.0	200
220	28,500	26,900	5.4	220

*Testing speed 0.015 in./min.

+Total plastic decrease was determined from load-platen displacement curve at point of failure.

Comparison of Compressive Strengths of Pu-2.4 at. % Zr Alloy and Unalloyed Plutonium. From J. M. Taylor, HW-SA-2560.

Hardness

Zr 307

HARDNESS OF Pu-Zr ALLOYS

From J. M. Taylor, as reported by H. R. Gardner in Chapter 4, The Plutonium Handbook, 1966.

Composition, at. % Zr	Diamond Pyramid Hardness, 5 kg Load	Treatment
0.24	300	As-Cast
0.65	269	As-Cast
1.7	107	As-Cast
2.4	117	Annealed 24 hr at 220°C and oil quenched.

ROOM TEMPERATURE HARDNESS FIGURES

From D. M. Poole et al. in Plutonium 1960, p. 640.

Alloy Composition	Treatment	Vickers Hardness Number, VHN
Zr-5 at. % Pu	Rolled	207
Zr-10 at. % Pu	Rolled	209
Zr-20 at. % Pu	Rolled	189
Zr-30 at. % Pu	Rolled	108
Zr-40 at. % Pu	Rolled	97

Corrosion Data for Pu and for Pu-Zr Alloy; Exposed to Air Dried With MgClO_4 at 75°C . From J. T. Waber in Proc. Second Geneva Internat. Conf., vol. 6, p. 212.

Corrosion Data for Several Delta-Phase Pu Alloys, Rolled and Annealed; Exposed to Air Containing 20% Relative Humidity at 35°C . From J. T. Waber in Proc. Second Geneva Internat. Conf., vol. 6, p. 211.

MERIT RATIOS FOR Pu-Zr ALLOYS EXPOSED TO AIR AT 20% RELATIVE HUMIDITY AND 35°C

From J. T. Waber in Proc. Second Geneva Internat. Conf., vol. 6, p. 211.

Composition, at. % Zr	900 Hr	4300 Hr	8730 Hr
7.5	22	152	226
10.0	22	133	197

Comparison of the Corrosion Behaviors of Plutonium-Zirconium Alloys and Unalloyed Plutonium Exposed to Air at 75°C and 50% Relative Humidity. From J. T. Waber et al., J. Nucl. Mater., vol. 3, p. 206. 1961.

MERIT RATIOS FOR DELTA-PHASE Pu-Zr ALLOYS EXPOSED TO AIR AT 50% RELATIVE HUMIDITY AND 75°C

J. T. Waber et al., J. Nucl. Mater., vol. 3, p. 206. 1961.

Zr, at. %	Merit Ratio Observed	
	at 500 h	at 1000 h
4.3	1.22	0.61
6.0	1.1	—
8.9	17.1	7.42

Oxidation of Pu-Zr Alloys Air Dried Over Magnesium Perchlorate.
From D. M. Poole et al. in *Plutonium 1960*, p. 630.

Reactions with Gases — Inert Gases

Zr 401.4

Oxidation of Rolled Pu-Zr Alloys in Dry CO_2 at 700°C .
From D. M. Poole et al. in *Plutonium 1960*, p. 633.

Oxidation of Rolled Pu-Zr Alloys in CO_2 Dried Over Magnesium Perchlorate at 800°C . From D. M. Poole et al. in *Plutonium 1960*, p. 633.

Oxidation of Arc Cast Plutonium-Zirconium Alloys in Dry CO_2 at 600°C .
From M. J. F. Notley et al., AERE-R-4070.

Oxidation of Arc Cast Plutonium-Zirconium Alloys in Dry CO_2 at 700°C .
From M. J. F. Notley et al., AERE-R-4070.

Oxidation of Rolled Plutonium-Zirconium Alloys in Dry CO_2 at 600°C .
From M. J. F. Notley et al., AERE-R-4070.

Oxidation of Arc Cast Plutonium-Zirconium Alloys in Dry CO_2 at 800°C .
From M. J. F. Notley et al., AERE-R-4070.

Plutonium-Yttrium Phase Diagram. From L. J. Wittenberg and G. R. Grove, MLM-1184.

PART III
TERNARY ALLOYS

1

2

3

4

5

6

7

Pu-Co-Ce Alloys. Thermal Analysis Results and Binary Diagrams.
 From D. M. Poole et al. in *Plutonium 1969*, p. 644.

Pu-Co-Ce Alloys Filtration Results. From D. M. Poole et al. in *Plutonium* 1960, p. 645.

Possible 375°C Isothermal Section for the System Pu-Co-Ce. From D. M. Poole et al. in *Plutonium* 1960, p. 645.

F = Proposed Fuel Alloy Composition
X = X-Ray Sample Composition

Cerium-Cobalt-Plutonium Alloys. From J. K. Critchley, AERE-M-488.

Density Variation in Liquid and Solid 14 at.% Pu-25 at.% Co-61 at.% Ce Alloy.
 From D. M. Poole and J. L. Nichols, AERE-R-3122.

Density of Pu-Ce-Co Eutectic Alloy as a Function of Temperature.
 From L. V. Jones et al., *Am. Soc. Metals, Trans. Quart.*, vol. 55, p. 824. 1962.

$$\rho = 9.082 - 2.31 \times 10^{-4} T$$

where:

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

$$T = ^\circ\text{C}$$

19.6 at.% Pu, 56.2 at.% Ce, 24.2 at.% Co

From L. V. Jones et al., *Am. Soc. Metals, Trans. Quart.*, vol. 55, p. 825. 1962.

Ce-Co 202.1

Thermal Expansion

The value of the coefficient of expansion over the linear portion of the curve is equal to $-25 \times 10^{-6}/^\circ\text{C}$.

The volume coefficient of expansion of the liquid over the range 420-600°C is $72 \times 10^{-6}/^\circ\text{C}$.

Extrapolation of the solid and liquid density curves indicate a volume change on melting of +4%. From D. M. Poole *et al.* in *Plutonium 1960*, p. 646.

Dilatometer Record of Selected Pu-Co-Ce Alloy. From D. M. Poole *et al.* in *Plutonium 1960*, p. 646.

Ce-Co 202.2

Thermal Conductivity

Thermal Conductivity of 14 at.% Pu-25 at.% Co-61 at.% Ce Calculated From Observed Resistivity. From D. M. Poole *et al.* in *Plutonium 1960*, p. 647.

Heat Capacity of the Plutonium-Cerium-Cobalt Eutectic Alloy (20 at. % Pu-56 at. % Ce-24 at. % Co) as a Function of Temperature. From L. J. Wittenberg and G. R. Grove, MLM-1184.

Temperature of and Volume Change during Transition

Ce-Co 202.5

See end of Section Ce-Co 202.3.

Heats of Transition

Ce-Co 202.6

See end of Section Ce-Co 202.3.

Ce-Co 203.1

Electrical Conductivity

Measured Resistivity of Selected 14 at. % Pu-25 at. % Co-61 at. % Ce Alloy.
From D. M. Poole and J. L. Nichols, AERE-R-3122.

Ce-Co 206

Viscosity

Viscosities of Plutonium-Cerium-Cobalt Molten Alloys as a Function of Temperature. From L. J. Wittenberg and G. R. Grove, MLM-1184.

EQUATIONS FOR VISCOSITY DATA*

From L. J. Wittenberg and G. R. Grove, MLM-1184.

Composition	m	b	Standard Deviation, Poise	Activation Energy, cal/g-atom
50 wt. % Pu-40 wt. % Ce-10 wt. % Co	1.6545	0.8518	± 0.0039	7571
34 wt. % Pu-56 wt. % Ce-10 wt. % Co	1.4656	0.7175	± 0.0043	6707

Viscosity of Pu-Ce-Co Eutectic Alloy as a Function of Temperature 19.6 at. % Pu, 56.2 at. % Ce, 24.2 at. % Co. From L. V. Jones et al., *Am. Soc. Metals, Trans. Quart.*, vol. 55, p. 823, 1962.

CALCULATED VISCOSITIES OF Pu-Ce-Co

From L. V. Jones et al., *Am. Soc. Metals, Trans. Quart.*, vol. 55, p. 823, 1962.

Temp. °C	Period, Sec.	Logarithmic Decrement	Density, g/cm ³	Viscosity Centipoise
Pu-Ce-Co				
801	2.665	0.0243603	8.893	5.08
720	2.668	0.0259293	8.913	5.93
683	2.666	0.0267754	8.923	6.44
681	2.669	0.0264774	8.924	6.26
632	2.669	0.0284750	8.937	7.54
579	2.670	0.0306603	8.949	9.16
528	2.670	0.0321430	8.962	10.42
451	2.674	0.0359024	8.978	14.28
446	2.674	0.0369210	8.980	15.54

See first table in Section Ce-Co 600

THE INTERGRANULAR PENETRATION (IGP) AND DISSOLUTION OF
CERAMICS BY Pu-Co-Ce ALLOYS
(Conditions: 200 h at 750°C, static, isothermal)

From B. J. Thamer in Corrosion of Reactor Materials, Vol. II, p. 310.

Ceramic	Test Fuel	Observations
TiC _{0.93} +2.6 wt. % C		No IGP or dissolution
TaC _{1.00} +0.1 wt. % C	19 at. % Pu	No IGP or dissolution
ZrC _{0.93} +1.9 wt. % C	55.6 at. % Ce	Some IGP, no dissolution
HfC _{0.91} +0.1 wt. % C	24.7 at. % Co	No IGP or dissolution
BeO		Not visibly attacked, 120 ppm Be produced in fuel
MgO		Not visibly attacked, 600 ppm Mg produced in fuel
Al ₂ O ₃		Not visibly attacked, less than 200 ppm Al produced in fuel
TiB _{1.77}		No IGP, less than 200 ppm Ti produced in fuel
ZrB _{1.8}		No IGP, 20 ppm Zr produced in fuel
CaO	25.7 at. % Pu 49.2 at. % Ce	Extensive IGP and transgranu- lar penetration, 150 ppm Ca produced in fuel
ThO ₂	25.1 at. % Co	No IGP, 90-195 ppm Th produced in fuel
ZrO ₂		Extensive IGP, 10-25 ppm Zr produced in fuel

ATTACK OF NIOBIUM, MOLYBDENUM AND TANTALUM CONTAINERS BY LOW MELTING
POINT PLUTONIUM ALLOYS AFTER 7 DAYS AT 760°C

From D. M. Poole et al. in Plutonium 1960, p. 648.

Alloy	Container	Approximate Angle Of Contact With Wall (Measured Through Liquid)	Appearance of Interface	Depth Of Visible Inter- action, in.	Analysis Of Contents, wt. %
Pu-Co-Ce	Nb	0°	Irregular attack, white angular compound particles formed.	~0.0005	0.09 Nb
	Mo	25°	Extensive intergranular attack after 6 weeks at 800°C.	(0.01)	(10 Mo)
	Ta	35°	Localized attack, non- adherent film and de- tached needle particles.	~0.0005	~0.5 Ta

Plutonium-Cerium-Copper Phase Diagram. From L. J. Wittenberg and G. R. Grove, MLM-1184.

Copper-Rich Corner of the Plutonium-Cerium-Copper Phase Diagram.
 From L. J. Wittenberg and G. R. Grove, MLM-1184.

ATTACK OF NIOBIUM, MOLYBDENUM AND TANTALUM CONTAINERS BY LOW MELTING
POINT PLUTONIUM ALLOYS AFTER 7 DAYS AT 760°CFrom D. M. Poole *et al.* in *Plutonium* 1960, p. 648.

<u>Alloy</u>	<u>Container</u>	<u>Approximate Angle Of Contact With Wall (Measured Through Liquid)</u>	<u>Appearance of Interface</u>	<u>Depth Of Visible Inter- action, in.</u>	<u>Analysis Of Contents, wt. %</u>
Pu-Cu-Ce	Nb	0°	Rough reaction layer plus occasional compound needles.	~ 0.0001	0.02 Nb
	Mo	0°	Extensive intergranular penetration.	~ 0.0025	~ 3.0 Mo
	Ta	20-125°	Interrupted smooth re- action layer below liquid surface. Above liquid level there were occasional signs of extensive uneven attack.	<0.0001	~ 0.2 Ta

Partial Diagram of the Plutonium-Cerium-Nickel Ternary System.
From L. J. Wittenberg and G. R. Grove, MIM-1184.

ATTACK OF NIOBIUM, MOLYBDENUM AND TANTALUM CONTAINERS BY LOW MELTING
POINT PLUTONIUM ALLOYS AFTER 7 DAYS AT 760°C

From D. M. Poole et al. in *Plutonium 1960*, p. 648.

Alloy	Container	Approximate Angle Of Contact With Wall (Measured Through Liquid)	Appearance of Interface	Depth Of Visible Inter- action, in.	Analysis Of Contents, wt. %
Pu-Ni-Ce	Nb	25-35°	Continuous adherent layer.	~ 0.0001	0.001 Nb
	Mo	-	Extensive intergranular penetration and solution.	~ 0.0015	~ 0.8 Mo
	Ta	45-90°	Continuous adherent layer.	< 0.0001	0.2 Ta

Mo-U 101

Phase Diagrams

From P. G. Mardon et al. in *Plutonium 1960*, p. 343.

From P. G. Mardon et al. in *Plutonium 1960*, p. 344.

From P. G. Mardon et al. in *Plutonium 1960*, p. 344.

From P. G. Mardon et al. in *Plutonium 1960*, p. 345.

From P. G. Mardon et al. in *Plutonium 1960*, p. 345.

1000°C Isotherm. From P. G. Mardon *et al.* in *Plutonium 1960*, p. 336.

900°C Isotherm. From P. G. Mardon *et al.* in *Plutonium 1960*, p. 336.

800°C Isotherm. From P. G. Mardon *et al.* in *Plutonium 1960*, p. 337.

750°C Isotherm. From P. G. Mardon *et al.* in *Plutonium 1960*, p. 337.

700°C Isotherm. From P. G. Mardon et al. in *Plutonium 1960*, p. 338.

600°C Isotherm. From P. G. Mardon et al. in *Plutonium 1960*, p. 340.

650°C Isotherm. From P. G. Mardon et al. in *Plutonium 1960*, p. 338.

550°C Isotherm. From P. G. Mardon et al. in *Plutonium 1960*, p. 340.

450°C Isotherm. From P. G. Mardon et al. in *Plutonium 1960*, p. 341.

Liquidus Contours. From P. G. Mardon et al. in *Plutonium 1960*, p. 334.

Solidus Contours. From P. G. Mardon et al. in *Plutonium 1960*, p. 334.

Change in Length as a Function of Time for Specimens Held at Various Temperatures. 68% U-20% Pu-12% Mo. From R. Boucher in *Plutonium* 1960, p. 361.

Change in Length as a Function of Time for Specimens Held at Various Temperatures. 70% U-20% Pu-10% Mo. From R. Boucher in *Plutonium* 1960, p. 362.

Change in Length as a Function of Time for Specimens Held at Various Temperatures. 72% U-20% Pu-8% Mo. From R. Boucher in *Plutonium* 1960, p. 363.

Curves of $\frac{\Delta L}{L}$ Versus Temperature. 74% U-20% Pu-6% Mo. From R. Boucher in *Plutonium* 1960, p. 365.

Curves of $\frac{\Delta L}{L}$ Versus Temperature. 75% U-20% Pu-6% Mo. From R. Boucher in *Plutonium* 1960, p. 366.

Transformation Behaviour of U-17 at.% Pu-17 at.% Mo Alloy Quenched From the γ -U Field. From P. G. Mardon in *Plutonium* 1960, p. 389.

T-T-T Curves for U-17 at.% Pu-17 at.% Mo Alloy Quenched From the γ -U Field. From P. G. Mardon in *Plutonium* 1960, p. 390.

Transformation Behaviour of U-10 at.% Pu-13 1/2 at.% Mo Alloy Quenched From the γ -U Field. From P. G. Mardon in *Plutonium 1960*, p. 390.

T-T-T Curves for U-10 at.% Pu-13 1/2 at.% Mo Alloy as Determined Metallographically. From P. G. Mardon in *Plutonium 1960*, p. 391.

Expansion vs temperature and expansion vs time curves.
Δl, temperature curves are solid lines.
Δl, time curves are dotted lines, with a dot for every 10 minutes.

Expansion vs temperature and expansion vs time curves.

Δ 1, temperature curves are solid lines.

Δ 1, time curves are dotted lines, with a dot for every 10 minutes.

Effect of Temperature on Hardness of Homogenized and Rolled Uranium-Molybdenum-Plutonium Alloys, Arc Cast Unless Otherwise Stated. From P. M. French, as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Effect of Temperature on Hardness of Homogenized and Forged Uranium-Molybdenum-Plutonium Alloys, Resistance Cast. From P. M. French, as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Effect of Temperature on Hardness of Homogenized Uranium-Molybdenum-Plutonium Alloys, Resistance Cast. From P. M. French, as reported by H. R. Gardner in Chapter 4, *The Plutonium Handbook*, 1966.

Room Temperature Vickers Hardness of Quenched Uranium-Molybdenum-Plutonium Alloys. From P. G. Mardon et al. in Plutonium 1960, p. 335.

Vickers Hardness of Quenched U-Mo-Pu Alloys. From D. M. Poole et al. in Plutonium 1960, p. 641.

ROOM TEMPERATURE HARDNESS FIGURES FOR URANIUM-MOLYBDENUM-PLUTONIUM ALLOYS

From D. M. Poole et al. in Plutonium 1960, p. 642.

Alloy Composition		Heat Treatment	Vickers Hardness Number (V, H, N ₁)
at. % Mo	at. % Pu		
5	5	Rolled	492
5	15	Rolled	413
10	5	Rolled	160
10	10	Rolled	252
10	15	Rolled	351
15	5	Rolled	266, 400
15	15	Arc cast	303
20	5	Rolled	272, 423
20	10	Rolled	259, 308
20	15	Arc cast	325
25	2.5	Rolled	442
25	5	Rolled	426
25	5	Arc cast	327
25	7.5	Rolled	408
30	5	Rolled	282
30	10	Arc cast	308

HOT HARDNESS FIGURES FOR URANIUM-MOLYBDENUM-PLUTONIUM ALLOYS

From D. M. Poole et al. in Plutonium 1960, p. 642.

Alloy Composition		Heat Treatment	Temperature, °C						
			25	200	300	400	500	600	700
13.5 at. % Mo 10 at. % Pu		Arc cast	171	241	208	217	107	29	
		800°C 4 days	228	182	153		113	41	
		800°C 4 days					49	34	18
20 at. % Mo 15 at. % Pu		Arc cast		247	229	218	142	108	52
		Arc cast					188	155	94
		Arc cast					314	339	135
25 at. % Mo 5 at. % Pu		Arc cast		280	239	251	259	193	121

Variation in results caused by slow reaction kinetics below 600°C.

CHANGE OF HARDNESS WITH TIME AT 500°C FOR A U-20 at. % Mo-15 at. % Pu ALLOY

From D. M. Poole et al. in Plutonium 1960, p. 642.

Time, min	0	5	10	20	30	40
Hardness V, H, N ₁	181	161	144	138	137	117

Oxidation of U-Pu and U-Mo-Pu Alloys in Air Dried Over Magnesium Perochlorate. From D. M. Poole et al. in *Plutonium 1960*, p. 630.

Inert Gases

Mo-U 401.4

Oxidation in Dry CO_2 .

U-Mo-Pu Alloys. A number of alloys of various compositions within the γ field have been oxidized and gave linear or increasing rates, but visual examination showed that all the attack was confined to a few regions and that the remainder of the specimen remained bright and apparently unoxidized; etched or mechanically-polished specimens behaved in the same way. Metallographic examination showed deep oxidation cavities with large cracks radiating from them and oxidation appeared to have proceeded down such cracks and grain boundaries; no evidence could be found of segregation of impurities which could explain the site of the attack. Careful oxidation of a previously prepared and examined metallographic surface did not reveal any correlation between microstructure and the area of attack.

The overall rate of oxidation of the ternary alloys is low and it would appear that if the pitting could be eliminated their oxidation resistance would be extremely good. Such pitting has been observed in high molybdenum U-Mo alloys but has not been explained or eliminated even for these binary alloys.

It appears that a surface layer protects the specimen, for once attack starts it is fairly rapid. Attack is then propagated by cracks, mainly along grain boundaries, which open under the stress caused by the oxide formation. It has been suggested that grains may become thermally insulated from the bulk of the material and that the temperature and rate of attack then rise rapidly. From D. M. Poole et al. in *Plutonium 1960*, pp. 635, 636.

Oxidation of Plutonium-Uranium-Molybdenum Alloys in Dry CO_2 at 600°C. From M. J. F. Nottley et al., *AFRE R-1070*.

The interaction at temperatures between 600 and 650°C between a range of U-Mo-Pu alloys and 18:8:1 stainless steel has been studied. Alloy specimens in the form of taper pins were pressed into steel blocks and after heating were sectioned, examined metallographically and the extent of the reaction zones estimated visually. From D. M. Poole et al. in *Plutonium 1960*, p. 637.

Mechanically polished and lightly electropolished in 100 cm³ acetic acid, 25 cm³ water, 5 g chromic oxide at 1.75 V for 10 sec.

Compatibility of U-Mo-Pu Alloys with 18:8:1 Stainless Steel 600°C. From D. M. Poole et al. in *Plutonium 1960*, p. 637.

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