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MASTER

PLUTONIUM-238 ISOTOPIC FUEL FORM DATA SHEETS

AEC Research and Development REPORT

MONSANTO RESEARCH CORPORATION

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OPERATED FOR

UNITED STATES ATOMIC ENERGY COMMISSION

U. S. GOVERNMENT CONTRACT NO. AT-33-1-GEN-53

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Chemistry

PLUTONIUM-238 ISOTOPIC FUEL FORM DATA SHEETS

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Issued: October 31, 1968

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MONSANTO RESEARCH CORPORATION

A Subsidiary of Monsanto Company

MOUND LABORATORY

Miamisburg, Ohio

operated for

UNITED STATES ATOMIC ENERGY COMMISSION

U S GOVERNMENT CONTRACT NO AT-33-1-GEN-53

FOREWORD

This report presents a compilation of data to September 1, 1968, for isotopic fuel forms of plutonium-238 which have been studied and for which data have been accumulated at Mound Laboratory. Data were obtained from the open literature and unpublished Mound sources.

Since some properties have not been determined for plutonium-238, analogous properties of plutonium-239 are given whenever it could be assumed that these properties were not altered by the isotope or isotopic composition. Whenever plutonium-239 data are given, this isotope is noted; otherwise data were obtained from plutonium-238.

Analogous data for isotopic fuel form of polonium-210 are published in MLM-1563.

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PLUTONIUM-238

(half-life 87.404 ± 0.041 years)

A. METAL

REFERENCES

1. Typical Composition

a. <u>Plutonium</u>		Concentration (wt %)
^{238}Pu		0.0001
^{238}Pu		80.27
^{239}Pu		15.87
^{240}Pu		3.00
^{241}Pu		0.72
^{242}Pu		0.14
b. <u>Actinide Impurities</u>		Concentration (wt %)
^{234}U		0.188, increases at the rate of decay of ^{238}Pu
^{237}Np		0.032

The total of other isotopic impurities including ^{231}Pa , ^{232}Th , ^{233}U , ^{235}U , ^{236}U and ^{227}Ac does not exceed 0.1 wt % of the metal.

c. <u>Cation Impurities</u>	<u>Concentration (wt %)</u>	
	<u>Min.</u>	<u>Max.</u>
Aluminum	0.01	0.04
Boron	0.01	0.04
Calcium	0.01	0.05
Chromium	0.05	0.07
Copper	0.01	0.05
Iron	0.06	0.07
Magnesium	0.01	0.90

REFERENCES

<u>Cation Impurities</u>	<u>Concentration (wt %)</u>	
	<u>Min.</u>	<u>Max.</u>
Sodium	0.06	0.76
Nickel	0.05	0.07
Lead	0.01	0.13
Silicon	0.01	0.06

2. Specific Power (based on 80% ^{238}Pu in the element plutonium)

- a. 0.45 W g^{-1}
- b. 13.7 Ci g^{-1}

3. Power Density (bulk power density)

$6.8 - 7.3 \text{ W cm}^{-3}$ (dependent upon sample size and temperature)

4. Radiation

2

<u>Type</u>	<u>Energy (MeV)</u>	<u>Emission</u> (particles $\text{W}^{-1} \text{ sec}^{-1}$)
		<u>(calc.)</u>
a. Alpha 1	5.491	7.95×10^{11}
2	5.448	3.20×10^{11}
3	5.352	1.5×10^9
4	5.200	5×10^7
5	5.000	7×10^4
6	4.700	1.3×10^6
b. Beta	None	
c. Gamma 1	0.767	$\sim 5 \times 10^5$
2	0.203	4.4×10^4
3	0.1531	1.0×10^7
4	0.0998	9×10^7
5	0.0435	4.2×10^8
6	0.017 (x-ray)	1.5×10^{11}

d. Bremsstrahlung Negligible

e. Neutrons (spontaneous fission) $2.5 \times 10^3 \text{ n sec}^{-1} \text{ g}^{-1} \text{ }^{238}\text{Pu}$

5. Critical Mass

A neutron production cross section experiment with ^{238}Pu in a fast spectrum revealed that ^{238}Pu metal has a critical mass of the same order of magnitude as ^{239}Pu metal. Calculations indicate that this mass is probably in the order of 7.8 kg.

3

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium..

4

6. Compatibility with Materials of Containment

Table 1 shows the results of experiments conducted at Mound Laboratory in which samples of ^{238}Pu metal were encapsulated in various test containers. The test containers were encapsulated in Hastelloy X secondary containers and heated in a muffle furnace at various temperatures.

Table 1

COMPATIBILITY TESTS WITH ^{238}Pu METAL

<u>Liner</u>	<u>Temperature (°C)</u>	<u>Time (days)</u>	<u>Results</u>
Molybdenum	550	32	Intergranular attack 0.008 in.
Re-50 wt % Mo	550	46	Intergranular attack
Rhenium	550	115	No attack
Tantalum	550	252	Intergranular attack 0.007 in.
Ta-10 wt % W	550	121	No attack
Molybdenum	600	267	Complete intergranular attack
Re-50 wt % Mo	600	378	Complete intergranular attack
Rhenium	600	365	Intergranular attack 0.013 in.
W-25 wt % Re	600	345	Complete penetration
Tantalum	600	268	Complete penetration at weld
Ta-10 wt % W	600	370	Complete intergranular attack

7. Thermophysical Properties

a. Density of bulk ^{238}Pu

15 to 16 g cm⁻³ (dependent upon sample size and temperature)

Density of ^{239}Pu (g cm ⁻³)	Metallic Phase		
	Alpha 19.8	Beta 17.8	Gamma 17.1
b. Linear Thermal Expansion of ^{239}Pu (cm cm ⁻¹ °C ⁻¹)	67x10 ⁻⁶	41x10 ⁻⁶	35x10 ⁻⁶
Volume Change at Trans- formation of ^{239}Pu (%)	8.30 to 8.95 (α→β)	2.30 to 2.45 (β→γ)	4.4 to 7.8 (γ→δ)
c. Specific Heat of ^{239}Pu (cal g-atom ⁻¹ °C ⁻¹)	8.0 to 8.8	8.2 to 8.5	8.6 to 8.9
d. Temperature of Phase Change of ^{238}Pu Produc- tion Grade Metal (°C)	129±19 (α→β)	236±16* 279± 9 (β→γ)	329±6* 347±5 (γ→δ)
e. Latent Heat of Phase Change of ^{239}Pu (cal g-atom ⁻¹)	803±10 (α→β)	152±15 (β→γ)	125±5 (γ→δ)
f. Vapor Pressure of ^{239}Pu (atm)	1.20x10 ^{-5.5} at 25°C	3.9x10 ^{-4.0} at 127°C	3.7x10 ^{-3.1} at 227°C

*Two distinct temperatures have been observed for these transformations.

This is most probably due to impurities. The specific impurities causing this have not been identified.

REFERENCES

Metallic Phase				
Delta 15.9	Delta-Prime 16.0	Epsilon 16.5	Liquid 16.6 to 16.4 (664-788°C)	
-8.6x10 ⁻⁶	-596x10 ⁻⁶	15x10 ⁻⁶	93.x10 ⁻⁶ (cm ³ cm ⁻³ °C ⁻¹)	5, 6, 7, 8, 9 9, 10
-0.45 to -0.96 (δ→δ')	-1.72 to -3.71 heating (δ'→ε) 1.72 to 1.81 cooling (ε→δ')	-2.4 (ε→Liq.)		9, 11
9.0	8.5	8.4 (490-600°C)	10.2 (675-1000°C)	12, 13, 14
436±11 (δ→δ')	479±10 (δ'→ε)	575-615† (ε→Liq.)		
20±10 (δ→δ')	444±10 (δ'→ε)	693±10 (ε→Liq.)		12
3.6x10 ⁻²⁵ at 327°C	--	5.6x10 ⁻¹⁵ at 640°C	**	15, 16

**Log P (atm) = 4.913 - 17420 (1/T) for liquid ²³⁹Pu from 1100 to 1800°K.

REFERENCES

- g. Thermal Conductivity of ^{239}Pu
(see Table 2)

- h. Thermal Diffusivity of ^{239}Pu
(see Table 2)

- i. Viscosity of Liquid ^{239}Pu 17

 $\text{Log}_{10} \eta = 0.672 (1/T) + 0.037,$

 where η is the viscosity in centipoise and
 T is the temperature $\times 10^{-3}$, in $^{\circ}\text{K}$,
 over the range 918 to 1223°K

- j. Surface Tension of Liquid ^{239}Pu (high purity) 18

 $550 \text{ dynes cm}^{-1}$ at 640°C

- k. Total Hemispherical Emittance of ^{239}Pu 19

 $0.37 \pm 1.5\%$ at 88.7°C

- l. Spectral Emissivity

 Not available

Table 2

CALCULATED THERMAL CONDUCTIVITY OF ^{239}Pu
 BASED UPON MEASURED THERMAL DIFFUSIVITY

Temp. (°C)	Heat Capacity (cal g ⁻¹ °C ⁻¹)	Density (g cm ⁻³)	Thermal Diffusivity (cm ² sec ⁻¹)	Thermal Conductivity (cal °C ⁻¹ sec ⁻¹ cm ⁻¹)
375	0.03665	15.80	0.0252	0.0146
400	0.03665	15.80	0.0254	0.0147
425	0.03665	15.80	0.0280	0.0162
450	0.03665	15.80	0.0281	0.0163
475	0.03556	16.00	0.0281	0.0158
525	0.03372	16.30	0.0281	0.0152
550	0.03372	16.30	0.0281	0.0154
575	0.03372	16.30	0.0281	0.0154
600	0.03372	16.30	0.0280	0.0154
625	0.03372	16.30	0.0257	0.0141
675	0.04226	16.60	0.0237	0.0166
700	0.04226	16.57	0.0236	0.0165
725	0.04226	16.53	0.0219	0.0153
750	0.04226	16.49	0.0211	0.0147
775	0.04226	16.45	0.0197	0.0137
800	0.04226	16.41	0.0196	0.0136
825	0.04226	16.38	0.0181	0.0125
850	0.04226	16.34	0.0177	0.0122
875	0.04226	16.30	0.0175	0.0121
900	0.04226	16.26	0.0169	0.0116
925	0.04226	16.22	0.0159	0.0109
950	0.04226	16.19	0.0166	0.0114
975	0.04226	16.15	0.0170	0.0116
1000	0.04226	16.11	0.0174	0.0118

REFERENCES

m. Crystallography of ^{239}Pu

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Crystal form	<u>Alpha</u> Monoclinic $P2_1/m$	<u>Beta</u> BC mono- clinic $I2/m$	<u>Gamma</u> FC ortho- rhombic $Fddd$	<u>Delta</u> FCC	<u>Delta Prime</u> BC tetra- gonal $I4/mmm^*$	<u>Epsilon</u> BCC $Im3m$
Lattice constants ($\text{\AA}$)	$a = 6.182$ $b = 4.826$ $c = 10.956$ $\beta = 101.74^\circ$	$a = 9.284$ $b = 10.463$ $c = 7.859$ $\beta = 92.13^\circ$	$a = 3.159$ $b = 5.768$ $c = 10.162$	4.6371	$a = 3.327$ $c = 4.482$	3.6361
Metallic radius ($\text{\AA}$)	1.58 (25°C)	1.60 (93°C)	1.601 (235°C)	1.640 (320°C)	1.638 (465°C)	1.622 (490°C)
Metallic radius at room temperature ($\text{\AA}$)	1.58	1.59	1.589	1.644	1.644	1.594

*21

22

n. Solubilities
(see Table 3)

o. Diffusion Rates

^{239}Pu through Al	at 843°K	$D = 2.1 \times 10^{-9} \text{ cm}^2 \text{ sec}^{-1}$	23
	at 873°K	$D = 6.4 \times 10^{-9} \text{ cm}^2 \text{ sec}^{-1}$	23
Self-diffusion of ^{239}Pu	$D = 4.5 \times 10^{-3} \text{ exp } (-23,800/RT)$	$\text{cm}^2 \text{ sec}^{-1}$	from 623° to 713°K
	$D = 2.1 \times 10^{-5} \text{ exp } (-16,700/RT)$	$\text{cm}^2 \text{ sec}^{-1}$	from 488° to 583°K
	$D = 2.2 \times 10^{-2} \text{ exp } (-18,500/RT)$	$\text{cm}^2 \text{ sec}^{-1}$	from 773° to 885°K
	$D = 2.4 \times 10^{-4} \text{ exp } (-5,157/RT)$	$\text{cm}^2 \text{ sec}^{-1}$	from 918° to 1223°K

24

25

26

27

Table 3

SOLUBILITIES
(Reaction of ^{238}Pu Metal with Various Solvents)

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Solvents	Reaction
Acetic Acid	Unattacked by glacial acid, even when hot; slowly attacked by dilute acid
Hydrobromic Acid	Rapid dissolution by concentrated or dilute acid
Hydrochloric Acid	Rapid dissolution by concentrated or dilute acid
Hydrofluoric Acid	Slowly attacked; briquets made by pressing ^{238}Pu metal turnings will often dissolve rapidly and completely, forming insoluble PuF_4
Nitric Acid	No attack at any concentration; in the presence of 0.005 <u>M</u> HF, boiling concentrated acid will dissolve plutonium
Perchloric Acid (72%)	Rapid dissolution
Phosphoric Acid (85%)	Rapid dissolution
Sulfuric Acid	Concentrated acid caused initially slow reaction to cease; dilute acid attacked metal slowly
Trichloroacetic Acid	Rapid dissolution by concentrated acid; reacted slowly in dilute acid
Water	Reacted slowly at room temperature; slight increase in reaction rate with increase of temperature

8. Mechanical Properties

	²³⁹ Pu Phase				
	Alpha	Beta	Gamma	Delta	
a. Hardness, Vickers	261 at 25°C 171 at 115°C See other reference	58 at 125°C 42 at 175°C	26 at 215°C 6.3 at 310°C	6 at 330°C 0.9 at 440°C	29 30
b. Short Term Mechanical Strength					
Ultimate strength (lb in. ⁻²)	50,900 at 30°C 33,100 at 110°C	12,100 at 130°C 2,940 at 200°C	4,420 at 230°C 2,020 at 300°C	895 at 325°C --	31
Tensile strength	See Figures 1 and 2				29
Yield strength (lb in. ⁻²)	32,100 at 30°C 12,300 at 110°C	10,400 at 130°C 2,210 at 200°C	3,860 at 230°C 1,650 at 300°C	790 at 325°C --	31
Ultimate compressive strength (lb in. ⁻²)	140,100 to 178,000 at 29°C 63,500 to 85,000 at 110°C	-- --	-- --	-- --	31
c. Long Term Mechanical Strength					
Creep elongation of ²³⁹ Pu(see Figure 3)					31
Elastic moduli of ²³⁹ Pu(see Table 4)					32
Temperature and pressure coefficients for some elastic properties of ²³⁹ Pu(see Table 5)					33

FIGURE 1 - Tensile curves of ^{239}Pu after direct heating (insert shows tests on gamma and delta phases).

FIGURE 2 - Tensile curves of ^{239}Pu after beta phase annealing at 175°C.

FIGURE 3 - Creep of ^{239}Pu metal at 10,000 psi stress.

Table 4

ELASTIC CONSTANTS OF ^{239}Pu AT VARIOUS TEMPERATURES

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

Table 5

ELASTIC PROPERTIES AND SOUND VELOCITIES OF ALPHA ^{239}Pu at 30°C

Property	Value ^a	Pressure Coefficient ^b ($\times 10^{-6} \text{ bar}^{-1}$)	Temperature Coefficient ^c ($\times 10^{-5} \text{ }^\circ\text{C}^{-1}$)
Young's modulus	$(9.93 \pm 0.03) \times 10^{11} \text{ dynes cm}^{-2}$ $(14.40 \pm 0.04) \times 10^6 \text{ lb in.}^{-2}$	$+18 \pm 1$	-127 ± 8
Shear modulus	$(4.34 \pm 0.01) \times 10^{11} \text{ dynes cm}^{-2}$ $(6.29 \pm 0.01) \times 10^6 \text{ lb in.}^{-2}$	$+14 \pm 1$	-145 ± 10
Poisson's ratio	0.15 ± 0.01	$+27 \pm 7$	$+138 \pm 71$
Compressibility	$(2.14 \pm 0.02) \times 10^{-6} \text{ bar}^{-1}$	-28.5 ± 3	$+68 \pm 32$
Rod velocity (v_0)	$(2.244 \pm 0.004) \times 10^5 \text{ cm sec}^{-1}$	$+7.8 \pm 0.6$	-56 ± 4
Shear velocity (v_T)	$(1.483 \pm 0.002) \times 10^5 \text{ cm sec}^{-1}$	$+6.1 \pm 0.7$	-65 ± 5
Infinite medium velocity (v_L)	$(2.301 \pm 0.003) \times 10^5 \text{ cm sec}^{-1}$	$+9.2 \pm 0.4$	-48 ± 6

^aMeasurements by pulse technique on sample having $\rho = 19.722 \pm 0.005 \text{ g cm}^{-3}$ at 30°C

^bMeasurements by pulse technique on sample having $\rho = 19.62 \text{ g cm}^{-3}$ at 30°C

^cMeasurements by resonance technique on two different samples ($\rho = 19.5 \text{ g cm}^{-3}$ and 19.6 g cm^{-3})

9. Chemical Properties

a. Heat and Free Energy of Formation, Entropy

Thermodynamic properties of ^{239}Pu (see Table 6) 34

Selected thermodynamic properties for $^{239}\text{Pu(g)}$ (see Table 7) 34

Entropy of transformation for ^{239}Pu (calculated from referenced data) 12

<u>Transformation</u>	<u>S_{T}° (cal g-atom⁻¹ °C⁻¹)</u>	<u>Transformation</u>	<u>S_{T}° (cal g-atom⁻¹ °C⁻¹)</u>
$\alpha \rightarrow \beta$	2.05	$\delta \rightarrow \delta'$	0.03
$\beta \rightarrow \gamma$	0.32	$\delta' \rightarrow \epsilon$	0.59
$\gamma \rightarrow \delta$	0.21	$\epsilon \rightarrow \text{Liq.}$	0.76

b. Chemical Reactions and Reaction Rates of ^{239}Pu

Oxygen: Plutonium reacts slowly with O_2 in dry air to form PuO_2 . The oxidation is accelerated by presence of moisture in air. In pure oxygen, plutonium forms PuO_2 according to the rate equation $W = K_{\text{a}} t^m$, where W is the weight gain per unit area, K is a rate constant, and m is a constant representing time dependence. At 345°C $K = 320$ and $m = 2.2$; at 400°C , $K = 480$ and $m = 1.4$. More recent data indicate that, in general, plutonium corrodes by two or more linear rates (reaction controlled) below 220°C , and an initial parabolic rate (diffusion controlled), followed by a linear rate, above 220°C . A linear rate generally continues until breakaway occurs. See Figure 4. 35 36

Nitrogen: Plutonium does not react with N_2 except above 1000°C , then a surface nitride forms. 35

Water and steam: Plutonium reacts with water and steam to form the oxide or hydroxide. 35

Hydrogen: Plutonium reacts with hydrogen to form PuH_2 and PuH_3 . 37

Solubility of materials in liquid plutonium (see Table 8). 38

Table 6

SELECTED THERMODYNAMIC FUNCTIONS FOR CONDENSED ^{239}Pu

Temp (°K)	cal g-atom ⁻¹ deg ⁻¹			kcal g-atom ⁻¹ (H _T ^o - H ₂₉₈ ^o)
	(C _p ^o)	(S _T ^o)	$[-(G_T^o - H_{298}^o)/T]$	
α Crystal Phase				
298	7.670	13.180	13.180	0.000
300	7.680	13.227	13.180	0.014
392	8.670	15.402	13.448	0.766
β Phase				
392	8.150	17.450	13.448	1.569
400	8.170	17.600	13.532	1.627
477	8.550	19.069	14.308	2.271
γ Phase				
477	8.540	19.388	14.308	2.423
500	8.580	19.788	14.553	2.618
584	9.090	21.156	15.403	3.360
δ Phase				
584	9.000	21.370	15.403	3.485
600	9.000	21.609	15.567	3.625
700	9.000	22.996	16.532	4.525
731	9.000	23.386	16.814	4.804
δ' Phase				
731	11.200	23.413	16.814	4.824
753	11.200	23.744	17.011	5.070
ε Phase				
753	8.400	24.334	17.011	5.514
800	8.400	24.844	17.457	5.909
900	8.400	25.833	18.334	6.749
911	8.400	25.935	18.426	6.841
Liquid				
911	8.500	26.696	18.426	7.534
1000	8.500	27.488	19.197	8.291
1100	8.500	28.298	19.988	9.141
1200	8.500	29.038	20.712	9.991
1300	8.500	29.718	21.379	10.841
1400	8.500	30.348	21.998	11.691
1500	8.500	30.935	22.574	12.541

Table 6
(Continued)

Temp (°K)	cal g-atom ⁻¹ deg ⁻¹			kcal g-atom ⁻¹ (H _T ^o - H ₂₉₈ ^o)
	(C _T ^o)	(S _T ^o)	$[-(G_T^o - H_{298}^o)/T]$	
1600	8.500	31.483	23.114	13.391
1700	8.500	31.998	23.622	14.241
1800	8.500	32.484	24.101	15.091
1900	8.500	32.944	24.554	15.941
2000	8.500	33.380	24.984	16.791
2100	8.500	33.795	25.394	17.641
2200	8.500	34.190	25.785	18.491
2300	8.500	34.568	26.159	19.341
2400	8.500	34.930	26.517	20.191
2500	8.500	35.277	26.860	21.041
2600	8.500	35.610	27.190	21.891
2700	8.500	35.931	27.508	22.741
2800	8.500	36.240	27.815	23.591
2900	8.500	36.538	28.110	24.441
3000	8.500	36.826	28.396	25.291

Table 7

THERMODYNAMIC FUNCTIONS FOR ^{239}Pu IDEAL GAS

Temp (°K)	cal g-atom ⁻¹ deg ⁻¹			kcal g-atom ⁻¹		
	(C _p ^o)	(S _f ^o)	$[-(G_f^o - H_{298}^o)/T]$	(H _f ^o - H ₂₉₈ ^o)	(ΔH _f ^o)	(ΔG _f ^o)
298	4.984	42.316	42.316	0.000	82.800	74.113
300	4.985	42.347	42.317	0.009	82.795	74.059
400	5.103	43.794	42.513	0.512	81.685	71.208
500	5.392	44.961	42.889	1.036	81.218	68.631
600	5.822	45.980	43.321	1.596	80.771	66.148
700	6.318	46.914	43.768	2.202	80.477	63.735
800	6.817	47.791	44.217	2.859	79.750	61.393
900	7.281	48.621	44.661	3.564	79.615	59.106
1000	7.697	49.410	45.096	4.314	78.823	56.901
1100	8.061	50.161	45.523	5.102	78.761	54.712
1200	8.378	50.877	45.939	5.924	78.733	52.527
1300	8.652	51.558	46.346	6.776	78.735	50.343
1400	8.888	52.208	46.741	7.654	78.763	48.159
1500	9.090	52.829	47.127	8.553	78.812	45.971
1600	9.259	53.421	47.502	9.470	78.879	43.779
1700	9.396	53.986	47.867	10.403	78.962	41.583
1800	9.503	54.527	48.222	11.349	79.058	39.380
1900	9.581	55.043	48.567	12.303	79.162	37.174
2000	9.631	55.535	48.903	13.264	79.273	34.963
2100	9.654	56.006	49.231	14.228	79.387	32.744
2200	9.655	56.455	49.549	15.194	79.503	30.520
2300	9.634	56.884	49.858	16.159	79.618	28.291
2400	9.595	57.293	50.160	17.120	79.729	26.058
2500	9.542	57.684	50.453	18.077	79.836	23.819
2600	9.477	58.057	50.738	19.028	79.937	21.575
2700	9.403	58.413	51.016	19.972	80.031	19.330
2800	9.322	58.754	51.286	20.909	80.118	17.078
2900	9.237	59.079	51.550	21.837	80.196	14.827
3000	9.150	59.391	51.806	22.756	80.265	12.570

Table 8

SOLUBILITIES OF C, Ta, W, and Re IN LIQUID ^{239}Pu

Temperature (°C)	Solubility, mole fraction x 10 ³			
	Carbon	Tantalum	Tungsten	Rhenium
700	13.6 ± 0.3	---	0.038 ± 0.001	15.7 ± 0.4
750	16.1 ± 0.6	0.85 ± 0.02	0.072 ± 0.003	18.9 ± 0.8
800	22.6 ± 1.4	1.19 ± 0.02	0.105 ± 0.002	23.5 ± 2.2
850	26.7 ± 0.8	1.90 ± 0.08	0.159 ± 0.005	27.5 ± 0.5
900	35.7 ± 1.3	2.67 ± 0.10	0.255 ± 0.011	32.7 ± 0.6
950	44.7 ± 2.7	3.52 ± 0.13	0.379 ± 0.002	40.5 ± 2.6

FIGURE 4 - The linear oxidation rates of unalloyed ^{239}Pu metal in air and oxygen (moisture content of air, 10^4 ppm, and of oxygen, 40-1000 ppm).

REFERENCES

10. Biological Tolerances

(see Table 9)

39, 40

11. Shielding Data

a. Attenuation Factors for Gamma Shielding Materials

<u>Material</u>	<u>Density (g cm⁻³)</u>	<u>Thickness Required to Reduce Intensity of 800 keV Gamma Rays to 1% of Incident Value (cm)</u>	<u>Attenuating Layer (g cm⁻²)</u>
Concrete	2.35	24.4	57.34
Iron	7.87	8.8	69.26
Hastelloy C	8.94	7.8	69.73
Haynes alloy No. 25	9.13	7.7	70.30
Lead	11.36	4.7	53.39
Tantalum	16.6	3.6	59.76
Uranium	19.07	2.5	47.68
Tungsten	19.3	3.0	57.90

Table 9
RADIOBIOLOGICAL TOLERANCES OF ^{238}Pu

Radionuclide and Type of Decay	Location of Reference	Permissible Burden in Total Body q(μCi)	Radiation Protection Guides				
			For a 40-hr week		For 168-hr week ^c		
			(RPG) _{water} μCi cm ⁻³	(RPG) _{air} μCi cm ⁻³	(RPG) _{water} μCi cm ⁻³	(RPG) _{air} μCi cm ⁻³	
²³⁸ Pu(α, γ)	(Sol.) {	Bone	0.04	10 ⁻⁴	2x10 ⁻¹²	5x10 ⁻⁵	7x10 ⁻¹³
		Liver	0.2	6x10 ⁻⁴	8x10 ⁻¹²	2x10 ⁻⁴	3x10 ⁻¹²
		Kidney	0.3	8x10 ⁻⁴	10 ⁻¹¹	3x10 ⁻⁴	4x10 ⁻¹²
		GI(LLI) ^a	---	8x10 ⁻⁴	2x10 ⁻⁷	3x10 ⁻⁴	6x10 ⁻⁸
		Total Body	0.3	10 ⁻³	10 ⁻¹¹	4x10 ⁻⁴	5x10 ⁻¹²
	(Insol.) {	Lung ^b		--	3x10 ⁻¹¹	--	10 ⁻¹¹
		GI(LLI)	---	8x10 ⁻⁴	10 ⁻⁷	3x10 ⁻⁴	5x10 ⁻⁸

^aThe abbreviations GI and LLI refer to gastrointestinal tract and lower large intestine, respectively.

^bCurrently accepted lung burden is $0.016 \mu\text{Ci}$. This value was calculated by the standard formula as given by ICRP Committee II on Permissible Dose for Standard Radiation (1959).

^cUse 1/10 of these values for off-site environmental levels

b. Attenuation Factors for Neutron Shielding Materials

REFERENCES

Thickness (cm) required to reduce intensity of neutrons of indicated energies to one-half of incident value

<u>Material</u>	<u>1 MeV</u>	<u>2 MeV</u>	<u>4 MeV</u>
Polyethylene	2.7	3.9	5.0
Paraffin	3.2	4.6	6.0
Water	3.2	4.6	6.0
Lucite	4.2	6.0	7.8
Chemtree-13	4.9	6.6	8.2
Concrete	5.8	8.3	10.8
Masonite	6.7	9.7	12.6
LiH	3.6	5.2	6.8
Benelex-70	2.7	3.9	5.0

c. Unshielded Dose Rate Data

(see Tables 10 and 21)

12. Electrical Properties of ^{239}Pu

a. Electrical Resistivity (see Table 11)

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	<u>Alpha</u>	<u>Beta</u>	<u>Gamma</u>	<u>Delta</u>	<u>Delta-Prime</u>	<u>Epsilon</u>
b. Thermoelectric Power ($\mu\text{V}^\circ\text{C}^{-1}$)	15	10	9.2	3.7	2.3	4.4

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Table 10

GAMMA AND NEUTRON RADIATION DOSE RATES FROM ^{238}Pu
METAL HEAT SOURCES AS A FUNCTION OF DISTANCE*

Thermal Content (W)	Gamma radiation dose rate in mrem hr ⁻¹ at a distance (measured from center of source to active surface of detection chamber) of:			Neutron dose rate in mrem hr ⁻¹ at a distance (measured from center of source to active center of detector) of:		
	<u>10 cm</u>	<u>15 cm</u>	<u>20 cm</u>	<u>10 cm</u>	<u>15 cm</u>	<u>20 cm</u>
1.5605	1.2	0.61	0.30	1.1	0.44	0.25
1.5901	1.2	0.58	0.31	1.0	0.43	0.25
1.5735	1.2	0.53	0.27	1.2	0.50	0.28
1.5684	1.1	0.53	0.28	1.1	0.46	0.27
1.6002	1.3	0.61	0.32	1.7	0.76	0.44
1.6174	1.2	0.51	0.29	1.3	0.56	0.32

*Plutonium metal encapsulated in a 0.02 in. tantalum
inner liner and a 0.040 in. Haynes alloy No. 25
outer capsule.

Table 11
RESISTIVITY VALUES OF ^{239}Pu SPECIMENS

Temperature (°K)	Resistivity ($\mu\Omega\text{-cm}$)	
	Specimen 1	Specimen 2
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

B. PLUTONIUM DIOXIDE MICROSPHERES*

REFERENCES

1. Typical Composition, PuO₂

- a. Oxygen 11.8 wt %
- b. Plutonium 88.2 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
²³⁶ Pu	~0.00012
²³⁸ Pu	80.2
²³⁹ Pu	15.9
²⁴⁰ Pu	3.022
²⁴¹ Pu	0.643
²⁴² Pu	0.132

- c.

<u>Actinide Impurities</u>	<u>Concentration (wt %)</u>
²⁴¹ Am	0.0033
²³⁷ Np	0.130
²³⁴ U	0.140, increases at the rate of decay of ²³⁸ Pu.

The total of other isotopic impurities including ²³¹Pa, ²³²Th, ²³³U, ²³⁵U, ²³⁶U, and ²²⁷Ac does not exceed 1 wt % of the fuel.

- d.

<u>Cation Impurities</u>	<u>Concentration (wt %)</u>
Aluminum	0.10
Calcium	0.04
Chromium	0.03
Copper	0.03
Iron	0.40
Magnesium	0.02
Nickel	0.07
Silicon	0.04

2. Specific Power (based on 80% ²³⁸Pu in the element plutonium)

- a. 0.40 W g⁻¹
- b. 12.1 Ci g⁻¹

3. Power Density (bulk power density)

2.5-2.8 W cm⁻³ (nominal)

* Spherical particles having nominal diameter between 50-250 μm.

4. Radiation

a -d. (see Section A.4.a -d)

e. Neutrons Higher neutron flux than spontaneous fission due to (α, n) reaction with ^{17}O and ^{18}O , $\sim 2 \times 10^4 \text{ n sec}^{-1} \text{ g}^{-1} \text{ }^{238}\text{Pu}$ (see Figure 5 and Table 12)

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5. Critical Mass

The critical mass of $^{238}\text{PuO}_2$ microspheres is expected to be larger than ^{238}Pu metal due to the smaller density and due to the neutron moderation effect caused by the oxygen atoms.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium.

4

6. Compatibility with Materials of Containment

Free energy change values for reactions between PuO_2 and metals should aid in selection of potential encapsulation material. Table 13 shows the possible reactions between PuO_2 and various possible container materials and the free energy change for each.

FIGURE 5 - Neutron energy spectrum for PuO_2 microspheres

Table 12

NEUTRON EMISSION RATE FROM ^{238}Pu CONTAINING
VARYING QUANTITIES OF ^{18}O

<u>Weight of ^{238}Pu (g)</u>	<u>Metal Emission Rate (n sec⁻¹g⁻¹ ^{238}Pu)</u>	^{18}O <u>Content (%)</u>	<u>Oxide Emission Rate (n sec⁻¹g⁻¹ ^{238}Pu)</u>	
			<u>Measured</u>	<u>Computed</u>
2.36	9.8×10^3	0.20	1.5×10^4	1.8×10^4
1.69	9.5×10^3	0.003	8.6×10^3	-
2.10	4.3×10^3	0.103	1.3×10^4	1.1×10^4
2.04	3.6×10^3	0.027	4.2×10^3	5.4×10^3
1.79	3.6×10^3	0.003	3.7×10^3	3.7×10^3
1.43	4.6×10^3	0.101	1.2×10^4	1.1×10^4
1.68	4.6×10^3	0.202	1.5×10^4	1.8×10^4

Table 13

STANDARD FREE ENERGY CHANGE FOR PuO_2 - METAL
REACTIONS BETWEEN 1273° and 2273°K

Metal	Reaction	Free Energy Change at		
		1273°K	1773°K	2273°K
Ta	$2 \text{ Ta} + 10 \text{ PuO}_2 \rightarrow \text{Ta}_2\text{O}_5 + 5\text{Pu}_2\text{O}_3$	+ 36	+ 27	- 7
W	$\text{W} + 4 \text{ PuO}_2 \rightarrow \text{WO}_2 + 2\text{Pu}_2\text{O}_3$	+ 69	+ 60	+ 36
Mo	$\text{Mo} + 4 \text{ PuO}_2 \rightarrow \text{MoO}_2 + 2\text{Pu}_2\text{O}_3$	+ 77	+ 72	+ 55
Nb	$\text{Nb} + 2 \text{ PuO}_2 \rightarrow \text{NbO} + \text{Pu}_2\text{O}_3$	+ 6	+ 2	- 7
Ti	$3 \text{ Ti} + 10 \text{ PuO}_2 \rightarrow \text{Ti}_3\text{O}_5 + 5\text{Pu}_2\text{O}_3$	- 63	- 73	-105
Re	$\text{Re} + 4 \text{ PuO}_2 \rightarrow \text{ReO}_2 + 2\text{Pu}_2\text{O}_3$	+104	+ 98	+ 77
Ru	$\text{Ru} + 4 \text{ PuO}_2 \rightarrow \text{RuO}_2 + 2\text{Pu}_2\text{O}_3$	+157	-	-
Ir	$\text{Ir} + 4 \text{ PuO}_2 \rightarrow \text{IrO}_2 + 2\text{Pu}_2\text{O}_3$	+162	+157	+134
Os	$\text{Os} + 8 \text{ PuO}_2 \rightarrow \text{OsO}_4 + 4\text{Pu}_2\text{O}_3$	+285	+259	+213
Hf	$\text{Hf} + 4 \text{ PuO}_2 \rightarrow \text{HfO}_2 + 2\text{Pu}_2\text{O}_3$	- 52	- 55	- 67
Zr	$\text{Zr} + 4 \text{ PuO}_2 \rightarrow \text{ZrO}_2 + 2\text{Pu}_2\text{O}_3$	- 48	- 50	- 61

7. Thermophysical Properties

a. Density of Individual Microspheres

Theoretical 11.46 g cm^{-3} 44
 Production grade $9.8 - 10.4 \text{ g cm}^{-3}$

b. Linear Thermal Expansion Coefficient for $^{239}\text{PuO}_2$ 45

Temperature ($^{\circ}\text{C}$)	Expansion Coefficient ($\text{cm cm}^{-1} \text{ } ^{\circ}\text{C}^{-1}$)
100	8.06×10^{-6}
200	9.42×10^{-6}
300	9.87×10^{-6}
400	10.20×10^{-6}
500	10.97×10^{-6}
600	11.48×10^{-6}
700	12.54×10^{-6}
800	12.70×10^{-6}
900	12.70×10^{-6}
1000	14.40×10^{-6}

c. Bulk Density

$\sim 6.9 \text{ g cm}^{-3}$ (varies directly with particle density
 and inversely with void volume between particles)

d. Heat Capacity

Temperature ($^{\circ}\text{K}$)	Smoothed Data ($\text{cal g}^{-1} \text{ } ^{\circ}\text{K}^{-1}$)	46
300	0.0608*	
400	0.0698	
500	0.0750	
600	0.0780	
700	0.0797	
800	0.0806	
900	0.0808	
1000	0.0810	
1100	0.0817	

(see also calculated values in Table 14) 34

* Extrapolated value

Table 14

SELECTED THERMODYNAMIC FUNCTIONS FOR $^{239}\text{PuO}_2$ (MOL WT 271.058) CRYSTAL

Temp. (°K)	cal mole ⁻¹ deg ⁻¹			kcal mole ⁻¹		
	(C _p ^o)	(S _T ^o)	$\frac{-(G_T^o - H_{298}^o)/T}{H_{298}^o}$	(H _T ^o - H ₂₉₈ ^o)	-(ΔH _f ^o)	-(ΔG _f ^o)
298	16.400	19.700	19.700	0.000	252.870	240.203
300	16.500	19.802	19.700	0.030	252.867	240.125
400	18.250	24.807	20.371	1.774	253.447	235.893
500	19.230	28.990	21.688	3.651	253.292	231.532
600	19.910	32.558	23.210	5.609	253.096	227.207
700	20.450	35.669	24.772	7.628	252.755	222.918
800	20.880	38.428	26.310	9.695	252.870	218.649
900	21.280	40.911	27.797	11.803	252.416	214.398
1000	21.650	43.172	29.223	13.950	252.638	210.130
1100	22.000	45.253	30.587	16.133	252.144	205.905
1200	22.280	47.179	31.890	18.347	251.628	201.723
1300	22.550	48.974	33.136	20.589	251.093	197.587
1400	22.760	50.652	34.328	22.854	250.542	193.490
1500	22.970	52.230	35.469	25.141	249.976	189.434
1600	23.150	53.718	36.564	27.447	249.397	185.418
1700	23.320	55.127	37.615	29.771	248.805	181.438
1800	23.470	56.464	38.625	32.110	248.205	177.492
1900	23.610	57.737	39.598	34.465	247.595	173.579
2000	23.730	58.951	40.535	36.832	246.978	169.700
2100	23.850	60.112	41.440	39.211	246.354	165.851
2200	23.940	61.223	42.314	41.600	245.727	162.032
2300	24.040	62.290	43.160	43.999	245.094	158.243
2400	24.130	63.315	43.978	46.408	244.457	154.479
2500	24.220	64.302	44.772	48.825	243.818	150.745
2675	24.380	65.945	46.105	53.078	242.688	144.270

e. Enthalpy	REFERENCES
(see Table 14)	34
f. Temperature of Phase Transformation	
Melting with partial decomposition at $2232 \pm 80^\circ\text{C}$ under one atmosphere of helium.	
g. Latent Heats of Phase Transformation	
$\Delta H_{f,u}$ for $^{239}\text{PuO}_2 = 16.8 \pm 1.3 \text{ kcal mole}^{-1}$ (calculated)	47
$\Delta H_{f,b}$ for $^{239}\text{PuO}_2 = 130.2 \pm 2.3 \text{ kcal mole}^{-1}$	48
h. Vapor Pressure for $^{239}\text{PuO}_2$	49
$\log P = 7.381 - \frac{28,890}{T}$	
where $T = 2,200$ to $1,900^\circ\text{K}$ and P is total pressure in atmospheres. (see also Figures 6 and 7.)	
i. Thermal Conductivity for Pressed and Sintered $^{239}\text{PuO}_2$	50
(see Table 15)	
j. Thermal Diffusivity for Pressed and Sintered $^{239}\text{PuO}_2$	50
(see Table 15)	
k. Viscosity of $^{239}\text{PuO}_2$	
32 centipoise ($\pm 25\%$) at melting point (calculated)	
l. Surface Tension of $^{239}\text{PuO}_2$	
525 dynes cm^{-1} ($\pm 15\%$) at melting point	
m. Total Hemispherical Emittance	
Not available	
n. Spectral Emissivity	
Not Available	
o. Crystallography $^{239}\text{PuO}_2$	
FCC structure	
Space group $\text{Fm}\bar{3}\text{m}$	
$a = 5.400 \pm 0.003 \text{ \AA}$	
Ionic radius $0.93 \text{ \AA}$	44

FIGURE 6 - Temperature dependence of the partial pressures of $PuO_2(g)$ and $PuO(g)$. (The temperature dependence of total pressure is represented by the P_t curve.)

FIGURE 7 - Temperature dependence of the vapor pressure of PuO₂ from several studies.

Table 15

EXPERIMENTAL THERMAL DIFFUSIVITY DATA AND CALCULATED
THERMAL CONDUCTIVITY DATA FOR PNEUMATICALLY
IMPACTED PuO_2
(Two samples)

Temp. (°C)	Thermal Diffusivity (α) ($\text{cm}^2 \text{ sec}^{-1}$)	Heat Capacity (Cp) ($\text{cal mole}^{-1} \text{ } ^\circ\text{K}^{-1}$)	Thermal Conductivity (K) ($\text{W cm}^{-1} \text{ } ^\circ\text{K}^{-1}$)
104	0.0237	17.85	0.0700
113	0.0272	18.00	0.0810
147	0.0238	18.45	0.0732
170	0.0211	18.67	0.0650
243	0.0176	19.34	0.0560
249	0.0204	19.38	0.0653
287	0.0174	19.63	0.0564
316	0.0178	19.83	0.0582
358	0.0160	20.08	0.0530
392	0.0166	20.26	0.0550
441	0.0156	20.53	0.0524
531	0.0137	20.90	0.0470
579	0.0128	21.09	0.0495
606	0.0128	21.20	0.0445
670	0.0117	21.34	0.0405
730	0.0112	21.65	0.0394
786	0.0104	21.86	0.0370
868	0.00946	22.12	0.0340
912	0.00897	22.24	0.0323
984	0.00857	22.43	0.0312
1046	0.00786	22.59	0.0288
1130	0.00744	22.76	0.0274
1165	0.00730	22.85	0.0268
1225	0.00695	22.97	0.0256
1258	0.00651	23.03	0.0242
1318	0.00624	23.13	0.0232
1375	0.00598	23.23	0.0214
1414	0.00569	23.30	0.0213
1516	0.00524	23.45	0.0196
1615	0.00496	23.59	0.0186
1633	0.00455	23.61	0.0171
1645	0.00441	23.63	0.0166
1655	0.00455	23.64	0.0171

p. Solubilities

Solubility in mineral acids is the same as that for PuO_2 powder except the microspheres dissolve more slowly.

RATE OF RELEASE OF Pu FROM $^{238}\text{PuO}_2$
MICROSPHERES IN DISTILLED WATER AND SEA WATER

<u>Number Microspheres</u>	<u>Total Surface Area (measured) (mm^2)</u>	<u>Type Water</u>	<u>Temperature</u>	<u>Sample Rate of Release^a ($\mu\text{g Pu day}^{-1}\text{mm}^{-2}$)</u>
446	35.81	Florida sea water	Ambient	1.02×10^{-3}
515	43.58	Florida sea water	Ambient	1.23×10^{-3}
628	54.69	Florida sea water	Ambient	1.00×10^{-3}
917	82.69	Distilled water	Ambient	1.52×10^{-3}
518	56.32	Distilled water	Ambient	1.27×10^{-3}
885	76.79	Distilled water	Ambient	1.49×10^{-3}

^aRate of release based upon 13 mo exposure.

q. Diffusion Rates

Not available

8. Mechanical Propertiesa. Microhardness of $^{238}\text{PuO}_2$ Microspheres

<u>Load (g)</u>	<u>Vickers No.</u>
15	1739
25	1590
50	1448
100	1114

REFERENCES

b. Crush Strength of $^{238}\text{PuO}_2$ Microspheres

Microsphere diameter (μm)	Nominal Crush Strength (g)
105	125
149	200
177	260
210	310

9. Chemical Properties

a. Heat of Formation

(see Table 14) 32

b. Free Energy of Formation

(see Table 14) 34

c. Absolute Entropy

(see Table 14) 34

d. Entropy of Formation

(see Table 14) 34

e. Chemical Reactions

(see Table 13)

10. Biological Tolerances

A single pig was fed a massive dose (~ 1 Ci) of $^{238}\text{PuO}_2$ 51
microspheres with no grossly evident damage to the gastro-
intestinal tract, and negligible deposition in the probable
most critical organs, bones, and liver. Though "one
experiment from one pig can scarcely be considered definitive
for man, . . . , the results from this one pig were so unequivocal
as to leave little doubt as to the negligible ingestion hazard
from this material Any conceivable hazard from ingestion
of this material would certainly be far outweighed by the
accompanying hazard of inhalation."

Plutonium-238 dioxide microspheres ($\sim 50\mu\text{m}$) dispersed in 52
air were inhaled by beagle dogs. The particles were de-
posited in the nasal pharynx region of the respiratory
tract and excreted in the feces over a period of a few days.
Apparently no particles were deposited in the lower respira-

REFERENCES

tory tract -- or if they were, clearance was rapid, and complete. In 30 dogs, 50, 120 and 300 μm particles of $^{238}\text{PuO}_2$ deposited in the lungs by intubation were cleared within 10 days. However, 9 dogs retained particles for several months, up to a year in two cases. No biological effects have been seen except for a possible lymphopenia in one which has retained a 300 μm particle for over a year.

Protracted feeding to several dogs of huge amounts (0.55 Ci) 53 of $^{238}\text{PuO}_2$ microspheres of 188 μm average diameter resulted in no gross change in the gastrointestinal tract. This experiment suggests that accidental ingestion by man of one or several microspheres containing $^{238}\text{PuO}_2$ presents no serious biological consequences. Any conceivable hazard arising from ingestion of $^{238}\text{PuO}_2$ microspheres would be insignificant relative to the potential hazard arising from inhalation.

(see also Table 19)

11. Shielding Data

(see Section A.11)

12. Electrical Properties

a. Electrical Resistivity of $^{239}\text{PuO}_2$ 54

800 ohm-cm at 1250°K

4×10^{10} ohm-cm at 298°K (by extrapolation) 55

(see Figure 8)

FIGURE 8 - Electrical resistivity of $^{239}\text{PuO}_2$ as a function of temperature for oxygen:plutonium ratios of 2.00, 1.96, 1.92, 1.84, and 1.72. Activation energies for electronic conduction ΔE are also given.

1

2

3

4

C. HIGH ASSAY PLUTONIUM DIOXIDE MICROSPHERES*

REFERENCES

1. Typical Composition

- a. Oxygen 11.8 wt %
- b. Plutonium 88.2 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
^{236}Pu	0.00006
^{238}Pu	91.600
^{239}Pu	7.380
^{240}Pu	0.837
^{241}Pu	0.156
^{242}Pu	0.018

- c. Actinide Impurities Concentration
(wt %)

^{237}Np	0.111
^{234}U	0.366, increases at rate of decay of ^{238}Pu
^{235}U	0.010

- d. Cation Impurities Concentration
(wt %)

Aluminum	0.03
Boron	0.08
Calcium	0.05
Copper	0.07
Iron	0.05
Magnesium	0.01
Nickel	0.07
Silicon	0.03
Zinc	0.07

2. Specific Power (based on 91.6% ^{238}Pu in the element plutonium)

- a. 0.46 W g⁻¹
- b. 13.9 Ci g⁻¹

3. Power Density (bulk power density)

3.0 W cm⁻³(nominal)

4. Radiation

a-d. (see Section A.4.a-d)

* High assay plutonium contains approximately 90 wt % ^{238}Pu .

e. Neutrons

Measured specific yield approximately same as
80% ^{238}Pu in plutonium. $2.0 \times 10^4 \text{ n sec}^{-1} \text{g}^{-1} \text{ }^{238}\text{Pu}$

5. Critical Mass

As yet undetermined but expected to be as given in
Section B.5

6. Compatibility with Materials of Containment

(see Section B.6)

7. Thermophysical Properties

a. Density of Individual Microspheres

10.56 g cm^{-3}

b-q. (see Section B.7.b-q)

8. Mechanical Propertiesa. Hardness of PuO_2 microspheres

(see Section B.8.a)

b. Crush Strength of PuO_2 microspheres (nominal)

173 g for average particle diameter 123 μm

9-12. (see Section B.9-12)

D. LOW ASSAY PLUTONIUM DIOXIDE MICROSPHERES*

1. Typical Composition

a. Oxygen

11.8 wt %

b. Plutonium

88.2 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
^{236}Pu	0.00006
^{238}Pu	23.57
^{239}Pu	59.52
^{240}Pu	10.36
^{241}Pu	5.61
^{242}Pu	1.06

c. Actinide Impurities Concentration
(wt %)

^{237}Np	0.255
^{241}Am	0.394
^{232}Th	0.010
^{234}U	0.162, increases at rate of decay of ^{238}Pu
^{235}U	0.010

d. Cation Impurities Concentration
(wt %)

Aluminum	0.03
Boron	0.07
Calcium	0.01
Iron	0.49
Silicon	0.17

2. Specific Power (based on 23.6% ^{238}Pu in the element plutonium)a. 0.12 W g⁻¹b. 3.59 Ci g⁻¹

* Low assay plutonium contains approximately 23% wt % ^{238}Pu .

3. Power Density (bulk power density)

0.76 W cm⁻³ (nominal)

4. Radiation

a-d. (see Section B.4.a-d)

e. Neutrons

Measured specific yield approximately same
as 80% ²³⁸Pu in plutonium. 1.9x10⁴ n sec⁻¹ g⁻¹ ²³⁸Pu

5. Critical Mass

Not available

6. Compatibility with Materials of Containment

(see Section B.6)

7. Thermophysical Properties

a. Density of Individual Microspheres

10.33 g cm⁻³

b-q.

(see Section B.7.b-q)

8. Mechanical Properties

a. Hardness of PuO₂ Microspheres

(see Section B.8.a)

b. Crush Strength of PuO₂ Microspheres (nominal)

140 g for average particle diameter of 90 μm

9-12.

(see Section B.9-12)

E. PLUTONIUM DIOXIDE

1. Typical Composition, PuO₂

a. Oxygen

11.8 wt %

b. Plutonium

88.2 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
²³⁸ Pu	~0.00012
²³⁹ Pu	80.2
²⁴⁰ Pu	15.9
²⁴¹ Pu	3.022
²⁴² Pu	0.643
²⁴³ Pu	0.132

c. Actinide Impurities Concentration
(wt %)

²⁴¹ Am	0.0033
²³⁷ Np	0.130
²³⁴ U	0.140, increases at the rate of decay of ²³⁸ Pu

The total of other isotopic impurities including ²³¹Pa, ²³²Th, ²³³U, ²³⁵U, ²³⁶U, and ²²⁷Ac does not exceed 1 wt % of the fuel.

d. Cation Impurities Concentration
(wt %)

Aluminum	0.002
Calcium	0.005
Cadmium	0.001
Chromium	0.004
Iron	0.001
Magnesium	0.001
Nickel	0.005
Lead	0.006
Silicon	0.010
Tin	0.001
Zinc	0.005

2. Specific Power (based on 80% ^{238}Pu in the element plutonium)

- a. 0.40 W g^{-1}
- b. 12.1 Ci g^{-1}

3. Power Density (based on 80% ^{238}Pu in the element plutonium and theoretical density)

4.58 W cm^{-3}

4. Radiation

(see Section B.4)

5. Critical Mass

No significant difference is expected in the critical mass of $^{238}\text{PuO}_2$ and $^{238}\text{PuO}_2$ microspheres except for the small change that may result from a difference in density. The critical mass of PuO_2 is expected to be larger than for ^{238}Pu metal due to the smaller density and due to the neutron moderation effect caused by the oxygen atoms.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium.

4

6. Compatibility with Materials of Containment

Free energy change values for reactions between PuO_2 and metals should aid in selection of potential encapsulation material. Table 13 shows the possible reactions between PuO_2 and various possible container materials and the free energy change for each.

7. Thermophysical Properties

(see Section B.7)

8. Mechanical Properties

Not available

9. Chemical Properties

(see Section B.9)

REFERENCES

10. Biological Tolerances

(see Section B.10)

11. Shielding Data

(see Section A.11)

12. Electrical Properties

(see Section B.12)

F. PLUTONIUM MONOCARBIDE

1. Typical Composition

Average stoichiometry over single phase solid solution region $\text{PuC}_{0.85}$.

- a. Carbon 3.8-4.4 wt %
- b. Plutonium 96.2-95.6 wt %

2. Specific Power (based on 80% ^{238}Pu in the element plutonium)

- a. 0.43 W g^{-1} (calculated)
- b. 13.1 Ci g^{-1} (calculated)

3. Power Density (based on 80% ^{238}Pu in the element plutonium and theoretical density)

5.8 W cm^{-3} (calculated)

4. Radiation

Approximately same as metal (see Section A.4)

5. Critical Mass

The critical mass of ^{238}PuC is expected to be slightly larger than for ^{238}Pu metal due to the smaller density and due to the neutron moderation effect caused by the carbon atoms.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium. 4

6. Compatibility of ^{238}PuC with Materials of Containment 56

<u>Material</u>	<u>Temperature ($^{\circ}\text{C}$)</u>	<u>Reaction Observed</u>
Molybdenum	1400	No reaction
Niobium	1400	Reaction
Stainless Steel	1000	100 μm penetration in 11 days
Tantalum	1000	20 μm penetration in 11 days
Vanadium	1400	Reaction
Zirconium	1400	Reaction
Tungsten	1400	No Reaction

7. Thermophysical Properties of ^{239}PuC

- a. Density 57

13.6 g cm⁻³ (theoretical)

- b. Coefficient of Linear Thermal Expansion 58

<u>Temperature (°C)</u>	<u>Coefficient (x 10⁶)</u>
100	8.9
200	9.5
300	10.1
400	10.7
500	11.2
600	11.8
700	12.4
800	12.9

- c. Specific Heat
(see Table 16) 34

- d. Enthalpy
(see Table 16) 34

- e. Temperature of Phase Transformations 59
Melting point 1654°C

- f. Latent Heat of Phase Transformation
Not available

- g. Vapor Pressure
6.75x10⁻⁸ atm at 1550°C 60
2.2x10⁻⁸ atm at 1530°C 61

- h. Thermal Conductivity 62
(see Figure 9)

- i. Thermal Diffusivity
0.0106 cm² sec⁻¹ [calculated from (h), (c), and (a)]
at 298°K

Table 16

SELECTED THERMODYNAMIC FUNCTIONS OF PLUTONIUM-239
MONOCARBIDE (MOL WT 249.269) CRYSTAL

Temperature (°K)	cal mole ⁻¹ deg ⁻¹			kcal mole ⁻¹		
	(C _p)	(S° _T)	[-(G° _T - H° ₂₉₈)/T]	(H° _T - H° ₂₉₈)	(-ΔH _f °)	(-ΔG _f °)
298	9.785	20.000	20.000	0.000	0.250	1.439
300	9.880	20.061	20.000	0.018	0.251	1.450
400	11.520	23.147	20.410	1.095	0.495	2.008
500	12.360	25.814	21.231	2.292	0.560	2.390
600	12.870	28.115	22.191	3.554	0.626	2.759
700	13.220	30.126	23.184	4.860	0.582	3.118
800	13.490	31.910	24.165	6.196	1.020	3.450
900	13.710	33.511	25.116	7.556	0.914	3.761
1000	13.900	34.966	26.029	8.936	1.505	4.016
1100	14.070	36.299	26.903	10.335	1.401	4.272
1200	14.230	37.530	27.738	11.750	1.291	4.537
1300	14.380	38.675	28.536	13.181	1.178	4.813
1400	14.520	39.746	29.299	14.626	1.055	5.096
1500	14.660	40.752	30.029	16.085	0.925	5.387
1600	14.790	41.703	30.729	17.557	0.787	5.692
1700	14.920	42.603	31.402	19.043	0.640	6.003
1800	15.040	43.459	32.048	20.541	0.484	6.322
1900	15.160	44.276	32.670	22.051	0.319	6.651
1927	15.190	44.490	32.834	22.461	0.272	6.742

FIGURE 9 - Thermal conductivity of plutonium monocarbide.

REFERENCES

j. Viscosity

Not available

k. Surface Tension

Not available

l. Total Hemispherical Emittance

Not available

m. Spectral Emissivity

Not available

n. Crystallography

57

FCC, NaCl type

$$a = 4.97 \pm 0.01 \text{ \AA}$$

$$Z = 4$$

$$D_x = 13.6$$

Space group: Fm3m

Atomic Positions: $(0,0,0; 0, \frac{1}{2}, \frac{1}{2}; \frac{1}{2}, 0, \frac{1}{2}; \frac{1}{2}, \frac{1}{2}, 0) +$

4 Pu in $0,0,0,$

4 C in $\frac{1}{2}, \frac{1}{2}, \frac{1}{2},$

Interatomic distances: Pu-6 C = 2.48 Å
C-6 Pu = 2.48 Å

o. Solubilities

63

Plutonium monocarbide is reactive and is easily hydrolyzed by boiling water or cold dilute acid (only slight attack by HNO₃ unless heated with hot, concentrated HNO₃ containing a little NaF).

p. Diffusion Rates

Not available

8. Mechanical Properties of ²³⁹PuC

a. Microhardness

1100 - 1300 kg mm⁻² (50g load)

64

1000 kg mm⁻² (100g load)

65

9. Chemical Properties of ^{239}PuC
 - a. Heat of Formation

34

(see Table 16)
 - b. Free Energy of Formation

34

(see Table 16)
 - c. Entropy

34

(see Table 16)
 - d. Chemical Reactions and Reaction Rates

66

(see Figure 10)
10. Biological Tolerances

(see Table 9)
11. Shielding Data

(see Section A.11)
12. Electrical Properties of ^{239}PuC
 - a. Electrical Resistivity

67

$$\rho \text{ } (\mu\Omega\text{-cm}) (298 - 1000^\circ\text{K})$$

$$\rho = 263.30 - 1.966 \times 10^{-2}T - 1.171 \times 10^{-5}T^2 + 2.246 \times 10^{-8}T^3$$
 - b. Thermoelectric Power

67

$$\alpha \text{ } (\mu\text{V}^\circ\text{K}^{-1}) (298 - 1000^\circ\text{K})$$

$$\alpha = -2.43 + 3.396 \times 10^{-2}T - 3.445 \times 10^{-5}T^2 + 1.163 \times 10^{-8}T^3$$

FIGURE 10 - Free energy of formation data for carbides.

1. Typical Composition, PuN

- a. Nitrogen 5.5 wt %
- b. Plutonium 94.5 wt %

2. Specific Power (based on 80% ^{238}Pu in the element plutonium)

- a. 0.43 W g^{-1} (calculated)
- b. 12.9 Ci g^{-1} (calculated)

3. Power Density (based on 80% ^{238}Pu in the element plutonium and theoretical density)

6.1 W cm^{-3} (calculated)

4. Radiation

Approximately same as the metal (see Section A.4) except for gamma radiation which is likely to be higher because of the $^{14}\text{N}(\alpha, p)^{17}\text{O}$ reaction which has a 0.8 MeV gamma ray associated with it. The intensity of this gamma ray has not been measured at this time.

5. Critical Mass

The critical mass of ^{238}PuN is expected to be slightly larger than for ^{238}Pu metal due to the smaller density and due to the neutron moderation effect caused by the nitrogen atoms.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium.

4

6. Compatibility of ^{239}PuN with Materials of Containment

67

(see Table 17)

7. Thermophysical Properties of ^{239}PuN

a. Density

68

14.22 g cm^{-3} (theoretical)

b. Coefficient of Linear Thermal Expansion

69'

$11.2 \times 10^{-6} \text{ cm cm}^{-1} \text{ } ^\circ\text{C}^{-1}$ (25 1000°C)

Table 17

COMPATIBILITY OF ^{239}PuN WITH MATERIALS OF CONTAINMENT

Cladding	Condition	Temperature (°C $\pm$ 25)	Time (hr)	Results
Iron	Wrought	1300	100	No reaction
Type 304 Stainless Steel	Wrought	1300	100	No reaction
Inconel	Wrought	1300	100	No reaction
Molybdenum	Wrought	1288	50	No reaction
Molybdenum	Powder	1371	200	PuO_{2-x} + molybdenum oxide at interface
Molybdenum	Wrought	1650	96	Reaction at interface and precipitation in molybdenum
Tantalum	Wrought	1288	50	No reaction
Tantalum	Powder	1371	200	PuO_{2-x} + tantalum oxide at interface
Tantalum	Wrought	1650	96	Precipitation (Ta_2O_5) in tantalum
Niobium	Wrought	1288	50	No reaction
Niobium	Powder	1371	200	PuO_{2-x} + niobium nitrides at interface
Niobium	Wrought	1650	96	PuO_{2-x} with original PuN particle at inter- face and precipitation in niobium
Tungsten	Wrought	1288	50	No reaction
Tungsten	Powder	1371	200	PuO_{2-x} at interface
Tungsten	Wrought	1650	96	Reaction at interface and free plutonium in PuN
Pt-40 wt % Rh	Wrought	1482	-	Eutectic formation

REFERENCES

- c. Specific Heat
(see Table 18) 34
- d. Enthalpy
(see Table 18) 34
- e. Temperature of Phase Transformations 34
Melting point $2570 \pm 30^\circ\text{C}$ at one atmosphere of nitrogen
- f. Latent Heats of Phase Transformations
Not available
- g. Vapor Pressure

Temperature (°K)	Vapor Pressure (atm)	
1523	1.6×10^{-9}	71
1623	9.9×10^{-9}	71
1723	6.8×10^{-8}	71
1823	3.1×10^{-7}	71
1985	6.1×10^{-6}	72
2090	2.3×10^{-5}	72
2195	8.0×10^{-5}	72
2300	2.2×10^{-4}	72
- h. Thermal Conductivity
(see Table 19) 73
- i. Thermal Diffusivity
(see Table 19) 73
- j. Viscosity
Not available
- k. Surface Tension
Not available
- l. Total Hemispherical Emittance
Not available

Table 18

SELECTED THERMODYNAMIC PROPERTIES OF ^{239}PuN
(MOL WT 253.067) CRYSTAL

Temp- erature (°K)	cal mole ⁻¹ deg ⁻¹			kcal mole ⁻¹		
	(C _p ^o)	(S _T ^o)	[-(G ^o - H ^o ₂₉₈)/T]	(H _T ^o - H ₂₉₈ ^o)	(-ΔH _f ^o)	(-ΔG _f ^o)
298	12.750	14.200	14.200	0.000	75.700	69.184
300	12.780	14.279	14.200	0.024	75.697	69.140
400	13.600	18.074	14.712	1.345	76.337	66.963
500	14.160	21.173	15.704	2.734	76.290	64.632
600	14.520	23.788	16.839	4.169	76.218	62.418
700	14.790	26.047	17.997	5.635	76.016	60.019
800	15.000	28.036	19.130	7.125	76.282	57.717
900	15.180	29.813	20.220	8.634	75.993	55.414
1000	15.360	31.422	21.261	10.161	76.394	53.075
1100	15.520	32.893	22.252	11.705	76.094	50.702
1200	15.670	34.250	23.196	13.256	75.785	48.467
1300	15.810	35.510	24.096	14.839	75.467	46.204
1400	15.940	36.687	24.953	16.426	75.040	43.963
1500	16.070	37.791	25.773	18.027	74.804	41.751
1600	16.200	38.832	26.557	19.640	74.458	39.558
1700	16.320	39.818	27.308	21.266	74.104	37.385
1800	16.440	40.754	28.029	22.904	73.740	35.236
1900	16.560	41.646	28.723	24.555	73.366	33.108
2000	16.670	42.498	29.390	26.216	72.984	31.010
2100	16.770	43.314	30.034	27.888	72.593	28.910
2200	16.870	44.097	30.656	29.570	72.194	26.840
2300	16.970	44.849	31.256	31.262	71.786	24.785
2400	17.070	45.578	31.833	32.964	71.370	22.751
2500	17.160	46.270	32.401	34.672	70.950	20.732
2600	17.250	46.958	32.948	36.425	70.485	18.734
2700	17.330	47.618	33.479	38.175	70.024	16.754
2800	17.410	48.250	33.996	39.912	69.578	14.789
2843	17.440	48.515	34.213	40.661	69.383	13.944

Table 19

CALCULATED INTERPOLATED VALUES OF THERMAL
CONDUCTIVITY OF PuN

Temperature (°C)	Specific Heat ^a (cal g ⁻¹ °C ⁻¹)	Thermal Diffusivity (cm ² sec ⁻¹)	Density ^b (g cm ⁻³)	Thermal Conductivity ^c (cal sec ⁻¹ cm ⁻¹ °C ⁻¹)
250	0.052	0.045	14.16	0.033
300	0.053	0.044	14.13	0.033
400	0.054	0.042	14.09	0.032
500	0.055	0.042	14.05	0.032
600	0.055	0.037	14.01	0.028
700	0.055	0.036	13.97	0.028
800	0.056	0.035	13.93	0.027
900	0.057	0.038	13.88	0.030
1000	0.058	0.038	13.84	0.031
1050	0.060	0.038	13.82	0.031
1150	0.063	0.035	13.78	0.030
1200	0.064	0.035	13.76	0.031
1300	0.067	0.035	13.22	0.032
1400	0.070	0.038	13.68	0.036

^a Specific heat values are for uranium nitride.

^b Densities were calculated from the measured density at room temperature and the linear-expansion data for plutonium nitride.

^c Thermal conductivity = specific heat × density × thermal diffusivity.

- m. Spectral Emissivity
Not available
- n. Crystallography 69
FCC, NaCl type
 $a = 4.905 \pm 0.001 \text{ \AA}$
 $Z = 4$
 $D_x = 14.22$
Space Group: Fm3m
Atomic positions same as for carbide
Interatomic distances: Pu-6N = $2.45 \text{ \AA}$
N-6Pu = $2.45 \text{ \AA}$
- o. Diffusion Rates
Not available
8. Mechanical Properties of ^{239}PuN 70
- a. Microhardness
478 DPN at 93.7% theoretical density
503 DPN at 96.5% theoretical density
9. Chemical Properties of ^{239}PuN
- a. Enthalpy of Formation
(see Table 18) 34
- b. Free Energy of Formation
(see Table 18) 34
- c. Entropy of Formation
(see Table 18) 34
- d. Reactions and Reaction Rates 70
In air at room temperature PuN powder completely oxidized in a few days, whereas bulk PuN oxidized only 5% after 30 days. In glove box atmosphere (nitrogen) bulk PuN resisted oxidation forming an adherent oxide film which increases very slowly.

REFERENCES

In water at room temperature, only a thin oxide film was noted after 24 hr; whereas in boiling water PuN completely disintegrated in 15 min to a residue of complex composition.

10. Biological Tolerances

(see Table 9)

11. Shielding Data

(see section A.11)

12. Electrical Properties

Not available

1. Typical Composition

- a. Zirconium 8.74 wt %
- b. Plutonium 91.26 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
^{238}Pu	73
^{239}Pu	15.06
^{240}Pu	2.28
^{241}Pu	0.73
^{242}Pu	0.073

- c. Impurities are the same as for the metal

2. Specific Power (calculated)

- a. 0.41 W g^{-1}
- b. 12.25 Ci g^{-1}

3. Power Density (calculated)

5.6 W cm^{-3}

4. Radiation

Approximately same as the metal (see Section A.4)

5. Critical Mass

The critical mass of ^{238}Pu - 20 at.% Zr alloy is expected to be slightly larger than for ^{238}Pu metal.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium.

4

6. Compatibility with Materials of Containment

(see Table 20)

7. Thermophysical Properties of the ^{239}Pu -Zr Alloy

74

- a. Density

14 g cm^{-3}

Table 20

COMPATIBILITY OF CONTAINER MATERIALS
WITH Pu - 20 ATOM % Zr ALLOY

<u>Container Material</u>	<u>Temperature (°C)</u>	<u>Dura- tion (days)</u>	<u>Remarks</u>
Haynes alloy No. 25	600	10	0.015 in. penetration (radiograph)
	500	60	0.015 in. penetration (radiograph)
Tantalum	600	10	Little or no reaction
	500	38	Little or no reaction
Haynes alloy No. 25	600	255	Complete penetration of 0.040 in. end cap
Tantalum	600	240	Primary container intact

REFERENCES

b. Thermal Expansion Coefficient

Not available

c. Specific Heat (calculated)

0.045 cal g⁻¹ °C⁻¹

d. Temperature of Phase Transformations

Indeterminate, melting begins at 730°C
and continues to approximately 1000°C

e. Latent Heat of Phase Transformations (calculated)

Heat of fusion 13 cal g⁻¹

f. Vapor pressure (calculated)

Partial Pressure of ²³⁹Pu 11.6x10⁻⁵ mm Hg at 1500°K

g. Thermal Conductivity

Not available

h. Thermal Diffusivity

Not available

i. Viscosity

Probably <10 centipoise

j. Surface Tension

~700 dynes cm⁻¹

k. Total Hemispherical Emittance

Not available

l. Spectral Emissivity

Not available

m. Crystallography

a = 4.6306 Å at 400°C for delta phase
a = 3.6412 Å at 500°C for epsilon phase
a = 3.6480 Å at 600°C for epsilon phase
a = 3.6553 Å at 700°C for epsilon phase

75

- n. Solubilities
Not available
- o. Diffusion Rates
Not available
- 8. Mechanical Properties
Not available
- 9. Chemical Properties
 - a. Heat of Formation
Not available
 - b. Free Energy of Formation
Not available
 - c. Entropy
Not available
 - d. Chemical Reactions and Reaction Rates
Slight oxidation in O_2 at a pressure of 2×10^{-3} atm and temperature of $1000^\circ C$ after 5 min;
30% oxidation after 30 min
- 10. Biological Tolerances
(see Table 9 and 21)
- 11. Shielding Data
(see Section A.11)
- 12. Electrical Properties
 - a. Electrical resistivity
Not available
 - b. Temperature coefficient of resistivity
Not available

Table 21

GAMMA AND NEUTRON RADIATION DOSE RATES FROM ^{238}Pu
METAL HEAT SOURCES^a AS A FUNCTION OF DISTANCE

Distance from Center of Source to Center of Detector (cm)	Thermal Content (W)	Neutron (mrem hr ⁻¹)	Gamma (mrem hr ⁻¹)	Total (mrem hr ⁻¹)
20.3	107.9	32	9.3	41.3
25		21	7.2	28.2
50		5	1.7	6.7
100		1.6	0.7	2.3
20.3	104.8	27	7.0	34.0
25		17	5.2	23.2
50		4	1.5	5.5
100		1.2	0.6	1.8
20.3	103.0	28	8.1	36.1
25		17	6.3	23.3
50		5	1.6	6.6
100		1.3	0.7	2.0
20.3	105.7	27	9.0	34.0
25		16	6.1	22.1
50		4	1.5	5.5
100		1.2	0.6	1.8

^a Pu-20 at. % Zr alloy encapsulated in 0.020 in. wall tantalum inner container and 0.100 in. wall Haynes alloy No. 25 outer container.

1. Typical Composition

- a. Zirconium 4.08 wt %
- b. Plutonium 95.92 wt %

<u>Isotope</u>	<u>Concentration (wt %)</u>
^{238}Pu	76.74
^{239}Pu	15.83
^{240}Pu	2.40
^{241}Pu	0.77
^{242}Pu	0.09

- c. Impurities are the same as for the metal

2. Specific Power (calculated)

- a. 0.44 W g^{-1}
- b. 13.1 Ci g^{-1}

3. Power Density (calculated)

6.5 W cm^{-3}

4. Radiation

Approximately same as the metal (see Section A.4)

5. Critical Mass

The critical mass of ^{238}Pu - 10 at.% Zr alloy is expected to be slightly larger than for ^{238}Pu metal.

Subcritical neutron multiplication experiments predict that ^{238}Pu will not become critical in a well-moderated solution or well-moderated heterogeneous medium.

4

6. Compatibility with Materials of Containment

(see Table 20)

7. Thermophysical Properties of the ^{239}Pu -Zr Alloy

- a. Density

74

14.8 g cm^{-3} (solid) (calculated)
 15.36 g cm^{-3} (liquid) 901°C
 15.26 g cm^{-3} (liquid) 949°C
 15.16 g cm^{-3} (liquid) 1000°C

b. Thermal Expansion Coefficient

 $7 \times 10^{-7} \text{ cm cm}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ (360}^{\circ}\text{C to 450}^{\circ}\text{C)}$

c. Specific Heat (heat capacity)

 $7.9 \text{ cal mole}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ (solid) (calculated)}$
 $9.9 \text{ cal mole}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ (solid) (calculated)}$

d. Temperature of Phase Transformations

 Melting temperature $> 615^{\circ}\text{C}$

e. Latent Heat of Phase Transformations

 Heat of fusion $9 \pm 3 \text{ cal g}^{-1}$

 Heat of vaporization $93 \text{ kcal mole}^{-1} \text{ (calculated)}$

f. Vapor Pressure

 $\log P \text{ (atm)} = 7.2 - \frac{210 \times 10^4}{T} \text{ (1100 - 1800}^{\circ}\text{K) (calculated)}$

g. Thermal Conductivity

 $4 \times 10^{-2} \text{ cal cm}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ sec}^{-1} \text{ (350-500}^{\circ}\text{C) (estimated)}$

h. Thermal Diffusivity

Not available

i. Viscosity

Not available

j. Surface Tension

Not available

k. Total Hemispherical Emittance

Not available

l. Spectral Emissivity

Not available

m. Crystallography

 $a = 4.6354 \text{ \AA} \text{ at } 400^{\circ}\text{C} \text{ for delta phase}$
 $a = 3.6402 \text{ \AA} \text{ at } 500^{\circ}\text{C} \text{ for epsilon phase}$

REFERENCES

- a = 3.6477 Å at 600°C for epsilon phase
- a = 3.6555 Å at 700°C for epsilon phase

n. Solubilities

Not available

o. Diffusion Rates

Not available

8. Mechanical Properties

Not available

9. Chemical Properties

a. Heat of Formation

Not available

b. Free Energy of Formation

Not available

c. Entropy

Not available

d. Chemical Reactions and Rates

Not available

10. Biological Tolerances

(see Table 9 and 21)

11. Shielding Data

(see Section A.11)

12. Electrical Properties

a. Electrical Resistivity

Not available

b. Temperature Coefficients of Resistivity

Not available

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