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ORNL-4357
UC-4 - Chemistry

OAK RIDGE NATIONAL LABORATORY
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U.S. ATOMIC ENERGY COMMISSION

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ISOTOPES DEVELOPMENT CENTER

CURIUM DATA SHEETS

S. J. Rimshaw
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Isotopes Division

JANUARY 1969

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
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U.S. ATOMIC ENERGY COMMISSION

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CURIUM DATA SHEETS

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I. CURIUM-244

A. CURIUM-244 METAL

Half-life: 18.1 y

1, 2

1. Composition

a. Radionuclidic abundance

3

The anticipated isotopic composition of ^{244}Cm product resulting from a large-scale production program is represented by the actual isotopic composition of the first product batch resulting from the 1968-1969 SRL campaign shown below. The mass spectrographic analysis yielding these data was performed 18 months after reactor discharge.

Isotopic Composition of Curium Product

<u>Isotopic mass</u>	<u>% Abundance</u>
242	0.043
243	0.024
244	95.08
245	0.729
246	4.02
247	0.066
248	0.038

b. Radiochemical purity

The ^{244}Cm product will contain small amounts of fission products formed in the irradiation process and not removed in the chemical separations process. From the predicted performance of the chemical process and the calculated quantities of fission products associated with the curium after irradiation, the gamma activities of the fission-product impurities can be calculated and are tabulated in the table in Section I.A.3.c. (page 3) in the column labeled "From Impurities." Almost all of the gamma rays above 1 Mev are from ^{144}Pr and $^{152-154}\text{Eu}$, and those below 1 Mev are primarily from ^{95}Zr - ^{95}Nb , ^{144}Ce , ^{106}Rh , and ^{103}Ru - ^{103}Rh .

Fission products will also be formed by the spontaneous fission of ^{244}Cm and ^{252}Cf , which is present at an estimated maximum of 4×10^{-5} wt % of the ^{244}Cm . The gamma activities from these two isotopes are tabulated under the columns labeled "From Fission Products of ^{244}Cm and ^{252}Cf ."

Americium-243 and ^{252}Cf which are formed in the irradiation process are removed during chemical processing except for an estimated 0.5 wt % ^{243}Am and $<4 \times 10^{-5}$ wt % ^{252}Cf in the ^{244}Cm product.

CURIUM-244 METALREFERENCE
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c. Chemical purity

The following elemental impurity limits have been set as objectives for the ^{244}Cm process by Savannah River Plant during the CY 1968-1969 campaign:

<u>Elemental impurities</u>	<u>Maximum wt % of Cm</u>
Li + Na + K (total)	0.1
Si + Zn (total)	0.1
Fe + Cr + Ni (total)	0.2
Any other single impurity (except Am, Zr)	0.2
Total of all impurities (except Am, Zr)	1.0
Total of all impurities (including Am, Zr)	3.0

Plutonium-240 as a decay product of ^{244}Cm will be present in amounts increasing with time following chemical processing.

2. Specific Power

- a. 2.84 w/g of ^{244}Cm (100% ^{244}Cm isotope) 4, 5, 6
 2.70 w/g of pure curium element (95.08% ^{244}Cm isotope)
 2.62 w/g of curium product (97% chemically pure)
- b. Specific power values are based on 81.3 Ci/g of ^{244}Cm (100%) and 34.95 w/kCi of ^{244}Cm .

3. Radiation

a. Alpha particles

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Nuclide	Max E, Mev	Av E, Mev	Abundance, %	w/kCi	Particles w ⁻¹ sec ⁻¹
^{244}Cm	5.801	5.801	76.7	{ 34.3	0.825 x 10 ¹²
	5.759	5.759	23.3		0.252 x 10 ¹²

The volume of helium from alpha decay as a function of decay time is given in the following table.

Volume of helium, ^a cm ³ of He per g of ^{244}Cm	<u>Time</u>	
	Years	Half-lives
6.15	1.8	0.1
11.8	3.6	0.2
17.3	5.4	0.3
22.1	7.2	0.4
26.9	9.1	0.5
31.2	10.9	0.6
35.3	12.7	0.7
39.1	14.5	0.8

CURIUM-244 METALREFERENCE
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continued

Volume of helium, ^a cm ³ of He per g of ²⁴⁴ Cm	Time	
	Years	Half-lives
42.6	16.3	0.9
45.9	18.1	1.0
59.3	27.1	1.5
68.9	36.2	2.0
80.3	54.3	3.0
86.1	72.4	4.0
88.9	90.5	5.0
91.7	181.0	10.0

^aStandard conditions

b. Beta particles

None

c. Gamma

The significant gamma emissions of product-grade ²⁴⁴Cm 4 are listed in the following table. The gamma emissions result from the following:

- (1) Decay of curium nuclides and of ²⁴³Am (based on 0.02 wt % ²⁴²Cm, 0.002 wt % ²⁴³Cm, 95.3 wt % ²⁴⁴Cm, and 0.5 wt % ²⁴³Am.
- (2) Spontaneous fission of ²⁴⁴Cm and ²⁵²Cf (based on a maximum of 4×10^{-5} wt % ²⁵²Cf).
- (3) Decay of fission products resulting from the spontaneous fission of ²⁴⁴Cm and ²⁵²Cf.
- (4) Decay of fission products formed in the irradiation process and not removed in the chemical separation process.

Significant Gamma Rays of Curium-244 Product

Energy, Mev	Abundance, photons/(sec)(w ²⁴⁴ Cm product)									Total
	From decay of nuclides				From spontaneous fissions		From fission products of		From impu- rities	
	²⁴² Cm	²⁴³ Cm	²⁴⁴ Cm	²⁴³ Am	²⁴⁴ Cm	²⁵² Cf	²⁴⁴ Cm	²⁵² Cf		
0.0-0.5	4.1 x 10 ⁶	3.6 x 10 ⁶	2.5 x 10 ⁸	1.0 x 10 ⁷	4.1 x 10 ⁶	4.9 x 10 ⁵	2.2 x 10 ⁶	1.9 x 10 ⁵	2.2 x 10 ⁷	3.0 x 10 ⁸
0.5-1.0	3.0 x 10 ⁴	—	2.2 x 10 ⁶	—	2.6 x 10 ⁶	2.5 x 10 ⁵	6.7 x 10 ⁶	6.0 x 10 ⁵	7.5 x 10 ⁶	2.0 x 10 ⁷
1.0-2.0	9.0 x 10 ²	—	—	—	1.9 x 10 ⁶	1.8 x 10 ⁵	1.5 x 10 ⁶	1.3 x 10 ⁵	1.1 x 10 ⁶	4.9 x 10 ⁶
2.0-3.0	—	—	—	—	6.0 x 10 ⁵	4.9 x 10 ⁴	6.0 x 10 ⁵	5.2 x 10 ²	3.7 x 10 ⁵	1.6 x 10 ⁶
3.0-4.0	—	—	—	—	1.8 x 10 ⁵	1.3 x 10 ⁴	—	—	—	1.9 x 10 ⁵
4.0-5.0	—	—	—	—	6.0 x 10 ⁴	3.7 x 10 ³	—	—	—	6.4 x 10 ⁴
5.0-6.0	—	—	—	—	3.3 x 10 ⁴	1.0 x 10 ³	—	—	—	3.3 x 10 ⁴
6.0-7.0	—	—	—	—	5.6 x 10 ³	1.5 x 10 ²	—	—	—	5.6 x 10 ³

d. Bremsstrahlung

None

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e. Neutrons

4.19×10^6 neutrons $\text{sec}^{-1} \text{w}^{-1}$ of ^{244}Cm from spontaneous fission (half-life for spontaneous fission is 1.4×10^7 y).

7, 8, 9

1.51×10^5 neutrons $\text{sec}^{-1} \text{w}^{-1}$ of ^{244}Cm from (α, n) reaction on oxygen in Cm_2O_3 .

7

3.5×10^5 neutrons $\text{sec}^{-1} \text{w}^{-1}$ of ^{244}Cm from estimated maximum of ^{252}Cf content of 4×10^{-5} wt %.

The energy distribution of spontaneous fission neutrons from ^{244}Cm is given in the following table. 4

Energy, Mev	Abundance, neutrons $\text{sec}^{-1} \text{w}^{-1}$ of ^{244}Cm
0.3-0.4	1.51×10^5
0.4-0.6	3.13×10^5
0.6-0.8	3.20×10^5
0.8-1.0	2.77×10^5
1.0-1.2	2.84×10^5
1.2-1.4	2.80×10^5
1.4-1.6	2.44×10^5
1.6-1.8	2.19×10^5
1.8-2.0	1.98×10^5
2.0-2.2	1.80×10^5
2.2-2.4	1.65×10^5
2.4-2.6	1.58×10^5
2.6-2.8	1.30×10^5
2.8-3.0	1.08×10^5
3.0-3.2	1.01×10^5
3.2-3.4	0.97×10^5
3.4-3.6	0.93×10^5
3.6-3.8	0.75×10^5
3.8-4.0	0.79×10^5
4.0-4.4	1.04×10^5
4.4-4.8	0.86×10^5
4.8-5.2	0.65×10^5
5.2-5.6	0.50×10^5
5.6-6.0	0.40×10^5
6.0-6.4	2.95×10^4
6.4-6.8	2.12×10^4
6.8-7.2	1.47×10^4
7.2-7.6	1.12×10^4
7.6-8.0	0.90×10^4
8.0-8.8	1.01×10^4
8.8-9.6	2.95×10^3
9.6-10.4	3.1×10^3
10.4-11.2	2.05×10^3
11.2-12.8	1.40×10^3

The energy distribution of neutrons occurring as a result of the collision of fast alpha particles from ^{244}Cm decay with oxygen atoms in Cm_2O_3 is given in the following table.

Neutrons from (α, n) Reactions with Oxygen

Energy, Mev	Abundance, neutrons $\text{sec}^{-1} \text{ w}^{-1}$ of ^{244}Cm
0.2	1.62×10^2
0.4	0.68×10^3
0.6	0.83×10^3
0.8	1.69×10^3
1.0	2.70×10^3
1.2	0.43×10^4
1.4	0.61×10^4
1.6	0.83×10^4
1.8	1.01×10^4
2.0	1.19×10^4
2.2	1.33×10^4
2.4	1.40×10^4
2.6	1.40×10^4
2.8	1.37×10^4
3.0	1.22×10^4
3.2	1.01×10^4
3.4	0.79×10^4
3.6	0.50×10^4
3.8	3.02×10^3
4.0	2.01×10^3
4.2	1.37×10^3
4.4	0.86×10^3
4.6	0.72×10^2

4. Critical Mass

The critical mass of unreflected and reflected spheres of ^{244}Cm and $^{244}\text{Cm}_2\text{O}_3$ have been calculated by C. W. Craven, Jr., at ORNL using the cross-section data available as of November 1965. The results, shown in the following table, agree within 10% of the results obtained in the replacement experiment at Los Alamos. The critical mass equations used are

$$\text{Cm: } M_c = 2450/\rho^2 \quad (\text{kg})$$

$$\text{Cm}_2\text{O}_3: M_c = 2370/\rho^2 \quad (\text{kg})$$

Calculated Critical Mass of ^{244}Cm and $^{244}\text{Cm}_2\text{O}_3$

Core		Reflector		Critical mass, kg	Critical radius, cm
Mixture	Density, g/cm ³	Mixture	Thickness, cm		
Cm^a	14.0	Bare	—	12.5	5.97
Cm_2O_3^a	10.60	Bare	—	21.1	7.8031
Cm_2O_3	9.01	Bare	—	29.2	9.1803
Cm_2O_3	10.60	Au-H ₂ O	4.0-15.0	11.9	6.4540
Cm_2O_3	10.60	Au-H ₂ O	2.0-7.5	13.5	6.7188
Cm_2O_3	10.60	Au-H ₂ O	0.5-2.0	16.5	7.1966

^aAssumed composition: 98.07 wt % ^{244}Cm and 1.93 wt % ^{241}Pu .

5. Compatibility with Materials of Containment

6. Thermophysical Properties

a. Density

13.51 g/cm³ of metal

11

b. Coefficient of thermal expansion

12 (Am)

$$\alpha_a = 7.5 \times 10^{-6}/^\circ\text{C}$$

$$\alpha_c = 6.2 \times 10^{-6}/^\circ\text{C}$$

c. Specific heat and enthalpy

(1) Specific heat

$$0.0270 \text{ cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$$

13 (Nd)

(2) Enthalpy in cal/mole

$$H_t - H_0 = 6.48 + 3.53 \times 10^{-3} t^2 + 1.49 \times 10^{-6} t^3$$

14 (Nd)

(Nd temperature is 0-400°C and t is in °C)

d. Temperatures of phase transformations

(1) Melting point

$$1340 \pm 40^\circ\text{C}$$

15

$$1350 \pm 60^\circ\text{C}$$

16

(2) Boiling point

$$3525 \pm 130^\circ\text{C}$$

17

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e.	Latent heats of phase transformations	
	ΔH fusion 3.2 kcal/mole (Richard's rule)	17
	$\Delta H_{1600^\circ K}^\circ$ vaporization 82.6 ± 2.7 kcal/mole	17
f.	Vapor pressure	
	$\log_{10} P = 4.74 \pm 0.37 - [(18,060 \pm 590)/T]$	17
	(T is in $^\circ K$ and P is in atm)	
g.	Thermal conductivity	
	$0.021 \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ }^\circ\text{C}^{-1}$ at 26°C	18 (Gd)
h.	Thermal diffusivity	
	$0.575 \text{ cm}^2/\text{sec}$ at 26°C	
	This value was calculated by dividing the product of the specific heat and density into the thermal conductivity.	
i.	Viscosity	
	2.5 centipoises at 1340°C	19
j.	Surface tension	
	500 dyn/cm	20
k.	Total hemispherical emittance	
	0.37 at 89°C	21 (Pu)
l.	Spectral emissivity	
	0.55	22 (Er)
	A higher value of 0.9 can be assumed if the metal surface is oxidized or if impurities are present.	
m.	Crystallography	
	Double hexagonal close packed	11
	$a = 3.496 \pm 0.003 \text{ \AA}$ $c = 11.331 \pm 0.005 \text{ \AA}$	
n.	Solubilities	
	Reacts strongly with water	23
o.	Diffusion rates	
7.	<u>Mechanical Properties</u>	
a.	Hardness	
	Vicker's 97.7	24 (Dy)

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b. Crush strength

7741 kg/cm²

24 (Tm)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

Zero - by definition of standard state

(2) Free energy of formation

Zero - by definition of standard state

(3) Entropy

 $S_{298}^{\circ} = 18 \text{ cal } ^{\circ}\text{C}^{-1} \text{ mole}^{-1}$

15

b. Chemical reactions and reaction rates

(1) Oxygen at room temperature - slow

11

(2) Oxygen at elevated temperature - fast

11

(3) Nitrogen at room temperature - very slow

25

(4) Nitrogen at elevated temperature - slow

25

(5) Water at room temperature - fast

23

(6) Hydrogen at room temperature - slow

23

(7) Hydrogen at elevated temperature - fast

23

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ²⁴⁴Cm in air and water are shown in the following table.

26

Maximum Permissible Body Burdens and Maximum Permissible Concentrations
for Radionuclides in Air and in Water for Occupational Exposure²⁶

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max permissible burden in total body, q(μCi)	Max permissible concentrations, μCi/cm ³				
			For 40-hr week		For 168-hr week		
			Water	Air	Water	Air	
²⁴⁴ ₉₆ Cm (α, γ)	(Sol) {	<u>Bone</u>	0.1	<u>2 x 10⁻⁴</u>	<u>9 x 10⁻¹²</u>	<u>7 x 10⁻⁵</u>	<u>3 x 10⁻¹²</u>
		Liver	0.2	3 x 10 ⁻⁴	10 ⁻¹¹	9 x 10 ⁻⁵	4 x 10 ⁻¹²
		Kidney	0.2	4 x 10 ⁻⁴	2 x 10 ⁻¹¹	10 ⁻⁴	6 x 10 ⁻¹²
		Total Body	0.3	6 x 10 ⁻⁴	3 x 10 ⁻¹¹	2 x 10 ⁻⁴	9 x 10 ⁻¹²
		GI (LLI) ^a		8 x 10 ⁻⁴	2 x 10 ⁻⁷	3 x 10 ⁻⁴	6 x 10 ⁻⁸
	(Insol) {	<u>Lung</u>			<u>10⁻¹⁰</u>		<u>3 x 10⁻¹¹</u>
		<u>GI (LLI)^a</u>		<u>8 x 10⁻⁴</u>	<u>10⁻⁷</u>	<u>3 x 10⁻⁴</u>	<u>5 x 10⁻⁸</u>

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

10. Shielding Data

Gamma dose rates with water, iron, lead, and uranium shielding are given in Figs. 1-5 for ^{244}Cm power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 w. Neutron dose rates with water shielding are given in Fig. 6. Neutron dose rates on shielding with Be, CH, CH_2 , or LiH can be estimated by using Fig. 6 in conjunction with Fig. 7.

Fig. 1. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-244 as a Function of Distance from Center of Source.

Fig. 2. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

Fig. 3. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

Fig. 4. Gamma Dose Rates from Lead-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

Fig. 5. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

Fig. 6. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance is 100 cm.

Fig. 7. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth from a Unit Point Isotropic Fission Source.

B. CURIUM SESQUIOXIDE (Cm_2O_3)1. Composition

a. Radionuclidic abundance

See Section I.A.1.a.

b. Radiochemical purity

See Section I.A.1.b.

c. Chemical purity

See Section I.A.1.c.

d. Phase composition of various curium oxides

27-32

$\text{CmO}_{2.00}$	$\text{CmO}_{1.52-1.62}$ (C-type)
$\text{CmO}_{1.83}$ (Cm_6O_{11})	$\text{CmO}_{1.50}$ (B- and A-type)
$\text{CmO}_{1.71}$ (Cm_7O_{12})	

2. Specific Powera. 2.46 w/g of 100% pure Cm_2O_3 (86.5% ^{244}Cm isotope)
2.38 w/g of 97% pure Cm_2O_3 (83.9% ^{244}Cm isotope)

4, 5, 6

b. Specific power values are based on 81.3 Ci/g of ^{244}Cm (100%) isotope and 34.95 w/kCi of ^{244}Cm .3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility with Materials of ContainmentSee ORNL-4359, Compatibility Data Sheets for Cerium-144, Cesium-137, Curium, and Strontium-90 (classified).6. Thermophysical Properties

a. Density (calculated from lattice parameters)

C-type (bcc)	10.70 g/cm ³ at room temperature	29
B-type (monoclinic)	11.67 g/cm ³ at room temperature	29
A-type (hex)	11.4 g/cm ³ at 1640°C	29
	11.1 g/cm ³ at 1750°C	
	11.0 g/cm ³ at 1910°C	

CURIUM SESQUIOXIDE (Cm_2O_3)REFERENCE
COLUMN

- b. Coefficient of thermal expansion
 B-type (monoclinic) Cm_2O_3 29, 30, 31
 0.60% over 25-680°C
 0.85% over 25-940°C
 1.4% over 25-1300°C
- c. Specific heat and enthalpy
 (1) Specific heat in $\text{cal g}^{-1} \text{ } ^\circ\text{C}^{-1}$
 $3.7 \times 10^{-2} + 2.91 \times 10^{-5}T \text{ (} ^\circ\text{K)}$ 33 (Am_2O_3)
 (2) Enthalpy
- d. Temperatures of phase transformations
 (1) Phase transitions
 C-type Cm_2O_3 (bcc) transforms irreversibly to 29, 31, 32,
 B-type Cm_2O_3 (monoclinic) between 800-1300°C 34, 35
 depending on degree of crystallinity of cubic
 form.
 B-type Cm_2O_3 (monoclinic) transforms 29, 31, 32,
 reversibly to A-type Cm_2O_3 (hex) at 1600°C. 34, 35
 (2) Melting point
 $2265 \pm 20^\circ\text{C}$ 16, 36
 $2180 \pm 20^\circ\text{C}$ (production oxide) 16, 36
 $2230 \pm 25^\circ\text{C}$ (SRL production, Batch 1) 3
 (3) Boiling point
 $3700 \pm 200^\circ\text{C}$ 32, 37
 (4) Thermogravimetric analytical work on the 27, 28
 decomposition of CmO_2 to Cm_2O_3 at SRL con- 32, 36
 firmed previous work at ORNL and indicated
 some variations from earlier SRL results.
 Stable oxide phases and temperature ranges
 of stability in various atmospheres are:

Phase	Composition	Range of stability in indicated atmosphere, $^\circ\text{C}$		
		Oxygen	Helium	4% H_2 - 96% He
CmO_2	$\text{CmO}_{2.0}$	<400	<400	<250
Cm_6O_{11}	$\text{CmO}_{1.83}$	440-450	Unstable	Unstable
Cm_7O_{12}	$\text{CmO}_{1.71}$	460-720	450-520	Unstable
Cm_2O_3				
C-type	$\text{CmO}_{1.62-1.52}$	750-870 ^a	600-900	530-750
B-type	$\text{CmO}_{1.50}$	>850	>950	>850

^aHeating terminated at 870°C.

CURIUM SESQUIOXIDE (Cm₂O₃)REFERENCE
COLUMN

e. Latent heats of phase transformations

ΔH fusion	29 kcal/mole (Richard's rule)	37
ΔH° vaporization	133.0 ± 2.7 kcal/mole of gas between 1600 and 2250°C	32, 37

f. Vapor pressure

$$\log_{10} P_E \text{ (atm)} = 7.32 (\pm 0.26) - \frac{29,050 (\pm 590)}{T (^\circ\text{K})} \quad 32, 35, 37$$

at 1800-2600°K, where P_E is an artificial pressure of Cm₂O₃(g). The vapor species in the vaporization reaction are unknown. P_E is related to the actual vapor pressure by a proportionality constant, k , given as follows for vaporization to other gaseous species:

$$\begin{aligned} k &= 1.415 \text{ for CmO(g) + CmO}_2\text{(g)} \\ k &= 1.567 \text{ for CmO(g) + O(g)} \\ k &= 1.869 \text{ for Cm(g) + O(g)} \\ k &= 1.414 \text{ for Cm(g) + CmO}_2\text{(g)} \end{aligned}$$

g. Thermal conductivity

38

Thermal conductivity, cal cm ⁻¹ sec ⁻¹ °C ⁻¹	Molar heat capacity, cal °C ⁻¹ mole ⁻¹	Temp, °C
0.00347	31.50	27
0.00378	35.00	127
0.00389	38.32	327
0.00392	40.26	527
0.00399	41.80	727
0.00393	43.06	927
0.00393	44.02	1127
0.00388	44.80	1327
0.00384	45.14	1427

These values were calculated from the thermal diffusivities of Chikalla.³⁸ The density of the hot-pressed pellet was assumed to remain constant at 11.24 g/cm³. Values of the molar heat capacities assumed for ²⁴⁴Cm are those of Pu₂O₃.

h. Thermal diffusivity

39

Thermal diffusivity, cm ² /sec	Temperature, °C
0.0053	27
0.0052	127
0.0049	327
0.0047	527
0.0046	727
0.0044	927
0.0043	1127
0.0042	1327
0.0041	1427

CURIUM SESQUIOXIDE (Cm_2O_3)REFERENCE
COLUMN

- h. Thermal diffusivity (continued)
Preliminary data on a hot-pressed (30 min at 1380°C) Cm_2O_3 pellet having a density of 11.24 g/cm^3 .
- i. Viscosity
- j. Surface tension
- k. Total hemispherical emittance
- l. Spectral emissivity
0.20 to 0.57 22 (ThO_2)
The precise value is a function of the roughness of the material surface, the presence of impurities, and the effects of radiation.
- m. Crystallography
Body-centered cubic, C-type rare-earth oxide structure with variable lattice parameter, produced by reducing CmO_2 . 40, 41
 $a = 10.922 \pm 0.001 \text{ (CmO}_{1.62})$ to $10.997 \pm 0.003 \text{ (CmO}_{1.52})$ at room temperature
Hexagonal, H-type rare-earth oxide structure, obtained by irreversible transformation or reaction of B-type Cm_2O_3 on noble metals on heating at 1500°C . 30
 $a = 3.863 \pm 0.01 \text{ \AA}$ at 1750°C on Ir
 $c = 6.174 \pm 0.001 \text{ \AA}$ at 1750°C on Ir
Cubic with superstructure, related to bcc structure of C-type Cm_2O_3 , possibly $\text{CmO}_{1.72}$, obtained by heating CmO_2 between 470 and 700°C in oxygen (1 atm). 29
 $a = 5.450 \pm 0.001 \text{ \AA}$ at room temperature after 470°C in O_2
 $a = 5.461 \pm 0.001 \text{ \AA}$ at room temperature after 700°C in O_2
Cubic, related to fcc structure of CmO_2 , possibly $\text{CmO}_{1.83}$, obtained on heating at 450°C in oxygen. 29
 $a = 5.435 \pm 0.001 \text{ \AA}$ at room temperature
Supporting data on crystallography of Cm_2O_3 . 30, 32
- n. Solubilities
Insoluble in water 23
- o. Diffusion rates
Helium release from $^{244}\text{Cm}_2\text{O}_3$ microspheres and pellets has been correlated to obtain the "apparent diffusion coefficients" for microspheres in the range of 390 to 1200°C and for pellets in the range of 1100 to 1400°C . 42

CURIUM SESQUIOXIDE (Cm_2O_3)REFERENCE
COLUMN

o. Diffusion rates (continued)

Helium diffusion coefficient, cm^2/sec	Temperature, $^{\circ}\text{C}$
---	------------------------------------

Microspheres

4.1×10^{-10}	390
1.74×10^{-9}	600
2.7×10^{-9}	800
4.1×10^{-9}	1000
2.58×10^{-9}	1100
2.77×10^{-9}	1200
3.45×10^{-9}	1200

Cylindrical Pellets

5 $\times 10^{-6}$	1100
5.8 $\times 10^{-6}$	1200
7 $\times 10^{-6}$	1300
5 $\times 10^{-5}$	1400

7. Mechanical Properties

a. Hardness

b. Crush strength

1900 kg/cm^2 43 (CeO_2)8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

Phase	$-\Delta H_f^{\circ}$ (298°K), kcal/mole	
-------	--	--

$\text{CmO}_{1.50}$	215 ± 7	37
$\text{CmO}_{1.71}$	218 ± 10 (est)	44
$\text{CmO}_{1.83}$	225 ± 10 (est)	
$\text{CmO}_{2.00}$	236 ± 8 (est)	44

(2) Free energy of formation of $\text{CmO}_{1.50}$ ΔG_f° (298°K) = -205 ± 7 kcal/mole (calc)

32, 37

(3) Entropy of $\text{CmO}_{1.50}$ $S_{298}^{\circ} = 19.4$ eu

45

CURIUM SESQUIOXIDE (Cm_2O_3)REFERENCE
COLUMN

b. Chemical reactions and reaction rates

- (1) Oxidation of B-type Cm_2O_3 in oxygen (1 atm) 16, 30, 31,
32, 35

<u>Heating temp, °C</u>	<u>Time</u>	<u>Result</u>
75	4 hr	No oxidation
175	4 hr	No oxidation
220	8 hr	80-90% oxidation to CmO_2
290	2 hr	Complete oxidation to CmO_2
360	10 min	Oxidation to 40% Cm_7O_{12} -60% CmO_2
360	30 min	Complete oxidation to CmO_2
450	15 min	Complete oxidation to $\text{CmO}_{1.71}$ ^a
480	15 min	Complete oxidation to $\text{CmO}_{1.71}$
505	4 hr	70-80% oxidation to $\text{CmO}_{1.71}$
530	2 hr	<10% oxidation to $\text{CmO}_{1.71}$
570	2 hr	No oxidation
750	4 hr	No oxidation

^aThe intermediate phase $\text{CmO}_{1.71}$ is produced at somewhat lower temperatures (450°C) by reoxidation of Cm_2O_3 rather than by thermal decomposition of CmO_2 (470°C).

- (2) Nitrogen — no reaction 23
- (3) Water — possible hydration reaction 23
- (4) Inorganic acids — soluble in acids 23

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given under Section I.A.9. 26

10. Shielding Data

The dose rates are given under Section I.A.10.

C. CURIUM OXYSULFIDE ($\text{Cm}_2\text{O}_2\text{S}$)1. Composition

a. Radionuclidic abundance

See Section I.A.1.a.

b. Radiochemical purity

See Section I.A.1.b.

c. Chemical purity

See Section I.A.1.c.

2. Specific Power

- a. 2.39 w/g of 100% pure $\text{Cm}_2\text{O}_2\text{S}$ (84.1% ^{244}Cm isotope) 4, 5, 6
 2.32 w/g of 97% pure $\text{Cm}_2\text{O}_2\text{S}$ (81.6% ^{244}Cm isotope)

- b. Specific power values are based on 81.3 Ci/g of ^{244}Cm and 34.95 w/kCi of ^{244}Cm .

3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility with Materials of Containment6. Thermophysical Properties

a. Density

9.95 g/cm³46 ($\text{Pu}_2\text{O}_2\text{S}$)

b. Coefficient of thermal expansion

0.60% over 25-680°C

0.85% over 25-940°C

1.4% over 25-1300°C

29, 30, 31
(Cm_2O_3)

c. Specific heat and enthalpy

(1) Specific heat in cal g⁻¹ °C⁻¹ $3.62 \times 10^{-2} + 2.83 \times 10^{-5}T$ (°K)33 (Am_2O_3)

(2) Enthalpy

CURIUM OXYSULFIDE ($\text{Cm}_2\text{O}_2\text{S}$)REFERENCE
COLUMN

- d. Temperatures of phase transformations
- (1) Melting point
2000°C 47 ($\text{Ce}_2\text{O}_2\text{S}$)
 - (2) Boiling point
3130°C 33 (Am_2O_3)
- e. Latent heats of phase transformations
- ΔH fusion 17 kcal/mole 33 (Am_2O_3)
 - ΔH vaporization 85 kcal/mole 33 (Am_2O_3)
- f. Vapor pressure
- g. Thermal conductivity
- Values for the thermal conductivity of curium oxysulfide have not been derived but probably are in the same order of magnitude as the values for Cm_2O_3 which are given in Section I.B.6.g. 38 (Cm_2O_3)
- h. Thermal diffusivity
- Values for the thermal diffusivity of curium oxysulfide have not been derived but probably are in the same order of magnitude as the values for Cm_2O_3 which are given in Section I.B.6.h. 39 (Cm_2O_3)
- i. Viscosity
- j. Surface tension
- k. Total hemispherical emittance
- l. Spectral emissivity
- 0.20 to 0.57 22 (ThO_2)
- The emissivity value depends on the roughness of the material surface, radiation effects, and the presence of impurities.
- m. Crystallography
- Hexagonal 46 ($\text{Pu}_2\text{O}_2\text{S}$)
- $a = 4.008 \text{ \AA}$ $c = 6.769 \text{ \AA}$
- The cell constants should be slightly smaller for $\text{Cm}_2\text{O}_2\text{S}$ due to the actinide contraction.
- n. Solubilities
- (1) Soluble in strong acids ($\text{Ce}_2\text{O}_2\text{S}$) 48
 - (2) Insoluble in acetic acid ($\text{Ce}_2\text{O}_2\text{S}$) 48

CURIUM OXYSULFIDE (Cm₂O₂S)

- o. Diffusion rates

7. Mechanical Properties

- a. Hardness
- b. Crush strength

8. Chemical Properties

- a. Heat and free energy of formation, entropy

- (1) Heat of formation

$$\Delta H_f^\circ = -430 \text{ kcal/mole (approximated by Ce}_2\text{O}_2\text{S)} \quad 47$$

- (2) Free energy of formation

$$\Delta F_f^\circ = -414 \text{ kcal/mole (calculated by}$$

$$\Delta F_f^\circ = \Delta H_f^\circ - T\Delta S_f^\circ)$$

- (3) Entropy

$$S_{298}^\circ = 34.3 \text{ eu (calculated by Latimer's method)} \quad 49$$

- b. Chemical reactions and reaction rates 46

- (1) Air at room temperature — slow
- (2) Air at elevated temperature — fast
- (3) Water at room temperature — no reaction
- (4) Inorganic acids at room temperature — reacts

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ²⁴⁴Cm in air and in water are given in the ²⁴⁴Cm Metal Source Form, Section I.A.9. 26

10. Shielding Data

The radiation dose rates are given under the ²⁴⁴Cm Metal Source Form, Section I.A.10.

D. CURIUM FLUORIDE (CmF₃)1. Composition

a. Radionuclidic abundance

See Section I.A.1.a.

b. Radiochemical purity

See Section I.A.1.b.

c. Chemical purity

See Section I.A.1.c.

2. Specific Power

- a. 2.19 w/g of 100% pure CmF₃ (77.1% ²⁴⁴Cm isotope)
 2.12 w/g of 97% pure CmF₃ (74.8% ²⁴⁴Cm isotope)

4, 5, 6

- b. Specific power values are based on 81.3 Ci/g of ²⁴⁴Cm (100%) and 34.95 w/kCi of ²⁴⁴Cm.

3. Radiation

The radiation is given under Section I.A.3.

4. Critical Mass

See Section I.A.4.

5. Compatibility with Materials of Containment6. Thermophysical Properties

a. Density

9.80 g/cm³

50

b. Coefficient of thermal expansion

$a = 19.74 \times 10^{-6} + 2.62 \times 10^{-8} t + 0.15 \times 10^{-10} t^2$
 (t is in °C with a temperature range of 26-296°C)

51 (BaF₂)

c. Specific heat and enthalpy

(1) Specific heat in cal g⁻¹ °C⁻¹ $7.21 \times 10^{-2} + 2.06 \times 10^{-5} T$ (°K)33 (AmF₃)

(2) Enthalpy in cal

 $H_f - H_{298} = 21 T + 3.5 \times 10^{-3} T^2$

33

(estimated from other actinide data)

CURIUM FLUORIDE (CmF₃)REFERENCE
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d. Temperatures of phase transformations

(1) Melting point

1406°C

52

(2) Boiling point

2330°C

14

This value is the average of the boiling points of LaF₃, CeF₃, and PrF₃.

e. Latent heats of phase transformations

 ΔH fusion 9 kcal/mole33 (CeF₃) ΔH vaporization 62 kcal/mole33 (CeF₃)

f. Vapor pressure

<u>Vapor pressure, torr</u>	<u>Temperature, °C</u>
5.07 x 10 ⁻⁷	853
7.18 x 10 ⁻⁶	943
1.486 x 10 ⁻⁴	1033
1.725 x 10 ⁻³	1141
5.820 x 10 ⁻³	1196

53

Vapor pressures are for AmF₃.

g. Thermal conductivity

<u>Thermal conductivity, cal cm⁻¹ sec⁻¹ °C⁻¹</u>	<u>Temperature, °C</u>
0.0296	0
0.0251	100

54 (BaF₂)

h. Thermal diffusivity

<u>Thermal diffusivity, cm²/sec</u>	<u>Temperature, °C</u>
0.0399	0
0.0321	100

Calculated by dividing the product of the specific heat and the room temperature density into the thermal conductivity.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

A value of 0.9 can be assumed.

l. Spectral emissivity

CURIUM FLUORIDE (CmF₃)

- m. Crystallography
Hexagonal, LaF₃-type, space group P6₃/mmc 55
 $a = 4.041 \pm 0.001 \text{ \AA}$ $c = 7.179 \pm 0.002 \text{ \AA}$
- n. Solubilities
- o. Diffusion rates
- 7. Mechanical Properties
 - a. Hardness
 - b. Crush strength
- 8. Chemical Properties
 - a. Heat and free energy of formation, entropy
 - (1) Heat of formation
 $\Delta H_f^\circ = -357 \text{ kcal/mole}$ 15
 (estimated from other actinide data)
 - (2) Free energy of formation
 $\Delta F_f^\circ = -339 \text{ kcal/mole}$ 15
 - (3) Entropy
 $S_{298}^\circ = 29 \text{ eu}$ (estimated from other actinide data) 33
 - b. Chemical reactions and reaction rates 23
 - (1) Air at room temperature — no reaction
 - (2) Air at elevated temperature — forms oxyfluoride
 - (3) Nitrogen — no reaction
 - (4) Water — insoluble
 - (5) Inorganic acids — insoluble in weak inorganic acid
- 9. Biological Tolerances
 Maximum permissible body burdens and maximum
 permissible concentrations of ²⁴⁴Cm in air and
 in water are given under Section I.A.9. 26
- 10. Shielding Data
 The dose rates are given under Section I.A.10.

II. CURIUM-242A. CURIUM-242 OXIDE CERMET

Half-life: 163 d

1, 5, 7, 9

1. Composition

a. Radionuclidic abundance

The composition of the product will depend on the irradiation history of the ^{241}Am target as well as the cooling time after removal from the pile. The product is expected to be at least 40% ^{242}Cm . If it is not this high, an Am-Cm separation is used to lower the americium content of the product.

The analysis for a typical batch of ^{241}Am with a total integrated neutron dose of 1.3×10^{21} and with a 90-day cooling and processing period (with all the plutonium removed) is as follows:

56

<u>Isotope</u>	<u>% Abundance</u>
^{241}Am	47.5
^{242}Am	1.6
^{243}Am	7.7
^{242}Cm	41.9
^{243}Cm	0.5
^{244}Cm	0.8

The decay of ^{242}Cm to ^{238}Pu is illustrated in the following table. A 10-g product with 40% ^{242}Cm and 60% other actinides is assumed. The decay is shown for 163 days.

<u>Time, days</u>	<u>^{242}Cm, g</u>	<u>^{238}Pu, g</u>
0	4.00	0
16	3.73	0.27
32	3.48	0.52
65	3.03	0.97
81.5	2.83	1.17
98	2.46	1.54
163	2.00	2.00

The oxide mixture will be AmO_2 and Cm_2O_3 . This will be suspended in a neutral matrix material to give the prescribed power density:

30 vol % oxide mixture
70 vol % matrix material

CURIUM-242 OXIDE CERMETREFERENCE
COLUMN

b. Radiochemical purity

The only important heat contributor to the ^{242}Cm source material is ^{242}Cm . The following table shows the contribution of each isotope to 10 g of the oxide mixture.

56

Heat Contribution of Each Isotope of the ^{242}Cm Product

Nuclide	Half-life	Specific activity, w/g	% of nuclide	Heat contribution	
				watts	%
^{241}Am	458 y	0.106	47.5	0.50	0.1
^{242}Am	152 y	0.034	1.6	0.05	0.01
^{243}Am	7650 y	0.006	7.7	0.005	0.001
^{242}Cm	163 d	120.0	41.9	502.8	99.8
^{243}Cm	32 y	1.44	0.5	0.07	0.015
^{244}Cm	18.1 y	2.78	0.8	0.22	0.05
^{238}Pu	89 y	0.55			

The ^{242}Cm product has contained up to 30 Ci of ^{144}Ce per 8.33 g of ^{242}Cm . Trace amounts of ^{103}Ru - ^{106}Ru and ^{95}Zr - ^{95}Nb have been found in the feed but do not contribute materially to the power or radiation of the source.

The above contaminations can be reduced to much lower levels by additional processing.

2. Specific Powera. 42.8 w/g of $\text{AmO}_2\text{-Cm}_2\text{O}_3$ (35.7% ^{242}Cm metal)

It is assumed that there are 3320 Ci/g of ^{242}Cm and 36.1 w/kCi of ^{242}Cm .

8

b. 1186 Ci of ^{242}Cm per gram of $\text{AmO}_2\text{-Cm}_2\text{O}_3$ (35.7% ^{242}Cm metal)

7

3. Radiation

a. Alpha particles

7

Nuclide	Max E, Mev	Av E, Mev	Abundance, %	w/kCi	Particles $\text{w}^{-1} \text{sec}^{-1}$
^{242}Cm	6.11	6.11	73.7	{ 36.10	0.755×10^{12}
	6.066	6.066	26.3		0.270×10^{12}

a. Alpha particles (continued)

The amount of helium produced by alpha decay of ^{242}Cm as a function of time is given in the following table.

Volume of helium, ^a cm ³ of He per g of ^{242}Cm	Time	
	Days	Half-lives
11.9	32.6	0.2
22.4	65.2	0.4
31.5	97.8	0.6
39.4	130.4	0.8
46.3	163	1.0
59.8	244	1.5
69.4	326	2.0
80.9	489	3.0
86.7	652	4.0
89.6	815	5.0
92.4	1630	10.0

^aStandard conditions.

b. Beta particles

None

c. Gamma

In addition to the gammas from the alpha decay, there are the prompt and fission-product gammas from the spontaneous fission of ^{242}Cm ($T_{1/2} = 7.2 \times 10^6$ y). The gamma-emission rates are given in the following table.

Gamma-emission rate, ^a photons sec ⁻¹ g ⁻¹	Photon energy, Mev
<u>Curium-242 Gammas</u>	
0.27×10^{14}	0.044
1.42×10^{10}	0.10
2.83×10^9	0.158
<u>Prompt Gammas</u>	
2.44×10^7	1.0
6.09×10^6	1.5
6.45×10^6	2.3
1.15×10^6	3.0
1.52×10^6	5.0

CURIUM-242 OXIDE CERMETREFERENCE
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Gamma-emission rate, ^a photons sec ⁻¹ g ⁻¹	Photon energy, Mev
<u>Fission-Product Gammas</u>	
2.16 x 10 ⁷	0.63
7.99 x 10 ⁶	1.1
9.36 x 10 ⁶	1.55
1.80 x 10 ⁶	2.38
2.66 x 10 ⁶	2.75

^a120-w source.

d. Bremsstrahlung

None

e. Neutrons

2.30 x 10⁷ neutrons sec⁻¹ g⁻¹ of ²⁴²Cm from
spontaneous fission (120-w source)

7

2.0 x 10⁷ neutrons sec⁻¹ g⁻¹ of ²⁴²Cm from (α,n)
reaction of oxygen in Cm₂O₃ (120-w source)The energy distribution of spontaneous fission neutrons
from ²⁴²Cm is given in the following table. 4

Spontaneous Fission Neutrons from Curium-242

Energy, Mev	Abundance, ^a neutrons sec ⁻¹ g ⁻¹ of ²⁴² Cm
0.3-0.4	7.7 x 10 ⁵
0.4-0.6	1.6 x 10 ⁶
0.6-0.8	1.6 x 10 ⁶
0.8-1.0	1.4 x 10 ⁶
1.0-1.2	1.4 x 10 ⁶
1.2-1.4	1.4 x 10 ⁶
1.4-1.6	1.2 x 10 ⁶
1.6-1.8	1.1 x 10 ⁶
1.8-2.0	1.0 x 10 ⁶
2.0-2.2	9.1 x 10 ⁵
2.2-2.4	8.4 x 10 ⁵
2.4-2.6	8.0 x 10 ⁵
2.6-2.8	6.5 x 10 ⁵
2.8-3.0	5.5 x 10 ⁵
3.0-3.2	5.0 x 10 ⁵
3.2-3.4	5.0 x 10 ⁵
3.4-3.6	4.7 x 10 ⁵
3.6-3.8	3.7 x 10 ⁵
3.8-4.0	4.1 x 10 ⁵

Spontaneous Fission Neutrons (continued)

Energy, Mev	Abundance, ^a neutrons sec ⁻¹ g ⁻¹ of ²⁴² Cm
4.0-4.4	5.2 x 10 ⁵
4.4-4.8	4.4 x 10 ⁵
4.8-5.2	3.2 x 10 ⁵
5.2-5.6	2.5 x 10 ⁵
5.6-6.0	1.9 x 10 ⁵
6.0-6.4	1.5 x 10 ⁵
6.4-6.8	1.1 x 10 ⁵
6.8-7.2	7.5 x 10 ⁴
7.2-7.6	5.6 x 10 ⁴
7.6-8.0	4.7 x 10 ⁴
8.0-8.8	5.0 x 10 ⁴
8.8-9.6	1.5 x 10 ⁴
9.6-10.4	1.6 x 10 ⁴
10.4-11.2	1.0 x 10 ⁴
11.2-12.8	7.1 x 10 ³

^a120-w source.

The energy distribution of neutrons occurring as a result of a collision of fast alpha particles from ²⁴²Cm decay with oxygen atoms in Cm₂O₃ is given in the following table.

4

Neutrons from (α ,n) Reactions with Oxygen

Energy, Mev	Abundance, ^a neutrons sec ⁻¹ g ⁻¹ of ²⁴² Cm
0.2	5.0 x 10 ³
0.4	1.0 x 10 ⁴
0.6	2.0 x 10 ⁴
0.8	2.5 x 10 ⁴
1.0	7.6 x 10 ⁴
1.2	1.5 x 10 ⁵
1.4	2.8 x 10 ⁵
1.6	4.5 x 10 ⁵
1.8	7.6 x 10 ⁵
2.0	1.0 x 10 ⁶
2.2	1.3 x 10 ⁶
2.4	1.7 x 10 ⁶
2.6	2.0 x 10 ⁶
2.8	2.1 x 10 ⁶
3.0	2.1 x 10 ⁶
3.2	2.1 x 10 ⁶
3.4	1.8 x 10 ⁶

Neutrons from (α ,n) Reactions (continued)

<u>Energy, Mev</u>	<u>Abundance,^a neutrons sec⁻¹ g⁻¹ of ²⁴²Cm</u>
3.6	1.5 x 10 ⁶
3.8	1.0 x 10 ⁶
4.0	6.5 x 10 ⁵
4.2	4.0 x 10 ⁵
4.4	2.8 x 10 ⁵
4.6	1.8 x 10 ⁵
4.8	5.0 x 10 ⁴

^a_{120-w} source.4. Critical Mass5. Compatibility with Materials of Containment

See ORNL-4359, Compatibility Data Sheets for Cerium-144, Cesium-137, Curium, and Strontium-90 (classified).

6. Thermophysical Properties

The thermophysical properties of a ²⁴²Cm oxide cermet will depend on the individual properties of the oxide and matrix material. With the selection of the proper refractory metal as the matrix material, it should be possible to reach a 0.06 cal cm⁻¹ sec⁻¹ °C⁻¹ thermal conductivity for the cermet.

7. Mechanical Properties

The mechanical properties of the metal-oxide mixture will depend strongly on the properties of the matrix material.

8. Chemical Properties

The chemical properties will depend on the individual properties of the oxide and matrix material.

9. Biological Tolerances

The ²⁴²Cm tolerances taken from reference 26 are given in the table on the following page.

CURIUM-242 OXIDE CERMETREFERENCE
COLUMN

Maximum Permissible Body Burdens and Maximum Permissible Concentrations
for Radionuclides in Air and in Water for Occupational Exposure²⁶

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max permissible burden in total body, q(μ Ci)	Max permissible concentrations, μ Ci/cm ³			
			For 40-hr week		For 168-hr week	
			Water	Air	Water	Air
²⁴² Cm (α , γ)	GI (LLI) ^a		7×10^{-4}	2×10^{-7}	2×10^{-4}	5×10^{-8}
	<u>Liver</u>	0.05	3×10^{-3}	10^{-10}	9×10^{-4}	4×10^{-11}
	Bone	0.09	5×10^{-3}	2×10^{-10}	2×10^{-3}	8×10^{-11}
	Kidney	0.2	9×10^{-3}	4×10^{-10}	3×10^{-3}	10^{-10}
	Total Body	0.2	0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
	(Insol) <u>Lung</u>			2×10^{-10}		6×10^{-11}
	GI (LLI) ^a		7×10^{-4}	10^{-7}	3×10^{-4}	4×10^{-8}

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

10. Shielding Data

Gamma dose rates with water, iron, lead, and uranium shielding are given in Figs. 8-12 for ²⁴²Cm power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 w. Neutron dose rates with water shielding are given in Fig. 13. Neutron dose rates on shielding with Be, Ch, CH₂, or LiH can be estimated by using Fig. 13 in conjunction with Fig. 7.

7

Fig. 8. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-242 as a Function of Distance from Center of Source.

Fig. 9. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

Fig. 10. Gamma Dose Rate from Lead-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

Fig. 11. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

Fig. 12. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

Fig. 13. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance is 100 cm. Refer to Fig. 7 for dose rates through other materials.

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