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ISOTOPES DEVELOPMENT CENTER

CURIUM DATA SHEETS

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JANUARY 1969

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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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

Isotopic mass	% Abundance
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 $^{152-154}Eu$, 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.

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:

Elemental impurities	Maximum wt % of Cm
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 5, 7

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	0.825×10^{12}
	5.759	5.759	23.3		0.252×10^{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	Time: Years	Time: 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

continued

Volume of helium,[a] cm^3 of He per g of ^{244}Cm	Time: Years	Time: 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

[a]Standard conditions

b. Beta particles

None

c. Gamma

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

(1) Decay of curium nuclides and of ^{243}Am (based on 0.02 wt % ^{242}Cm, 0.002 wt % ^{243}Cm, 95.3 wt % ^{244}Cm, and 0.5 wt % ^{243}Am.

(2) Spontaneous fission of ^{244}Cm and ^{252}Cf (based on a maximum of 4×10^{-5} wt % ^{252}Cf).

(3) Decay of fission products resulting from the spontaneous fission of ^{244}Cm and ^{252}Cf.

(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): From decay of nuclides				From spontaneous fissions		From fission products of		From impurities	Total
	^{242}Cm	^{243}Cm	^{244}Cm	^{243}Am	^{244}Cm	^{252}Cf	^{244}Cm	^{252}Cf		
0.0-0.5	4.1×10^6	3.6×10^6	2.5×10^8	1.0×10^7	4.1×10^6	4.9×10^5	2.2×10^8	1.9×10^5	2.2×10^7	3.0×10^8
0.5-1.0	3.0×10^4	–	2.2×10^6	–	2.6×10^6	2.5×10^5	6.7×10^6	6.0×10^5	7.5×10^6	2.0×10^7
1.0-2.0	9.0×10^2	–	–	–	1.9×10^6	1.8×10^5	1.5×10^6	1.3×10^5	1.1×10^6	4.9×10^6
2.0-3.0	–	–	–	–	6.0×10^5	4.9×10^4	6.0×10^5	5.2×10^2	3.7×10^5	1.6×10^6
3.0-4.0	–	–	–	–	1.8×10^5	1.3×10^4	–	–	–	1.9×10^5
4.0-5.0	–	–	–	–	6.0×10^4	3.7×10^3	–	–	–	6.4×10^4
5.0-6.0	–	–	–	–	3.3×10^4	1.0×10^3	–	–	–	3.3×10^4
6.0-7.0	–	–	–	–	5.6×10^3	1.5×10^2	–	–	–	5.6×10^3

d. Bremsstrahlung

None

REFERENCE COLUMN

e. Neutrons

4.19×10^6 neutrons sec^{-1} 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 sec^{-1} w^{-1} of ^{244}Cm from (α,n) reaction on oxygen in Cm_2O_3. 7

3.5×10^5 neutrons sec^{-1} 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 sec^{-1} 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

REFERENCE COLUMN

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. 4

Neutrons from (α,n) Reactions with Oxygen

Energy, Mev	Abundance, neutrons sec^{-1} 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 $^{244}Cm_2O_3$ 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 10

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

$$Cm_2O_3: \quad M_c = 2370/\rho^2 \quad (kg)$$

Calculated Critical Mass of ^{244}Cm and $^{244}Cm_2O_3$

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_2O	4.0-15.0	11.9	6.4540
Cm_2O_3	10.60	Au-H_2O	2.0-7.5	13.5	6.7188
Cm_2O_3	10.60	Au-H_2O	0.5-2.0	16.5	7.1966

[a]Assumed 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/cm^3 of metal — 11

b. Coefficient of thermal expansion — 12 (Am)

$\alpha_a = 7.5 \times 10^{-6}/°C$

$\alpha_c = 6.2 \times 10^{-6}/°C$

c. Specific heat and enthalpy

(1) Specific heat

0.0270 cal g^{-1} $°C^{-1}$ — 13 (Nd)

(2) Enthalpy in cal/mole

$$H_t - H_o = 6.48 + 3.53 \times 10^{-3}\, t^2 + 1.49 \times 10^{-6}\, t^3$$ — 14 (Nd)

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

d. Temperatures of phase transformations

(1) Melting point

1340 ± 40°C — 15

1350 ± 60°C — 16

(2) Boiling point

3525 ± 130°C — 17

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e. Latent heats of phase transformations

ΔH fusion 3.2 kcal/mole (Richard's rule) 17

$\Delta H^{\circ}_{1600^{\circ}K}$ 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 °K and P is in atm)

g. Thermal conductivity

0.021 cal cm^{-1} sec^{-1} $°C^{-1}$ at 26°C 18 (Gd)

h. Thermal diffusivity

0.575 cm^2/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 ± 0.003 Å c = 11.331 ± 0.005 Å

n. Solubilities

Reacts strongly with water 23

o. Diffusion rates

7. Mechanical Properties

a. Hardness

Vicker's 97.7 24 (Dy)

b. Crush strength

7741 kg/cm^2 — 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

$S^{\circ}_{298} = 18$ cal °C^{-1} 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 ^{244}Cm 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 Exposure[26]

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 Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
$^{244}_{96}$Cm	(Sol)	Bone	0.1	2×10^{-4}	9×10^{-12}	7×10^{-5}	3×10^{-12}
		Liver	0.2	3×10^{-4}	10^{-11}	9×10^{-5}	4×10^{-12}
		Kidney	0.2	4×10^{-4}	2×10^{-11}	10^{-4}	6×10^{-12}
(α, γ)		Total Body	0.3	6×10^{-4}	3×10^{-11}	2×10^{-4}	9×10^{-12}
		GI (LLI)[a]		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
	(Insol)	Lung			10^{-10}		3×10^{-11}
		GI (LLI)[a]		8×10^{-4}	10^{-7}	3×10^{-4}	5×10^{-8}

[a]The 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.

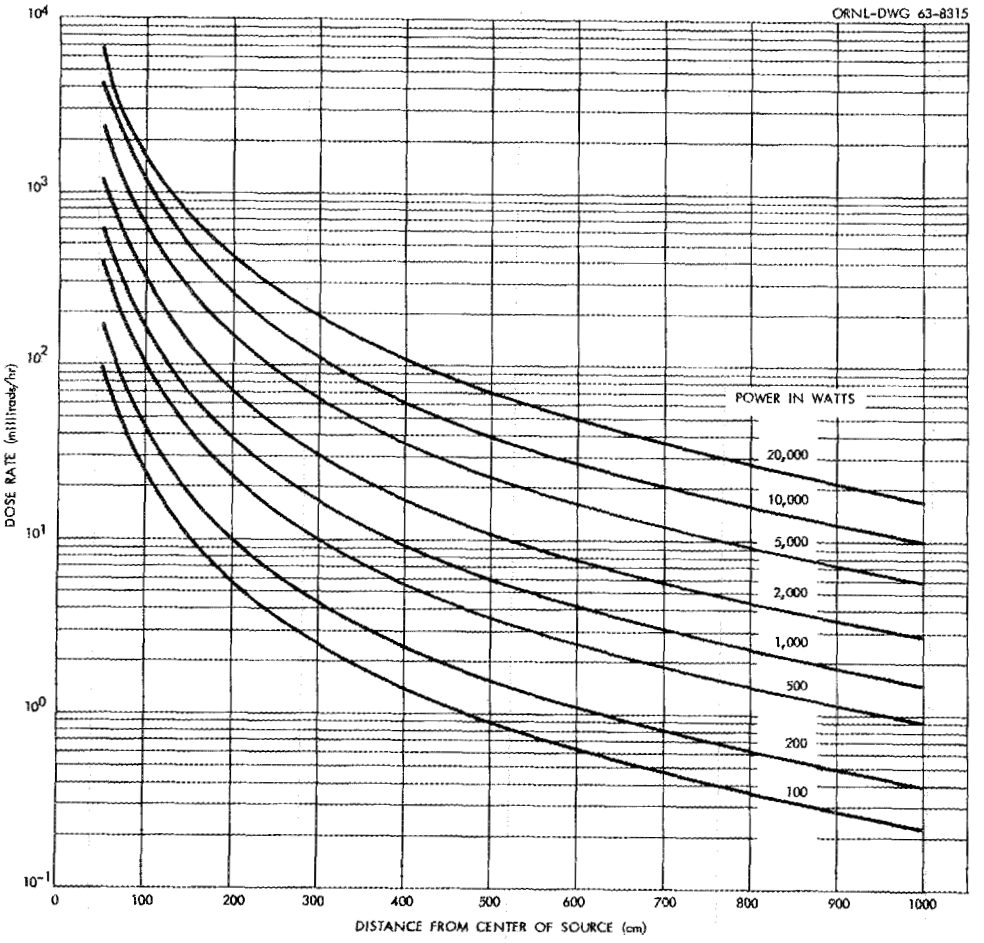

Fig. 1. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-244 as a Function of Distance from Center of Source.

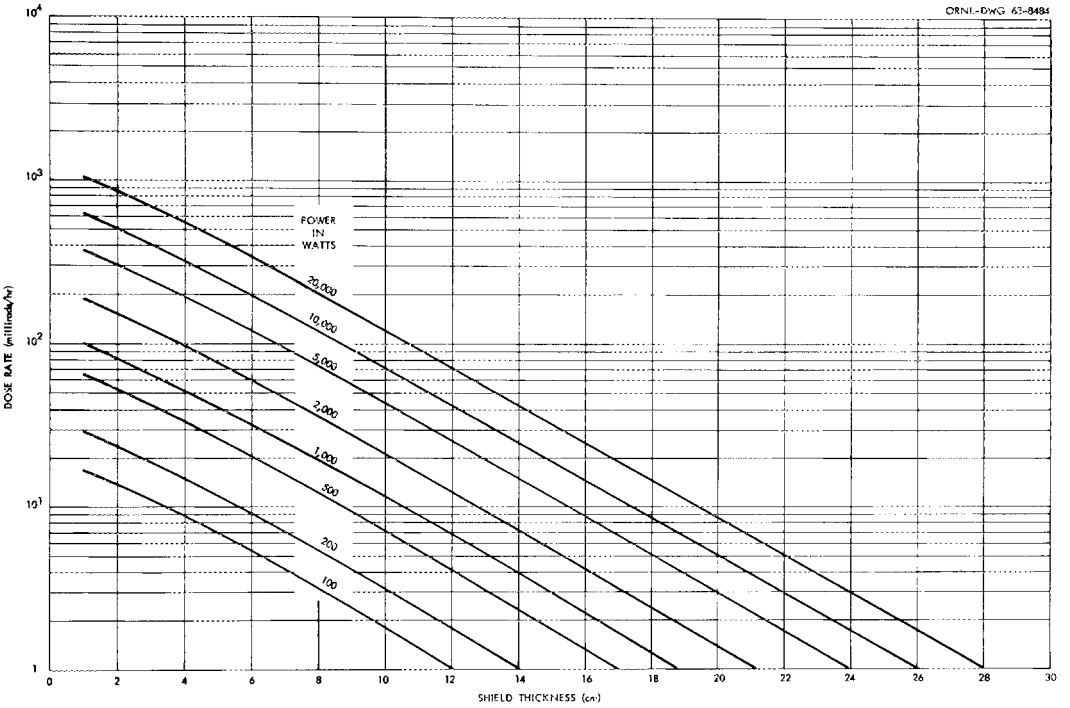

Fig. 2. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

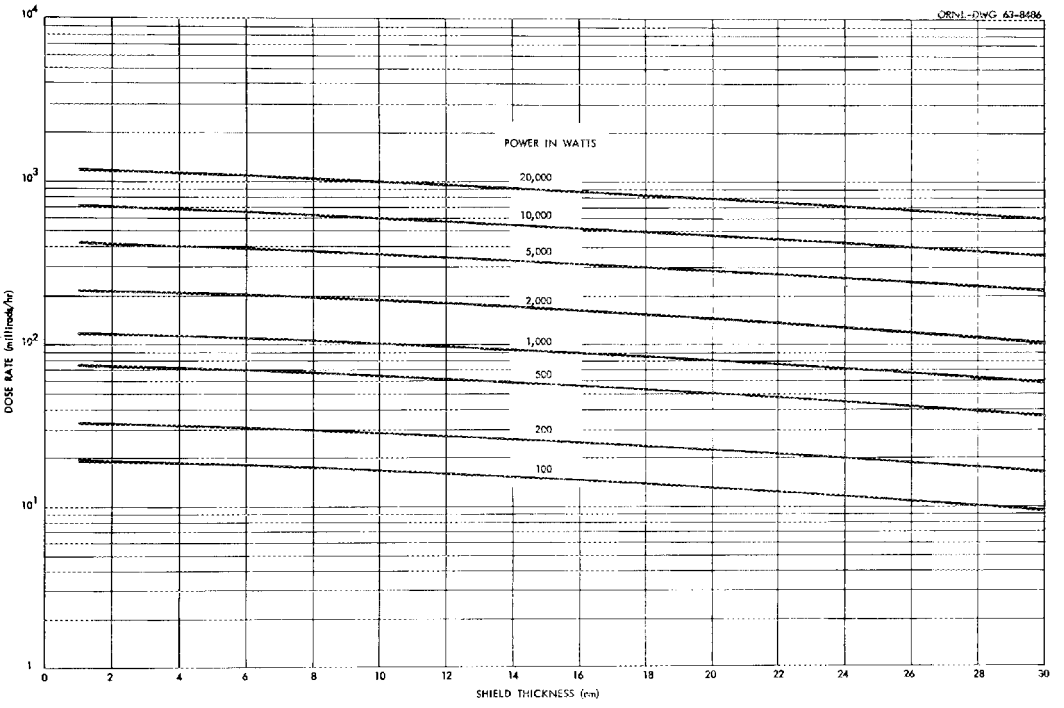

Fig. 3. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

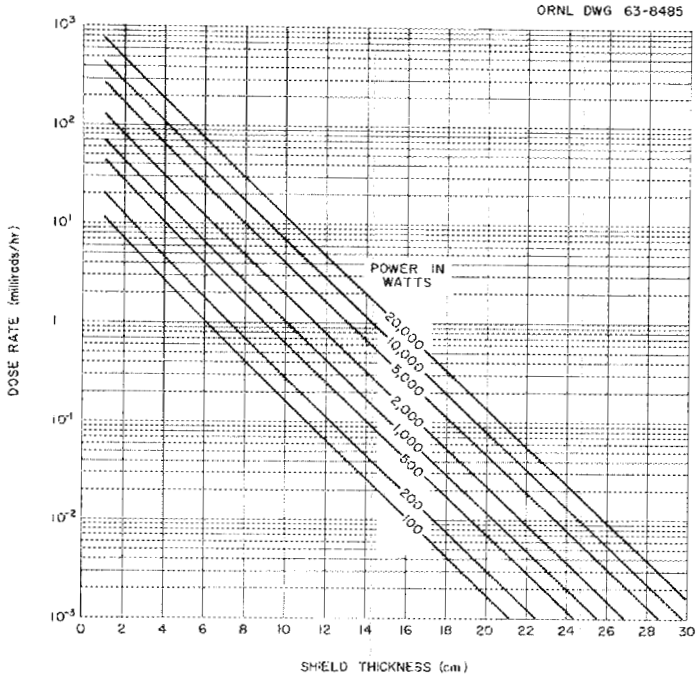

Fig. 4. Gamma Dose Rates from Lead-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

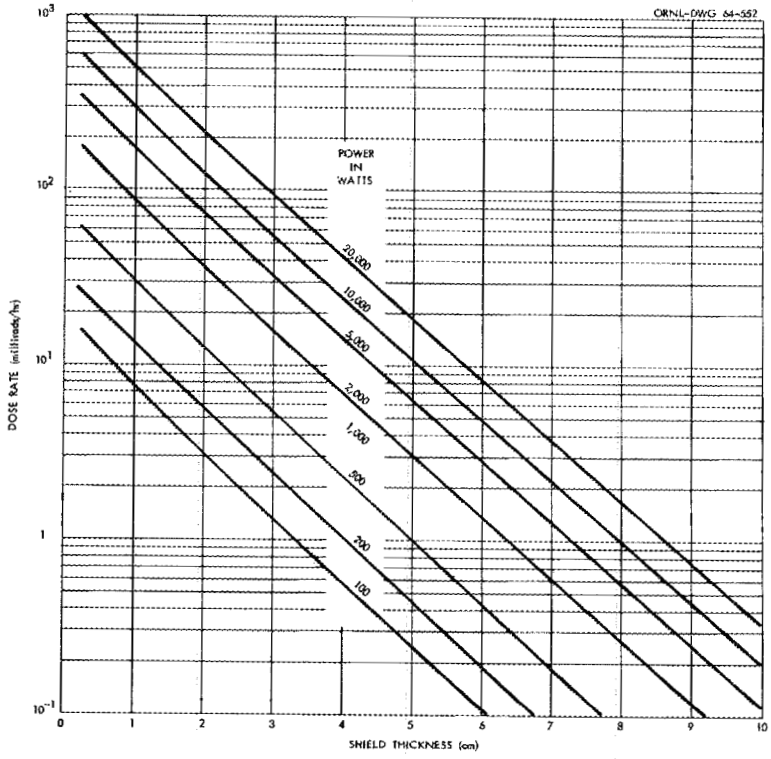

Fig. 5. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance is 100 cm.

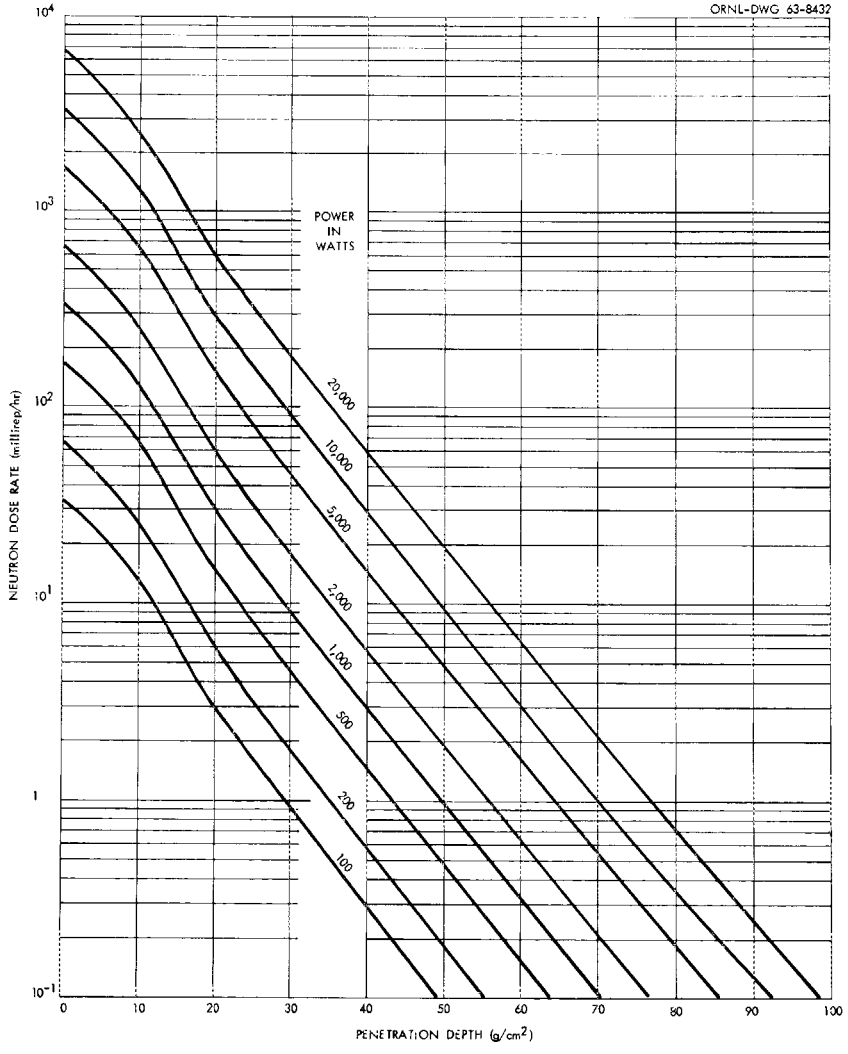

Fig. 6. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance is 100 cm.

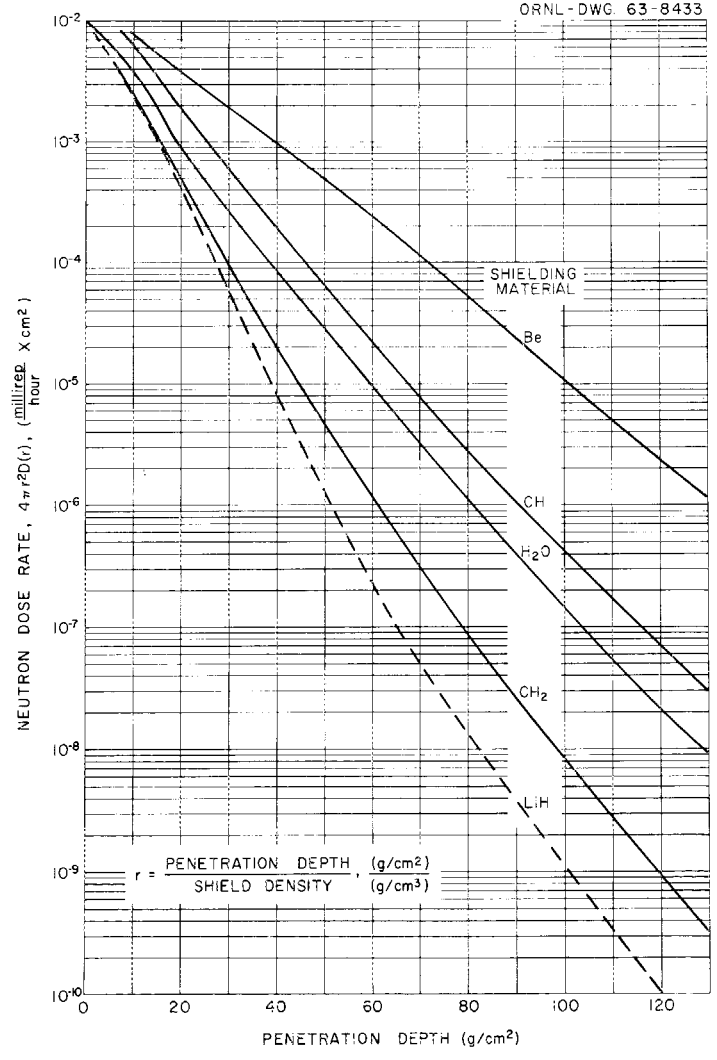

Fig. 7. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth from a Unit Point Isotropic Fission Source.

REFERENCE COLUMN

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

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

2. Specific Power

a. 2.46 w/g of 100% pure Cm_2O_3 (86.5% ^{244}Cm isotope) 4, 5, 6
2.38 w/g of 97% pure Cm_2O_3 (83.9% ^{244}Cm isotope)

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 Containment

See 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 cal g^{-1} $°C^{-1}$

$3.7 \times 10^{-2} + 2.91 \times 10^{-5}T$ (°K) — 33 (Am_2O_3)

(2) Enthalpy

d. Temperatures of phase transformations

(1) Phase transitions

C-type Cm_2O_3 (bcc) transforms irreversibly to B-type Cm_2O_3 (monoclinic) between 800-1300°C depending on degree of crystallinity of cubic form. — 29, 31, 32, 34, 35

B-type Cm_2O_3 (monoclinic) transforms reversibly to A-type Cm_2O_3 (hex) at 1600°C. — 29, 31, 32, 34, 35

(2) Melting point

2265 ± 20°C — 16, 36
2180 ± 20°C (production oxide) — 16, 36
2230 ± 25°C (SRL production, Batch 1) — 3

(3) Boiling point

3700 ± 200°C — 32, 37

(4) Thermogravimetric analytical work on the decomposition of CmO_2 to Cm_2O_3 at SRL confirmed previous work at ORNL and indicated some variations from earlier SRL results. Stable oxide phases and temperature ranges of stability in various atmospheres are: — 27, 28, 32, 36

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

[a]Heating terminated at 870°C.

CURIUM SESQUIOXIDE (Cm_2O_3) — REFERENCE COLUMN

e. Latent heats of phase transformations

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

f. Vapor pressure

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

at 1800-2600°K, where P_E is an artificial pressure of $Cm_2O_3(g)$. 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:

$k = 1.415$ for $CmO(g) + CmO_2(g)$
$k = 1.567$ for $CmO(g) + O(g)$
$k = 1.869$ for $Cm(g) + O(g)$
$k = 1.414$ for $Cm(g) + CmO_2(g)$

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/cm^3. Values of the molar heat capacities assumed for ^{244}Cm are those of Pu_2O_3.

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 ± 0.001 ($CmO_{1.62}$) to
10.997 ± 0.003 ($CmO_{1.52}$) 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 ± 0.01 Å at 1750°C on Ir
c = 6.174 ± 0.001 Å at 1750°C on Ir

Cubic with superstructure, related to bcc structure of C-type Cm_2O_3, possibly $CmO_{1.72}$, obtained by heating CmO_2 between 470 and 700°C in oxygen (1 atm). — 29

a = 5.450 ± 0.001 Å at room temperature after 470°C in O_2
a = 5.461 ± 0.001 Å at room temperature after 700°C in O_2

Cubic, related to fcc structure of CmO_2, possibly $CmO_{1.83}$, obtained on heating at 450°C in oxygen. — 29

a = 5.435 ± 0.001 Å 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 $^{244}Cm_2O_3$ 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

REFERENCE COLUMN

CURIUM SESQUIOXIDE (Cm_2O_3)

o. Diffusion rates (continued)

Helium diffusion coefficient, cm^2/sec	Temperature, °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	
5×10^{-6}	1100
5.8×10^{-6}	1200
7×10^{-6}	1300
5×10^{-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	
$CmO_{1.50}$	215 ± 7	37
$CmO_{1.71}$	218 ± 10 (est)	44
$CmO_{1.83}$	225 ± 10 (est)	
$CmO_{2.00}$	236 ± 8 (est)	44

(2) Free energy of formation of $CmO_{1.50}$

ΔG_f° (298°K) = -205 ± 7 kcal/mole (calc) — 32, 37

(3) Entropy of $CmO_{1.50}$

S_{298}° = 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

Heating temp, °C	Time	Result
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 $CmO_{1.71}$[a]
480	15 min	Complete oxidation to $CmO_{1.71}$
505	4 hr	70-80% oxidation to $CmO_{1.71}$
530	2 hr	<10% oxidation to $CmO_{1.71}$
570	2 hr	No oxidation
750	4 hr	No oxidation

[a]The intermediate phase $CmO_{1.71}$ 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.

REFERENCE COLUMN

C. CURIUM OXYSULFIDE (Cm_2O_2S)

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 Cm_2O_2S (84.1% ^{244}Cm isotope) — 4, 5, 6
2.32 w/g of 97% pure Cm_2O_2S (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 Containment

6. Thermophysical Properties

a. Density

9.95 g/cm^3 — 46 (Pu_2O_2S)

b. Coefficient of thermal expansion — 29, 30, 31 (Cm_2O_3)

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 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 (Cm_2O_2S)

REFERENCE COLUMN

d. Temperatures of phase transformations

(1) Melting point

2000°C — 47 (Ce_2O_2S)

(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 (Pu_2O_2S)

a = 4.008 Å c = 6.769 Å

The cell constants should be slightly smaller for Cm_2O_2S due to the actinide contraction.

n. Solubilities

(1) Soluble in strong acids (Ce_2O_2S) — 48

(2) Insoluble in acetic acid (Ce_2O_2S) — 48

CURIUM OXYSULFIDE (Cm_2O_2S) — REFERENCE COLUMN

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

ΔH_f° = -430 kcal/mole (approximated by Ce_2O_2S) — 47

(2) Free energy of formation

ΔF_f° = -414 kcal/mole (calculated by $\Delta F_f^\circ = \Delta H_f^\circ - T\Delta S_f^\circ$)

(3) Entropy

S_{298}° = 34.3 eu (calculated by Latimer's method) — 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 ^{244}Cm in air and in water are given in the ^{244}Cm Metal Source Form, Section I.A.9. — 26

10. Shielding Data

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

REFERENCE COLUMN

D. CURIUM FLUORIDE (CmF_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.

2. Specific Power

a. 2.19 w/g of 100% pure CmF_3 (77.1% ^{244}Cm isotope) — 4, 5, 6
2.12 w/g of 97% pure CmF_3 (74.8% ^{244}Cm isotope)

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

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

4. Critical Mass

See Section I.A.4.

5. Compatibility with Materials of Containment

6. Thermophysical Properties

a. Density

$9.80\ g/cm^3$ — 50

b. Coefficient of thermal expansion

$a = 19.74 \times 10^{-6} + 2.62 \times 10^{-8}\ t + 0.15 \times 10^{-10}\ t^2$ — 51 (BaF_2)

(t is in °C with a temperature range of 26-296°C)

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 (AmF_3)

(2) Enthalpy in cal

$H_T - H_{298} = 21\ T + 3.5 \times 10^{-3}\ T^2$ — 33

(estimated from other actinide data)

CURIUM FLUORIDE (CmF_3) — REFERENCE COLUMN

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 LaF_3, CeF_3, and PrF_3.

e. Latent heats of phase transformations

ΔH fusion	9 kcal/mole	33 (CeF_3)
ΔH vaporization	62 kcal/mole	33 (CeF_3)

f. Vapor pressure — 53

Vapor pressure, torr	Temperature, °C
5.07×10^{-7}	853
7.18×10^{-6}	943
1.486×10^{-4}	1033
1.725×10^{-3}	1141
5.820×10^{-3}	1196

Vapor pressures are for AmF_3.

g. Thermal conductivity — 54 (BaF_2)

Thermal conductivity, cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0296	0
0.0251	100

h. Thermal diffusivity

Thermal diffusivity, cm^2/sec	Temperature, °C
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 (CmF_3) — REFERENCE COLUMN

m. Crystallography

Hexagonal, LaF_3-type, space group $P6_3/mmc$ — 55

$a = 4.041 \pm 0.001$ Å $c = 7.179 \pm 0.002$ Å

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

$\Delta H_f^\circ = -357$ kcal/mole — 15

(estimated from other actinide data)

(2) Free energy of formation

$\Delta F_f^\circ = -339$ kcal/mole — 15

(3) Entropy

$S_{298}^\circ = 29$ 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 ^{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.

REFERENCE COLUMN

II. CURIUM-242

A. 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

Isotope	% Abundance
^{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.

Time, days	^{242}Cm, g	^{238}Pu, g
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

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	Heat contribution %
^{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 8.35 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 Power

a. 42.8 w/g of AmO_2-Cm_2O_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 AmO_2-Cm_2O_3 (35.7% ^{242}Cm metal) 7

3. Radiation

a. Alpha particles 7

Nuclide	Max E, Mev	Av E, Mev	Abundance, %	w/kCi	Particles w^{-1} 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

[a]Standard 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. 7

Gamma-emission rate,[a] photons sec^{-1} g^{-1}	Photon energy, Mev
Curium-242 Gammas	
0.27×10^{14}	0.044
1.42×10^{10}	0.10
2.83×10^{9}	0.158
Prompt Gammas	
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

Gamma-emission rate,[a] photons sec^{-1} g^{-1}	Photon energy, Mev
Fission-Product Gammas	
2.16×10^7	0.63
7.99×10^6	1.1
9.36×10^6	1.55
1.80×10^6	2.38
2.66×10^6	2.75

[a]120-w source.

d. Bremsstrahlung

None

e. Neutrons

2.30×10^7 neutrons sec^{-1} g^{-1} of ^{242}Cm from spontaneous fission (120-w source) 7

2.0×10^7 neutrons sec^{-1} g^{-1} of ^{242}Cm from (α,n) reaction of oxygen in Cm_2O_3 (120-w source)

The energy distribution of spontaneous fission neutrons from ^{242}Cm 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	7.7×10^5
0.4-0.6	1.6×10^6
0.6-0.8	1.6×10^6
0.8-1.0	1.4×10^6
1.0-1.2	1.4×10^6
1.2-1.4	1.4×10^6
1.4-1.6	1.2×10^6
1.6-1.8	1.1×10^6
1.8-2.0	1.0×10^6
2.0-2.2	9.1×10^5
2.2-2.4	8.4×10^5
2.4-2.6	8.0×10^5
2.6-2.8	6.5×10^5
2.8-3.0	5.5×10^5
3.0-3.2	5.0×10^5
3.2-3.4	5.0×10^5
3.4-3.6	4.7×10^5
3.6-3.8	3.7×10^5
3.8-4.0	4.1×10^5

Spontaneous Fission Neutrons (continued)

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

[a]120-w source.

The energy distribution of neutrons occurring as a result of a collision of fast alpha particles from ^{242}Cm decay with oxygen atoms in Cm_2O_3 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	5.0×10^3
0.4	1.0×10^4
0.6	2.0×10^4
0.8	2.5×10^4
1.0	7.6×10^4
1.2	1.5×10^5
1.4	2.8×10^5
1.6	4.5×10^5
1.8	7.6×10^5
2.0	1.0×10^6
2.2	1.3×10^6
2.4	1.7×10^6
2.6	2.0×10^6
2.8	2.1×10^6
3.0	2.1×10^6
3.2	2.1×10^6
3.4	1.8×10^6

Neutrons from (α,n) Reactions (continued)

Energy, Mev	Abundance,[a] neutrons sec^{-1} g^{-1} of ^{242}Cm
3.6	1.5×10^6
3.8	1.0×10^6
4.0	6.5×10^5
4.2	4.0×10^5
4.4	2.8×10^5
4.6	1.8×10^5
4.8	5.0×10^4

[a]120-w source.

4. Critical Mass

5. 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 ^{242}Cm 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 ^{242}Cm tolerances taken from reference 26 are given in the table on the following page. 26

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[26]

Radionuclide and type of decay		Organ of reference (critical organ underscored)	Max permissible burden in total body, q(μCi)	Max permissible concentrations, μCi/cm³ For 40-hr week Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
$^{242}_{96}Cm$ (α, γ)	(Sol)	GI (LLI)[a]		7×10^{-4}	2×10^{-7}	2×10^{-4}	5×10^{-8}
		Liver	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)	Lung			2×10^{-10}		6×10^{-11}
		GI (LLI)[a]		7×10^{-4}	10^{-7}	3×10^{-4}	4×10^{-8}

[a]The 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 ^{242}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. 13. Neutron dose rates on shielding with Be, Ch, CH_2, or LiH can be estimated by using Fig. 13 in conjunction with Fig. 7. 7

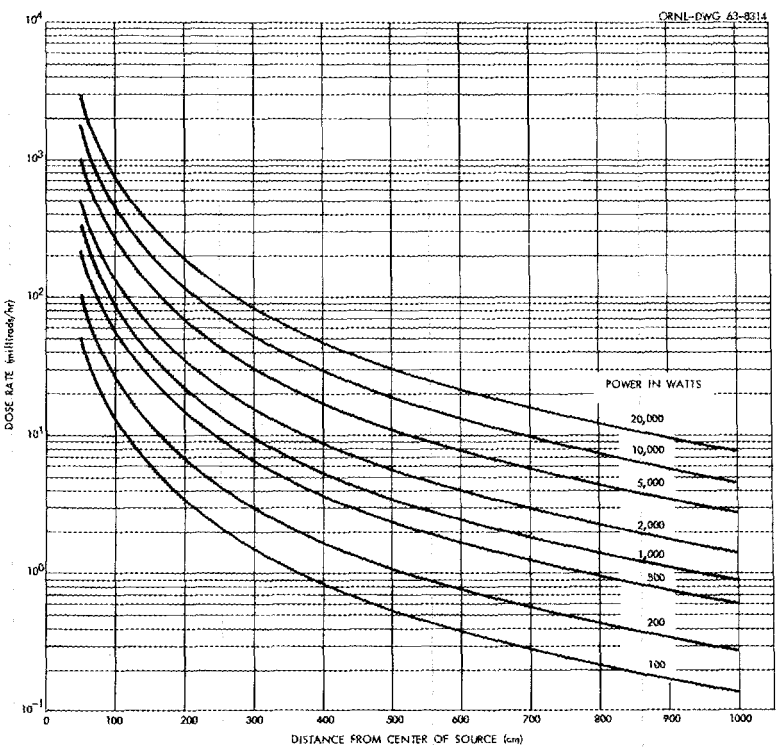

Fig. 8. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-242 as a Function of Distance from Center of Source.

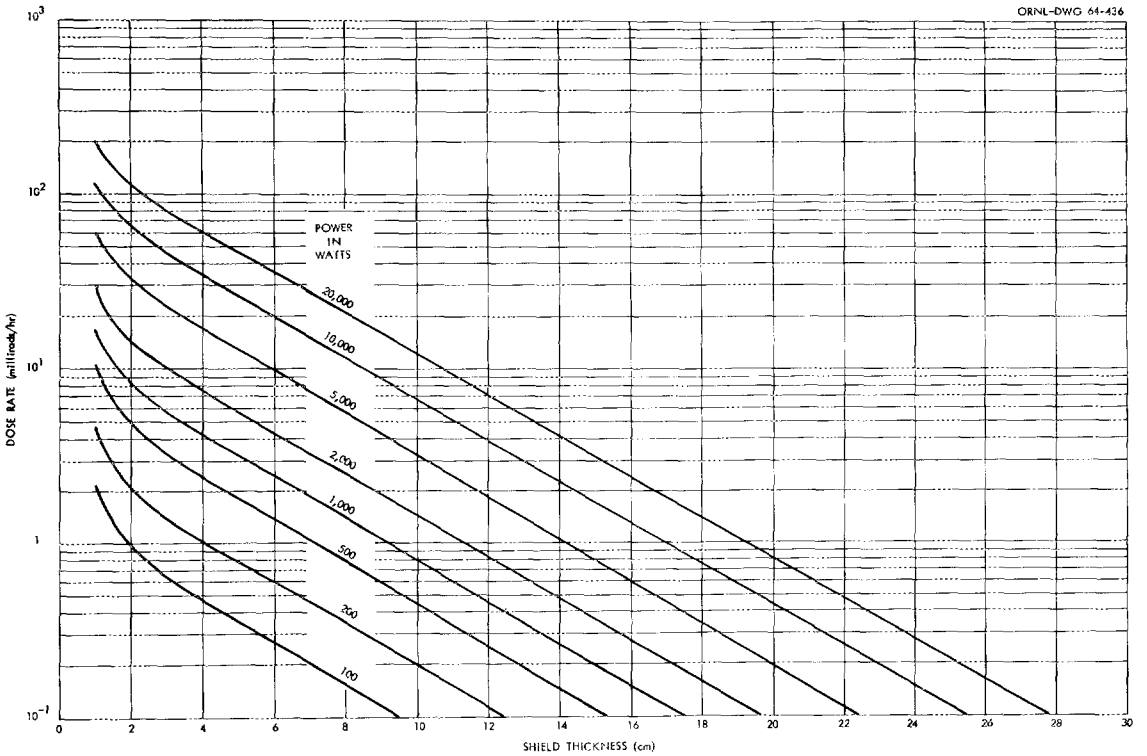

Fig. 9. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

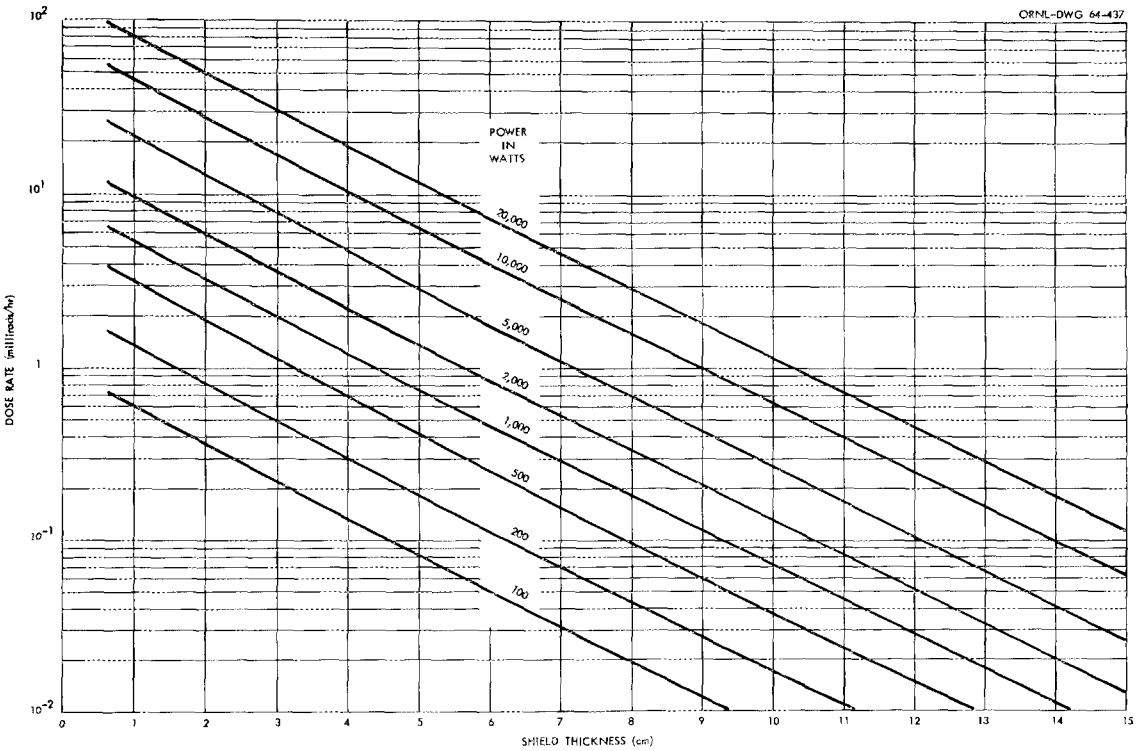

Fig. 10. Gamma Dose Rate from Lead-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

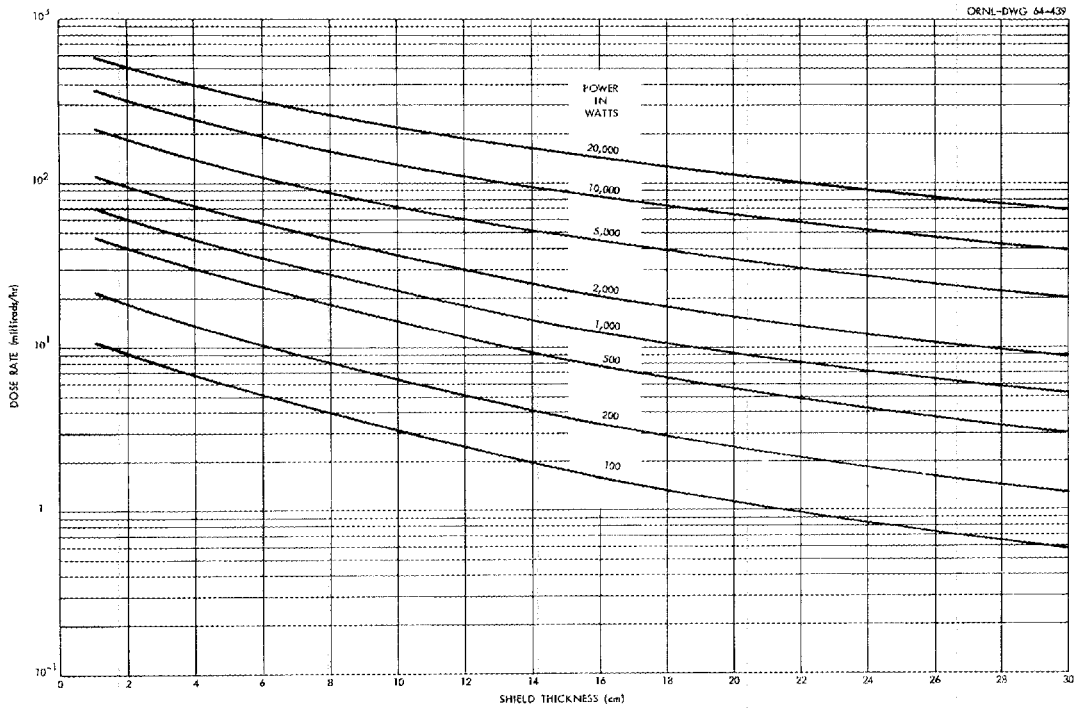

Fig. 11. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

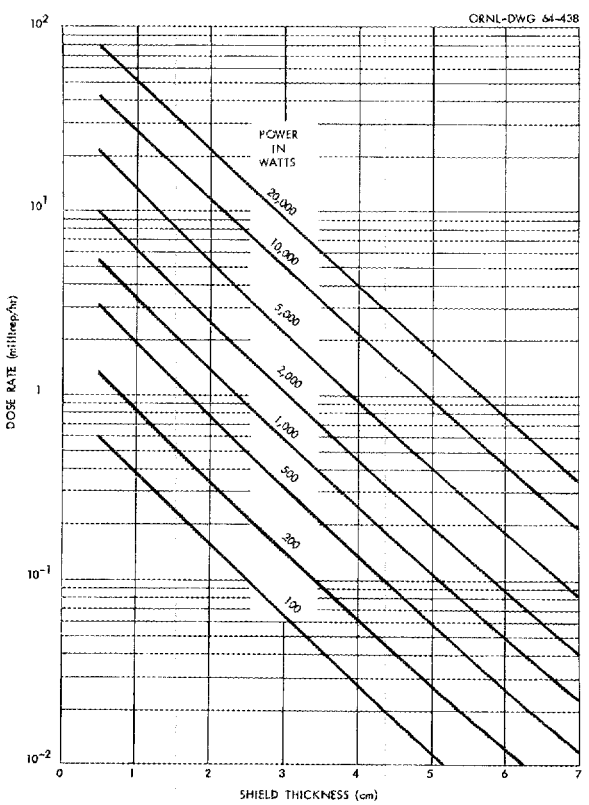

Fig. 12. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance is 100 cm.

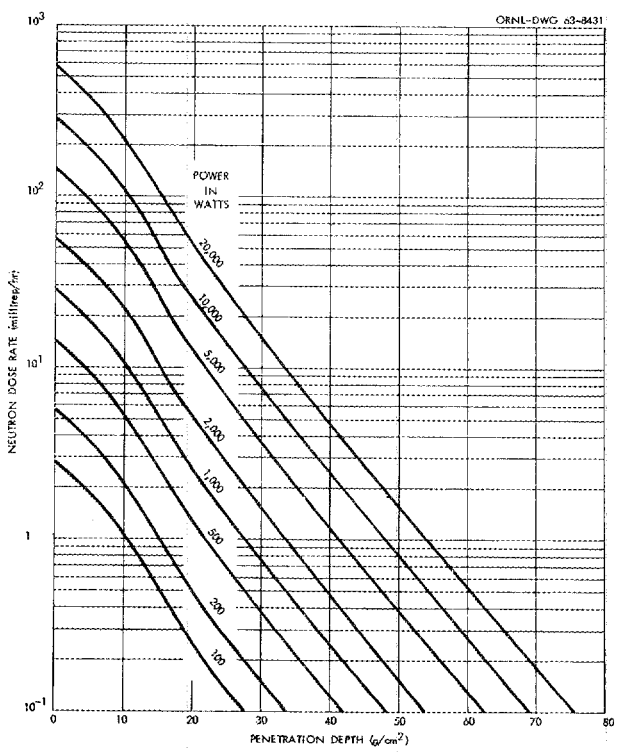

Fig. 13. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance is 100 cm. Refer to Fig. 7 for dose rates through other materials

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