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ORNL-4187
UC-4 – Chemistry

CURIUM DATA SHEETS

S. J. Rimshaw
E. E. Ketchen

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
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CURIUM DATA SHEETS

I. CURIUM-244 — REFERENCE COLUMN

A. CURIUM-244 METAL — HALF-LIFE: 18.1 y — 1

1. Composition

a. Radionuclidic abundance — 2

Element	Minimum, %	Maximum, %
Cm	99.5	99.8
Am	0.5	0.2

An average ^{244}Cm product will have the following analysis:

Isotope	% Abundance
^{244}Cm	95.5
^{245}Cm	1.6
^{246}Cm	2.7
^{243}Am	0.2

b. Radiochemical purity

Because of their long half-lives, the ^{245}Cm ($T_{1/2}$ = 8000 y), ^{246}Cm ($T_{1/2}$ = 6600 y), and ^{243}Am ($T_{1/2}$ = 8000 y) impurities act as inert diluents and contribute <0.1% of the total source power.

The radiations from these impurities are weak gammas or alpha particles and can be neglected because they are readily shielded. The prompt gammas and neutrons from the spontaneous fission will be only a few percent of that obtained from spontaneous fission of ^{244}Cm.

Since the ^{244}Cm decays to ^{240}Pu, the plutonium content in a 100% ^{244}Cm sample will slowly build up after the final purification step as shown in the following table.

Time, months	^{240}Pu, %
0	0
7.2	2.3
18	5.6
36	10.8
90	25.2

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ISOTOPES DEVELOPMENT CENTER

CURIUM DATA SHEETS

S. J. Rimshaw

E. E. Ketchen

Isotopes Division

DECEMBER 1967

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

CONTENTS

Page

I. CURIUM-244 1

A. CURIUM-244 METAL 1

B. CURIUM SESQUIOXIDE (Cm_2O_3) 17

C. CURIUM OXYSULFIDE (Cm_2O_2S) 22

D. CURIUM FLUORIDE (CmF_3) 25

II. CURIUM-242 29

A. CURIUM-242 OXIDE CERMET 29

III. REFERENCES FOR CURIUM 46

CURIUM DATA SHEETS

I. CURIUM-244 — REFERENCE COLUMN

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The radiations from these impurities are weak gammas or alpha particles and can be neglected because they are readily shielded. The prompt gammas and neutrons from the spontaneous fission will be only a few percent of that obtained from spontaneous fission of ^{244}Cm.

Since the ^{244}Cm decays to ^{240}Pu, the plutonium content in the sample will slowly build up after the final purification step as shown in the following table.

Time, months	^{240}Pu, %
0	0
7.2	2.7
18	6.4
36	12.3
90	27.8

2. Specific Power

a. 2.67 watts/g of metal (95.5% ^{244}Cm content) 2, 3, 4

It is assumed that there are 81 curies/g of ^{244}Cm and that there are 34.3 watts/kilocurie of ^{244}Cm.

b. 77.4 curies of ^{244}Cm per gram of metal 2, 3, 4

3. Radiation

a. Alpha particles 3, 5

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	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}
Total alpha power				34.3	

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

Volume of Helium as a Function of Decay Time

cm^3 of He per g of ^{244}Cm (standard conditions)	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
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

CURIUM-244 METAL

REFERENCE COLUMN

b. Beta particles — none

c. Gamma

The gammas come from three sources. First there are the gammas associated with the alpha decay of ^{244}Cm. Secondly, there are the prompt gammas from spontaneous fission. The fission-product gammas constitute the third gamma source. The gamma-emission rates are given in the following table. 2, 3, 5

Gamma-emission rate, photons sec^{-1} w^{-1} of ^{244}Cm	Photon energy, Mev
^{244}Cm gammas	
0.252×10^{12}	0.042
5.80×10^{7}	0.10
1.40×10^{7}	0.15
Prompt gammas from spontaneous fission	
4.34×10^{6}	1.0
1.084×10^{6}	1.5
1.15×10^{6}	2.3
2.03×10^{5}	3.0
2.71×10^{5}	5.0
Fission-product gammas	
3.84×10^{6}	0.63
1.42×10^{6}	1.1
1.66×10^{6}	1.55
3.20×10^{5}	2.38
4.73×10^{5}	2.75

d. Bremsstrahlung — none

e. Neutrons

4.19×10^{6} neutrons sec^{-1} w^{-1} of ^{244}Cm from spontaneous fission 5, 6, 7
(Half-life for spontaneous fission is 1.4×10^{7} y)

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

CURIUM-244 METAL

REFERENCE COLUMN

The energy distribution of spontaneous fission neutrons from ^{244}Cm is given in the following table. 2

Spontaneous Fission Neutrons From Curium-244

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. 2

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. 8

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

Core		Reflector			
Mixture	Density, g/cm^3	Mixture	Thickness, cm	Critical mass, kg	Critical radius, 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

Critical Mass Equations

Cm: $M_c = 2450/\rho^2$ (kg) Cm_2O_3: $M_c = 2370/\rho^2$ (kg)

[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 9

b. Coefficient of thermal expansion

$\alpha_a = 7.5 \times 10^{-6}/°C$ 10 (Am)

$\alpha_c = 6.2 \times 10^{-6}/°C$

c. Specific heat and enthalpy

(1) Specific heat

0.0270 cal g^{-1} $°C^{-1}$ 11 (Nd)

(2) Enthalpy in calories/mole

$H_t - H_o = 6.48 + 3.53 \times 10^{-3}\ t^2 + 1.49 \times 10^{-6}\ t^3$ 12 (Nd)

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

d. Temperatures of phase transformations

(1) Melting point – 1340°C 9

(2) Boiling point – 3100°C 13

(Average of terbium and gadolinium boiling points)

CURIUM-244 METAL

		REFERENCE COLUMN
e.	Latent heats of phase transformations	
	ΔH fusion 37.5 kcal/mole (Richard's rule)	11
	ΔH vaporization 77.0 kcal/mole (Trouton's rule)	11
f.	Vapor pressure	
	$\log_{10} P = 8.4 - 18{,}400/T$	14
	(T is in °K and P is in torr)	
	This is an average of neodymium, gadolinium, and terbium.	
g.	Thermal conductivity	
	0.021 cal cm^{-1} sec^{-1} $°C^{-1}$ at 26°C	15 (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	16
j.	Surface tension	
	500 dyn/cm	17
k.	Total hemispherical emittance	
	0.37 at 89°C	18 (Pu)
l.	Spectral emissivity	
	0.55	19 (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	9
	a = 3.496 ± 0.003 Å	
	c = 11.331 ± 0.005 Å	
n.	Solubilities	
	Reacts strongly with water	20
o.	Diffusion rates	

CURIUM-244 METAL

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

Vicker's – 97.7 — 13 (Dy)

b. Crush strength

7741 kg/cm^2 — 13 (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 (temperature)

$S^{\circ}_{298} = 15$ cal $°C^{-1}$ $mole^{-1}$ — 21 (Am)

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other)

(1) Oxygen at room temperature – slow — 9

(2) Oxygen at elevated temperature – fast — 9

(3) Nitrogen at room temperature – very slow — 22

(4) Nitrogen at elevated temperature – slow — 22

(5) Water at room temperature – fast — 20

(6) Hydrogen at room temperature – slow — 20

(7) Hydrogen at elevated temperature – fast — 20

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and water are shown in the table on the following page. — 23

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 watts. 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.

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[23]

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max. permissible burden in total body, q(μc)	Maximum permissible concentrations, μc/cm³ For 40-hr week Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
$_{96}Cm^{244}$	(Sol) Bone	0.1	2×10^{-4}	9×10^{-12}	7×10^{-5}	3×10^{-12}
(α,γ)	(Sol) Liver	0.2	3×10^{-4}	10^{-11}	9×10^{-5}	4×10^{-12}
	(Sol) Kidney	0.2	4×10^{-4}	2×10^{-11}	10^{-4}	6×10^{-12}
	(Sol) Total Body	0.3	6×10^{-4}	3×10^{-11}	2×10^{-4}	9×10^{-12}
	(Sol) GI (LLI)*		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
	(Insol) Lung			10^{-10}		3×10^{-11}
	(Insol) GI (LLI)*		8×10^{-4}	10^{-7}	3×10^{-4}	5×10^{-8}

*The abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

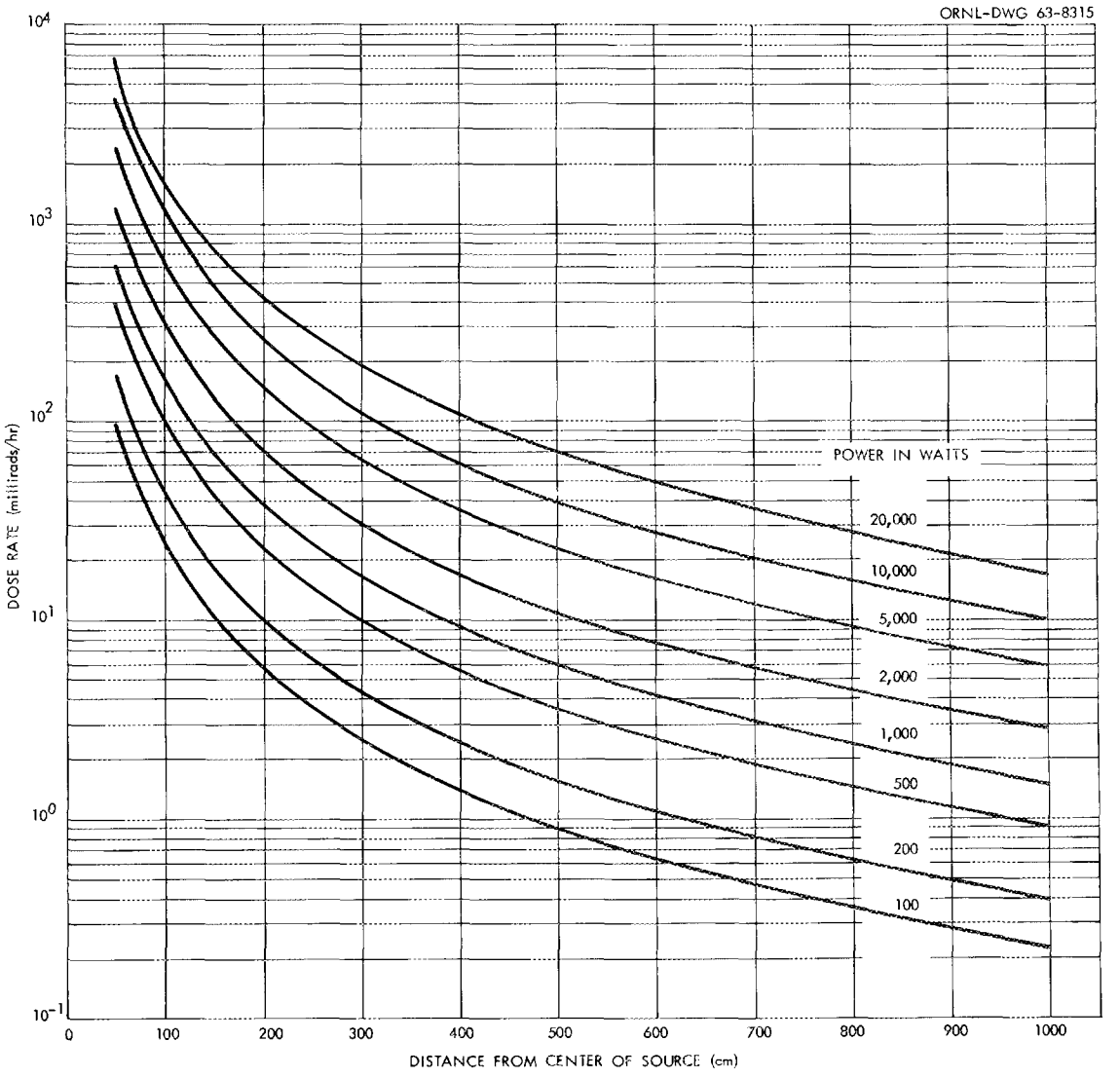

Fig. 1. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-244 as a Function of Distance from Center of Source.

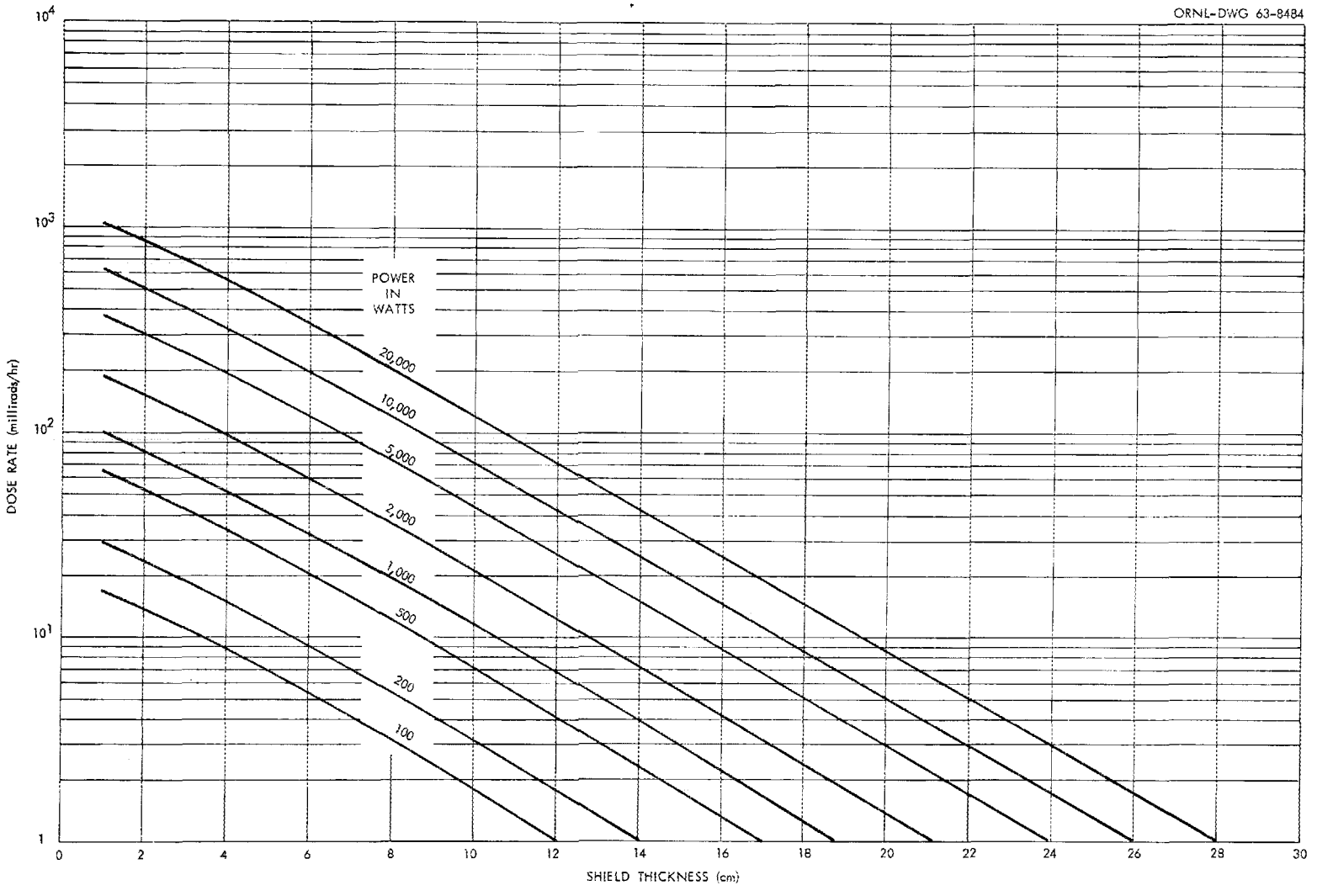

Fig. 2. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

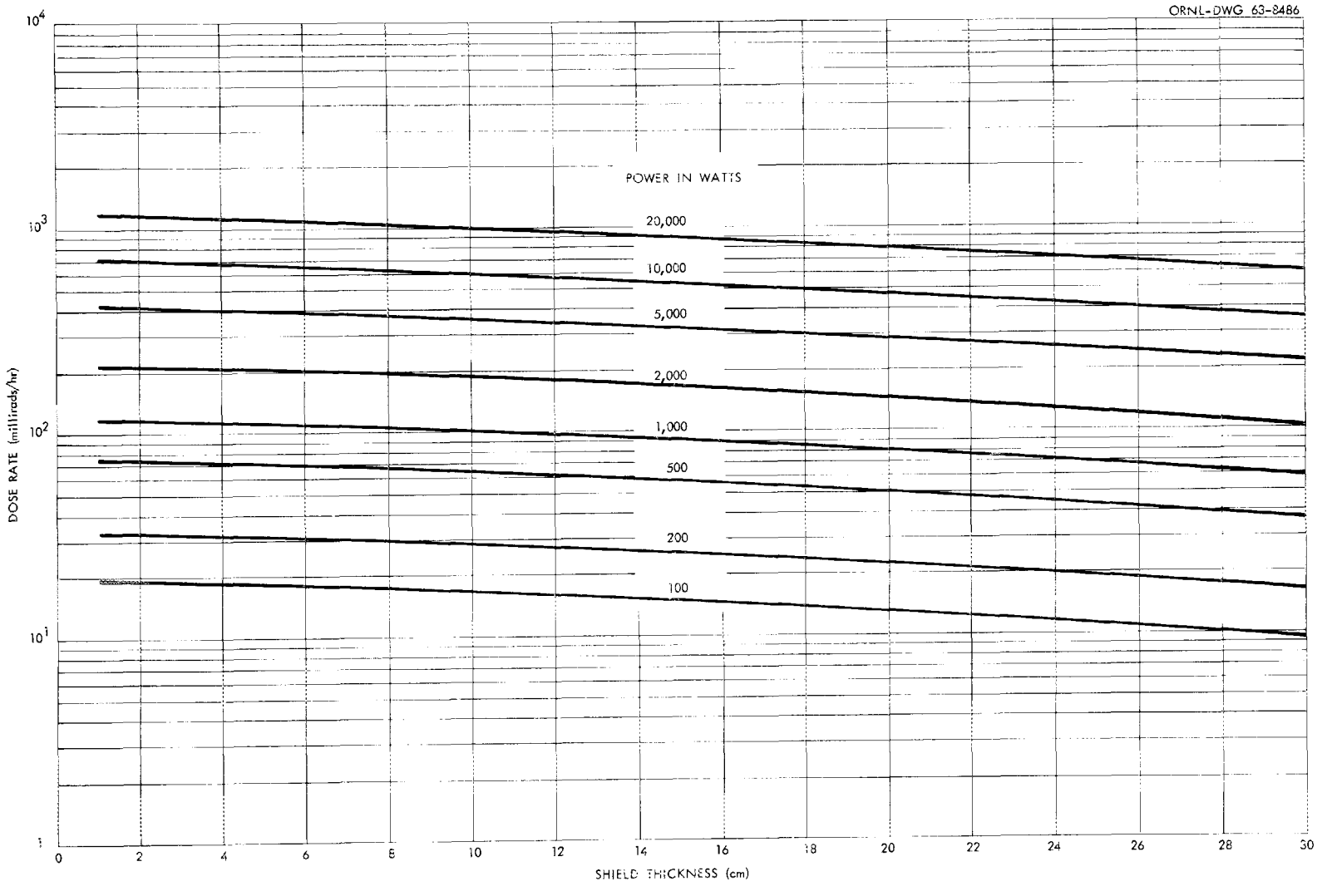

Fig. 3. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

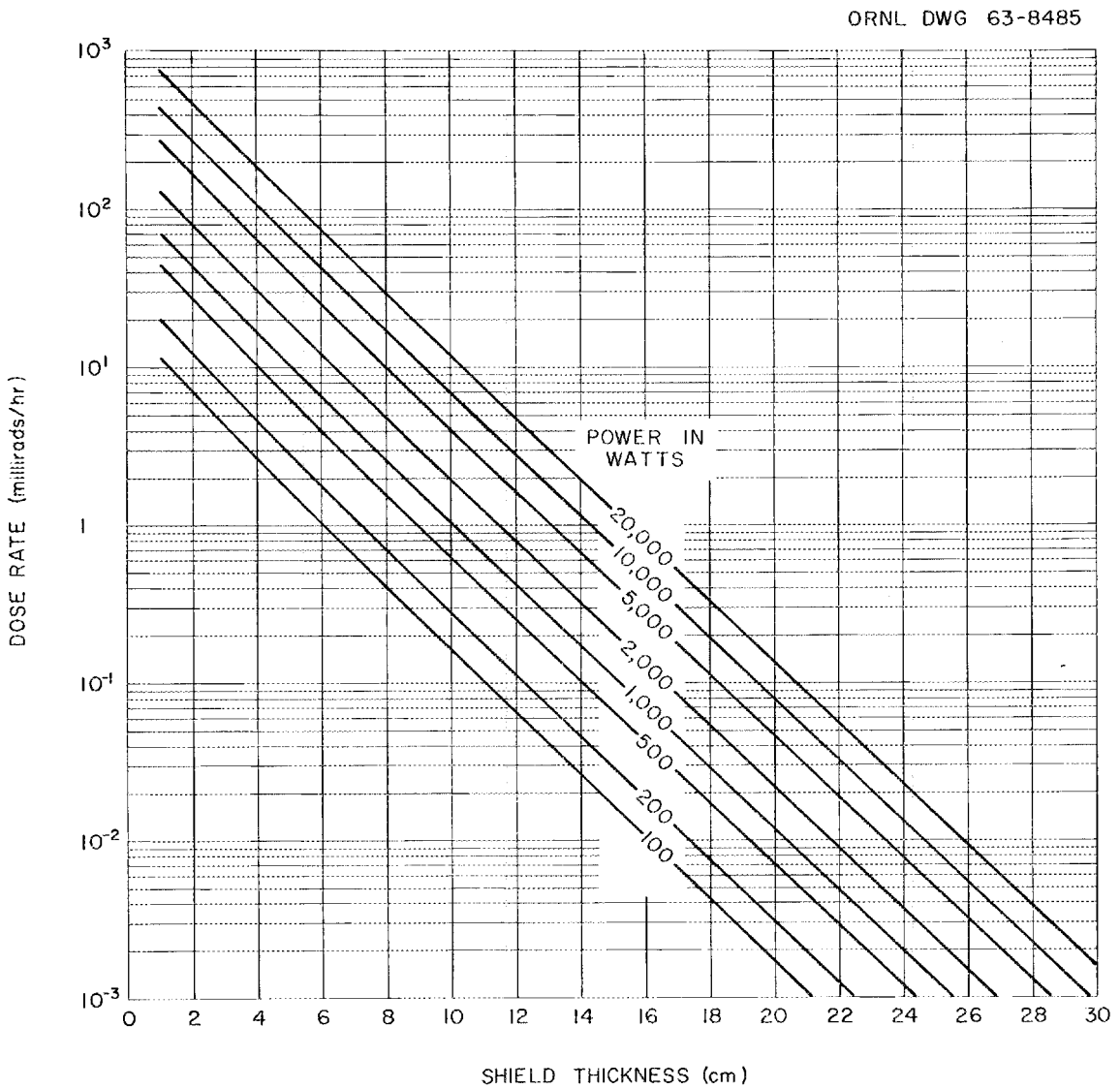

Fig. 4. Gamma Dose Rates from Lead-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

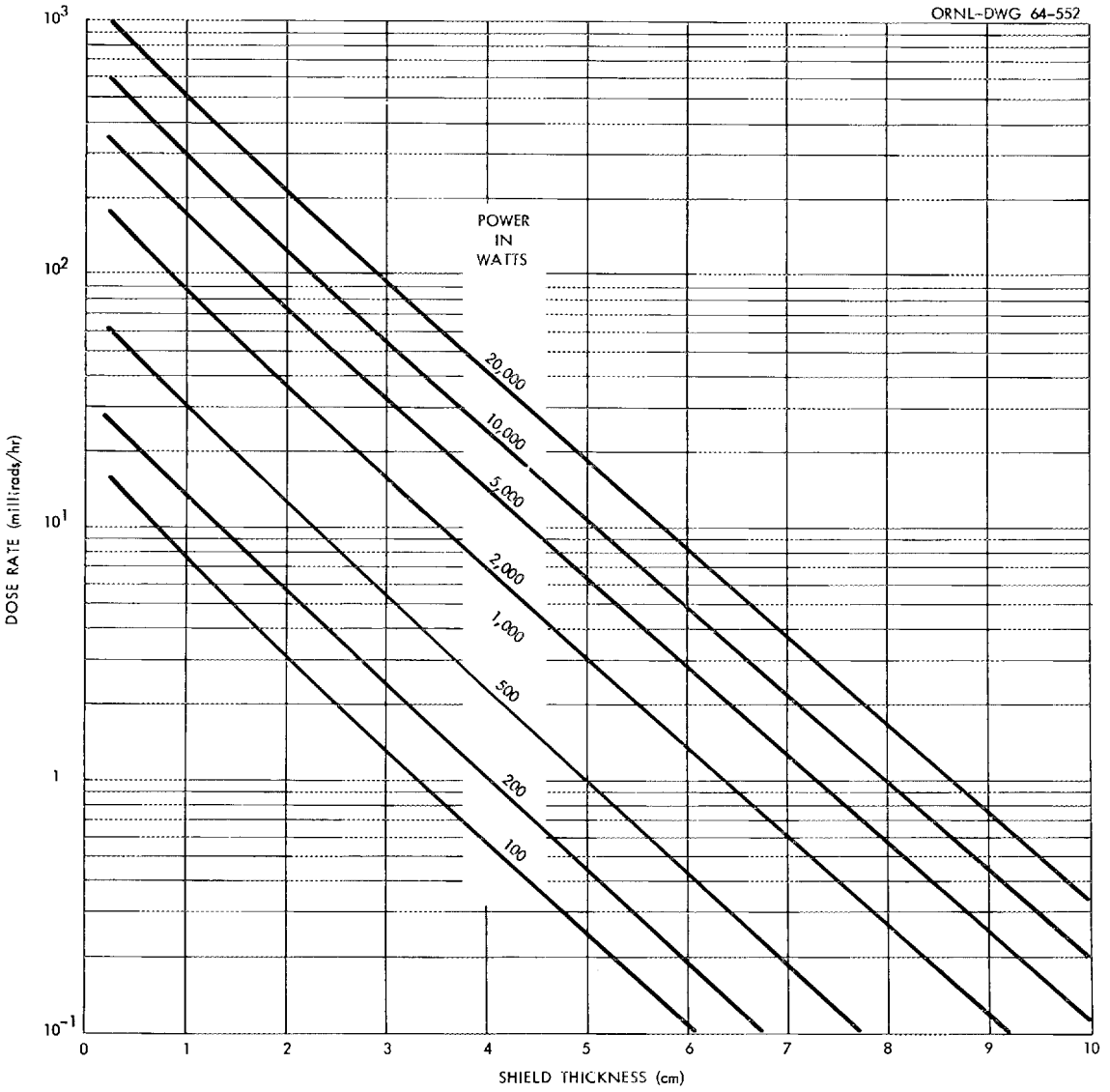

Fig. 5. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-244. Center of source to dose point separation distance = 100 cm.

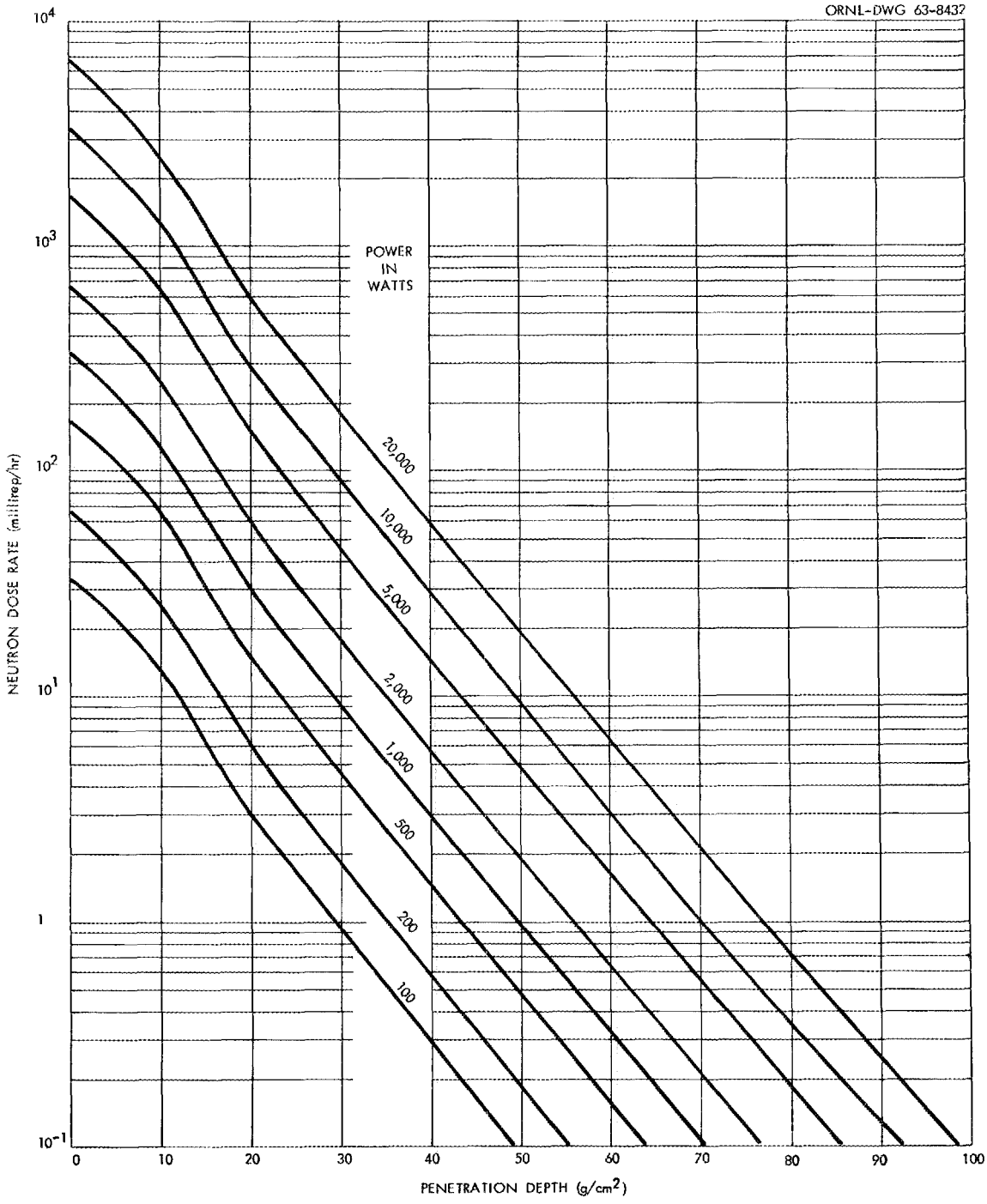

Fig. 6. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-244 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance = 100 cm.

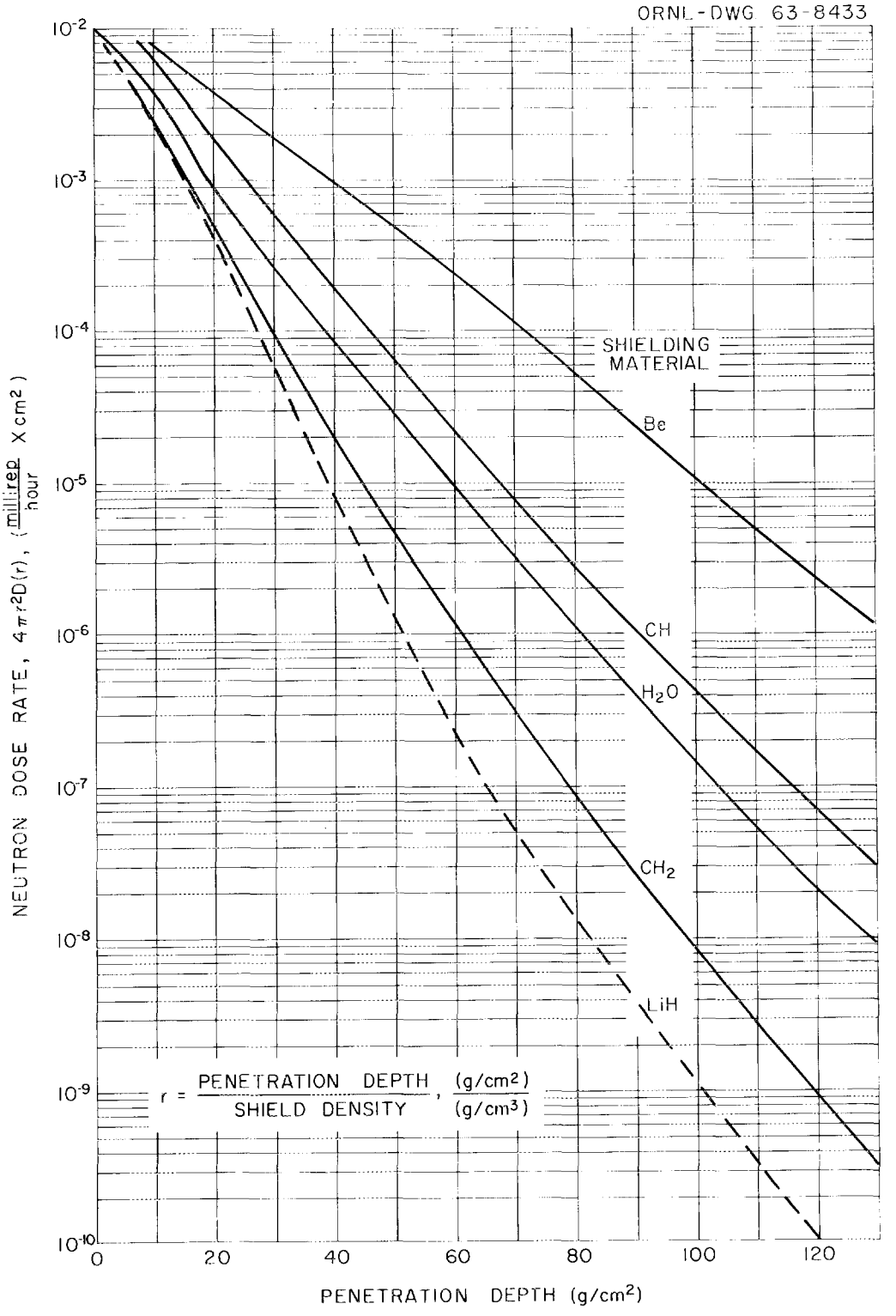

Fig. 7. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth from a Unit Point Isotropic Fission Source.

REFERENCE COLUMN

B. CURIUM SESQUIOXIDE (Cm_2O_3)

1. Composition

a. Radionuclidic abundance

See Section I.A.1.

b. Radiochemical purity

See Section I.A.1.

c. Phase composition of various curium oxides — 24, 25, 26

$CmO_{2.00}$	$CmO_{1.77}$	$CmO_{1.68}$
$CmO_{1.91}$	$CmO_{1.72}$	$CmO_{1.50}$
$CmO_{1.85}$		

2. Specific Power

a. 2.53 watts/g of pure Cm_2O_3 (91.0% ^{244}Cm metal)
2.42 watts/g of Cm_2O_3 (86.9% Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm metal and 34.3 watts/kilocurie of ^{244}Cm.

b. 73.7 curies of ^{244}Cm per gram of pure Cm_2O_3 (91.0% ^{244}Cm metal) — 2, 3, 4
70.5 curies of ^{244}Cm per gram of Cm_2O_3 (86.9% Cm metal)

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 USAEC Rpt. ORNL-4189, Compatibility Data Sheets for Cerium-144, Cesium-137, Curium, and Strontium-90 (classified).

6. Thermophysical Properties

a. Density

C-type (bcc) — 10.79 g/cm^3 at room temperature	27 (calc)
B-type (monoclinic) — 11.67 g/cm^3 at room temperature	28
A-type (hex) — 11.4 g/cm^3 at 1640°C	29
A-type (hex) — 11.1 g/cm^3 at 1750°C	27 (calc)
A-type (hex) — 11.0 g/cm^3 at 1910°C	27 (calc)

CURIUM SESQUIOXIDE (Cm_2O_3)

REFERENCE COLUMN

b. Thermal expansion

B-type (monoclinic) Cm_2O_3 — 30

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) — 31 (Am_2O_3)

(2) Enthalpy in calories/mole

d. Temperatures of phase transformations

(1) Melting point

C-type Cm_2O_3 (bcc) transforms to A-type Cm_2O_3 (hex) by self-radiation damage at room temperature in a few weeks. — 27

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. — 27

B-type Cm_2O_3 (monoclinic) transforms reversibly to A-type Cm_2O_3 (hex) at 1600°C. — 27

A-type Cm_2O_3 (hex) melts at 1950°C. — 27, 32

(2) Boiling point ~ 3130°C — 31 (Am_2O_3)

(3) Decomposition temperatures to lower oxides at oxygen pressures as cited: — 26

Oxide	Temperature, °C		
	P O_2 = 10^{-5}	3×10^{-3}	1 atm
$CmO_{2.00}$	360	391	440
$CmO_{1.91}$	Nonexistent	Nonexistent	520
$CmO_{1.85}$	520	625	>700
$CmO_{1.77}$	725	870	--
$CmO_{1.73}$	870	1065	--
$CmO_{1.68}$	1070	>1120	--
$CmO_{1.50}$	--	--	--

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole — 31 (Am_2O_3)

ΔH vaporization 114 ± 8 kcal/mole — 33

CURIUM SESQUIOXIDE (Cm_2O_3)

REFERENCE COLUMN

f. Vapor pressure 34

Temperature, °C	Experimental vaporization rate, g cm^{-2} sec^{-1}	Calculated vapor pressure of Cm_2O_3,* atm
1623	0.71×10^{-6}	0.30×10^{-7}
1628	0.15×10^{-5}	0.62×10^{-7}
1667	0.23×10^{-5}	0.97×10^{-7}
1694	0.30×10^{-5}	0.13×10^{-6}
1731	0.60×10^{-5}	0.26×10^{-6}
1749	0.63×10^{-5}	0.28×10^{-6}
1784	0.14×10^{-4}	0.64×10^{-6}
1816	0.13×10^{-4}	0.57×10^{-6}
1829	0.18×10^{-4}	0.82×10^{-6}

*Vapor pressure calculated assuming vaporization reaction $Cm_2O_3(s) = Cm_2O_3(g)$. Actual vaporization species is unknown. Vapor pressures calculated for other possible vaporization reactions of Cm_2O_3 are higher by factors up to 1.87.

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0245	100
0.0204	200
0.0143	400
0.0104	600
0.0081	800
0.0073	1000
0.0060	1200
0.0059	1400

35 (ThO_2)

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0478	100
0.0111	800
0.00645	1400

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

i. Viscosity

CURIUM SESQUIOXIDE (Cm_2O_3)

REFERENCE COLUMN

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 19 (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 produced by reducing CmO_2 in 1% O_2–99% He at 780°C. — 27

a = 10.97 ± 0.01 Å at room temperature

Monoclinic, B-type rare-earth oxide structure obtained by irreversible transformation from C-type on heating between 800-1300°C. — 27

a = 14.27 Å at room temperature

b = 3.65 Å at room temperature

c = 8.92 Å at room temperature

β = 100°16' at room temperature

A-type Cm_2O_3 (formed on W filament in 4% H_2/He). — 36

a = 3.845 ± 0.005 Å at 1650°C

c = 6.092 ± 0.005 Å at 1650°C

H-type Cm_2O_3 (formed on Ir filament in He). — 36

a = 3.863 ± 0.001 Å at 1750°C

c = 6.174 ± 0.001 Å at 1750°C

a = 3.888 ± 0.001 Å at 1910°C

c = 6.195 ± 0.002 Å at 1910°C

c = 6.022 Å at 20°C after quench from 1750°C (only 002 peak observed)

n. Solubilities

Insoluble in water — 20

o. Diffusion rates

CURIUM SESQUIOXIDE (Cm_2O_3)

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

b. Crush strength

1900 kg/cm^2 — 37 (CeO_2)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation (estimated from data on other actinide oxides) — 38

Phase	$-\Delta H^\circ_f$ (298°C), kcal/mole
$CmO_{2.00}$	236 ± 8
α ($CmO_{1.72}$)	218 ± 10
β ($CmO_{1.50}$)	207 ± 15
CmO	135 ± 10

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

ΔF°_f = -226 kcal/mole — calc

(3) Entropy

S°_{298} = 26 ± 4 eu — 33

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen liquid metals, other)

(1) Oxygen at room temperature — slow

(2) Oxygen at elevated temperature — fast — 20

(3) Nitrogen — no reaction

(4) Water — possible hydration reaction

(5) Inorganic acids — soluble in acids

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. — 23

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.

b. Radiochemical purity

See Section I.A.1.

2. Specific Power

a. 2.46 watts/g of pure Cm_2O_2S (88.4% ^{244}Cm metal)
2.35 watts/g of Cm_2O_2S (84.4% ^{244}Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm and 34.3 watts/kilocurie of ^{244}Cm.

b. 71.6 curies of ^{244}Cm per gram of pure Cm_2O_2S (88.4% ^{244}Cm metal) — 2, 3, 4
68.4 curies of ^{244}Cm per gram of Cm_2O_2S (84.4% ^{244}Cm metal)

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 — 39 (Pu_2O_2S)

b. Coefficient of thermal expansion

0.60% over 25-680°C — 30 (Cm_2O_3)
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) — 31 (Am_2O_3)

(2) Enthalpy in calories

CURIUM OXYSULFIDE (Cm_2O_2S)

REFERENCE COLUMN

d. Temperatures of phase transformations

(1) Melting point – 2000°C — 40 (Ce_2O_2S)

(2) Boiling point – 3130°C — 31 (Am_2O_3)

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole — 31 (Am_2O_3)

ΔH vaporization 85 kcal/mole — 31 (Am_2O_3)

f. Vapor pressure

g. Thermal conductivity — 35 (ThO_2)

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0245	100
0.0081	800
0.0059	1400

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0528	100
0.0116	800
0.00708	1400

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

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 19 (ThO_2)

The emissivity value depends on the roughness of the material surface, radiation effects, and the presence of impurities.

m. Crystallography

hexagonal — 39 (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.

CURIUM OXYSULFIDE (Cm_2O_2S)

REFERENCE COLUMN

n. Solubilities

(1) Soluble in strong acids (Ce_2O_2S) 41

(2) Insoluble in acetic acid (Ce_2O_2S) 41

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

$\Delta H^\circ_f = -430$ kcal/mole 40

(approximated by Ce_2O_2S)

(2) Free energy of formation

$\Delta F^\circ_f = -414$ kcal/mole

(calculated by $\Delta F^\circ_f = \Delta H^\circ_f - T\Delta S^\circ_f$)

(3) Entropy

$S^\circ_{298} = 34.3$ eu 42

(calculated by W. Latimer's method)

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other) 39

(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. 23

10. Shielding Data

The 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.

b. Radiochemical purity

See Section I.A.1.

2. Specific Power

a. 2.25 watts/g of pure CmF_3 (81.1% ^{244}Cm metal)
2.15 watts/g of CmF_3 (77.5% ^{244}Cm metal)

It is assumed that there are 81 curies/g of ^{244}Cm and 34.3 watts/kilocurie of ^{244}Cm.

b. 65.7 curies of ^{244}Cm per gram of pure CmF_3 (81.1% ^{244}Cm metal) — 2, 3, 4
62.7 curies of ^{244}Cm per gram of CmF_3 (77.5% ^{244}Cm metal)

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 — 43

b. Coefficient of thermal expansion

$$a = 19.74 \times 10^{-6} + 2.62 \times 10^{-8}\, t + 0.15 \times 10^{-10}\, t^2$$ — 44 (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) — 31 (AmF_3)

CURIUM FLUORIDE (CmF_3)

REFERENCE COLUMN

(2) Enthalpy in calories

$H_T - H_{298} = 21\ T + 3.5 \times 10^{-3}\ T^2$ — 31

(estimated from other actinide data)

d. Temperatures of phase transformations

(1) Melting point — 1406°C — 45

(2) Boiling point — 2330°C — 12

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 — 31 (CeF_3)

ΔH vaporization 62 kcal/mole — 31 (CeF_3)

f. Vapor pressure

Vapor pressure, torr	Temperature, °C	
5.07×10^{-7}	853	46
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

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	
0.0296	0	47 (BaF_2)
0.0251	100	

h. 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

CURIUM FLUORIDE (CmF_3)

REFERENCE COLUMN

k. Total hemispherical emittance
A value of 0.9 can be assumed.

l. Spectral emissivity

m. Crystallography
hexagonal, LaF_3-type, space group $P6_3/mmc$ 48
$a = 4.041 \pm 0.001$ 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
$\Delta H^\circ_f = -395$ kcal/mole 31
(estimated from other actinide data)

(2) Free energy of formation
$\Delta F^\circ_f = -375$ kcal/mole 31
(estimated from other actinide data)

(3) Entropy
$S^\circ_{298} = 29$ eu 31
(estimated from other actinide data)

b. Chemical reactions and reaction rates
(oxygen, nitrogen, water, steam, hydrogen, liquid metals, other)

(1) Air at room temperature — no reaction

(2) Air at elevated temperature — forms oxyfluoride 20

(3) Nitrogen — no reaction

(4) Water — insoluble

(5) Inorganic acids — insoluble in weak inorganic acid

CURIUM FLUORIDE (CmF_3)

REFERENCE COLUMN

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. 23

10. Shielding Data

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

II. CURIUM-242 — REFERENCE COLUMN

A. CURIUM-242 OXIDE CERMET — HALF-LIFE: 163 d — 1, 3, 5, 7

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: 49

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

CURIUM-242 OXIDE CERMET

REFERENCE 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. 49

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 curies 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 Power

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

It is assumed that there are 3320 curies/g of ^{242}Cm and 36.1 watts/kilocurie of ^{242}Cm. 6

b. 1186 curies of ^{242}Cm per gram of AmO_2-Cm_2O_3 (35.7% ^{242}Cm metal) 5

3. Radiation

a. Alpha particles 5

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	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}
Total power				36.10	

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

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 as a Function of Decay Time

cm^3 of He per g of ^{242}Cm (standard conditions)	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

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 ($T_{1/2}$ = 7.2×10^6 y). The gamma-emission rates are given in the following table. 5

Gamma-emission rate,* photons sec^{-1} g^{-1}	Photon energy, Mev
^{242}Cm 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

REFERENCE COLUMN

Gamma-emission rate,* 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

*120-watt source.

d. Bremsstrahlung — none

e. Neutrons

2.30×10^7 neutrons sec^{-1} g^{-1} of ^{242}Cm from spontaneous fission (120-watt source) 5

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

The energy distribution of spontaneous fission neutrons from ^{242}Cm is given in the following table. 2

Spontaneous Fission Neutrons From ^{242}Cm

Energy, Mev	Abundance,* 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

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

Spontaneous (continued)

Energy, Mev	Abundance,* 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

*120-watt 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. 2

Neutrons From (α,n) Reactions With Oxygen

Energy, Mev	Abundance,* 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

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

Neutrons (continued)

Energy, Mev	Abundance,* neutrons sec^{-1} g^{-1} of ^{242}Cm
3.0	2.1×10^6
3.2	2.1×10^6
3.4	1.8×10^6
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

*120-watt source.

4. Critical Mass

5. Compatibility With Materials of Containment

See USAEC Rpt. ORNL-4189, Compatibility Data Sheets for Cerium-144, Cesium-137, Curium, and Strontium-90 (classified).

6. Thermophysical Properties

a. Density

The density of oxide mixture is equal to 11.67 g/cm^3. 28

b. Coefficient of thermal expansion

46 (Nd_2O_3)

Linear coefficient of expansion, $°C^{-1}$	Temperature, °C
8.90×10^{-6}	300
10.60×10^{-6}	500
11.35×10^{-6}	800
11.41×10^{-6}	1050

The thermal coefficient of expansion of the cermet will depend markedly on the matrix material.

c. Specific heat and enthalpy

(1) Specific heat

Values will depend on the matrix material.

(2) Enthalpy

Values will depend on the matrix material.

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

d. Temperatures of phase transformations

(1) Melting point – 2000-2200°C for AmO_2-Cm_2O_3 mixture — 32

(2) Boiling point – 3400°C for AmO_2-Cm_2O_3 mixture — 31 (Am_2O_3)

e. Latent heats of phase transformations

ΔH fusion 17 kcal/mole — 31 (Am_2O_3)

ΔH vaporization 114 ± 8 kcal/mole — 33 (Cm_2O_3)

f. Vapor pressure

Will depend primarily on the matrix metal and on the temperature.

g. Thermal conductivity — 35 (ThO_2)

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C
0.0245	100
0.0143	400
0.0081	800
0.0059	1400

With the selection of the proper matrix material for cermet, it should be possible to reach a 0.06 cal cm^{-1} sec^{-1} $°C^{-1}$ thermal conductivity for the cermet.

h. Thermal diffusivity

Values will depend on the matrix material.

i. Viscosity

The viscosity will depend primarily on the properties of the matrix metal.

j. Surface tension

The surface tension will depend primarily on the properties of the matrix metal.

k. Total hemispherical emittance

l. Spectral emissivity

0.20-0.57 — 19 (ThO_2)

The matrix material will have a pronounced effect on the emissivity.

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

m. Crystallography

Body-centered cubic, C-type rare-earth oxide structure produced by reducing CmO_2 in 1% O_2–99% He at 780°C. 27

a = 10.97 ± 0.01 Å at room temperature

Monoclinic, B-type rare-earth oxide structure obtained by irreversible transformation from C-type on heating between 800-1300°C. 37

a = 14.27 Å at room temperature

b = 3.65 Å at room temperature

c = 8.92 Å at room temperature

β = 100°16' at room temperature

A-type Cm_2O_3 (formed on W filament in 4% H_2/He). 36

a = 3.845 ± 0.005 Å at 1650°C

c = 6.092 ± 0.005 Å at 1650°C

H-type Cm_2O_3 (formed on Ir filament in He). 36

a = 3.863 ± 0.001 Å at 1750°C

c = 6.174 ± 0.001 Å at 1750°C

a = 3.888 ± 0.001 Å at 1910°C

c = 6.195 ± 0.002 Å at 1910°C

c = 6.022 Å at 20°C after quench from 1750°C (only 002 peak observed)

n. Solubilities

Insoluble in water 20 (Cm_2O_3)

o. Diffusion rates

7. Mechanical Properties

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

a. Hardness

b. Crush strength

CURIUM-242 OXIDE CERMET

REFERENCE COLUMN

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation (estimated from data on other actinide oxides) 38

Phase	$-\Delta H^\circ_f$ (298°C), kcal/mole
$CmO_{2.00}$	236 ± 8
α ($CmO_{1.72}$)	218 ± 10
β ($CmO_{1.50}$)	207 ± 15
CmO	135 ± 10

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

$\Delta F^\circ_f = -226$ kcal/mole calc

(3) Entropy

$S^\circ_{298} = 26 \pm 4$ eu 33

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen liquid metals, other)

These properties will depend on the matrix material.

9. Biological Tolerances

The ^{242}Cm tolerances taken from Ref 23 are given in the table on the following page. 23

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 watts. 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. 14. 5

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[23]

Radionuclide and type of decay	Organ of reference (critical organ underscored)	Max. permissible burden in total body, q(μc)	Maximum permissible concentrations, μc/cm³ For 40-hr week Water	For 40-hr week Air	For 168-hr week Water	For 168-hr week Air
(Sol)	GI (LLI)*		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)*		7×10^{-4}	10^{-7}	3×10^{-4}	4×10^{-8}

*The abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

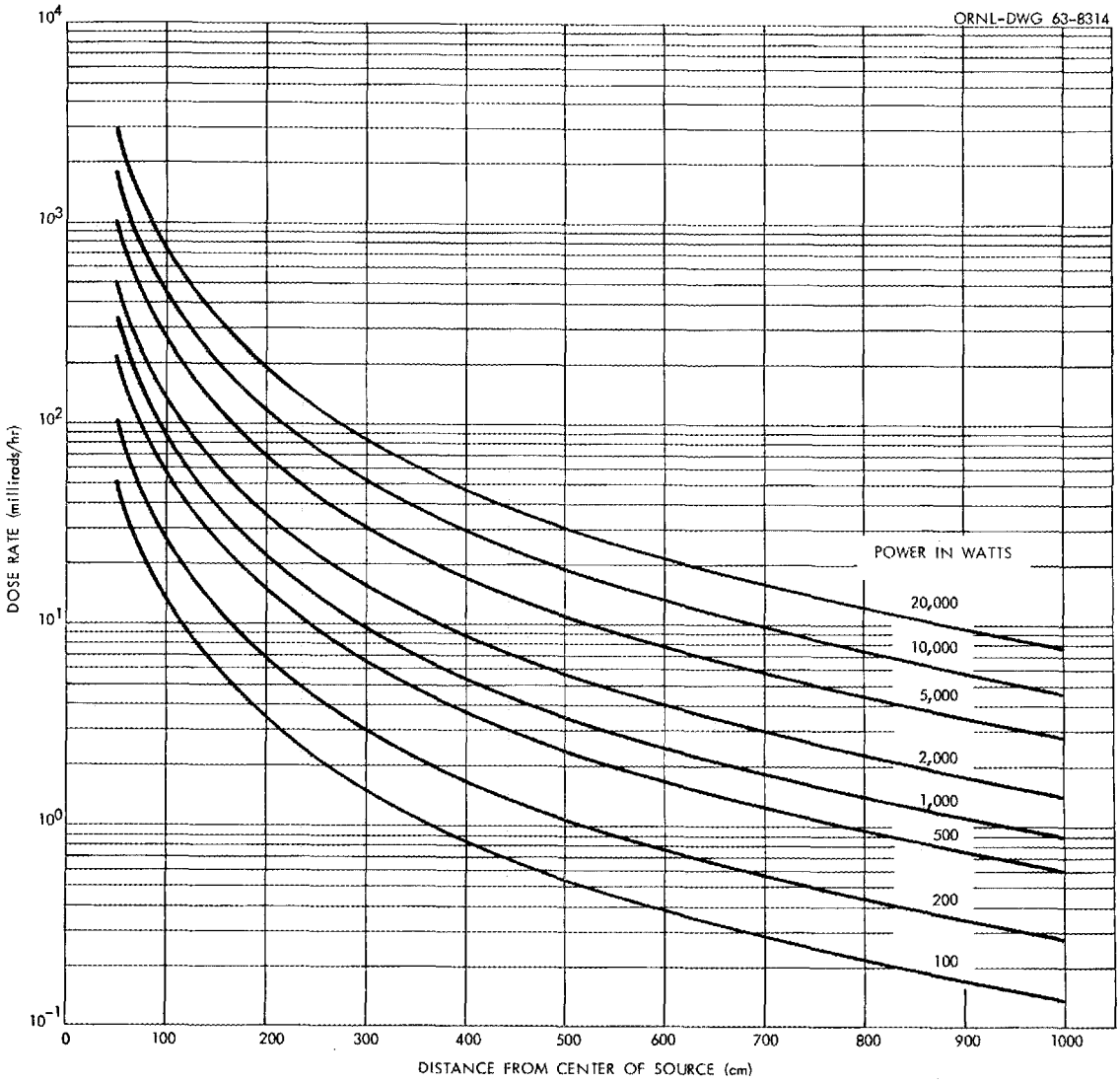

Fig. 8. Gamma Dose Rates from Unshielded Isotopic Power Sources of Curium-242 as a Function of Distance from Center of Source.

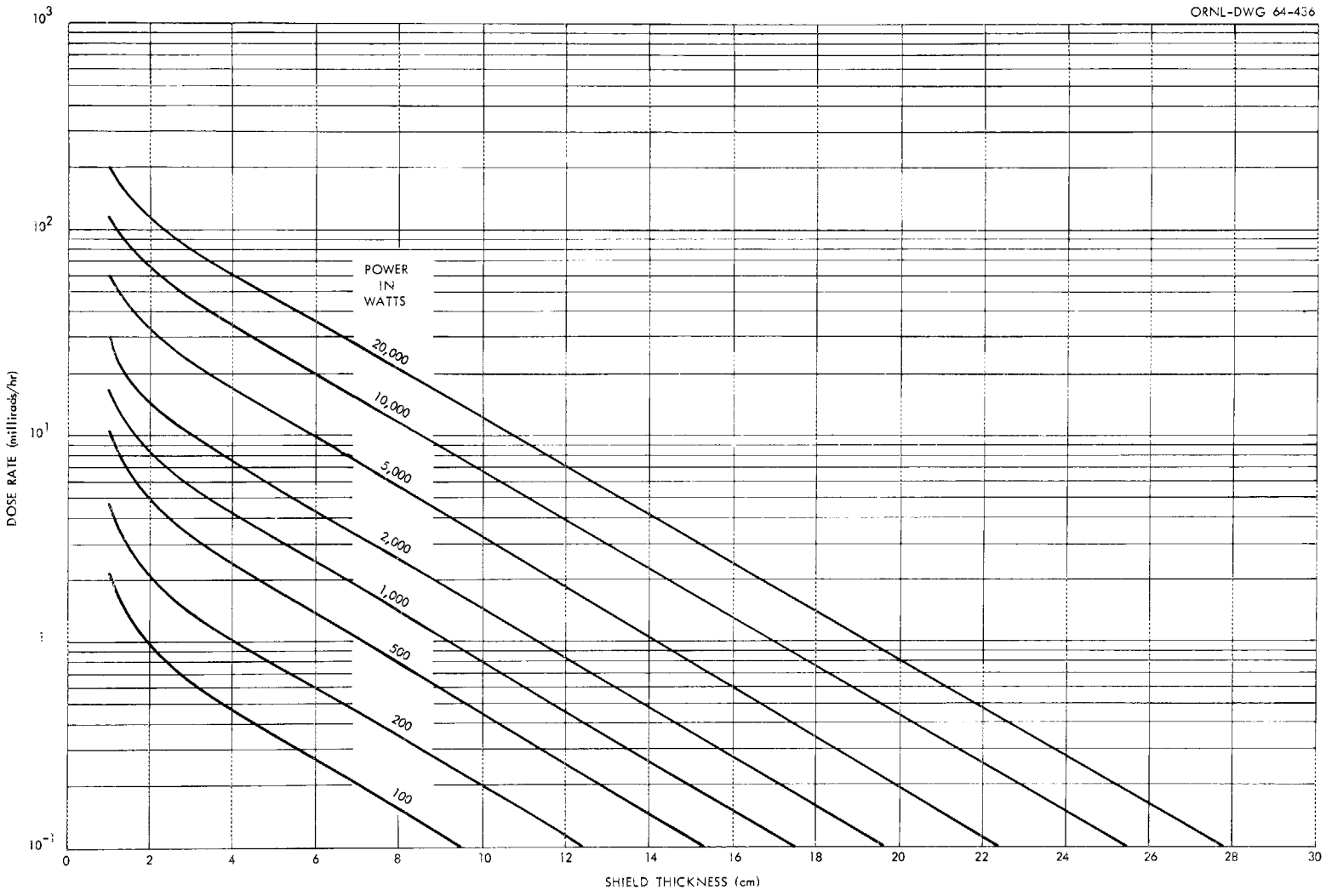

Fig. 9. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

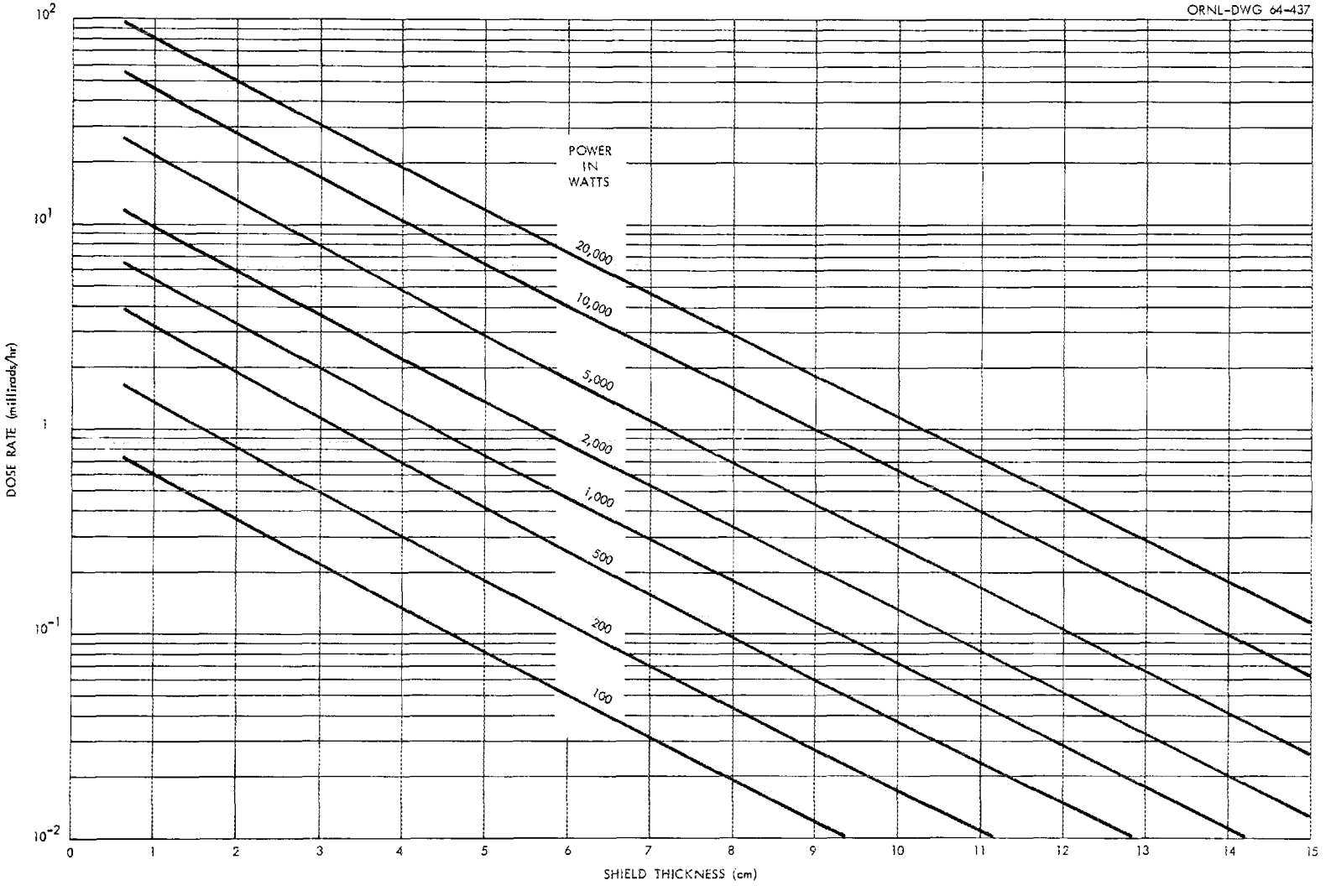

Fig. 10. Gamma Dose Rates from Lead-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

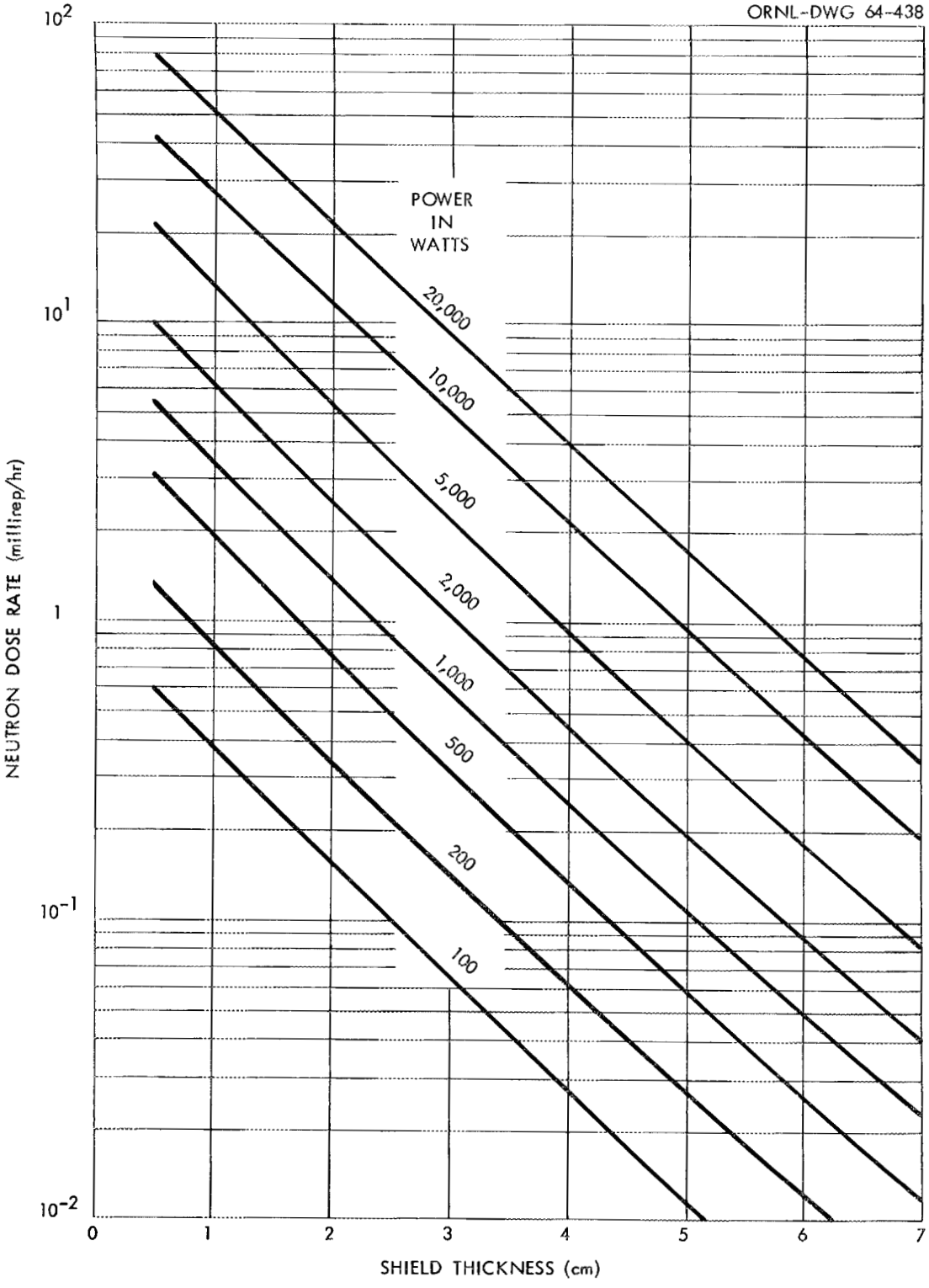

Fig. 11. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

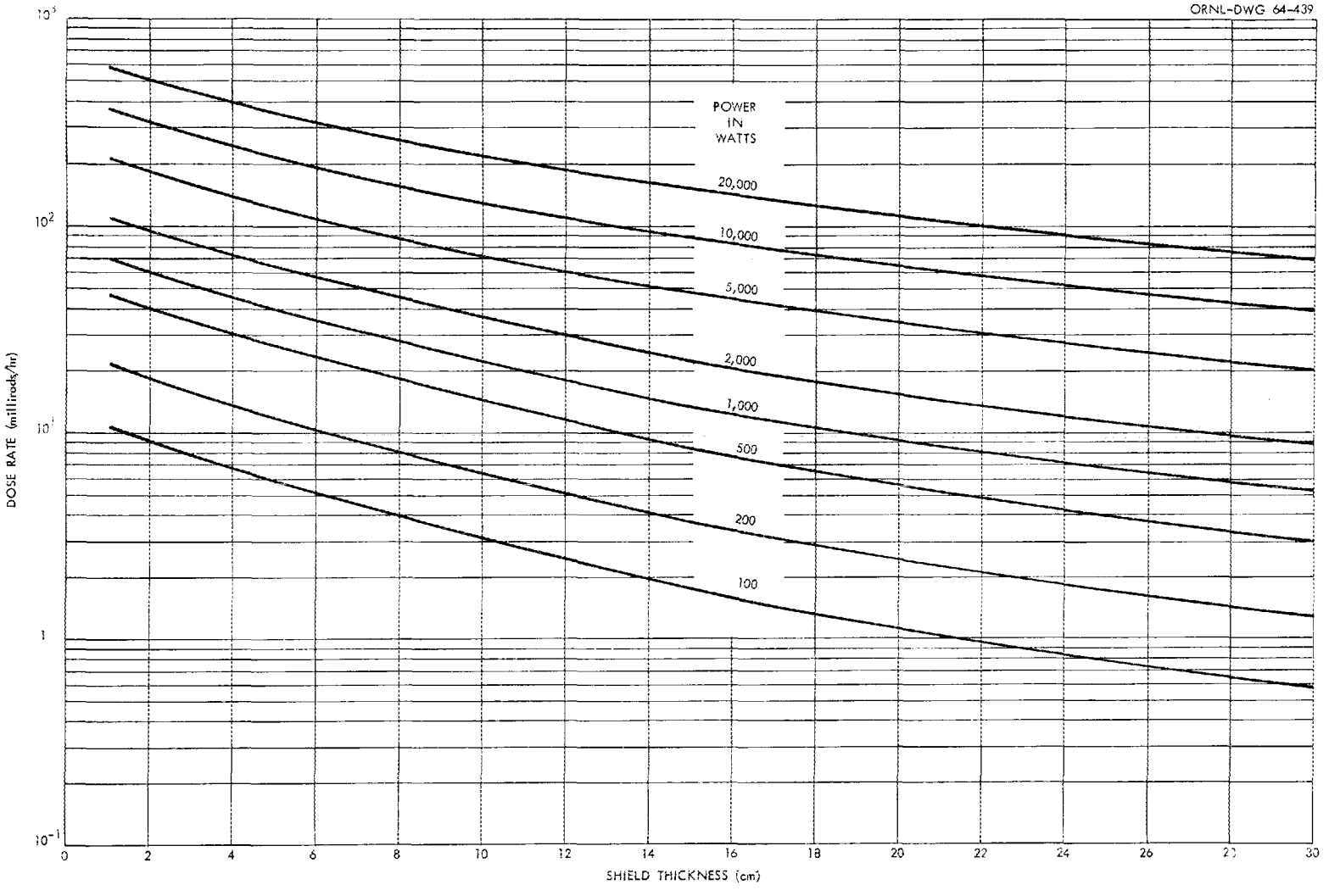

Fig. 12. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242. Center of source to dose point separation distance = 100 cm.

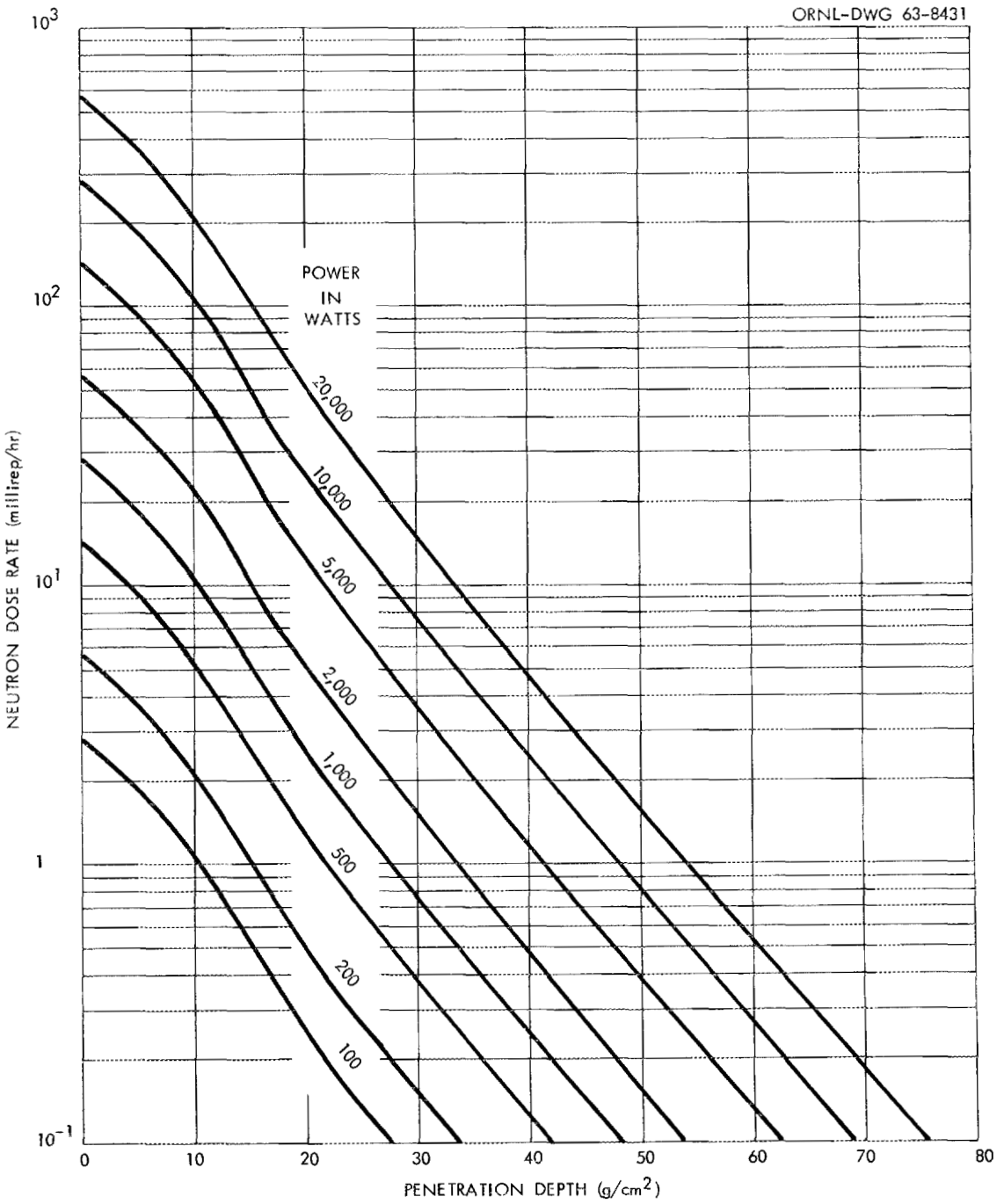

Fig. 13. Neutron Dose Rates from Water-Shielded Isotopic Power Sources of Curium-242 as a Function of Penetration Depth of Shielding Material. Center of source to dose point separation distance = 100 cm. Refer to Fig. 9 to obtain dose rates through other materials.

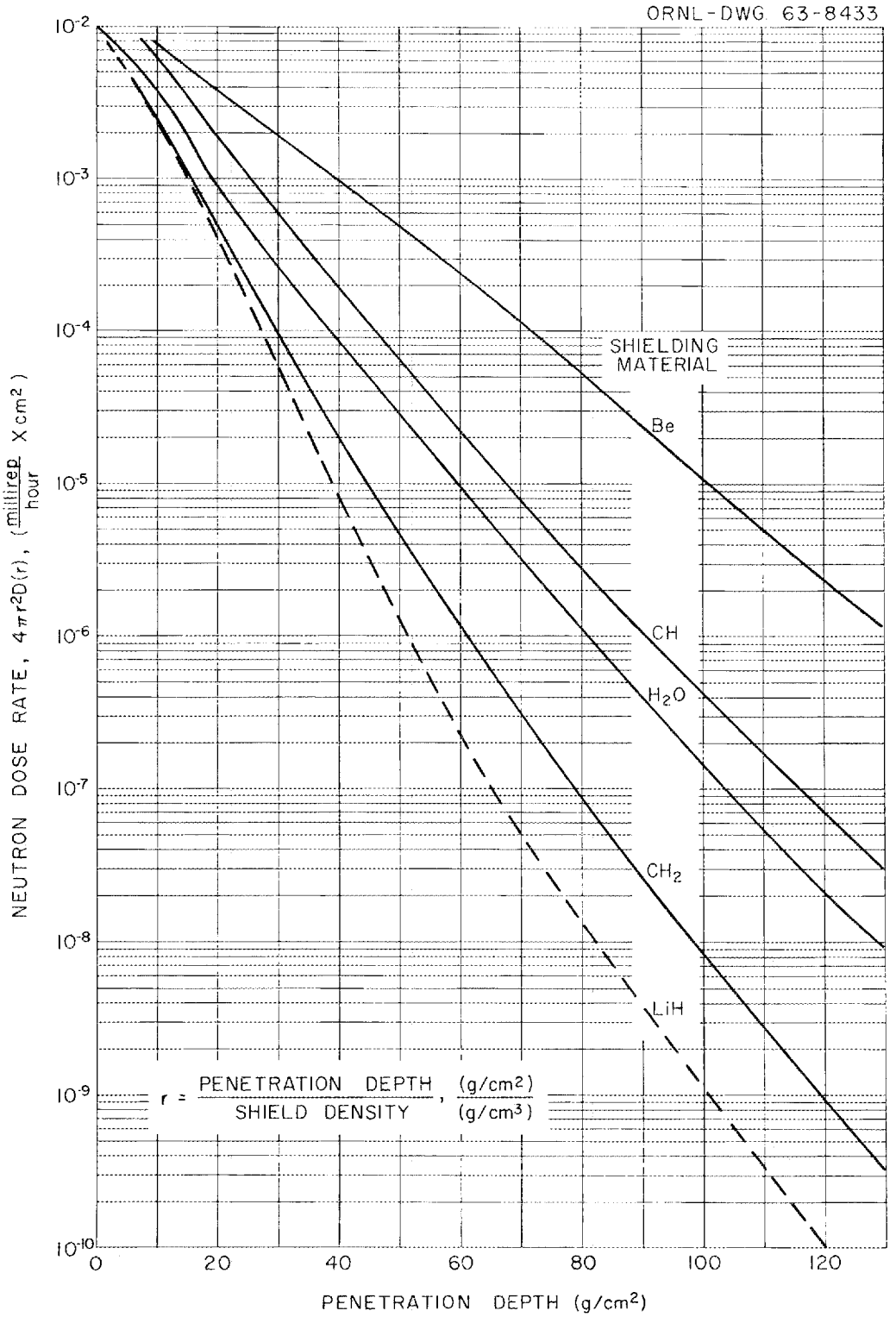

Fig. 14. Fast Neutron Dose Rate (Multiplied by $4\pi r^2$) in Various Materials as a Function of Penetration Depth from a Unit Point Isotropic Fission Source.

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