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UC-4 — Chemistry

CERIUM-144 DATA SHEETS

S. J. Rimshaw
E. E. Ketchen

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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ISOTOPES DEVELOPMENT CENTER

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S. J. Rimshaw
E. E. Ketchen

Isotopes Division

NOVEMBER 1967

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CERIUM-144 DATA SHEETS

I. FUEL FORM (as processed) — REFERENCE COLUMN

A. CEROUS OXIDE (Ce_2O_3) — HALF-LIFE: 285 d — 1

1. Composition

a. Radionuclidic abundance

With one year of cooling time after reactor discharge, the isotopic composition will be: — 2, 3

Isotope	% Abundance
^{144}Ce	13.3
^{142}Ce	42.7
^{140}Ce	44.0

At this isotopic composition, the specific activity of the cerium isotopes is 430 curies of ^{144}Ce per gram of cerium isotope or 7.91 x 0.43 = 3.40 watts/g of cerium isotope. The specific activity of the cerium isotopes decreases with increasing cooling time after reactor discharge as shown in the following table.

Specific Activity of ^{144}Ce per Gram of Cerium Isotopes as a Function of Cooling Time After Reactor Discharge With an Irradiation Time of 100 Days

Cooling time, days	Specific activity, curies of ^{144}Ce per g of cerium isotope
50	812
100	760
200	594
300	500
350	456
400	408
450	362
500	322

b. Radiochemical purity

The principal radiochemical impurity present in the ^{144}Ce product is ^{141}Ce ($T_{1/2}$ = 32.5 d), whose content depends on the length of time since reactor discharge as given in the following table.

REFERENCE COLUMN

Calculated Ratio of $^{141}Ce/^{144}Ce$ Activities as a Function of Cooling Time Since Reactor Discharge With an Irradiation Time of 200 Days

Cooling time, days	Calculated ratio of $^{141}Ce/^{144}Ce$ activities
50	0.98
100	0.38
150	0.15
200	0.06

The ^{141}Ce content is almost negligible after 200 days of cooling time.

The ^{147}Pm, ^{90}Sr, and ^{137}Cs contaminants are negligible compared with the ^{144}Ce-^{144}Pr radiation.

c. Cation composition

After purification, the cerium product contains >99% cerium and <1% neodymium. Neodymium also grows in from the decay of ^{144}Ce as shown in the following table. Hence, it is assumed that an average cerium product contains 95% cerium and 5% neodymium.

Time, days	^{144}Ce, %	^{142}Ce, %	^{140}Ce, %	^{144}Nd, %
0	13.3	42.7	44.0	0
57	11.6	42.7	44.0	1.7
114	10.1	42.7	44.0	3.2
171	8.7	42.7	44.0	4.6
228	7.6	42.7	44.0	5.7
285	6.65	42.7	44.0	6.65

2. Specific Power (based on fabrication 1 yr after reactor discharge)

a. 2.91 watts/g of pure Ce_2O_3 (85.4% Ce metal) 2
2.76 watts/g of 95% Ce_2O_3–5% Nd_2O_3

b. 367 curies ^{144}Ce per gram of pure Ce_2O_3 (85.4% Ce metal)
349 curies ^{144}Ce per gram of 95% Ce_2O_3–5% Nd_2O_3

REFERENCE COLUMN

3. Radiation

a. Alpha particles — none

b. Beta particles 4

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	Particles w^{-1} sec^{-1}
^{144}Ce	0.31	0.090	65	0.44	3.03×10^{12}
	0.22	0.060	5		0.233×10^{12}
	0.17	0.045	30		1.40×10^{12}
^{144}Pr	2.98	1.21	97.7	7.08	4.55×10^{12}
	2.3	0.89	1.3		0.061×10^{12}
	0.8	0.28	1.0		0.047×10^{12}
Total beta power				7.52	

c. Gamma 4

Nuclide	Energy, Mev	Abundance, %	w/kilocurie	Particles w^{-1} sec^{-1}
^{144}Ce	0.134	17	0.20	0.792×10^{12}
	0.10	2		0.093×10^{12}
	0.08	2		0.093×10^{12}
	0.04	17		0.792×10^{12}
^{144}Pr	2.2	0.8	0.19	0.037×10^{12}
	1.5	0.25		0.0117×10^{12}
	0.7	1.6		0.075×10^{12}
Total gamma power			0.39	
Total beta power			7.52	
Total gamma and beta power			7.91	

d. Bremsstrahlung 4

The production of bremsstrahlung photons from the 3.0-Mev ^{144}Pr beta in a cerium oxide matrix is given in the table on the following page.

e. Neutrons — none

Production of Bremsstrahlung Photons From
Praseodymium-144 Beta in Cerium Oxide Matrix

Maximum beta-particle energy 3.00 Mev
Average beta-particle energy 1.23 Mev

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons/beta particle	Photons w^{-1} sec^{-1}
0.100 ± 0.05	9.016×10^{-2}	4.10×10^{11}
0.200 ± 0.05	3.703×10^{-2}	1.68×10^{11}
0.300 ± 0.05	2.054×10^{-2}	9.35×10^{10}
0.400 ± 0.05	1.289×10^{-2}	5.86×10^{10}
0.500 ± 0.05	8.620×10^{-3}	3.92×10^{10}
0.600 ± 0.05	6.001×10^{-3}	2.73×10^{10}
0.700 ± 0.05	4.284×10^{-3}	1.95×10^{10}
0.800 ± 0.05	3.107×10^{-3}	1.41×10^{10}
0.900 ± 0.05	2.277×10^{-3}	1.04×10^{10}
1.000 ± 0.05	1.677×10^{-3}	7.63×10^{9}
1.100 ± 0.05	1.238×10^{-3}	5.63×10^{9}
1.200 ± 0.05	9.123×10^{-4}	4.15×10^{9}
1.300 ± 0.05	6.698×10^{-4}	3.05×10^{9}
1.400 ± 0.05	4.883×10^{-4}	2.22×10^{9}
1.500 ± 0.05	3.527×10^{-4}	1.60×10^{9}
1.600 ± 0.05	2.516×10^{-4}	1.14×10^{9}
1.700 ± 0.05	1.766×10^{-4}	8.04×10^{8}
1.800 ± 0.05	1.216×10^{-4}	5.53×10^{8}
1.900 ± 0.05	8.176×10^{-5}	3.72×10^{8}
2.000 ± 0.05	5.334×10^{-5}	2.43×10^{8}
2.100 ± 0.05	3.353×10^{-5}	1.53×10^{8}
2.200 ± 0.05	2.011×10^{-5}	9.15×10^{7}
2.300 ± 0.05	1.135×10^{-5}	5.16×10^{7}
2.400 ± 0.05	5.915×10^{-6}	2.69×10^{7}
2.500 ± 0.05	2.760×10^{-6}	1.26×10^{7}
2.600 ± 0.05	1.095×10^{-6}	4.98×10^{6}
2.700 ± 0.05	3.363×10^{-7}	1.53×10^{6}
2.800 ± 0.05	6.451×10^{-8}	2.94×10^{5}
2.900 ± 0.05	3.898×10^{-9}	1.77×10^{4}
3.000 ± 0.05	0.000	

Total bremsstrahlung energy, Mev/beta particle 5.075×10^{-2}

REFERENCE COLUMN

4. Critical Mass

Cerium-144 and ^{144}Pr are not fissionable.

5. Compatibility With Materials of Containment

6. Thermophysical Properties

a. Density

	Reference
6.867 grams/cm^3 – density of pure Ce_2O_3	5
6.89 grams/cm^3 – density of 95% Ce_2O_3–5% Nd_2O_3	5

b. Coefficient of thermal expansion

Linear coefficient of expansion, °C^{-1}	Temperature, °C	Reference
8.90×10^{-6}	300	
10.60×10^{-6}	500	6 (Nd_2O_3)
11.35×10^{-6}	800	
11.41×10^{-6}	1050	
11.0×10^{-6}	268	
11.1×10^{-6}	415	
11.3×10^{-6}	503	
11.5×10^{-6}	616	
11.7×10^{-6}	720	7 (CeO_2)
12.0×10^{-6}	845	
12.3×10^{-6}	975	
12.7×10^{-6}	1131	
12.9×10^{-6}	1310	

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} °C^{-1}

$9.24 \times 10^{-2} + (2.35 \times 10^{-5}\ T) - (6.76 \times 10^{2}\ T^{-2})$ 8

(T is in °K)

(2) Enthalpy in cal/mole for β-form Ce_2O_3

$H_T - H_{298} = 30.30\ T + (3.86 \times 10^{-3}\ T^2)$ 8

$+ (2.22 \times 10^5\ T^{-1}) - 10{,}122$

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point – 2190°C 9
2142 (in H_2) 10

(2) Boiling point – 3230°C 11

REFERENCE COLUMN

e. Latent heats of phase transformations

ΔH (fusion)	20 kcal/mole	11
ΔH (vaporization)	80 kcal/mole	11

f. Vapor pressure

$\log_{10} P = -24{,}000/T + 5.56$ — 12 (Nd_2O_3)

(T in °K and P in atm)

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	
0.0245	100	13 (ThO_2)
0.0204	200	
0.0143	400	
0.0104	600	
0.0081	800	
0.0073	1000	
0.0060	1200	
0.0059	1400	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0443	100
0.0235	400
0.0118	800
0.0074	1400

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

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 14 (ThO_2)

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

REFERENCE COLUMN

m. Crystallography

hexagonal — 5

$a = 3.888$ Å $c = 6.062$ Å

n. Solubilities

(1) Water — insoluble — 14

(2) Sulfuric acid — soluble

o. Diffusion rates

7. Mechanical Properties

a. Hardness

5 Mohs — 15

b. Crush strength

1900 kg/cm^2 — 15 (CeO_2)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

ΔH°_f = -435 kcal/mole — 7

(2) Free energy of formation

ΔF°_f = -415 kcal/mole — 7

(3) Entropy

S°_{298} = 33.5 eu — 7

b. Chemical reactions and reaction rates (oxygen, nitrogen, water, steam, hydrogen, liquid metals, other) — 16

(1) Oxygen at room temperature — will react

(2) Oxygen at elevated temperature — pyrophoric

(3) Nitrogen — no reaction

(4) Water — reacts

(5) Inorganic acids — soluble

9. Biological Tolerances — 17

Maximum permissible body burdens and maximum permissible concentration of ^{144}Ce-^{144}Pr in air and water were taken from Ref. 17 and are given in the table on the following page.

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[17]

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
$_{58}Ce^{144}$ (α,β^-,γ)	(Sol) GI (LLI)*		3×10^{-4}	8×10^{-8}	10^{-4}	3×10^{-8}
	Bone	5	0.2	10^{-8}	0.08	3×10^{-9}
	Liver	6	0.3	10^{-8}	0.1	4×10^{-9}
	Kidney	10	0.5	2×10^{-8}	0.2	7×10^{-9}
	Total Body	20	0.7	3×10^{-8}	0.3	10^{-8}
	(Insol) Lung			6×10^{-9}		2×10^{-9}
	GI (LLI)*		3×10^{-4}	6×10^{-8}	10^{-4}	2×10^{-8}

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

REFERENCE COLUMN

10. Shielding Data

The combined gamma and bremsstrahlung dose rates from ^{144}Ce-^{144}Pr power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts with iron, lead, and uranium shielding are given in Figs. 1 to 4. 4

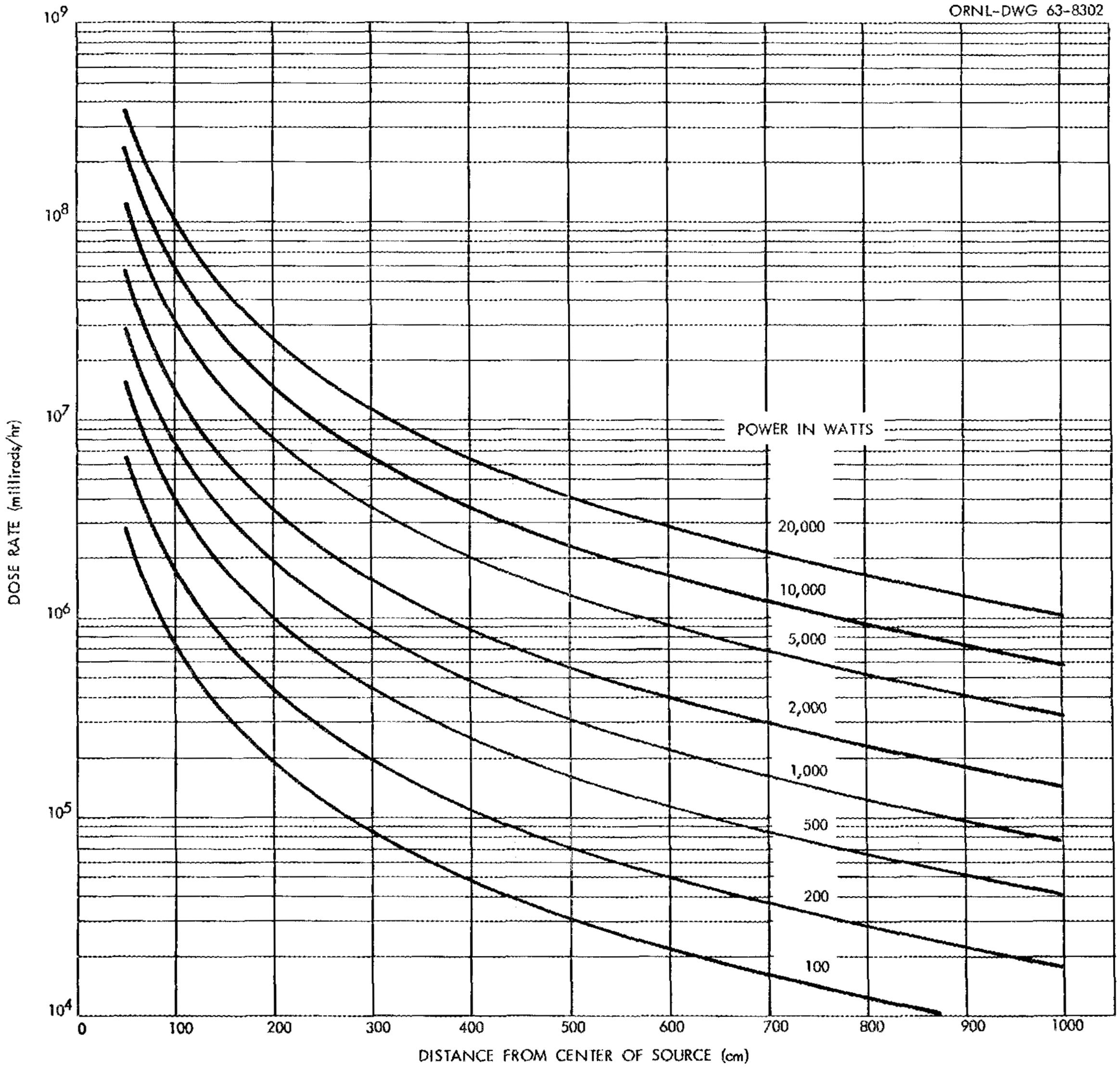

Fig. 1. Gamma Plus Bremsstrahlung Dose Rates From Unshielded Isotopic Power Sources of Cerium-144 as a Function of Distance From Center of Source.

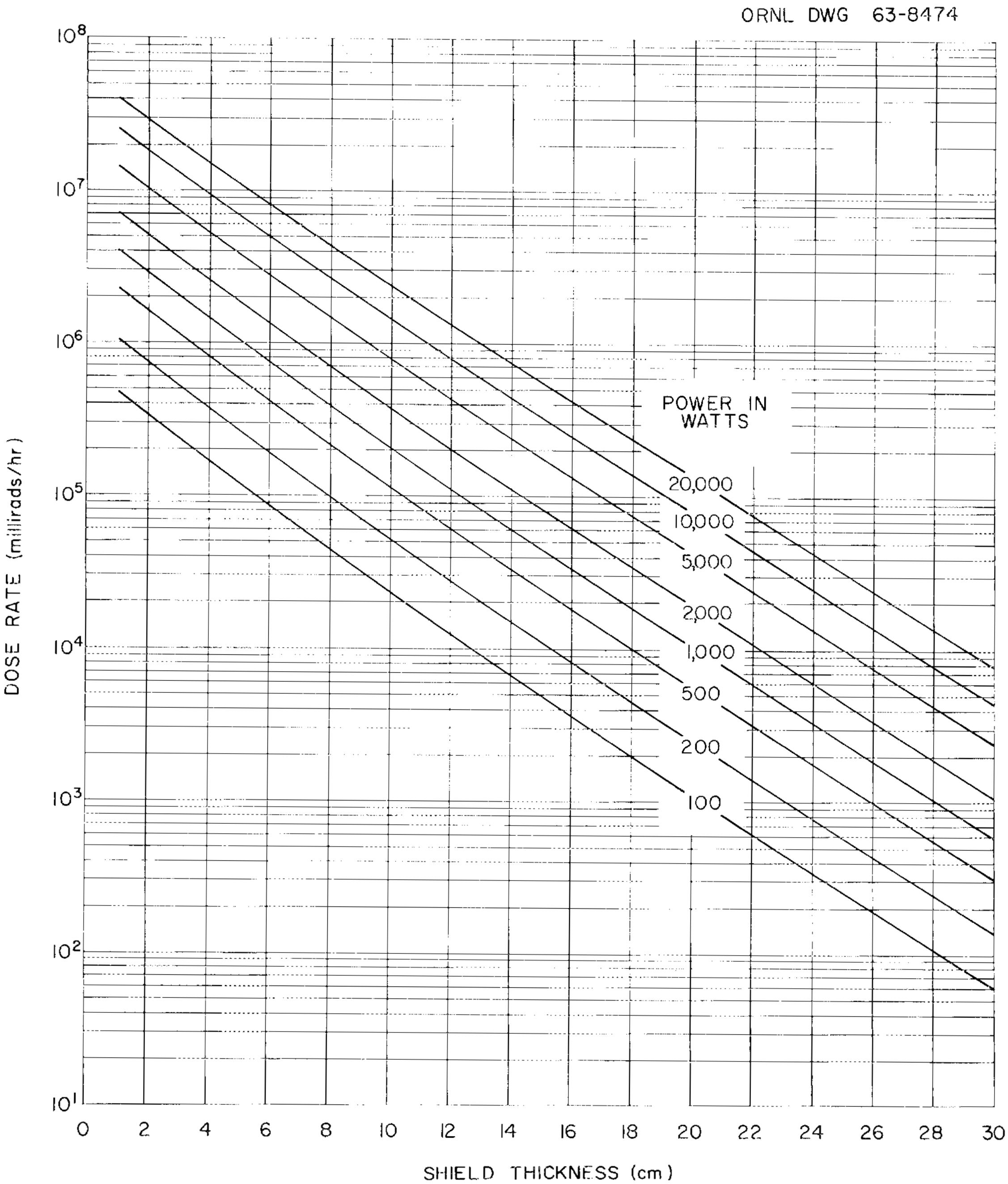

Fig. 2. Gamma Plus Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Cerium-144. Center of source to dose point separation distance = 100 cm.

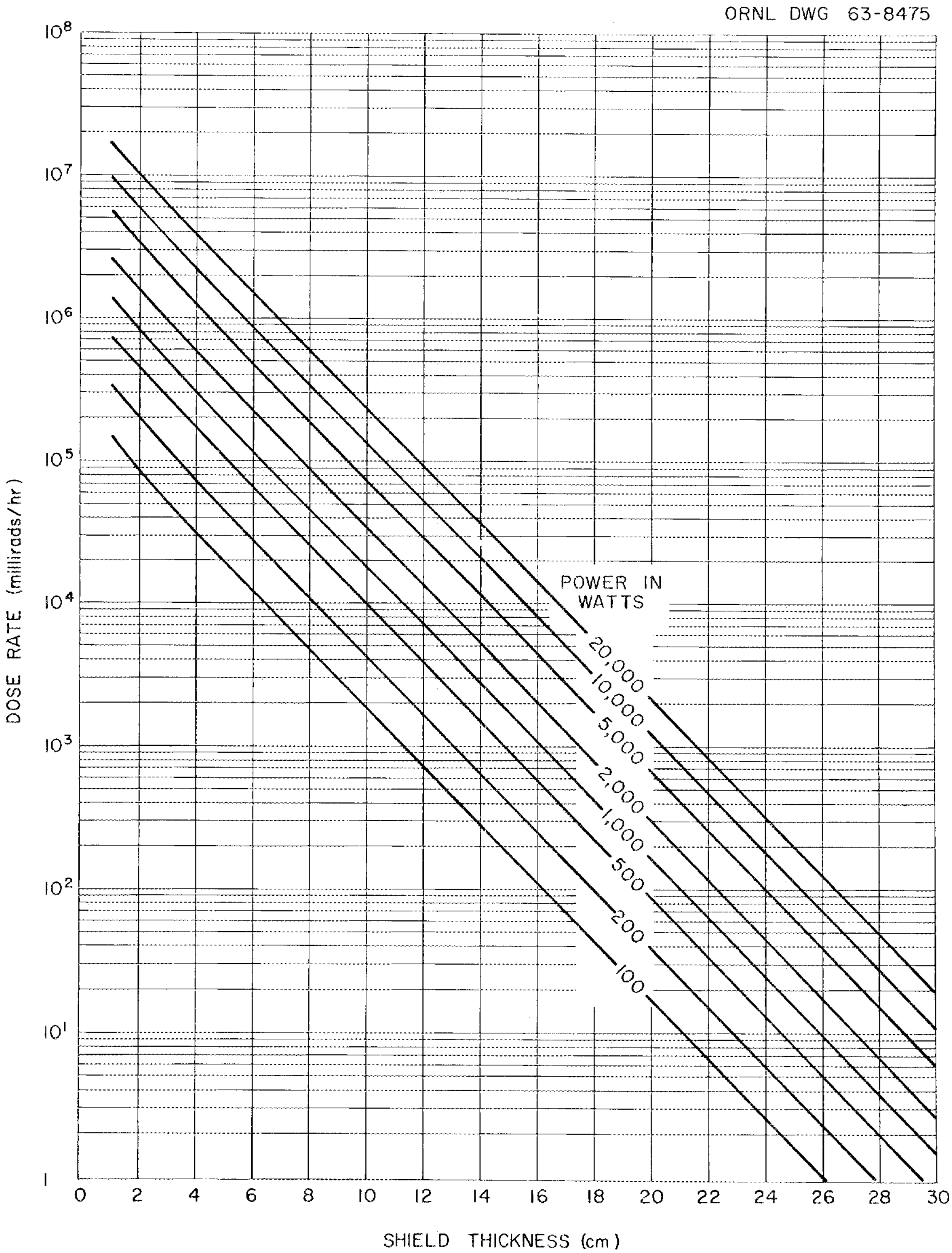

Fig. 3. Gamma Plus Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Cerium-144. Center of source to dose point separation distance = 100 cm.

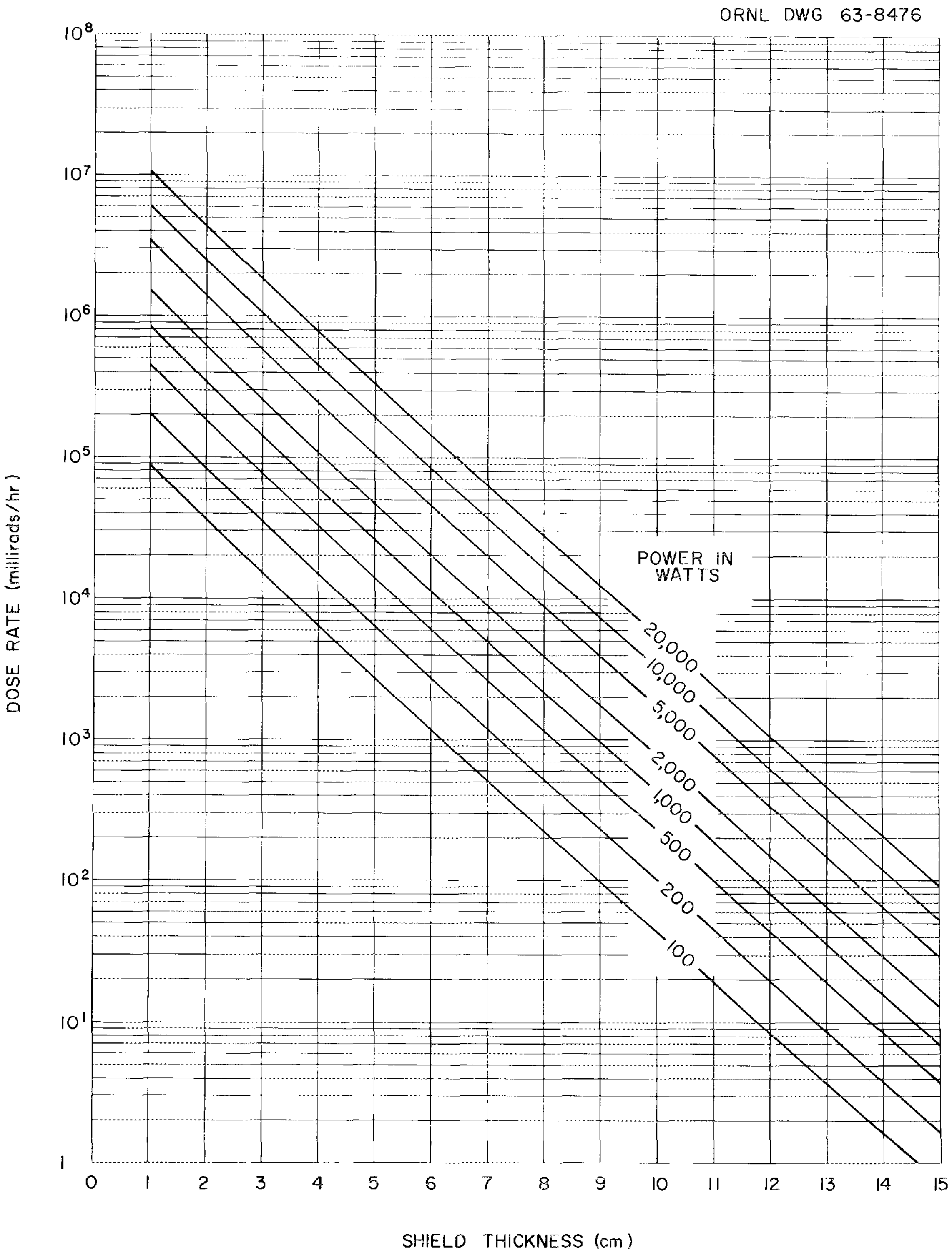

Fig. 4. Gamma Plus Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Sources of Cerium-144. Center of source to dose point separation distance = 100 cm.

REFERENCE COLUMN

B. CERIUM OXYSULFIDE (Ce_2O_2S)

1. Composition

a. Radionuclidic abundance

The radionuclidic abundances are given in Section I.A.1.

b. Radiochemical purity

The ^{147}Pm, ^{90}Sr, and ^{137}Cs contaminants should contribute a negligible amount of radiation compared with the ^{144}Ce-^{144}Pr radiation which is given under Section I.A.1.

c. Cation composition

It is assumed that an average cerium product will contain 95% cerium and 5% neodymium. The growth of neodymium with time is given under Section I.A.1.

2. Specific Power (based on fabrication 1 yr after reactor discharge)

a. 2.78 watts/g of pure Ce_2O_2S (85.4% Ce metal) 2
2.64 watts/g of 95% Ce_2O_2S–5% Nd_2O_2S

b. 350 curies of ^{144}Ce per gram of pure Ce_2O_2S (85.4% Ce metal)
333 curies of ^{144}Ce per gram of 95% Ce_2O_2S–5% Nd_2O_2S

3. Radiation

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

4. Critical Mass

Cerium-144, ^{144}Pr, and ^{144}Nd are not fissionable.

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

5.99 grams/cm^3 – density of pure Ce_2O_2S 18

6.01 grams/cm^3 – density of 95% Ce_2O_2S–5% Nd_2O_2S

REFERENCE COLUMN

b. Coefficient of thermal expansion

Linear coefficient of expansion, °C^{-1}	Temperature, °C	
8.90×10^{-6}	300	
10.60×10^{-6}	500	6 (Nd_2O_3)
11.35×10^{-6}	800	
11.41×10^{-6}	1050	

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} °C^{-1}

$9.24 \times 10^{-2} + (2.35 \times 10^{-5}\ T) - (6.76 \times 10^{2}\ T^{-2})$ — 8 (Ce_2O_3)

(T is in °K)

(2) Enthalpy in cal/mole for β-form Ce_2O_3

$H_T - H_{298} = 30.30\ T + (3.86 \times 10^{-3}\ T^2) + (2.22 \times 10^{5}\ T^{-1}) - 10{,}122$ — 8 (Ce_2O_3)

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point — 2000°C — 19

(2) Boiling point — 3230°C — 11 (Ce_2O_3)

e. Latent heats of phase transformations

ΔH (fusion) 20 kcal/mole — 11 (Ce_2O_3)

ΔH (vaporiation) 80 kcal/mole — 11 (Ce_2O_3)

f. Vapor pressure

g. Thermal conductivity

cal cm^{-1} sec^{-1} °C^{-1}	Temperature, °C	
0.0245	100	13 (ThO_2)
0.0204	200	
0.0143	400	
0.0104	600	
0.0081	800	
0.0073	1000	
0.0060	1200	
0.0059	1400	

REFERENCE COLUMN

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0443	100
0.0235	400
0.0118	800
0.0074	1400

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

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

0.20 to 0.57 — 14 (ThO_2)

The precise value will depend on the roughness of the material surface, the presence of impurities, and the effects of radiation.

m. Crystallography

hexagonal — 18

$a = 4.008$ Å $c = 6.834$ Å

n. Solubilities

(1) Insoluble in water — 20

(2) Insoluble in dilute acetic acids

(3) Soluble in strong mineral acids

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

$\Delta H°_f = -430$ kcal/mole — 19

REFERENCE COLUMN

a. Heat and free energy of formation, entropy (continued)

(2) Free energy of formation

$\Delta F^{\circ}{}_{f} = -416$ kcal/mole — Calculated

(calculated by $\Delta F^{\circ}{}_{f} = \Delta H^{\circ}{}_{f} - T\Delta S^{\circ}{}_{f}$)

(3) Entropy

$S^{\circ}_{298} = 42.9$ eu — 21, 22

(calculated by W. Latimer's method)

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

(1) Air at room temperature – very slow — 23

(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 concentration of ^{144}Ce-^{144}Pr in air and water are given under the Ce_2O_3 Source Form, Section I.A.9. — 17

10. Shielding Data

The combined gamma and bremsstrahlung dose rates from ^{144}Ce-^{144}Pr power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts with iron, lead, and uranium shielding were given under the Ce_2O_3 Source Form, Section I.A.10. — 4

REFERENCE COLUMN

C. CERIUM SULFIDE (Ce_2S_3)

1. Composition

a. Radionuclidic abundance

The radionuclidic abundances are given in Section I.A.1.

b. Radiochemical purity

The ^{147}Pm, ^{90}Sr, and ^{137}Cs contaminants should contribute a negligible amount of radiation compared with the ^{144}Ce-^{144}Pr radiation which is given under Section I.A.1.

c. Cation composition

It is assumed that an average cerium product will contain 95% cerium and 5% neodymium. The growth of neodymium with time is given under the Ce_2O_3 Source Form, Section I.A.1.

2. Specific Power (based on fabrication 1 yr after reactor discharge)

a. 2.54 watts/g of Ce_2S_3 (85.4% Ce metal) 2
2.41 watts/g of 95% Ce_2S_3–5% Nd_2S_3

b. 320 curies of ^{144}Ce per gram of Ce_2S_3 (85.4% Ce metal)
304 curies of ^{144}Ce per gram of 95% Ce_2S_3–5% Nd_2S_3

3. Radiation

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

4. Critical Mass

Cerium-144, ^{144}Pr, and ^{144}Nd are not fissionable.

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

5.19 grams/cm^3 – density of pure Ce_2S_3 24

5.21 grams/cm^3 – density of 95% Ce_2S_3–5% Nd_2S_3

	REFERENCE COLUMN
b. Coefficient of thermal expansion	
$(10.45 \pm 0.67) \times 10^{-6}/°C$	25
(20-1020°C temperature range)	
c. Specific heat and enthalpy	
(1) Specific heat in cal g^{-1} $°C^{-1}$	
0.0808	25
(2) Enthalpy in calories/mole	
d. Temperatures of phase transformations	
(1) Melting point – 1890°C	25
(2) Boiling point – decomposes to lower sulfide and sulfur vapor above 1890°C	25
e. Latent heats of phase transformations	
f. Vapor pressure	
Ce_2S_3 decomposes rapidly to Ce_3S_4 at 2300°C with sulfur vapor coming off. The decomposition starts below the melting point of 1890°C.	26
g. Thermal conductivity	
0.00091 cal sec^{-1} cm^{-1} $°C^{-1}$ at room temperature	27
h. Thermal diffusivity	
0.00217 cm^2/sec	
The thermal diffusivity is obtained by dividing the thermal conductivity by the product of the specific heat and the density.	
i. Viscosity	
j. Surface tension	
k. Total hemispherical emittance	
l. Spectral emissivity	
0.20 to 0.57	14 (ThO_2)
The value of the emissivity depends on the roughness of the surface of the material, the presence of impurities, and the effects of radiation.	

REFERENCE COLUMN

m. Crystallography

cubic — $a = 8.634$ Å — 26

n. Solubilities

(1) Insoluble in water — 20

(2) Soluble in dilute acetic acid

o. Diffusion rates

7. Mechanical Properties

a. Hardness (Vicker's microhardness)

403 ± 36 kg/mm^2 — 15

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

$\Delta H^\circ_f = -300.5$ kcal/mole — 26

(2) Free energy of formation

$\Delta F^\circ_f = -297$ kcal/mole — Calc from 28

(3) Entropy

$S^\circ_{298} = 43.1$ eu — 29

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

(1) Air at 300°C — slow — 23

(2) Air at 600°C — fast

(3) Water at 100°C — no reaction

(4) Alkali at room temperature — no reaction

(5) Organic and inorganic acids at room temperature — soluble

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentration of ^{144}Ce-^{144}Pr in air and water are given under the Ce_2O_3 Source Form, Section I.A.9. — 17

REFERENCE COLUMN

10. Shielding Data

The combined gamma and bremsstrahlung dose rates from ^{144}Ce-^{144}Pr power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts with iron, lead, and uranium shielding were given under the Ce_2O_3 Source Form, Section I.A.10. 4

REFERENCE COLUMN

D. CEROUS FLUORIDE (CeF_3)

1. Composition

a. Radionuclidic abundance

The radionuclidic abundances are given in Section I.A.1.

b. Radiochemical purity

The ^{147}Pm, ^{90}Sr, and ^{137}Cs contaminants should contribute a negligible amount of radiation compared with the ^{144}Ce-^{144}Pr radiation which is given under Section I.A.1.

c. Cation composition

It is assumed that an average cerium product will contain 95% cerium and 5% neodymium. The growth of neodymium with time is given under the Ce_2O_3 Source Form, Section I.A.1.

2. Specific Power (based on fabrication 1 yr after reactor discharge)

a. 2.43 watts/g of pure CeF_3 (85.4% Ce metal) 2
2.31 watts/g of 95% CeF_3–5% NdF_3

b. 306 curies of ^{144}Ce per gram of pure CeF_3 (85.4% Ce metal)
291 curies of ^{144}Ce per gram of 95% CeF_3–5% NdF_3

3. Radiation

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

4. Critical Mass

Cerium-144, ^{144}Pr, and ^{144}Nd are not fissionable.

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

6.16 grams/cm^3 – density of pure CeF_3 13

6.18 grams/cm^3 – density of 95% CeF_3–5% NdF_3

REFERENCE COLUMN

b. Coefficient of thermal expansion

$\alpha = 19.7 \times 10^{-6} + (2.62 \times 10^{-8}\ t) + (0.15 \times 10^{-10}\ t^2)$ — 30 (BaF_2)

where

t is in °C
temperature range is 26-296°C
value of α is for BaF_2

c. Specific heat and enthalpy

(1) Specific heat in cal g^{-1} $°C^{-1}$

$9.08 \times 10^{-2} + (5.14 \times 10^{-5}\ T) + (5.58 \times 10^{2}\ T^{-2})$ — 31

(T is in °K)

(2) Enthalpy in calories/mole

$H_T - H_{298} = 17.90\ T + (5.07 \times 10^{-3}\ T^2) - (1.1 \times 10^{5}\ T^{-1}) - 5419$ — 31

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point — 1437°C — 32

(2) Boiling point — 2148°C — 33

e. Latent heats of phase transformations

ΔH (fusion)	9.0 kcal/mole	11
ΔH (vaporization)	62.0 kcal/mole	11
ΔH (sublimation)	69.8 ± 2 kcal/mole	33

f. Vapor pressure

$\log_{10} P = -(2.046 \pm 0.014)(10^4/T) + (9.205 \pm 0.092)$ — 33

where

T is in °K
P is in atm
temperature is between 1373 and 1634°K

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	
0.0296	0	34 (BaF_2)
0.0251	100	

REFERENCE COLUMN

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0422	0
0.0340	100

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

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

A value of 0.9 can be assumed.

m. Crystallography

hexagonal 33

$a = 7.114$ Å $c = 7.273$ Å

n. Solubilities

$K_{sp} = 8.1 \pm 1.1 \times 10^{-16}$ in water 35

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

$\Delta H°_f = -391$ kcal/mole 36

(2) Free energy of formation

$\Delta F°_f = -372$ kcal/mole 36

(3) Entropy

$S°_{298} = 27.6$ eu 29

REFERENCE COLUMN

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

(1) Oxygen at room temperature — no reaction 37

(2) Oxygen at elevated temperature — forms oxyfluoride

(3) Nitrogen — no reaction

(4) Water — insoluble

(5) Inorganic acids — insoluble in weak acid

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentration of ^{144}Ce-^{144}Pr in air and water are given under the Ce_2O_3 Source Form, Section I.A.9. 17

10. Shielding Data

The combined gamma and bremsstrahlung dose rates from ^{144}Ce-^{144}Pr power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 watts with iron, lead, and uranium shielding were given under the Ce_2O_3 Source Form, Section I.A.10. 4

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