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AEC RESEARCH AND DEVELOPMENT REPORT

STRONTIUM-90 DATA SHEETS

(Title Unclassified)

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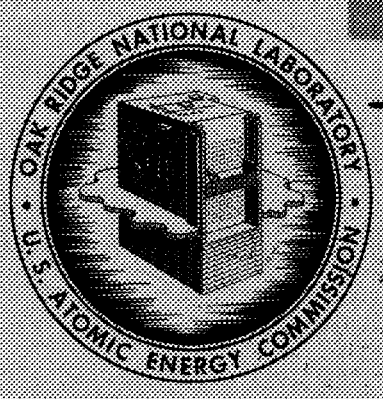

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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ISOTOPES DEVELOPMENT CENTER

STRONTIUM-90 DATA SHEETS

S. J. Rimshaw
E. E. Ketchen

ISOTOPES DIVISION

NOVEMBER 1966

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CONTENTS

STRONTIUM-90 DATA SHEETS

I. FUEL FORM (as processed) — REFERENCE COLUMN

A. STRONTIUM-90 METAL — HALF-LIFE: 28.0 y — 1

1. Composition

a. Radionuclidic abundance

Isotope	% Abundance
^{90}Sr	55.0
^{88}Sr	43.9
^{86}Sr	1.1

2, 3

These values were obtained by a mass-spectrometric analysis of fission-product strontium.

b. Radiochemical purity

The principal radionuclide other than ^{90}Sr is ^{89}Sr ($T_{1/2}$ = 50.4 d), whose content depends on the length of time since reactor discharge, as shown in the following table.

Calculated Ratios of $^{89}Sr/^{90}Sr$ Activities as a Function of Cooling Time Since Reactor Discharge With an Irradiation Time of 200 Days

Cooling time, days	Ratio of activities $^{89}Sr/^{90}Sr$
50	29
100	15
200	4.0
300	1.10
400	0.30

The ratio of ^{89}Sr to ^{90}Sr activities will decrease by a factor of ~2.0 for each 50 days of cooling time.

REFERENCE COLUMN

c. Chemical composition*

(1) Range of composition

Cation	Maximum, %	Minimum, %
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0
Zr	0	0

(2) Average chemical composition

Cation	Metal, %
Sr	95
Ca	3.5
Ba	1.0
Mg	0.5

The ^{144}Ce constitutes 0.03% of the radioactivity at a maximum. Cesium-137 has been found to be as high as 0.003% of the total activity. Ruthenium-106 has not been found in the strontium feed.

2. Specific Power

a. 0.529 watt/g of 100% strontium metal (55% ^{90}Sr)
0.503 watt/g of metal (95% Sr–5% Ca, Ba, Mg)

It is assumed that there are 142 curies/g of ^{90}Sr and 149 curies of ^{90}Sr per thermal watt.

b. 78.1 curies of ^{90}Sr per gram of 100% strontium metal (55% ^{90}Sr)
74.2 curies of ^{90}Sr per gram of 95% strontium metal 2, 4, 5

3. Radiation

a. Alpha particles – none

* Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

REFERENCE COLUMN

b. Beta particles 4, 6

Nuclide	Max E, Mev	Avg E, Mev	Abundance, %	w/kilocurie	Particles w^{-1} sec^{-1}
^{90}Sr	0.454	0.20	100	1.184	5.5×10^{12}
^{90}Y	2.27	0.944	100	5.588	5.5×10^{12}
Total power				6.772	

c. Gamma — none

d. Bremsstrahlung 4, 6

The high-energy bremsstrahlung photons from ^{90}Sr and ^{90}Y in matrices of SrO and $SrTiO_3$ are given in Appendix 1 (Tables 1-4). Sources of ^{90}Sr-^{90}Y activities require slightly more shielding than sources of ^{137}Cs-^{137}Ba activities because of the high energy of some of the bremsstrahlung radiation from ^{90}Y which emits a 2.27-Mev beta particle.

e. Neutrons — none

4. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

5. Compatibility With Materials of Containment

After an exposure of 2036 hr at 925°C to liquid strontium metal, it was found that molybdenum and stainless steel 321 showed good compatibility with liquid strontium metal; that wrought iron and Haynes 25 were worthy of further study; and that Hastelloy C, Hastelloy N, Hastelloy X, and titanium had dissolved and were incompatible with strontium metal. 7

No attack on molybdenum was observed after 5000-hr contact with liquid strontium metal at 1000°C. 8

REFERENCE COLUMN

6. Thermophysical Properties

a. Density

The theoretical density is 2.6 g/cm^3 for strontium element and 2.55 g/cm^3 for 95% Sr, 3.5% Ca, 1.0% Ba, 0.5% Mg. 9

b. Coefficient of thermal expansion

$20 \times 10^{-6}/°C$ 10

c. Specific heat and enthalpy

(1) Specific heat

0.0719 cal g^{-1} $°C^{-1}$ (25°C) 11

(2) Enthalpy in calories

$H_T - H_{298} = 5.31\ T + 1.66 \times 10^{-3}\ T^2 - 1731$ (298-862°K) 12

$H_T - H_{298} = 9.12\ T - 3582$ (862-1043°K)

ΔH transition = 200 calories at 862°K

d. Temperatures of phase transformations

(1) Melting point — 772°C 10

(2) Boiling point — 1372°C 10

e. Latent heats of phase transformations

ΔH transition ($\alpha \rightarrow \beta$) = 200 calories (589°C) 12

ΔH fusion (772°C) = 2400 calories 12

ΔH vaporization (1372°C) = 33,200 calories 11

f. Vapor pressure

Atmosphere	Temperature, °C	
5×10^{-12}	227	13
8.7×10^{-4}	727	
0.129	1127	
0.585	1327	
1.9	1527	
4.84	1727	

[redacted]

REFERENCE COLUMN

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	
0.3	20	14 (Ca)
0.385	100	15 (Be)
0.290	300	
0.247	500	
0.206	700	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
1.64	20

This value was calculated by dividing the thermal conductivity by the product of the specific heat and the density.

i. Viscosity

j. Surface tension

σ = 165 dyn/cm — 16, 17

k. Total hemispherical emittance

Will vary from 0.25-0.80 depending on the state of the sample, such as oxide coating, impurities. — 18

l. Spectral emissivity

Can also vary as stated above.

m. Crystallography

α		β		γ	
fcc	215°C	hcp	605°C	bcc	
a = 6.085 A		a = 4.32 A c = 7.06 A		a = 4.85 A	13, 19

n. Solubilities

Strontium metal reacts vigorously with water — 13

o. Diffusion rates

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

16-18 (Brinell) — 14 (Ca)

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

Zero — by definition of standard state

(2) Free energy of formation

Zero — by definition of standard state

(3) Entropy

S°_{298} = 12.5 eu — 20

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

(1) Oxygen — fast — 14, 21

(2) Nitrogen at room temperature — no reaction

(3) Nitrogen at elevated temperature — reacts

(4) Water — reacts

(5) Inorganic acids — reacts

9. Biological Tolerances

The ^{90}Sr tolerances taken from Ref. 22 are given in the table on the following page. — 22

10. Shielding Data

See the sections under Strontium Titanate, I.B.10, and Strontium Oxide, I.C.10, for shielding data.

Maximum Permissible Body Burdens and Maximum Permissible Concentrations for Radionuclides in Air and in Water for Occupational Exposure[22]

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
$_{38}Sr^{90}$ (β^-)	(Sol) Bone	2	4×10^{-6}	3×10^{-10}	10^{-6}	10^{-10}
	(Sol) Total Body	20	10^{-5}	9×10^{-10}	4×10^{-6}	3×10^{-10}
	(Sol) GI (LLI)*		10^{-3}	3×10^{-7}	5×10^{-4}	10^{-7}
	(Insol) Lung			5×10^{-9}		2×10^{-9}
	(Insol) GI (LLI)*		10^{-3}	2×10^{-7}	4×10^{-4}	6×10^{-8}

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

UNCLASSIFIED

REFERENCE COLUMN

B. STRONTIUM TITANATE ($SrTiO_3$)

1. Composition

a. Radionuclidic abundance

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

b. Radiochemical purity

The radiochemical purity is given in Section I.A.1.

c. Chemical composition*

(1) Range of composition

Cation	Maximum, %	Minimum, %
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0
Zr	0	0

(2) Average chemical composition

Cation	Metal, %	Titanate, %
Sr	95	92.4
Ca	3.5	5.5
Ba	1.0	0.9
Mg	0.5	1.2

The strontium metal content of pure $SrTiO_3$ is 47.75%.

The strontium metal content of average $SrTiO_3$ is 44.1%.

The as-processed $SrTiO_3$ will contain 24.3% ^{90}Sr. The ^{144}Ce constitutes 0.03% of the radioactivity at a maximum. The ^{137}Cs has been found to be as high as 0.003% of the total activity. The ^{106}Ru activity has not been found. These activities can be neglected compared to the bremsstrahlung radiation.

*Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

REFERENCE COLUMN

2. Specific Power 2, 4, 5

a. 0.250 watt/g of pure $SrTiO_3$ (26.3% ^{90}Sr metal)
0.232 watt/g of average $SrTiO_3$ (24.3% ^{90}Sr metal)

It is assumed that there are 142 curies/g of ^{90}Sr and 149 curies of ^{90}Sr per thermal watt.

b. 37.3 curies of ^{90}Sr per gram of pure $SrTiO_3$ (26.3% ^{90}Sr metal)
34.5 curies of ^{90}Sr per gram of average $SrTiO_3$ (24.3% ^{90}Sr metal)

3. Radiation

The radiation will be the same as given under Section I.A.3.

4. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

5. Compatibility With Materials of Containment

The following results were obtained on testing $SrTiO_3$. 23

Container material	Maximum penetration, mils 168 hr	500 hr	1000 hr
$SrTiO_3$ – 1000°C			
Haynes 25	Traces	0.1	0.2
Molybdenum	No attack	No attack	No attack
Nionel	1.5	1.7	2.0
Tungsten	Traces	0.2	1.5
TZM	No attack	No attack	No attack
$SrTiO_3$ – 1850°C			
Molybdenum	No attack	No attack	No attack
Niobium	No attack	--	No attack
Tantalum	No attack	Traces	3.0
Tungsten	No attack	--	No attack
TZM	No attack	Traces	5.0

6. Thermophysical Properties

a. Density

5.11 g/cm^3 – density of pure $SrTiO_3$ 24

5.03 g/cm^3 – density of average $SrTiO_3$

REFERENCE COLUMN

b. Coefficient of thermal expansion

$\alpha = 11.2 \times 10^{-6}/°C$ (100-700°C) 24

c. Specific heat and enthalpy

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

$0.154 + 1.11 \times 10^{-5} T - 2.49 \times 10^{3} T^{-2}$ 25

(T is in °K)

(2) Enthalpy in calories

$H_T - H_{298} = 28.23 T + 0.88 \times 10^{-3} T^2$ 26

$+ 4.66 \times 10^{5} T^{-1} - 10,058$

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point – 1910°C 27

(2) Boiling point – 2500-3000°C 9

e. Latent heats of phase transformations

ΔH fusion (not available)

ΔH vaporiation 71 kcal/mole 10

(calculated from Trouton's rule)

f. Vapor pressure

g. Thermal conductivity

Thermal conductivities at various temperatures are given for $SrTiO_3$ having a stoichiometric composition, for $SrTiO_3$ with 10% excess TiO_2, and for $SrTiO_3$ with 10% deficient TiO_2. 28

Temperature, °C	Thermal conductivity, cal cm^{-1} sec^{-1} $°C^{-1}$		
	Stoichiometric	10% excess in TiO_2	10% deficient in TiO_2
50	0.0069	0.0074	0.0073
100	0.0062	0.0072	0.0067
200	0.0052	0.0066	0.0063
300	0.0047	0.0059	0.0058
400	0.0043	0.0053	0.0054
500	0.0039	0.0047	0.0050
600	0.0033	0.0041	0.0046
700	0.0026	0.0032	0.0044
800	0.0019	0.0017	0.0042

REFERENCE COLUMN

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0102	50
0.0087	100
0.0069	200
0.0054	400
0.0040	600
0.0023	800

These values were calculated by dividing the thermal conductivity by the product of the specific heat and density.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

m. Crystallography

Cubic: a = 3.899 kX 13

n. Solubilities

The leach rate of $^{90}SrTiO_3$ containing 35 curies of ^{90}Sr per gram of titanate is ~0.05 mg cm^{-2} day^{-1} in water for the first ten days exposure and increases to ~1.0 mg cm^{-2} day^{-1} after 100 days of exposure with stoichiometric $SrTiO_3$. Excess TiO_2 decreases the solubility of $SrTiO_3$ in water. Radiation damage effects on the $SrTiO_3$ lattice probably account for the higher solubility of highly radioactive $SrTiO_3$ compared to the solubility of $SrTiO_3$ tagged with tracer amounts of activity. The results are summarized in Fig. 1. 29

With tracer levels of activity, release rates of 0.004 and 0.014 mg cm^{-2} day^{-1} were obtained on two strontium titanate pellets exposed to seawater. It is recognized that high radiation levels might have a significant effect on the solubility of $SrTiO_3$. 30

o. Diffusion rates

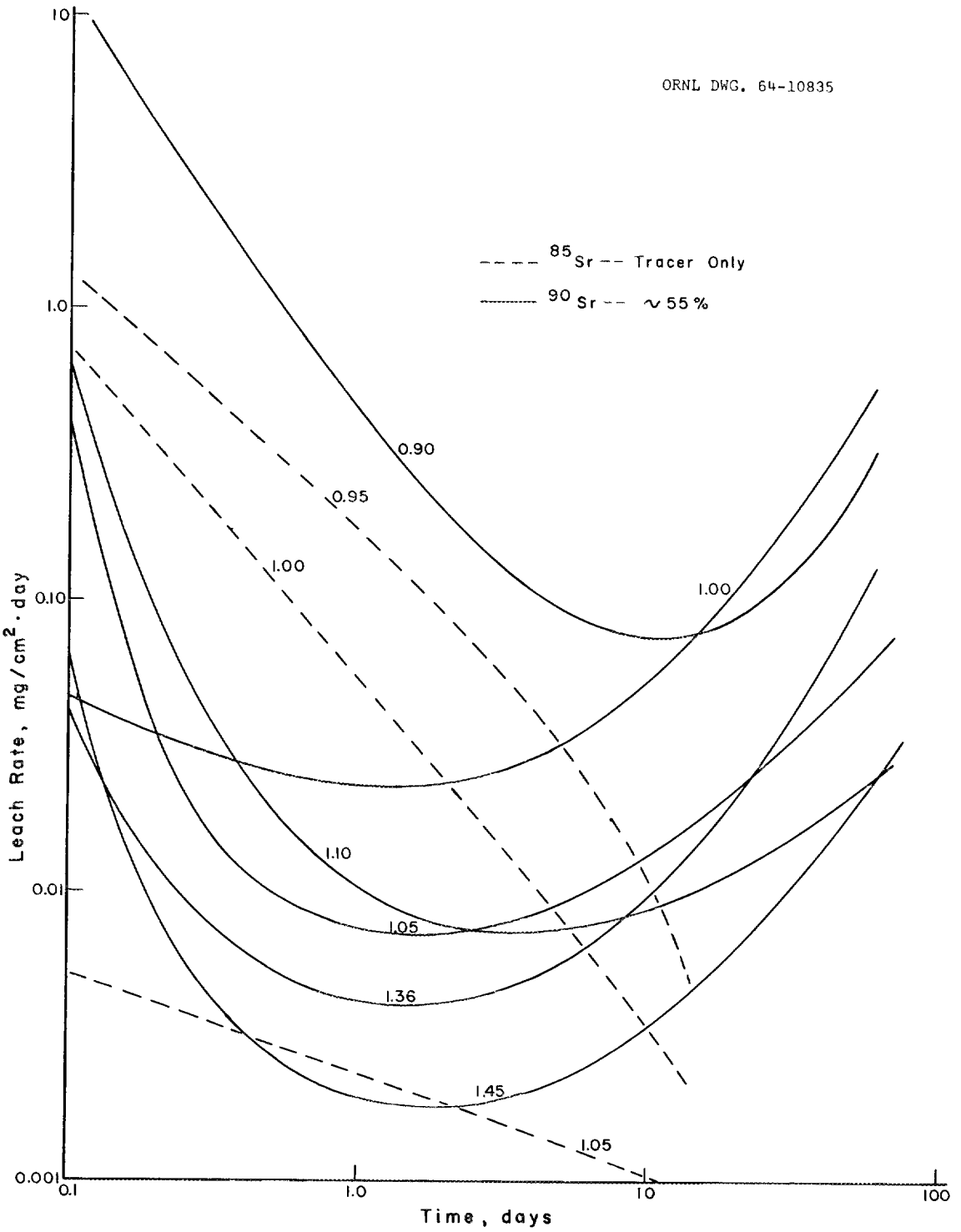

Fig. 1. Leach Rates of $SrTiO_3$ in Distilled Water for TiO_2/SrO Ratios of 0.90 to 1.45.

REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

b. Crush strength
19,100 lb/in.^{2} — 31 ($CaTiO_3$)

c. Bend strength
43 lb/in.^{2} — 28

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation
ΔH°_f = -399 kcal/mole — 32, 33
(calculated from available data)

(2) Free energy of formation
ΔF°_f = -379 kcal/mole — 32, 33
(calculated from available data)

(3) Entropy
S°_{298} = 26.0 eu — 34

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

(1) Oxygen – no reaction — 35

(2) Nitrogen – no reaction

(3) Water – decomposes

(4) Inorganic acids – soluble

9. Biological Tolerances

The ^{90}Sr tolerances are given under Strontium-90 Metal Fuel Form, Section I.A.9.

10. Shielding Data

Bremsstrahlung dose rates from ^{90}Sr 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. 2-5 for a $SrTiO_3$ matrix. These sources require significant shielding because of the high energy of some of the photons from the bremsstrahlung radiation. — 4

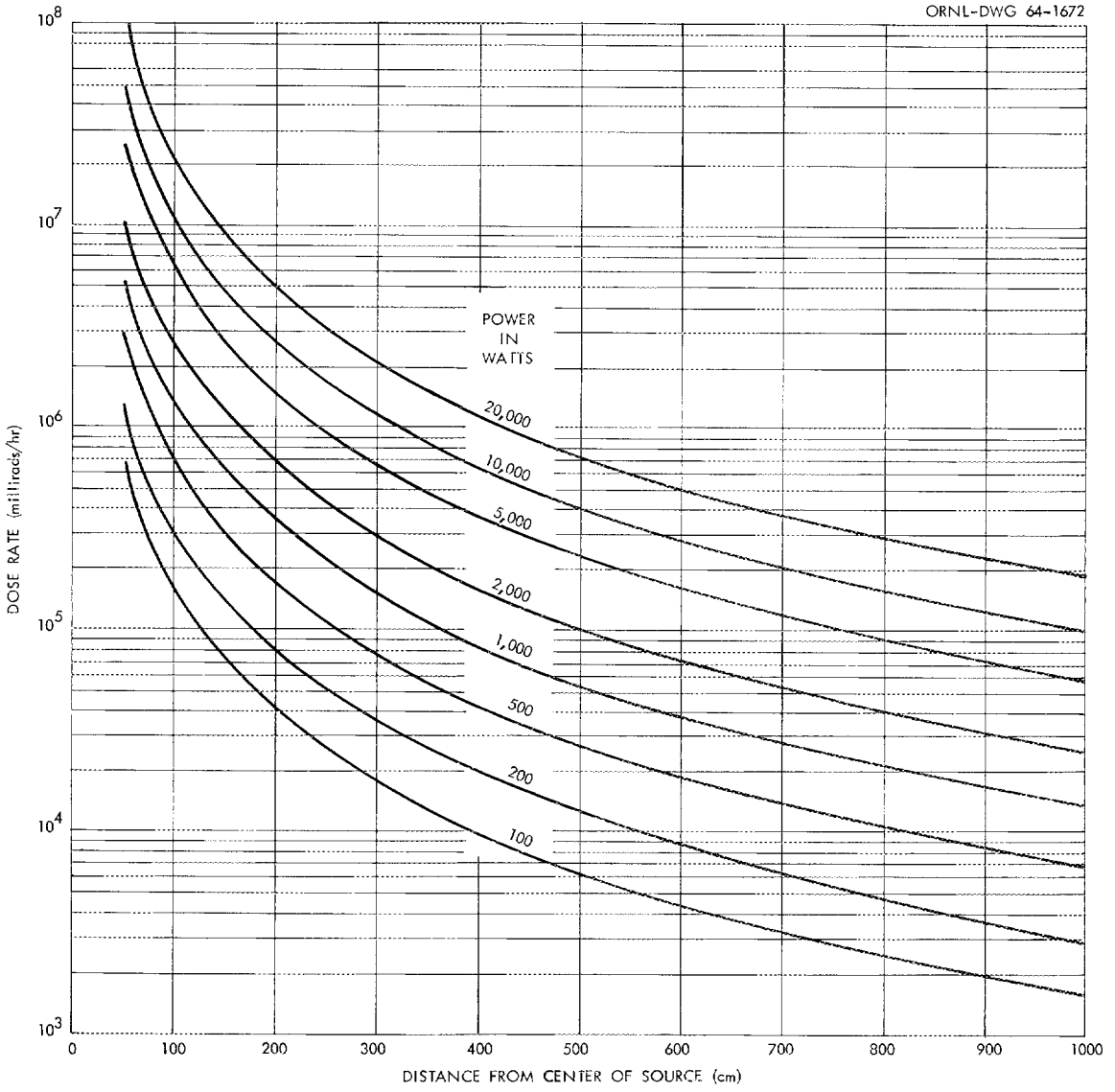

Fig. 2. Bremsstrahlung Dose Rates From Unshielded Isotopic Power Sources of Strontium-90 (Strontium Titanate) as a Function of Distance From Center of Source.

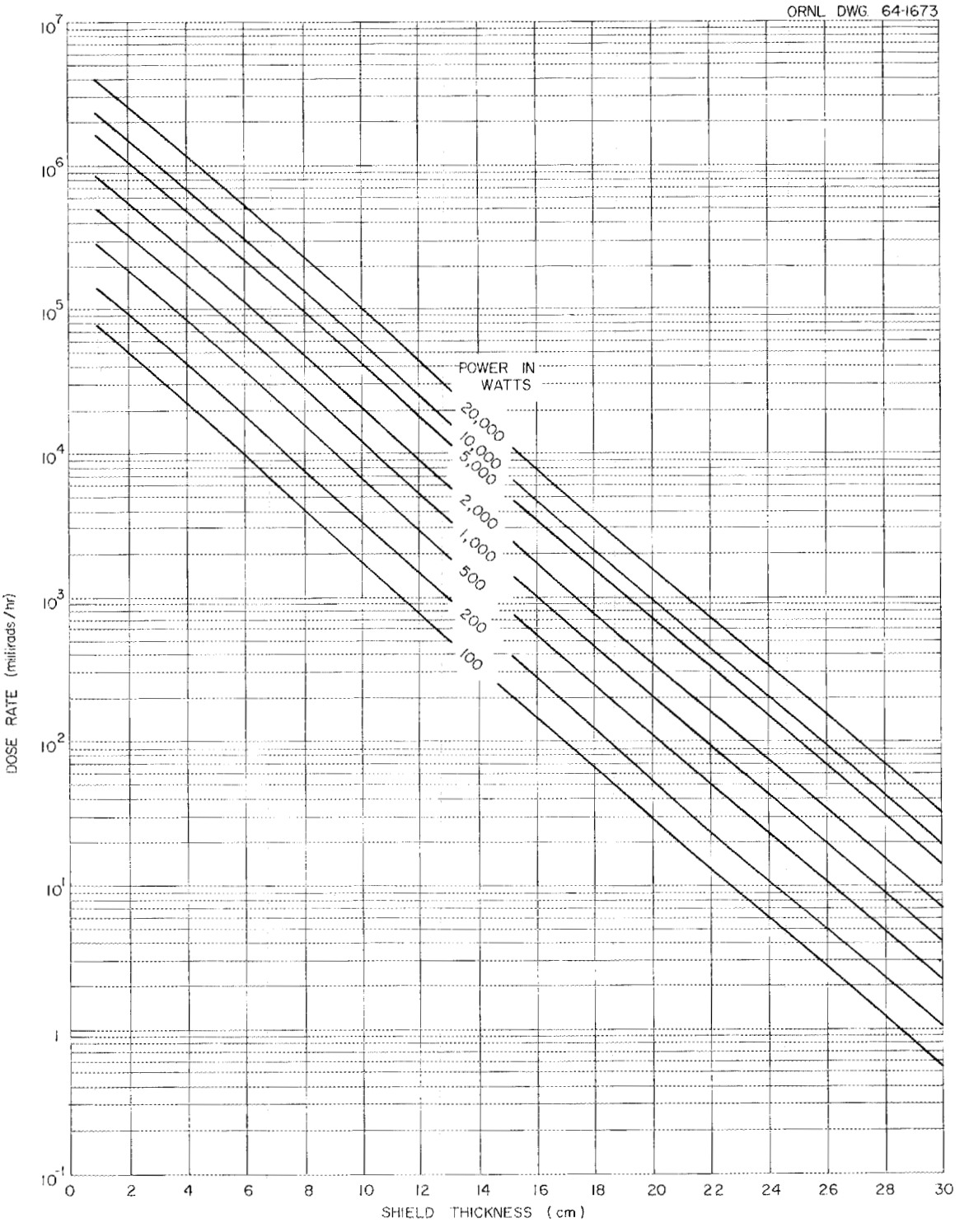

Fig. 3. Bremsstrahlung Dose Rates From Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

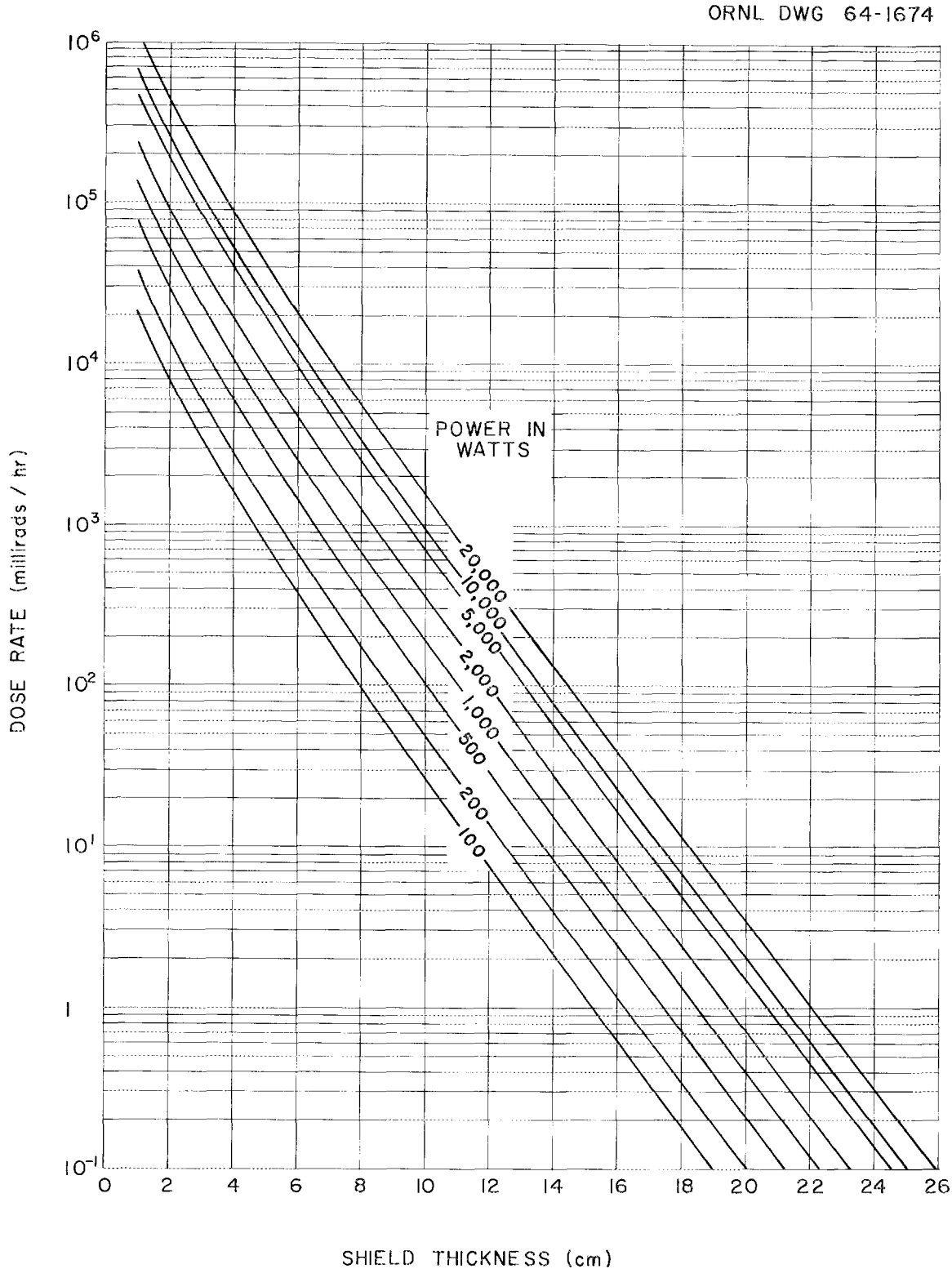

Fig. 4. Bremsstrahlung Dose Rates From Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

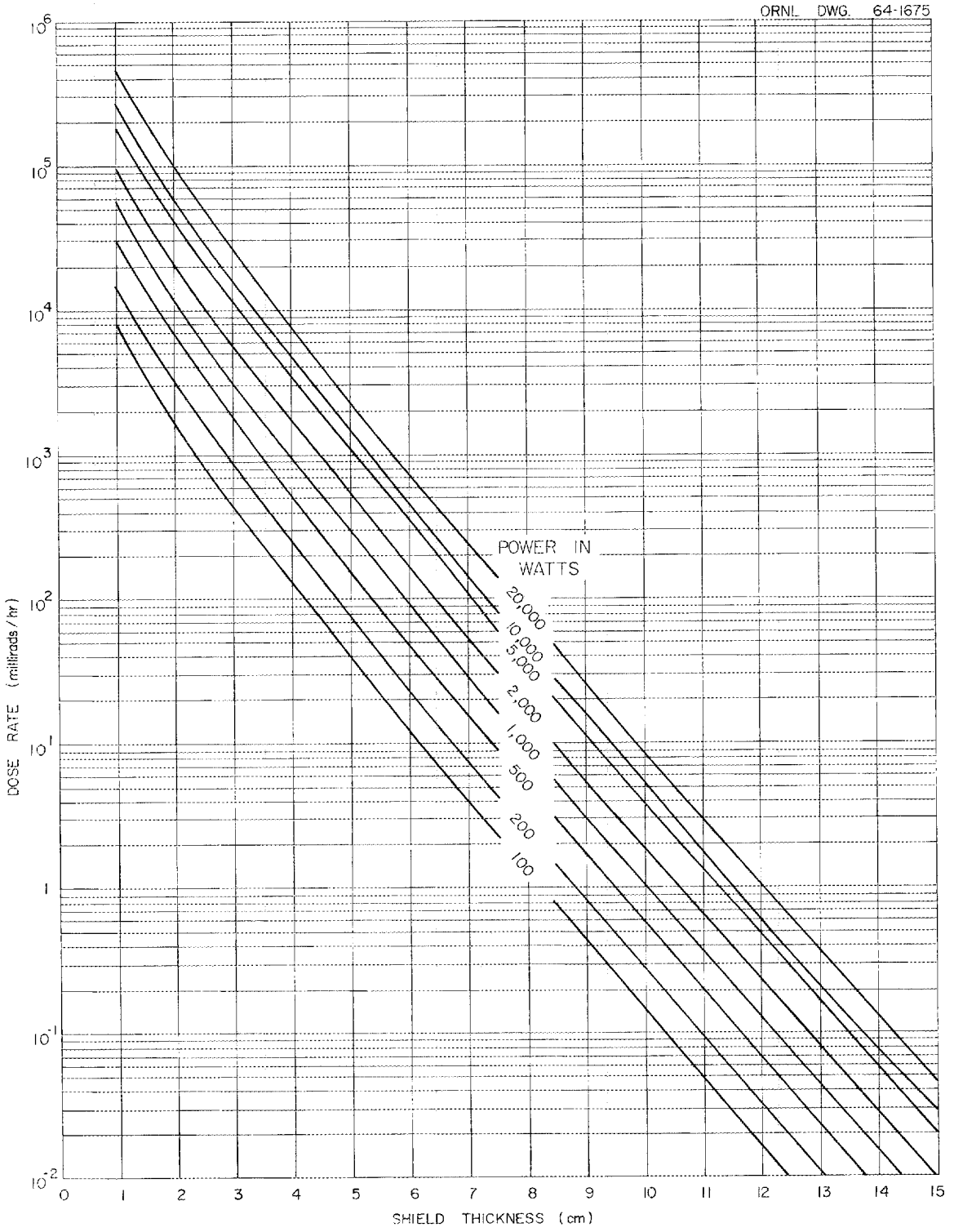

Fig. 5. Bremsstrahlung Dose Rates From Uranium-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

REFERENCE COLUMN

C. STRONTIUM OXIDE (SrO)

1. Composition

a. Radionuclidic abundance

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

b. Radiochemical purity

The radiochemical purity is given in Section I.A.1.

c. Chemical composition*

(1) Range of composition

Cation	Maximum, %	Minimum, %
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0
Zr	0	0

(2) Average chemical composition

Cation	Metal, %	Metal oxide, %
Sr	95	94.3
Ca	3.5	4.1
Ba	1.0	0.9
Mg	0.5	0.7

The strontium metal content of pure SrO is 84.56%.

The strontium metal content of average SrO is 79.7%.

The as-processed SrO will contain 43.8% ^{90}Sr. The ^{144}Ce constitutes 0.03% of the radioactivity at a maximum. The ^{137}Cs has been found to be as high as 0.003% of the radioactivity at a maximum. The ^{106}Ru activity has not been detected. These activities can be neglected compared to the total radiation.

*Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

REFERENCE COLUMN

2. Specific Power 2, 4, 5

a. 0.443 watt/g of pure SrO (46.5% ^{90}Sr metal)
0.417 watt/g of average SrO (43.8% ^{90}Sr metal)

It is assumed that there are 142 curies/g of ^{90}Sr and 149 curies of ^{90}Sr per thermal watt.

b. 66.0 curies of ^{90}Sr per gram of pure SrO (46.5% ^{90}Sr metal)
62.2 curies of ^{90}Sr per gram of average SrO (43.8% ^{90}Sr metal)

3. Radiation

The radiation will be the same as given under Section I.A.3.

4. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

5. Compatibility With Materials of Containment

The following results were obtained with SrO–7% BeO material at 1000°C: 23

Container material	Maximum penetration, mils		
	168 hr	500 hr	1000 hr
Haynes 25	2.0	2.0	4.0
Molybdenum	--	No attack	No attack
Nionel	--	4.0	4.0-8.0
N-155	1.0	1.5	2.0-4.0
Tungsten	No attack	No attack	No attack
TZM	No attack	No attack	No attack

6. Thermophysical Properties

a. Density

4.7 g/cm^3 – density of pure SrO 9

4.63 g/cm^3 – density of average SrO

b. Coefficient of thermal expansion

13.92 x 10^{-6}/°C (20-1200°C) 36

REFERENCE COLUMN

c. Specific heat and enthalpy

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

$0.119 + 1.08 \times 10^{-5} T - 1.74 \times 10^{3} T^{-2}$ 25

(T is in °K)

(2) Enthalpy in calories

$H_T - H_{298} = 12.13 T + 0.63 \times 10^{-3} T^2$ 12

$+ 1.55 \times 10^{5} T^{-1} - 4192$

d. Temperatures of phase transformations

(1) Melting point – 2430°C 9

(2) Boiling point – 3000°C 9

e. Latent heats of phase transformations

ΔH fusion 16.7 kcal/mole 37

ΔH vaporization (not available)

f. Vapor pressure

$\log P = 3.07 \times 10^{4} T^{-1} + 13.12$ 38

(T is in °K and P is in atm)

g. Thermal conductivity

cal cm^{-1} sec^{-1} $°C^{-1}$	Temperature, °C	39
2.85×10^{-5}	440	
3.01×10^{-5}	553	
3.45×10^{-5}	664	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
4.97×10^{-5}	440
5.20×10^{-5}	553
5.85×10^{-5}	664

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

i. Viscosity

REFERENCE COLUMN

j. Surface tension

1200 dyn/cm — 40 (MgO)

k. Total hemispherical emittance

l. Spectral emissivity

Total emissivity	Temperature, °C	
0.36	1000	
0.46	1400	
0.50	1800	38 (BeO)

Small amounts of impurities such as carbon or radiation darkening can increase these values significantly to ~0.9.

m. Crystallography

Cubic – face centered:

a = 5.1396 kX — 13

n. Solubilities

Reacts with water or HCl and goes into solution — 13

o. Diffusion rates

7. Mechanical Properties

a. Hardness

3.5 mohs — 31 (CaO)

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

ΔH°_f = -141.0 kcal/mole — 41

(2) Free energy of formation

ΔF°_f = -133.8 kcal/mole — 41

(3) Entropy

S°_{298} = 13.0 eu — 41

REFERENCE COLUMN

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

(1) Oxygen – no reaction 42

(2) Nitrogen – no reaction

(3) Water – forms $Sr(OH)_2$

(4) Inorganic acids – soluble

9. Biological Tolerances

The ^{90}Sr tolerances are given under Strontium-90 Metal Fuel Form, Section I.A.9.

10. Shielding Data

Bremsstrahlung dose rates from ^{90}Sr 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. 6-9 for a SrO matrix. These sources require significant shielding because of the high energy of some of the photons from the bremsstrahlung radiation.

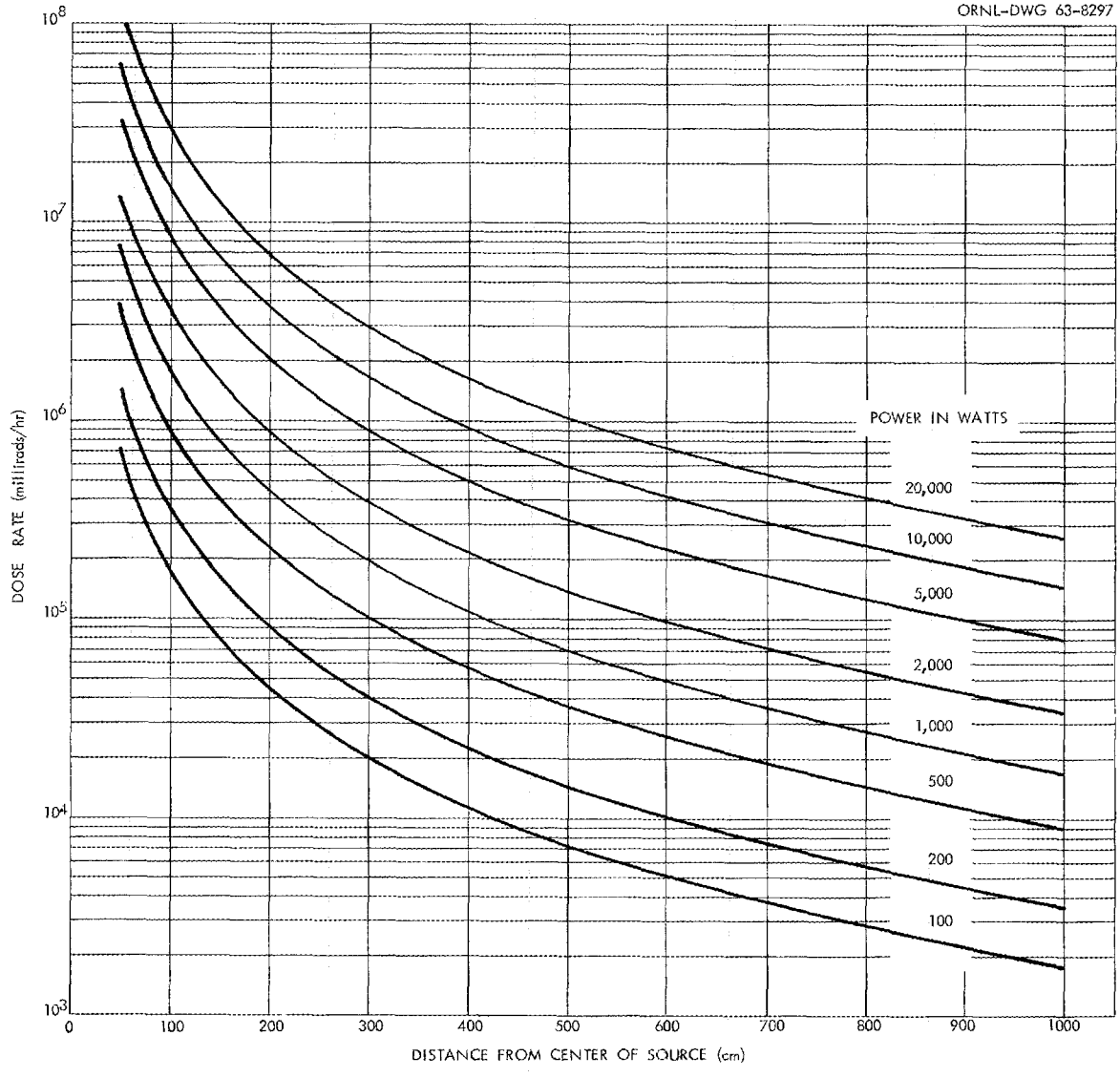

Fig. 6. Bremsstrahlung Dose Rates From Unshielded Isotopic Power Sources of Strontium-90 (Strontium Oxide) as a Function of Distance From Center of Source.

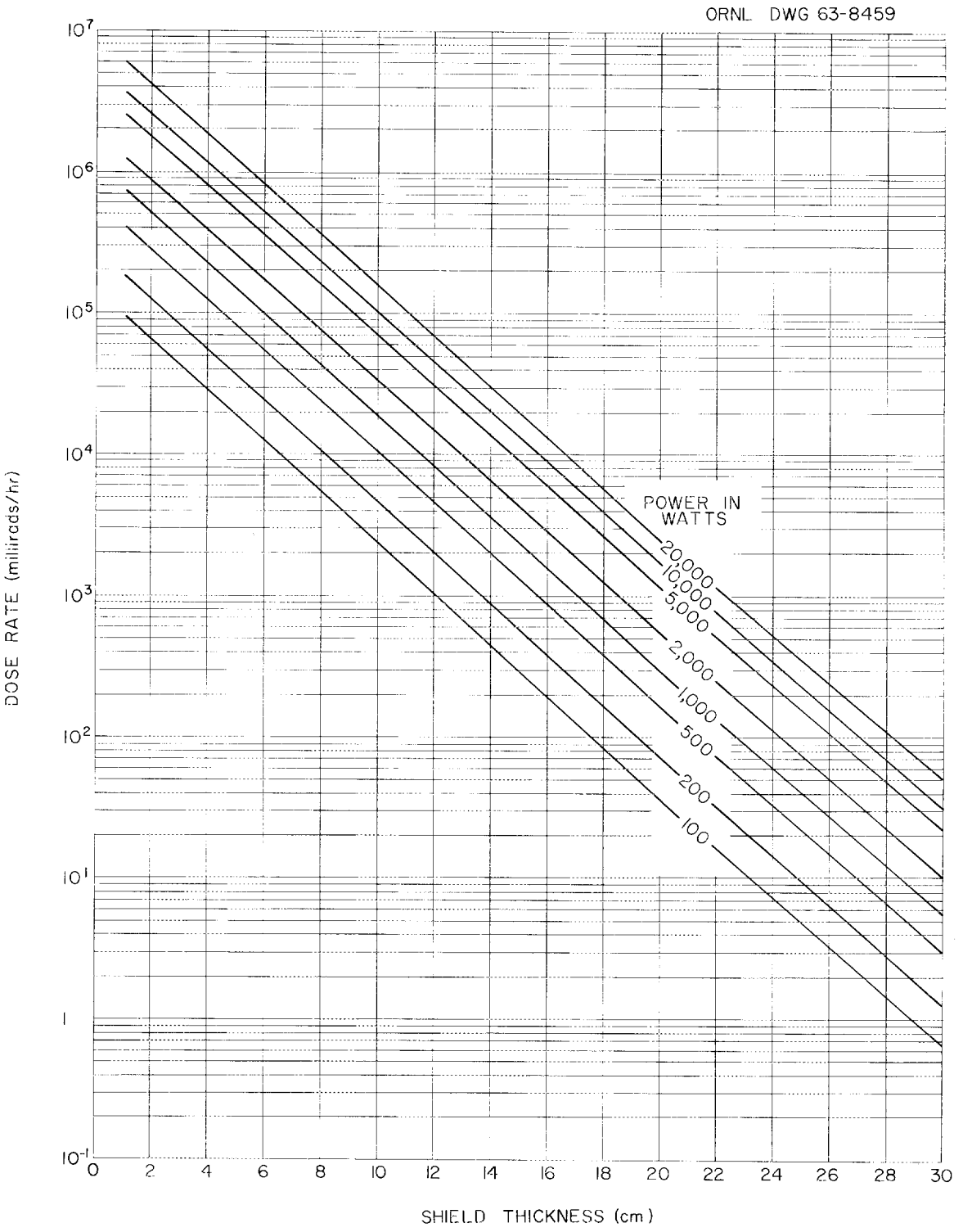

Fig. 7. Bremsstrahlung Dose Rates From Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

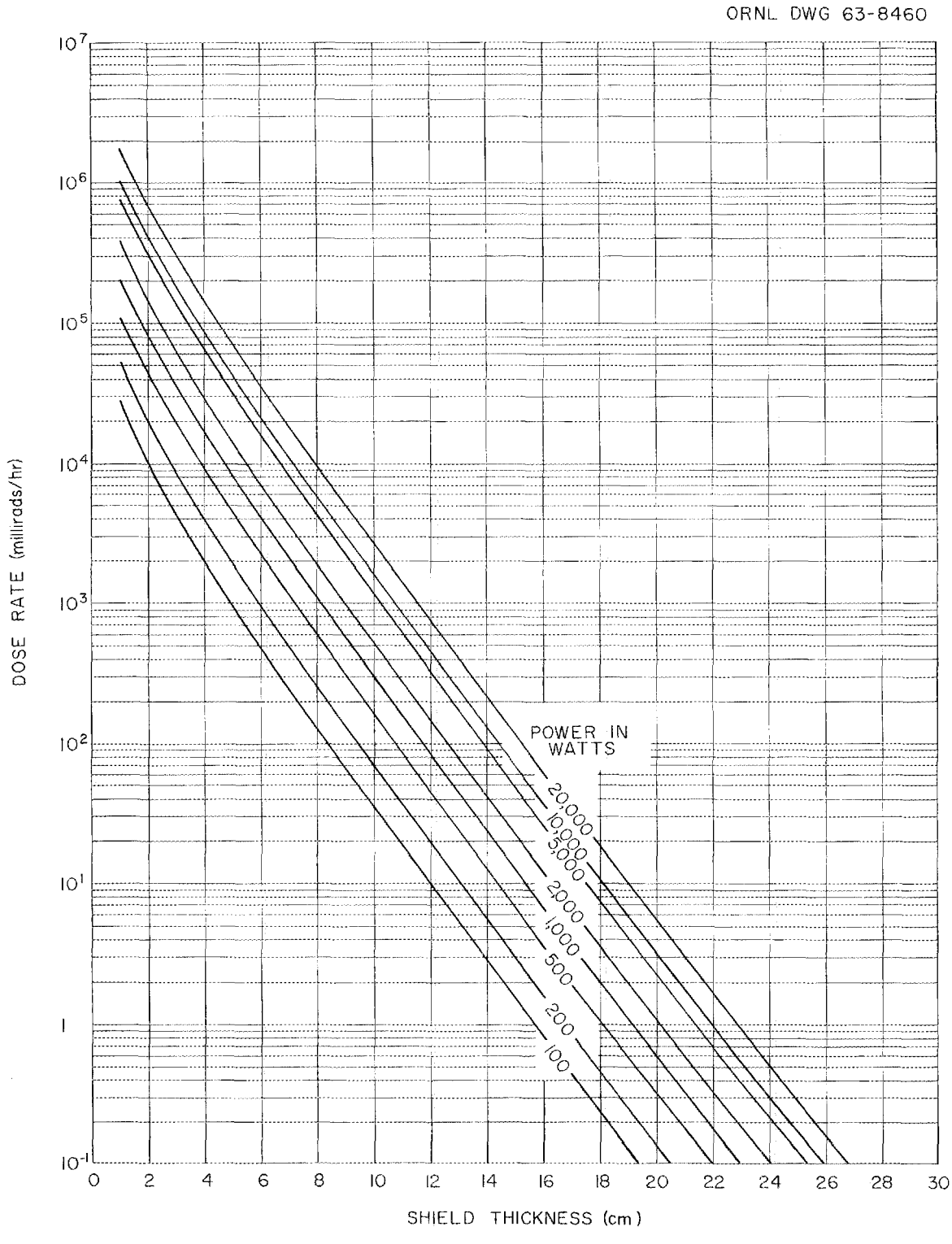

Fig. 8. Bremsstrahlung Dose Rates From Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

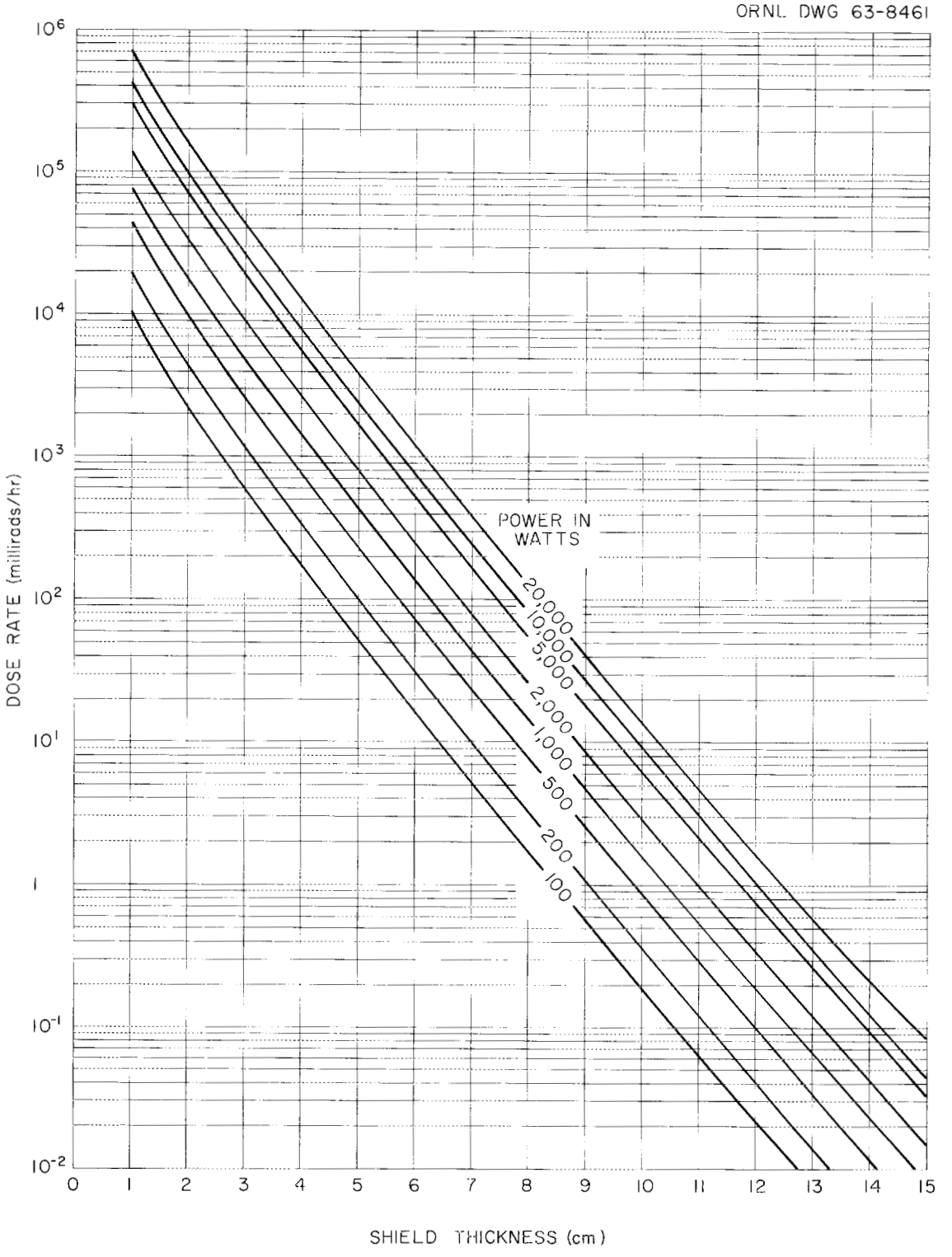

Fig. 9. Bremsstrahlung Dose Rates From Uranium-Shielded Isotopic Power Source of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

REFERENCE COLUMN

D. STRONTIUM FLUORIDE (SrF_2)

1. Composition

a. Radionuclidic abundance

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

b. Radiochemical purity

The radiochemical purity is given in Section I.A.1.

c. Chemical composition*

(1) Range of composition

Cation	Maximum, %	Minimum, %
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0
Zr	0	0

(2) Average chemical composition

Cation	Metal, %	Metal fluoride (MF_2), %
Sr	95	93.5
Ca	3.5	4.7
Ba	1.0	0.9
Mg	0.5	0.9

The strontium metal content of pure SrF_2 is 69.75%.

The strontium metal content of average SrF_2 is 65.2%.

The as-processed SrF_2 will contain 35.9% ^{90}Sr. The ^{144}Ce constitutes 0.03% of the radioactivity at a maximum. The ^{137}Cs has been found to be as high as 0.003% of the total activity. The ^{106}Ru activity has not been found. These activities can be neglected compared to the bremsstrahlung radiation.

2. Specific Power 2, 4, 5

a. 0.365 watt/g of pure SrF_2 (38.4% ^{90}Sr metal)
0.342 watt/g of average SrF_2 (35.9% ^{90}Sr metal)

*Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

It is assumed that there are 142 curies/g of ^{90}Sr and 149 curies of ^{90}Sr per thermal watt.

b. 54.4 curies of ^{90}Sr per gram of pure SrF_2 (38.4% ^{90}Sr metal)
50.9 curies of ^{90}Sr per gram of average SrF_2 (35.9% ^{90}Sr metal)

3. Radiation

The radiation will be the same as given under Section I.A.3.

4. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

5. Compatibility With Materials of Containment

Metallographic examination of test specimens exposed for 19 months at 925°C gave the following results. 28

Encapsulating material	Penetration, in. Maximum	Average
Simulated SrF_2 fuel (1 wt % Ca, 0.5 wt % Fe)		
Haynes 25	0.0006	nil
Ta liner in Haynes 25	Complete penetration of Ta liner	
Hastelloy C	0.001	0.0004
Hastelloy N	0.002	0.001
Hastelloy X	0.0075	0.0014
Simulated aged feed material (SrF_2 + 2-1/2 wt % Zr as ZrO_2)		
Haynes 25	0.0015	0.0008
Ta liner in Haynes	Complete penetration of Ta liner	
Hastelloy C	0.0007	0.0003
Hastelloy N	0.0028	0.0011
Hastelloy X	0.0055	0.0011

6. Thermophysical Properties

a. Density

4.29 g/cm^3 – density of pure SrF_2 43

4.20 g/cm^3 – density of average SrF_2

REFERENCE COLUMN

b. Coefficient of thermal expansion 44

$\alpha/°C = 15.72 \times 10^{-6} - 0.63 \times 10^{-8}\ t + 1.17 \times 10^{-10}\ t^2$

(t is in °C in temperature range of 28-284°C)

c. Specific heat and enthalpy

(1) Specific heat

$0.125 + 5.57 \times 10^{-5}\ T$ cal $g^{-1}\ °C^{-1}$ 37

(T is in °K)

(2) Enthalpy in calories

$H_T - H_{298} = 15.7\ T + 3.5 \times 10^{-3}\ T^2 - 4980$ 37

d. Temperatures of phase transformations

(1) Melting point – 1463°C 45

(2) Boiling point – 2477°C 37

e. Latent heats of phase transformations

ΔH fusion 4.3 kcal/mole 37

ΔH vaporization 71 kcal/mole 37

f. Vapor pressure

torr	Temperature, °C	
8.5	1822	13
15.0	1880	
25.7	1927	
31.0	1959	

g. Thermal conductivity

cal $cm^{-1}\ sec^{-1}\ °C^{-1}$	Temperature, °C	
0.0120	20	46
0.0055	300	
0.0030	725	

h. Thermal diffusivity

cm^2/sec	Temperature, °C
0.0219	20
0.0091	300
0.0043	725

These values were calculated by dividing the thermal conductivity by the product of the specific heat and a density of 3.86 g/cm^3.

REFERENCE COLUMN

i. Viscosity

$\text{Log } \eta = 0.781 + 436/T$ 47

(η is in centipoises and T is temperature in °K)

j. Surface tension

184 dynes/cm 48

k. Total hemispherical emittance

l. Spectral emissivity

A value of 0.9 can be assumed. 18

m. Crystallography

Cubic: a = 5.781 A 43

n. Solubilities

0.0009 mole/liter in water 18°C 13

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 = -290.3 kcal/mole 41

(2) Free energy of formation

ΔF°_f = -277.2 kcal/mole 41

(3) Entropy

S°_{298} = 20.5 eu 37

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

(1) Nitrogen -- no reaction

(2) Water -- slightly soluble 42

(3) Inorganic acids -- insoluble

REFERENCE COLUMN

9. Biological Tolerances

The ^{90}Sr tolerances are given under Strontium-90 Metal Fuel Form, Section I.A.9.

10. Shielding Data

See the sections under Strontium Titanate, I.B.10, and Strontium Oxide, I.C.10, for shielding data.

REFERENCE COLUMN

E. STRONTIUM ORTHOTITANATE (Sr_2TiO_4)

1. Composition

a. Radionuclidic abundance

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

b. Radiochemical purity

The radiochemical purity is given in Section I.A.1.

c. Chemical composition*

(1) Range of composition

Cation	Maximum, %	Minimum, %
Sr	97	92
Ca	5	2
Ba	2	0.5
Mg	2	0
Zr	0	0

(2) Average chemical composition

Cation	Metal, %	Orthotitanate, %
Sr	95	93.2
Ca	3.5	5.0
Ba	1.0	0.8
Mg	0.5	1.0

The strontium metal content of pure Sr_2TiO_4 is 61.05%.

The strontium metal content of average Sr_2TiO_4 is 56.89%.

The as-processed Sr_2TiO_4 will contain 31.3% ^{90}Sr. The ^{144}Ce constitutes 0.03% of the radioactivity at a maximum. The ^{137}Cs has been found to be as high as 0.003% of the total activity. The ^{106}Ru activity has not been found. These activities can be neglected compared to the bremsstrahlung radiation.

2. Specific Power

2, 4, 5

a. 0.320 watt/g of pure $SrTiO_4$ (33.6% ^{90}Sr metal)
0.298 watt/g of average $SrTiO_4$ (31.3% ^{90}Sr metal)

*Results of analyses on strontium titanate feed samples of the Fission Products Development Laboratory at Oak Ridge National Laboratory.

REFERENCE COLUMN

It is assumed that there are 142 curies/g of ^{90}Sr and 149 curies of ^{90}Sr per thermal watt.

b. 47.7 curies of ^{90}Sr per gram of pure Sr_2TiO_4 (33.6% ^{90}Sr metal)
44.4 curies of ^{90}Sr per gram of average Sr_2TiO_4 (31.3% ^{90}Sr metal)

3. Radiation

The radiation will be the same as given under Section I.A.3.

4. Critical Mass

Strontium-90 and ^{90}Y are not fissionable.

5. Compatibility With Materials of Containment

6. Thermophysical Properties

a. Density

$4.99\ g/cm^3$ – density of pure Sr_2TiO_4 49

$4.93\ g/cm^3$ – density of average Sr_2TiO_4 (hot pressed) 50

b. Coefficient of thermal expansion

$\alpha = 11.2 \times 10^{-6}/°C$ (100-700°C) 24 ($SrTiO_3$)

c. Specific heat and enthalpy

(1) Specific heat in cal/g

$0.135 + 1.34 \times 10^{-5}\ T - 1.63 \times 10^{3}\ T^{-2}$ 25

(T is in °K) (298-1800°K)

(2) Enthalpy in calories

$H_T - H_{298} = 38.45\ T + 1.92 \times 10^{-3}\ T^2 + 4.67 \times 10^{5}\ T^{-1} - 13{,}201$ 26

(T is in °K) (298-1800°K)

d. Temperatures of phase transformations

(1) Melting point – 1860 ± 20°C 51

(2) Boiling point – 2500-3000°C 9

REFERENCE COLUMN

e. Latent heats of phase transformations

ΔH fusion (not available)

ΔH vaporiation 71 kcal/mole 10

(calculated from Trouton's rule)

f. Vapor pressure

g. Thermal conductivity

0.0173 cal cm^{-1} sec^{-1} $°C^{-1}$ at 94% theoretical density at room temperature 24 ($SrTiO_3$)

h. Thermal diffusivity

cm^2/sec	Temperature, °C	
0.0267	20	($SrTiO_3$)

This value was calculated by dividing the thermal conductivity by the product of the specific heat and density.

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

m. Crystallography

Tetragonal body centered

a = 3.88 A c = 12.60 A 49

n. Solubilities

A static solubility study of titanate fuels using a particle size of <177 microns with 9 grams of fuel per 200 ml of dissolver solution gave the following results. 52

	Microgram of fuel per ml of dissolver sol			
Days	Deion. water	Natural seawater	Synthetic seawater	0.1 N HCl
	Sr_2TiO_4 at room temperature			
7	9,856	8,683	9,386	11,050
28	7,337	9,357	9,599	9,988
48	9,298	9,832	9,980	10,427
78	7,456	9,478	9,243	9,826
98	8,209	9,799	9,860	10,290
161	10,103	10,454	10,766	9,816

REFERENCE COLUMN

Days	Micrograms of fuel per ml of dissolver sol: Deion. water	Natural seawater	Synthetic seawater	0.1 N HCl
	Sr_2TiO_4 at 66°			
7	12,857	11,417	14,528	13,860
28	10,044	10,888	13,461	13,063
48	12,916	11,643	14,376	13,480
78	11,846	11,307	13,912	12,716
98	13,995	12,313	14,670	13,585
161	10,135	13,607	16,635	15,302

o. Diffusion rates

7. Mechanical Properties

a. Hardness

b. Crush strength

19,100 lb/in.^{2} 31 ($CaTiO_3$)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

ΔH°_f = -545.6 kcal/mole 32, 33

(calculated from available data)

(2) Free energy of formation

ΔF°_f = -518.2 kcal/mole 32

(calculated from available data)

(3) Entropy

S°_{298} = 38.0 ± 0.3 cal $^\circ C^{-1}$ mole^{-1} 25

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

(1) Oxygen – no reaction 50

(2) Nitrogen – no reaction

(3) Water – decomposes

(4) Inorganic acids – soluble

REFERENCE COLUMN

9. Biological Tolerances

The ^{90}Sr tolerances are given under Strontium-90 Metal Fuel Form, Section I.A.9.

10. Shielding Data

Bremsstrahlung dose rates from ^{90}Sr 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. 2-5 shown in Section I.B.10. These sources require significant shielding because of the high energy of some of the photons from the bremsstrahlung radiation. 4

APPENDIX 1

Table 1. Production of Bremsstrahlung Photons From Strontium-90 Beta in Strontium Oxide Matrix (Ref. 4)

Maximum beta-particle energy	0.545 Mev
Average beta-particle energy	0.201 Mev

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons w^{-1} sec^{-1}
0.020 ± 0.01	1.378×10^{-2}	7.58×10^{10}
0.040 ± 0.01	5.523×10^{-3}	3.04×10^{10}
0.060 ± 0.01	2.998×10^{-3}	1.65×10^{10}
0.080 ± 0.01	1.841×10^{-3}	1.01×10^{10}
0.100 ± 0.01	1.208×10^{-3}	0.66×10^{10}
0.120 ± 0.01	8.239×10^{-4}	0.45×10^{10}
0.140 ± 0.01	5.759×10^{-4}	3.17×10^{9}
0.160 ± 0.01	4.086×10^{-4}	2.25×10^{9}
0.180 ± 0.01	2.923×10^{-4}	1.61×10^{9}
0.200 ± 0.01	2.099×10^{-4}	1.15×10^{9}
0.220 ± 0.01	1.505×10^{-4}	0.83×10^{9}
0.240 ± 0.01	1.074×10^{-4}	0.59×10^{9}
0.260 ± 0.01	7.604×10^{-5}	0.42×10^{9}
0.280 ± 0.01	5.315×10^{-5}	2.92×10^{8}
0.300 ± 0.01	3.654×10^{-5}	2.01×10^{8}
0.320 ± 0.01	2.458×10^{-5}	1.35×10^{8}
0.340 ± 0.01	1.609×10^{-5}	0.88×10^{8}
0.360 ± 0.01	1.016×10^{-5}	0.56×10^{8}
0.380 ± 0.01	6.135×10^{-6}	3.37×10^{7}
0.400 ± 0.01	3.491×10^{-6}	1.92×10^{7}
0.420 ± 0.01	1.835×10^{-6}	1.01×10^{7}
0.440 ± 0.01	8.638×10^{-7}	0.48×10^{7}
0.460 ± 0.01	3.456×10^{-7}	1.90×10^{6}
0.480 ± 0.01	1.065×10^{-7}	5.86×10^{5}
0.500 ± 0.01	2.007×10^{-8}	1.10×10^{5}
0.520 ± 0.01	1.000×10^{-9}	5.50×10^{3}
0.540 ± 0.01	0.000	
Total bremsstrahlung energy, Mev/beta particle		1.411×10^{-3}

APPENDIX 1

Table 2. Production of Bremsstrahlung Photons From Yttrium-90 Beta in Strontium Oxide Matrix (Ref. 4)

Maximum beta-particle energy 2.27 Mev
Average beta-particle energy 0.944 Mev

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons w^{-1} sec^{-1}
0.100 ± 0.05	6.152×10^{-2}	3.38×10^{11}
0.200 ± 0.05	2.415×10^{-2}	1.33×10^{11}
0.300 ± 0.05	1.281×10^{-2}	0.70×10^{11}
0.400 ± 0.05	7.674×10^{-3}	4.22×10^{10}
0.500 ± 0.05	4.894×10^{-3}	2.69×10^{10}
0.600 ± 0.05	3.234×10^{-3}	1.78×10^{10}
0.700 ± 0.05	2.181×10^{-3}	1.20×10^{10}
0.800 ± 0.05	1.485×10^{-3}	8.17×10^{9}
0.900 ± 0.05	1.014×10^{-3}	5.58×10^{9}
1.000 ± 0.05	6.887×10^{-4}	3.79×10^{9}
1.100 ± 0.05	4.630×10^{-4}	2.55×10^{9}
1.200 ± 0.05	$3.0\ 0 \times 10^{-4}$	1.65×10^{9}
1.300 ± 0.05	1.973×10^{-4}	1.09×10^{9}
1.400 ± 0.05	1.231×10^{-4}	0.68×10^{9}
1.500 ± 0.05	7.337×10^{-5}	4.04×10^{8}
1.600 ± 0.05	4.117×10^{-5}	2.26×10^{8}
1.700 ± 0.05	2.125×10^{-5}	1.17×10^{8}
1.800 ± 0.05	9.740×10^{-6}	5.36×10^{7}
1.900 ± 0.05	3.728×10^{-6}	2.05×10^{7}
2.000 ± 0.05	1.058×10^{-6}	5.82×10^{6}
2.100 ± 0.05	1.670×10^{-7}	9.19×10^{5}
2.200 ± 0.05	4.768×10^{-8}	2.62×10^{4}
Total bremsstrahlung energy, Mev/beta particle	2.814×10^{-2}	

APPENDIX 1

Table 3. Production of Bremsstrahlung Photons From Strontium-90 Beta in Strontium Titanate Matrix (Ref. 4)

Maximum beta-particle energy	0.545 Mev
Average beta-particle energy	0.201 Mev

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons w^{-1} sec^{-1}
0.020 ± 0.01	1.009×10^{-2}	5.55×10^{10}
0.040 ± 0.01	4.044×10^{-3}	2.22×10^{10}
0.060 ± 0.01	2.195×10^{-3}	1.21×10^{10}
0.080 ± 0.01	1.348×10^{-3}	7.41×10^{9}
0.100 ± 0.01	8.845×10^{-4}	4.86×10^{9}
0.120 ± 0.01	6.034×10^{-4}	3.32×10^{9}
0.140 ± 0.01	4.217×10^{-4}	2.32×10^{9}
0.160 ± 0.01	2.993×10^{-4}	1.65×10^{9}
0.180 ± 0.01	2.141×10^{-4}	1.18×10^{9}
0.200 ± 0.01	1.537×10^{-4}	8.45×10^{8}
0.220 ± 0.01	1.103×10^{-4}	6.07×10^{8}
0.240 ± 0.01	7.871×10^{-5}	4.33×10^{8}
0.260 ± 0.01	5.571×10^{-5}	3.06×10^{8}
0.280 ± 0.01	3.895×10^{-5}	2.14×10^{8}
0.300 ± 0.01	2.678×10^{-5}	1.47×10^{8}
0.320 ± 0.01	1.801×10^{-5}	0.99×10^{8}
0.340 ± 0.01	1.179×10^{-5}	6.48×10^{7}
0.360 ± 0.01	7.448×10^{-6}	4.10×10^{7}
0.380 ± 0.01	4.497×10^{-6}	2.47×10^{7}
0.400 ± 0.01	2.559×10^{-6}	1.41×10^{7}
0.420 ± 0.01	1.345×10^{-6}	0.74×10^{7}
0.440 ± 0.01	6.333×10^{-7}	3.48×10^{6}
0.460 ± 0.01	2.534×10^{-7}	1.39×10^{6}
0.480 ± 0.01	7.807×10^{-8}	4.29×10^{5}
0.500 ± 0.01	1.472×10^{-8}	8.10×10^{4}
0.520 ± 0.01	7.336×10^{-10}	4.03×10^{3}
0.540 ± 0.01	0.000	
Total bremsstrahlung energy, Mev/beta particle	9.924×10^{-4}	

APPENDIX 1

Table 4. Production of Bremsstrahlung Photons From Yttrium-90 Beta in Strontium Titanate Matrix (Ref. 4)

Maximum beta-particle energy	2.27 Mev
Average beta-particle energy	0.944 Mev

Bremsstrahlung energy group, Mev	Within ΔE energy group	
	Photons per beta particle	Photons w^{-1} sec^{-1}
0.100 ± 0.05	4.537×10^{-2}	2.50×10^{11}
0.200 ± 0.05	1.782×10^{-2}	0.98×10^{11}
0.300 ± 0.05	9.456×10^{-3}	5.20×10^{10}
0.400 ± 0.05	5.665×10^{-3}	3.12×10^{10}
0.500 ± 0.05	3.613×10^{-3}	1.99×10^{10}
0.600 ± 0.05	2.389×10^{-3}	1.31×10^{10}
0.700 ± 0.05	1.611×10^{-3}	0.89×10^{10}
0.800 ± 0.05	1.098×10^{-3}	6.04×10^{9}
0.900 ± 0.05	7.493×10^{-4}	4.12×10^{9}
1.000 ± 0.05	5.092×10^{-4}	2.80×10^{9}
1.100 ± 0.05	3.425×10^{-4}	1.88×10^{9}
1.200 ± 0.05	2.264×10^{-4}	1.25×10^{9}
1.300 ± 0.05	1.460×10^{-4}	8.03×10^{8}
1.400 ± 0.05	9.110×10^{-5}	5.01×10^{8}
1.500 ± 0.05	5.434×10^{-5}	3.00×10^{8}
1.600 ± 0.05	3.050×10^{-5}	1.68×10^{8}
1.700 ± 0.05	1.576×10^{-5}	8.67×10^{7}
1.800 ± 0.05	7.220×10^{-6}	3.97×10^{7}
1.900 ± 0.05	2.764×10^{-6}	1.52×10^{7}
2.000 ± 0.05	7.850×10^{-7}	4.32×10^{6}
2.100 ± 0.05	1.239×10^{-7}	6.81×10^{5}
2.200 ± 0.05	3.540×10^{-9}	1.95×10^{4}
Total bremsstrahlung energy, Mev/beta particle	2.078×10^{-2}	

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