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# STRONTIUM-90 DATA SHEETS

S. J. Rimshaw
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OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
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ISOTOPES DEVELOPMENT CENTER

# STRONTIUM-90 DATA SHEETS

S. J. Rimshaw and E. E. Ketchen

Isotopes Division

MARCH 1969

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# STRONTIUM-90 DATA SHEETS

REFERENCE COLUMN

## I. FUEL FORM (as processed)

### A. STRONTIUM-90 METAL — Half-life: 28.6 y — 1

#### 1. Composition

a. Radionuclidic abundance — 2, 3

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

These values were obtained by a mass-spectrometric analysis of fission-product strontium. Average molecular weight of fission-product strontium is 89.08.

b. Radiochemical purity

The principal radionuclide other than $^{90}Sr$ is $^{89}Sr$ ($T_{1/2}$ = 50.5 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.

c. Chemical composition*

(1) Range of composition

| Cation | Maximum, wt % | Minimum, wt % |
|---|---|---|
| Sr | 97 | 92 |
| Ca | 5 | 2 |
| Ba | 2 | 0.5 |
| Mg | 2 | 0 |

One gram of $^{90}Sr$ will produce an average of 0.0232 g of $^{90}Zr$ after one year's decay.

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

(2) Average chemical composition

| Cation | Metal, wt % | Metal, atom % |
|---|---|---|
| Sr | 95 | 96.69 |
| Ca | 3.5 | 1.60 |
| Ba | 1.0 | 1.57 |
| Mg | 0.5 | 0.14 |

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 2, 4, 5

a. 0.513 w/g of 100% strontium metal (55% $^{90}Sr$)
0.487 w/g of metal (95% Sr-5% Ca, Ba, Mg)

It is assumed that there are 139 Ci/g of $^{90}Sr$ (100% $^{90}Sr$) and 148.9 Ci of $^{90}Sr$ per thermal watt or 0.933 w/g of 100% $^{90}Sr$.

b. 76.5 Ci of $^{90}Sr$ per gram of 100% strontium metal (55% $^{90}Sr$)
72.7 Ci of $^{90}Sr$ per gram of 95% strontium metal

3. Radiation

a. Alpha particles

None

b. Beta particles 1, 4, 6

| Nuclide | Max E, Mev | Av E, Mev | Abundance, % | w/kCi | Particles $w^{-1}$ $sec^{-1}$ |
|---|---|---|---|---|---|
| $^{90}Sr$ | 0.546 | 0.1963 | 100 | 1.164 | $5.51 \times 10^{12}$ |
| $^{90}Y$ | 2.284 | 0.9365 | 100 | 5.551 | $5.51 \times 10^{12}$ |
| Total power | | | | 6.715 | |

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 the Appendix (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 exposure of 2036 hr at 925°C to inactive 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 inactive liquid strontium metal at 1000°C. 8

The compatibility of inactive strontium metal with a number of container materials were determined and have been summarized below. 9

| Source material and exposure | Container material | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Superalloys | | | | Refractory metals | | | |
| | Hastelloy X | Haynes 25 | Ni-o-nel | N-155 | Mo | Ta | W | TZM |
| Strontium metal | | | | | | | | |
| 1000°C, 1000 hr | SR | NR | SR | MR | NR | SR | NR | NR |
| 1000°C, 5000 hr | | MR | | MR | | SR | NR | |
| 1000°C, 10,000 hr | | MR | MR | MR | NR | SR | SR | |

Legend: NR – Negligible or no reaction (compatible) SR – Slight reaction
MR – Major reaction

A number of reactions were dependent on time and temperature. For example, Haynes 25 with strontium metal showed no attack at 1000°C up to 1000 hr but fell into the major reaction classification after 5000 and 10,000 hr at 1000°C. This indicates that Haynes 25 should probably not be considered for use with strontium metal at temperatures >1000°C and times >5000 hr. For periods up to 1000 hr at 1000°C, strontium metal showed little or no reaction with any metal except N-155, in which areas of severe subsurface void formation were found up to 22 mils.

6. Thermophysical Properties

a. Density

(1) Theoretical density 10

2.6 g/cm$^3$ for strontium element
2.55 g/cm$^3$ for 95% Sr, 3.5% Ca, 1.0% Ba, and 0.5% Mg

(2) Liquid strontium density, g/cm$^3$ 11

$\rho = 2.648 - 2.62 \times 10^{-4}T$ (°K) (1225-1580°K)

STRONTIUM-90 METAL

REFERENCE COLUMN

b. Coefficient of thermal expansion

$2.0 \times 10^{-5}/°C$ 12

c. Specific heat and enthalpy

(1) Specific heat

$0.0719$ cal $g^{-1}$ $°C^{-1}$ (25°C) 13

(2) Enthalpy in cal/mole 14

$H_T - H_{298} = 5.13T + 1.66 \times 10^{-3}T^2 - 1731$ (298-862°K)

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

$\Delta H$ transition = 200 cal/mole (862°K)

d. Temperatures of phase transformations

(1) Melting point

772°C 12

(2) Boiling point

1372°C 12

e. Latent heats of phase transformations

$\Delta H$ transition ($\alpha \rightarrow \beta$) = 200 cal/mole (589°C) 14

$\Delta H$ fusion (772°C) = 2400 cal/mole 14

$\Delta H$ vaporization (1372°C) = 33,200 cal/mole 13

f. Vapor pressure 15

| Atmosphere | Temperature, °C |
|---|---|
| 0.026 | 944 |
| 0.066 | 1041 |
| 0.13 | 1116 |
| 0.47 | 1254 |
| 0.66 | 1315 |
| 1.95 | 1437 |
| 2.42 | 1567 |
| 5.32 | 1706 |

The vapor pressure is given by the following equation:

$$\text{Log } P_{atm} = 7.35 - [7370/T(°K)] .$$

g. Thermal conductivity

| Thermal conductivity, cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C | |
|---|---|---|
| 0.3 | 20 | 16 (Ca) |
| 0.385 | 100 | 17 (Be) |
| 0.290 | 300 | |
| 0.247 | 500 | |
| 0.206 | 700 | |

STRONTIUM-90 METAL

REFERENCE COLUMN

h. Thermal diffusivity

| 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, $erg/cm^2$

$\sigma = 392 - 0.085T$ (°K) (1152-1602°K) — 11

k. Total hemispherical emittance

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

l. Spectral emissivity

Can also vary as stated in k. above.

m. Crystallography

| $\alpha$ fcc | 215°C | $\beta$ hcp | 605°C | $\gamma$ bcc | |
|---|---|---|---|---|---|
| a = 6.085 Å | | a = 4.32 Å<br>c = 7.06 Å | | a = 4.85 Å | 19, 20 |

n. Solubilities

Strontium metal reacts vigorously with water — 20

o. Diffusion rates

7. Mechanical Properties

a. Hardness

16-18 (Brinell) — 16 (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

$S^{\circ}_{298} = 12.5$ eu 21

b. Chemical reactions and reaction rates 16, 22

(1) Oxygen — fast

(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 reference 23 are given below. 23

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(μCi) | Max permissible concentrations, μCi/cm³ For 40-hr week Water | For 40-hr week Air | For 168-hr week Water | For 168-hr week Air |
|---|---|---|---|---|---|---|---|
| $^{90}_{38}Sr$ ($\beta^-$) | (Sol) | Bone | 2 | $4 \times 10^{-6}$ | $3 \times 10^{-10}$ | $10^{-6}$ | $10^{-10}$ |
| | | Total Body | 20 | $10^{-5}$ | $9 \times 10^{-10}$ | $4 \times 10^{-6}$ | $3 \times 10^{-10}$ |
| | | GI (LLI)[a] | | $10^{-3}$ | $3 \times 10^{-7}$ | $5 \times 10^{-4}$ | $10^{-7}$ |
| | (Insol) | Lung | | | $5 \times 10^{-9}$ | | $2 \times 10^{-9}$ |
| | | GI (LLI)[a] | | $10^{-3}$ | $2 \times 10^{-7}$ | $4 \times 10^{-4}$ | $6 \times 10^{-8}$ |

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

10. Shielding Data

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

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, wt % | Minimum, wt % |
|---|---|---|
| Sr | 97 | 92 |
| Ca | 5 | 2 |
| Ba | 2 | 0.5 |
| Mg | 2 | 0 |

One gram of $^{90}Sr$ will produce an average of 0.0232 g of $^{90}Zr$ after one year's decay.

(2) Average chemical composition

| Metal oxide | Content, wt % | Titanate compound | Content, wt % |
|---|---|---|---|
| SrO | 52.5 | $SrTiO_3$ | 92.5 |
| CaO | 2.3 | $CaTiO_3$ | 5.6 |
| BaO | 0.5 | $BaTiO_3$ | 0.8 |
| MgO | 0.4 | $MgTiO_3$ | 1.1 |
| $TiO_2$ | 44.3 | | |

The strontium metal content of pure fission-product $SrTiO_3$ is 48.16%.

The strontium metal content of average fission-product $SrTiO_3$ is 44.55%.

The as-processed $SrTiO_3$ will contain 24.5% $^{90}Sr$. 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.

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

STRONTIUM TITANATE ($SrTiO_3$) — REFERENCE COLUMN

2. Specific Power — 2, 4, 5

a. 0.247 w/g of pure $SrTiO_3$ (26.5% $^{90}Sr$ metal)
0.235 w/g of average $SrTiO_3$ (24.5% $^{90}Sr$ metal)

It is assumed that there are 139 Ci/g of $^{90}Sr$ and 148.9Ci of $^{90}Sr$ per thermal watt.

b. 36.8 Ci of $^{90}Sr$ per gram of pure $SrTiO_3$ (26.5% $^{90}Sr$ metal)
34.1 Ci of $^{90}Sr$ per gram of average $SrTiO_3$ (24.5% $^{90}Sr$ metal)

3. Radiation

The radiation is 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 compatibilities of various inactive strontium compounds with a number of container materials were determined and have been summarized in the following table. 9

| Source material and exposure | Container material | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Superalloys | | | | Refractory metals | | | | |
| | Hastelloy X | Haynes 25 | Ni-o-nel | N-155 | Mo | Nb | Ta | W | TZM |
| Strontium metal (Sr) | | | | | | | | | |
| 1000°C, 1000 hr | SR | NR | SR | MR | NR | | SR | NR | NR |
| 1000°C, 5000 hr | | MR | | MR | | | SR | NR | |
| 1000°C, 10,000 hr | | MR | MR | MR | NR | | SR | SR | |
| Strontium oxide (SrO) | | | | | | | | | |
| 1000°C, 1000 hr | SR | | SR | SR | NR | NR | SR | SR | |
| 1850°C, 168 hr | | | | | SR | MR | SR | SR | |
| Strontium-9% beryllium oxide (SrO-9% BeO) | | | | | | | | | |
| 1000°C, 1000 hr | | MR | MR | SR | NR | | | NR | NR |
| Strontium fluoride ($SrF_2$) | | | | | | | | | |
| 1000°C, 1000 hr | SR | SR | SR | SR | NR | | SR | SR | |
| Strontium disilicide ($SrSi_2$) | | | | | | | | | |
| 1000°C, 168 hr | DR | DR | DR | DR | DR | | DR | DR | DR |
| Strontium titanate ($SrTiO_3$) | | | | | | | | | |
| 1000°C, 1000 hr | SR | SR | SR | SR | NR | | NR | NR | NR |
| 1850°C, 1000 hr | | | | | NR | SR | SR | NR | MR |

Legend: NR — Negligible or no reaction (compatible) SR — Slight reaction
DR — Destructive reaction (incompatible) MR — Major reaction

A number of reactions were dependent on time and temperature; for example, Haynes 25 with strontium metal showed no attack at 1000°C up to 1000 hr but fell into the major reaction classification after 5000 and 10,000 hr at 1000°C. This indicates that Haynes 25 should probably not be considered for use with strontium metal at temperatures >1000°C and times >5000 hr.

STRONTIUM TITANATE ($SrTiO_3$) REFERENCE COLUMN

For periods up to 1000 hr at 1000°C, strontium metal showed little or no reaction with any metal except N-155, in which areas of severe subsurface void formation were found up to 22 mils.

At 1000°C SrO showed only slight surface oxidation reaction with most of the metals.

Strontium fluoride ($SrF_2$) showed very little attack with the metals tested.

At 1000°C $SrSi_2$ showed extensive reaction with Hastelloy X, Haynes 25, Ni-o-nel, and N-155. Molybdenum, tantalum, and TZM were resistant to penetration by silicon metal which formed from the dissociation of $SrSi_2$ at 1000°C.

Strontium titanate was compatible with all the container materials exposed at 1000°C. Molybdenum and tungsten were compatible at 1850°C, while niobium and tantalum had a slight reaction at this temperature. TZM reacted to a depth of 5 mils for a major reaction classification.

More extensive compatibility tests of Haynes 25, Hastelloy C, and type 316 stainless steel with inactive $SrTiO_3$ and $Sr_2TiO_4$ have not indicated any serious interactions after 1000 and 5000 hr at 1100°C. However, these materials were attacked to a maximum depth of 0.007 in. when exposed to SrO under the same conditions. It is believed that these latter results are due to reaction of the container materials with water vapor or excess oxygen dissolved in the SrO. Mechanical properties tests of specimens exposed to all three strontium compounds did not reveal any deterioration when compared with control specimens heat treated in argon under similar conditions of time and temperature. 24

6. Thermophysical Properties

a. Density

5.11 g/cm$^3$ for pure $SrTiO_3$ 25
5.03 g/cm$^3$ for average $SrTiO_3$

b. Coefficient of thermal expansion

$\alpha = 11.2 \times 10^{-6}/°C$ (100-700°C) 25

The coefficient of expansion of $SrTiO_3$ has been determined up to 1400°C with a Brinkman Model 5440 dilatometer. To simulate a typical radioactive 26

strontium fuel, samples were prepared with a composition of 92 wt % Sr, 3.7 wt % Ca, 3.7 wt % Ba, and 0.3 wt % Mg. The hot-pressed $SrTiO_3$ sample was 1 in. in length and contained 5% excess $TiO_2$ over the stoichiometric ratio of $SrO \cdot TiO_2$.

The following table gives the values obtained for the mean coefficient of expansion for $SrTiO_3$ for the temperature intervals shown. The mean coefficient of expansion, $A_m$, is defined as

$$A_m(t_o,t) = \Delta l/l\Delta t \ ,$$

where

$A_m(t_o,t)$ = mean coefficient of expansion in the temperature interval, $\Delta t$, from $t_o$ to t°C,

$\Delta t$ = temperature interval,

$\Delta l$ = change in sample length over $\Delta t$,

$l$ = sample length at temperature $t_o$°C.

| Temperature interval, °C | Mean linear coefficient of expansion for $SrTiO_3$ |
|---|---|
| 0-100 | $10.8 \times 10^{-6}$/°C |
| 0-200 | $10.7 \times 10^{-6}$/°C |
| 0-300 | $10.7 \times 10^{-6}$/°C |
| 0-400 | $10.8 \times 10^{-6}$/°C |
| 0-500 | $10.9 \times 10^{-6}$/°C |
| 0-600 | $11.0 \times 10^{-6}$/°C |
| 0-700 | $11.1 \times 10^{-6}$/°C |
| 0-800 | $11.2 \times 10^{-6}$/°C |
| 0-900 | $11.3 \times 10^{-6}$/°C |
| 0-1000 | $11.4 \times 10^{-6}$/°C |
| 0-1100 | $11.6 \times 10^{-6}$/°C |
| 0-1200 | $11.7 \times 10^{-6}$/°C |
| 0-1300 | $12.0 \times 10^{-6}$/°C |
| 0-1400 | $12.1 \times 10^{-6}$/°C |

c. Specific heat and enthalpy

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

$$0.154 + 0.96 \times 10^{-5}T - 2.54 \times 10^{3}T^{-2} \quad (°K) \qquad 27$$

(2) Enthalpy in cal/mole

$$H_T - H_{298} = 28.23T + 0.88 \times 10^{-3}T^2 + 4.66 \times 10^{5}T^{-1} - 10{,}058 \ (°K) \qquad 28$$

STRONTIUM TITANATE ($SrTiO_3$) — REFERENCE COLUMN

d. Temperatures of phase transformations

(1) Melting point

2040°C — 29

(2) Boiling point

2500-3000°C — 10

(3) Phase changes at 1440 and 1640°C — 29

e. Latent heats of phase transformations

$\Delta H$ vaporization = 71 kcal/mole (calculated from Trouton's rule) — 12

f. Vapor pressure

g. Thermal conductivity

(1) $SrO:TiO_2$ = 1.00 — 30

The following equation was derived from data by a method of least mean squares:

$$1/k = 55.76 + 0.0673T \ (°K)$$

where k is the thermal conductivity in cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$. The data covered the range 350 to 900°C. The useful range of equation is 200 to 1400°C.

| Thermal conductivity,[a] cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C |
|---|---|
| 0.0114 ± 0.0015 | 200 |
| 0.0099 ± 0.0003 | 400 |
| 0.0088 ± 0.0001 | 600 |
| 0.0078 ± 0.0001 | 800 |
| 0.0071 ± 0.0002 | 1000 |
| 0.0065 ± 0.0003 | 1200 |
| 0.0060 ± 0.0003 | 1400 |

[a]Determined on theoretically dense pellets of stoichiometric $SrTiO_3$ with a composition of 51.03 wt % SrO, 1.92 wt % BaO, 2.42 wt % CaO, 0.28 wt % MgO, and 44.35 wt % $TiO_2$ simulating a freshly prepared Hanford product.

(2) Thermal conductivity of various $SrO-TiO_2$ compositions — 30, 31

The curves in Fig. 1 were obtained by interpolating the data for the stoichiometric SrO, $Sr_2TiO_4$, $SrTiO_3$, and $TiO_2$.

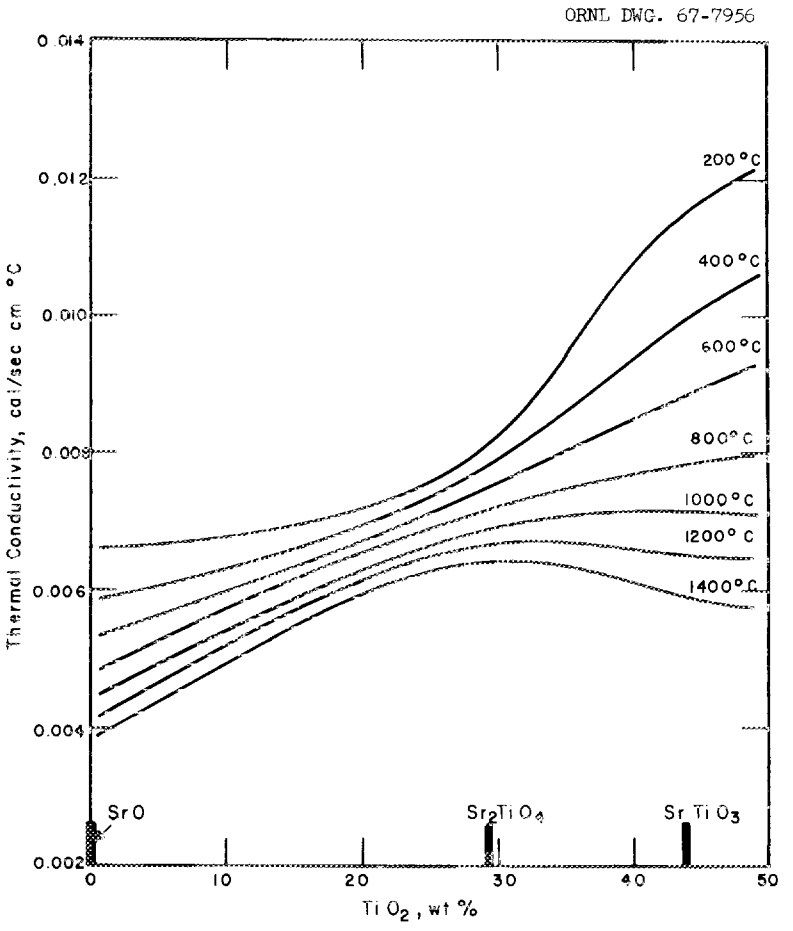


Fig. 1. Thermal Conductivity of Various $SrO-TiO_2$ Compositions.

(3) Thermal conductivity of radioactive strontium titanate 32, 33

Data were obtained on three hot-pressed pellets having 92, 92, and 98% theoretical densities with $TiO_2$/alkaline-earth oxide mole ratios of 0.86, 0.95, and 1.25. The ages of the $SrTiO_3$ in the pellets were 0.5, 3.5, and 4.25 years. It was found that the age of $SrTiO_3$ and the variation in pellet composition and theoretical density did not have an effect on the results within the limit of experimental error. A single equation for the thermal conductivity as a function of temperature was derived from the data by the method of least mean squares:

$$1/k = 82.65 + 0.112T \ (°K)$$

where k is the thermal conductivity in cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$. The data were measured

over a range of 350 to 850°C and are considered usable from 200 to 1400°C. Values of k as a function of temperature are given below at the 95% confidence level.

| Thermal conductivity, cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C |
|---|---|
| 0.00737 ± 0.00090 | 200 |
| 0.00632 ± 0.00025 | 400 |
| 0.00554 ± 0.00015 | 600 |
| 0.00493 ± 0.00016 | 800 |
| 0.00444 ± 0.00023 | 1000 |
| 0.00403 ± 0.00028 | 1200 |
| 0.00370 ± 0.00031 | 1400 |

h. Thermal diffusivity

(1) 100% dense inactive $SrTiO_3$ pellet

| Thermal diffusivity,[a] $cm^2/sec$ | Temperature, °C |
|---|---|
| 0.0151 | 200 |
| 0.0124 | 400 |
| 0.0107 | 600 |
| 0.0093 | 800 |
| 0.0083 | 1000 |
| 0.0075 | 1200 |
| 0.0068 | 1400 |

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

(2) Thermal diffusivity of radioactive strontium titanate (94.7% of theoretical density)

| Thermal diffusivity,[a] $cm^2/sec$ | Temperature, °C |
|---|---|
| 0.01068 | 200 |
| 0.00869 | 400 |
| 0.00739 | 600 |
| 0.00645 | 800 |
| 0.00574 | 1000 |
| 0.00511 | 1200 |
| 0.00461 | 1400 |

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

STRONTIUM TITANATE ($SrTiO_3$) REFERENCE COLUMN

i. Viscosity

j. Surface tension

k. Total hemispherical emittance

l. Spectral emissivity

m. Crystallography

Cubic: a = 3.899 kX 20

n. Solubilities

Leach rates were determined on five $^{90}SrTiO_3$ fuels 33, 34
having densities ranging from 62 to 92% of theoretical. The low density samples were recovered from SNAP-7A fuel capsules after seven years of operation. The high density samples were prepared by hot pressing. The samples were intact after an immersion of 76 days in distilled water. The data were fitted to a single equation by a method of least squares and are presented in Fig. 2 with the 95% confidence limits. A single equation to represent the data is as follows:

$$\ln R = -0.5235 \ln T - 2.5987$$

where

R = leach rate, mg $cm^{-2}$ $day^{-1}$
T = time, days.

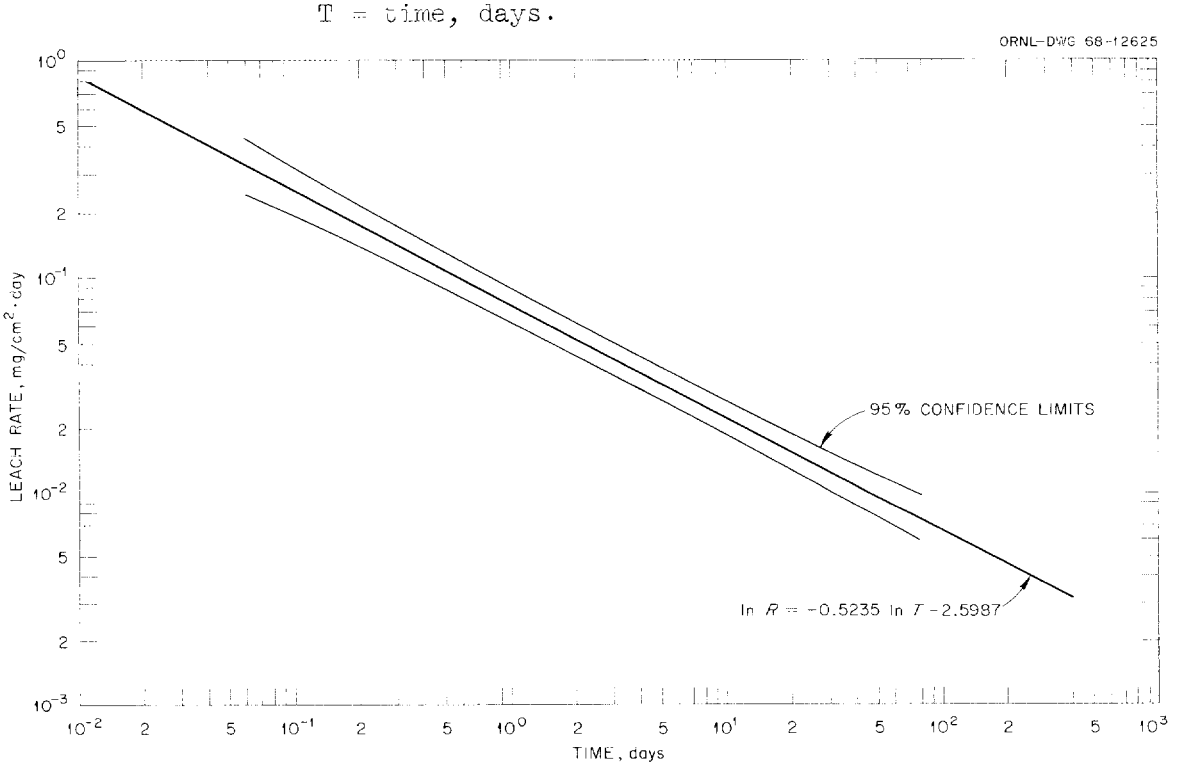


Fig. 2. Leach Rate of $^{90}SrTiO_3$ as a Function of Time.

| STRONTIUM TITANATE ($SrTiO_3$) | REFERENCE COLUMN |
|---|---|
| o. Diffusion rates | |
| 7. Mechanical Properties | |
| a. Hardness | |
| b. Crush strength | |
| 19,100 lb/in.$^2$ | 35 ($CaTiO_3$) |
| c. Bend strength | |
| 43 lb/in.$^2$ | 36 |
| 8. Chemical Properties | |
| a. Heat and free energy of formation, entropy | |
| (1) Heat of formation | |
| $\Delta H_f^\circ$ = -399 kcal/mole | 37, 38 |
| (calculated from available data) | |
| (2) Free energy of formation | |
| $\Delta F_f^\circ$ = -379 kcal/mole | 37, 38 |
| (calculated from available data) | |
| (3) Entropy | |
| $S_{298}^\circ$ = 26.0 eu | 39 |
| b. Chemical reactions and reaction rates | 40 |
| (1) Oxygen — no reaction | |
| (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 w with iron, lead, and uranium shielding are given in Figs. 3-6 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 |

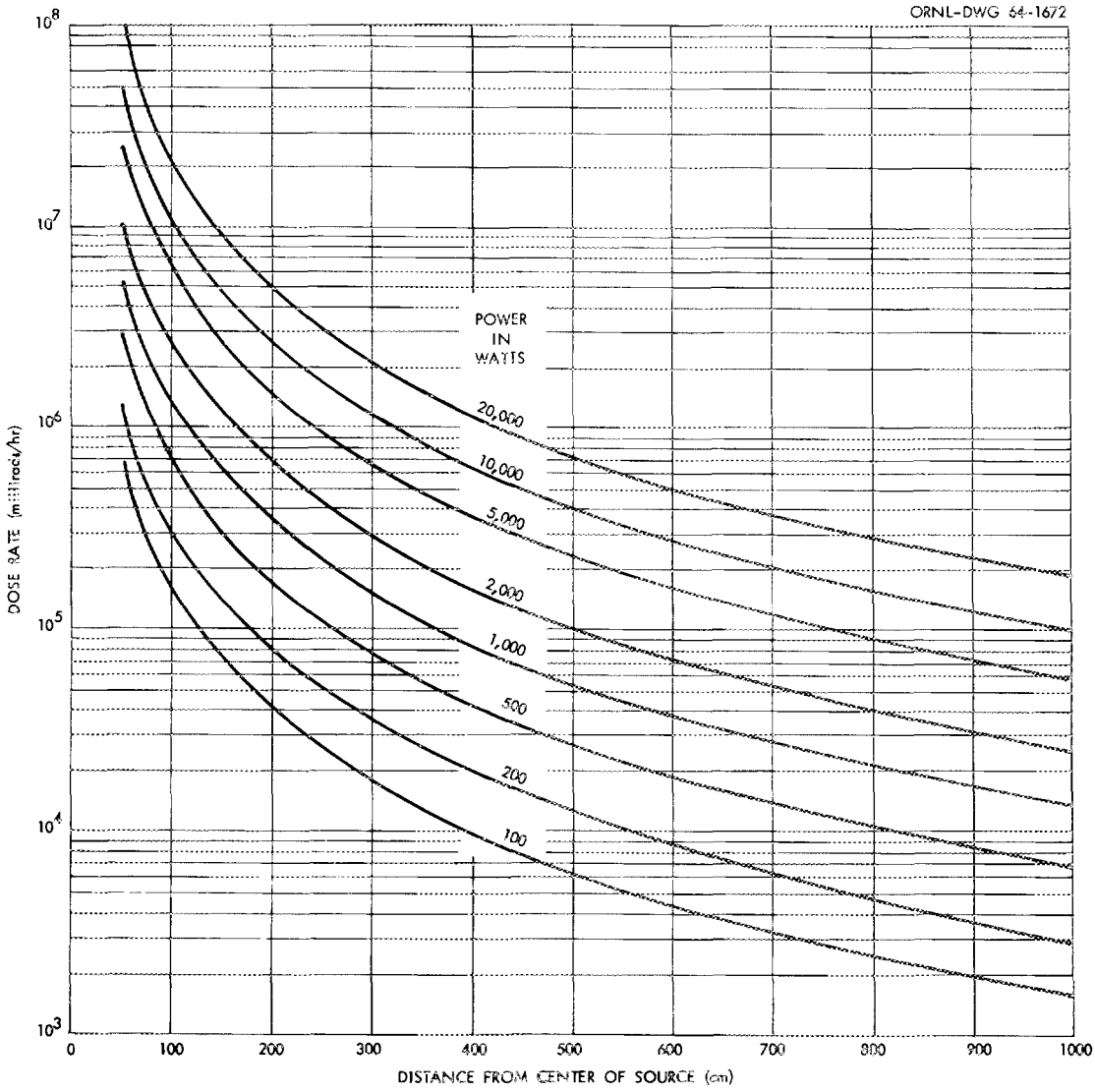


Fig. 3. Bremsstrahlung Dose Rates from Unshielded Isotopic Power Sources of Strontium-90 (Strontium Titanate) as a Function of Distance from Center of Source.

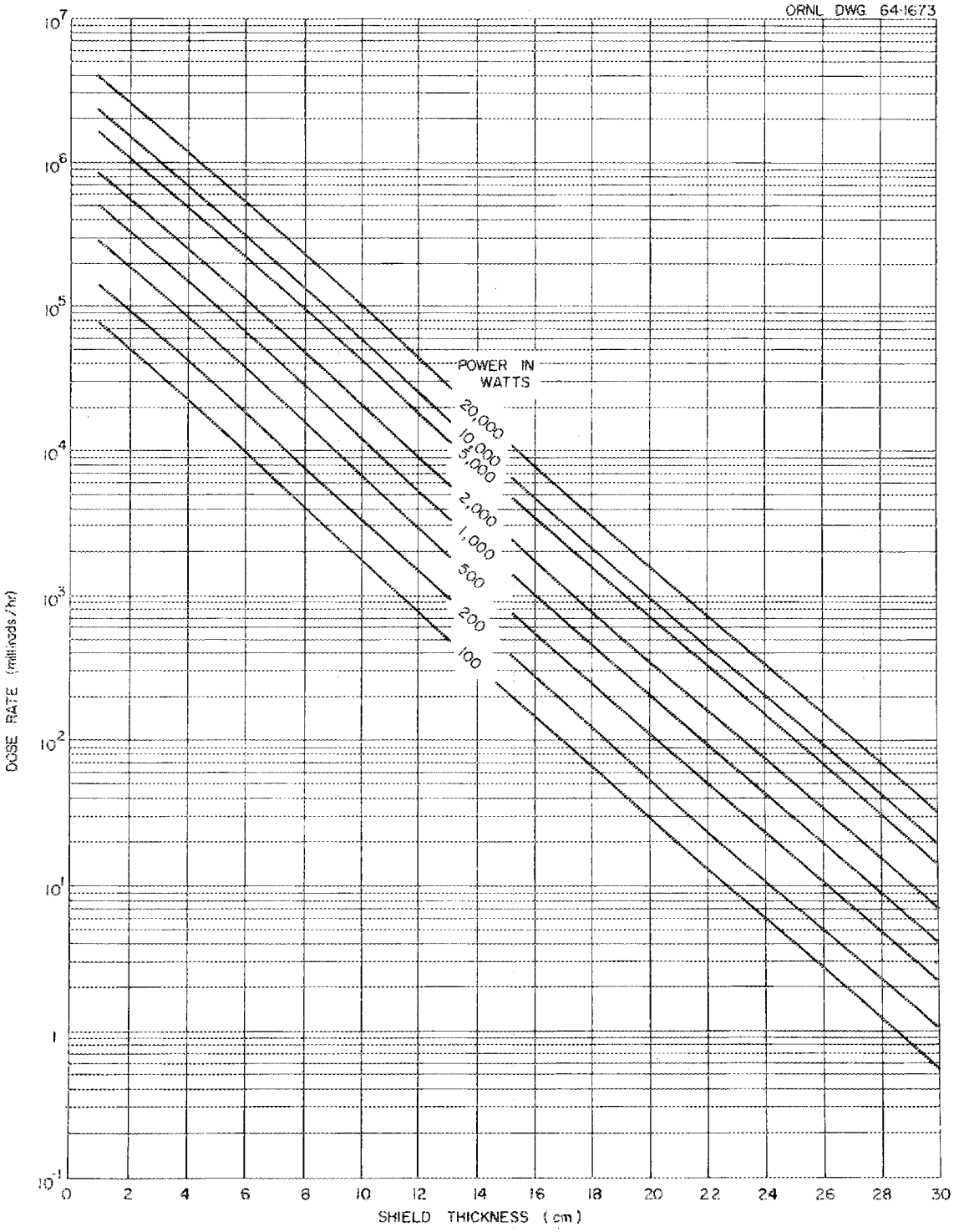


Fig. 4. Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

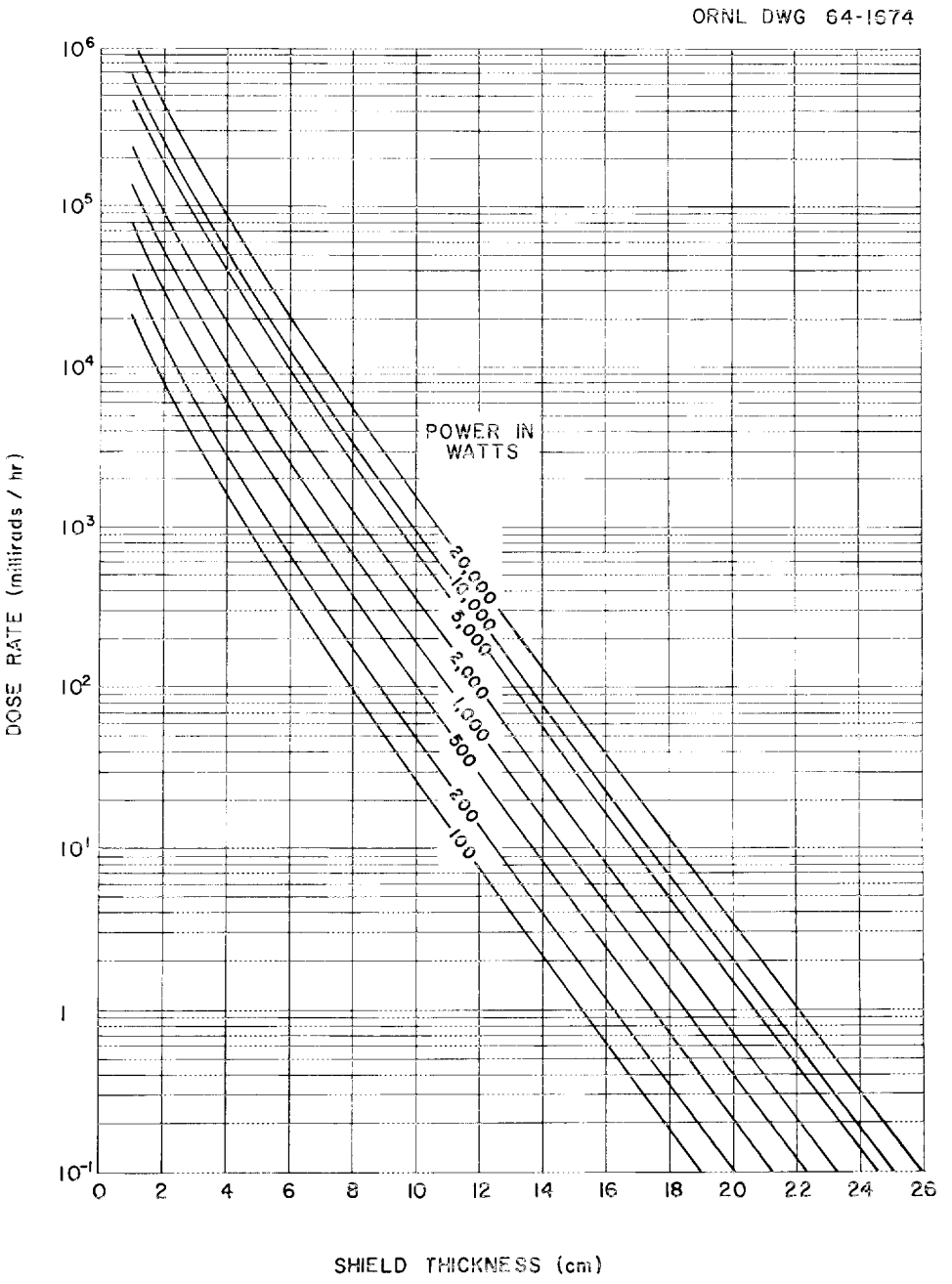


Fig. 5. Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.

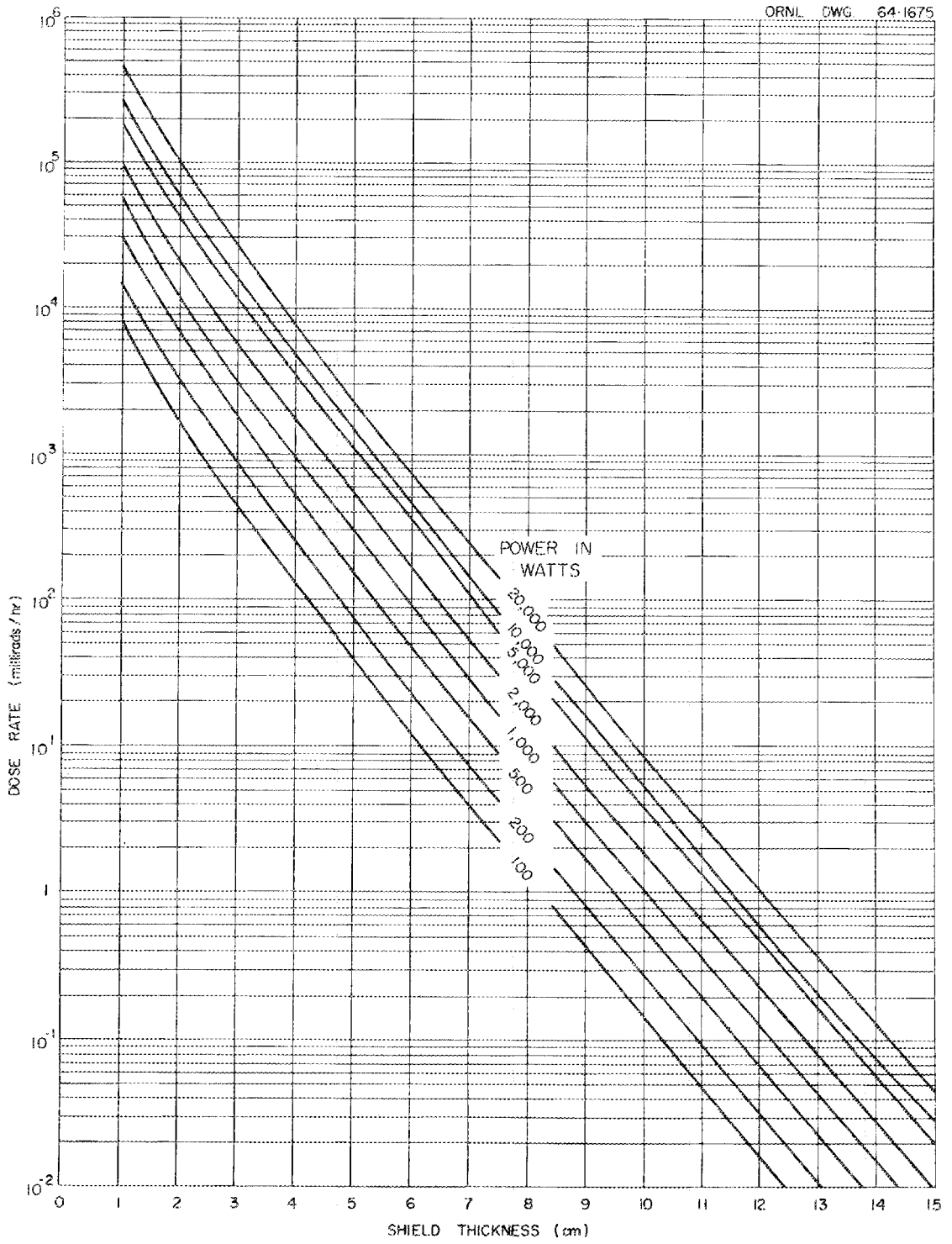


Fig. 6. Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point of separation of distance = 100 cm.

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, wt % | Minimum, wt % |
|---|---|---|
| Sr | 97 | 92 |
| Ca | 5 | 2 |
| Ba | 2 | 0.5 |
| Mg | 2 | 0 |

One gram of $^{90}Sr$ will produce an average of 0.0232 g of $^{90}Zr$ after one year's decay.

(2) Average chemical composition

| Cation | Metal, wt % | Metal oxide, wt % |
|---|---|---|
| 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 84.77%.

The strontium metal content of average SrO is 79.9%.

The as-processed SrO will contain 44.0% $^{90}Sr$. 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.

### 2. Specific Power 2, 4, 5

a. 0.435 w/g of pure SrO (46.6% $^{90}Sr$ metal)
0.411 w/g of average SrO (44.0% $^{90}Sr$ metal)

It is assumed that there are 139 Ci/g of $^{90}Sr$ and 148.9 Ci of $^{90}Sr$ per thermal watt.

b. 64.8 Ci of $^{90}Sr$ per gram of pure SrO (46.6% $^{90}Sr$ metal)
61.2 Ci of $^{90}Sr$ per gram of average SrO (44.0% $^{90}Sr$ metal)

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

STRONTIUM OXIDE (SrO)

REFERENCE COLUMN

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

See Section I.B.5.

6. Thermophysical Properties

a. Density

$\rho = 4.975\ g/cm^3$ 41

b. Coefficient of thermal expansion

The coefficient of expansion of SrO has been determined up to 1400°C with a Brinkman Model 5440 dilatometer. To simulate a typical radioactive strontium fuel, samples were prepared with a composition of 92 wt % Sr, 3.7 wt % Ca, 3.7 wt % Ba, and 0.3 wt % Mg. The SrO sample was 1/2 in. in length and was prepared by hot pressing. 26

The following table gives the values obtained for the mean coefficient of expansion for SrO for the temperature intervals shown. The mean coefficient of expansion, $A_m$, is defined as

$$A_m(t_o,t) = \Delta l/l\Delta t\ ,$$

where

$A_m(t_o,t)$ = mean coefficient of expansion in the temperature interval, $\Delta t$, from $t_o$ to t°C,

$\Delta t$ = temperature interval,

$\Delta l$ = change in sample length over $\Delta t$,

$l$ = sample length at temperature $t_o$°C.

| Temperature interval, °C | Mean linear coefficient of expansion for SrO |
|---|---|
| 0-100 | $11.0 \times 10^{-6}$/°C |
| 0-200 | $11.0 \times 10^{-6}$/°C |
| 0-300 | $11.1 \times 10^{-6}$/°C |
| 0-400 | $11.1 \times 10^{-6}$/°C |
| 0-500 | $11.1 \times 10^{-6}$/°C |
| 0-600 | $11.1 \times 10^{-6}$/°C |
| 0-700 | $11.1 \times 10^{-6}$/°C |

STRONTIUM OXIDE (SrO)

REFERENCE COLUMN

Table continued

| Temperature interval, °C | Mean linear coefficient of expansion for SrO |
|---|---|
| 0-800 | $11.2 \times 10^{-6}/°C$ |
| 0-900 | $11.2 \times 10^{-6}/°C$ |
| 0-1000 | $11.2 \times 10^{-6}/°C$ |
| 0-1100 | $11.2 \times 10^{-6}/°C$ |
| 0-1200 | $11.3 \times 10^{-6}/°C$ |
| 0-1300 | $11.3 \times 10^{-6}/°C$ |
| 0-1400 | $11.3 \times 10^{-6}/°C$ |

c. Specific heat and enthalpy

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

$0.117 + 1.22 \times 10^{-5}T - 1.50 \times 10^{3}T^{-2}$ 14

(T is in °K)

(2) Enthalpy in cal/mole

$H_T - H_{298} = 12.13T + 0.63 \times 10^{-3}T^2 + 1.55 \times 10^{5}T^{-1} - 4192$ 14

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point

2457°C 42

(2) Boiling point

3227°C 42

e. Latent heats of phase transformations

$\Delta H$ fusion 16.7 kcal/mole 43

$\Delta H$ vaporization (not available)

f. Vapor pressure

$\log P = 3.07 \times 10^{4}T^{-1} + 13.12$ 44

(T is in °K and P is in atm)

g. Thermal conductivity

(1) SrO = 100% 30

The following equation was derived from data by a method of least mean squares:

$$1/k = 109.51 + 0.0916T \ (°K)$$

where k is the thermal conductivity in cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$. The data covered the range 350 to 900°C. Useful range of the equation is 200 to 1400°C.

| Thermal conductivity,[a] cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C |
|---|---|
| 0.0066 ± 0.0006 | 200 |
| 0.0058 ± 0.0003 | 400 |
| 0.0053 ± 0.0001 | 600 |
| 0.0048 ± 0.0002 | 800 |
| 0.0044 ± 0.0003 | 1000 |
| 0.0041 ± 0.0004 | 1200 |
| 0.0038 ± 0.0004 | 1400 |

[a]Determined on theoretically dense pellets of SrO with a composition of 91.69 wt % SrO, 3.46 wt % BaO, 4.34 wt % CaO, and 0.51 wt % MgO simulating a freshly prepared Hanford product.

(2) Thermal conductivity of various $SrO-TiO_2$ compositions — 30, 31

These values are given in Section I.B.6.g.(2).

h. Thermal diffusivity

| Thermal diffusivity,[a] $cm^2/sec$ | Temperature, °C |
|---|---|
| 0.0122 | 200 |
| 0.0103 | 400 |
| 0.0091 | 600 |
| 0.0080 | 800 |
| 0.0072 | 1000 |
| 0.0066 | 1200 |
| 0.0060 | 1400 |

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

i. Viscosity

j. Surface tension

1200 dyn/cm — 45 (MgO)

k. Total hemispherical emittance

STRONTIUM OXIDE (SrO) — REFERENCE COLUMN

l. Spectral emissivity

| Total emissivity | Temperature, °C |
|---|---|
| 0.36 | 1000 |
| 0.46 | 1400 |
| 0.50 | 1800 |

44 (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 — 20

n. Solubilities

Reacts with water or HCl and goes into solution. — 20

The dissolution rate studies were performed using stable SrO pellets prepared by hot pressing at 1300°C and 4000 psi for 1 hr. In one test, a specimen weighing 43.962 g with an apparent density of 4.54 g/cm$^3$ was suspended from an analytical balance beam in a container through which a constant linear flow rate of 4.4 cm/min of distilled water was maintained. Periodic weighings of the specimen were recorded during a 7-day span. The dissolution rates for SrO calculated from the data in the experiment are shown in the following table. The values were calculated on the basis of the initial surface area of the pellet. These solubilities are a factor of $10^4$ to $10^5$ greater than those of strontium titanate. — 46

| Rate, g/cm$^2$.day | Time interval, days |
|---|---|
| 1.485 | 0-1 |
| 1.22 | 1-2 |
| 1.22 | 2-3 |
| 1.24 | 3-4 |
| 0.96 | 4-5 |
| 1.12 | 5-6 |
| 0.76 | 6-7 |

o. Diffusion rates

STRONTIUM OXIDE (SrO) — REFERENCE COLUMN

7. Mechanical Properties

a. Hardness

3.5 mohs — 47

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

$\Delta H_f^\circ = -141.0$ kcal/mole — 48

$\Delta H_f^\circ = -144.2 \pm 1.5$ kcal/mole — 27

$\Delta H_f^\circ = -140.50 \pm 0.20$ kcal/mole — 49

(2) Free energy of formation

$\Delta F_f^\circ = -133.8$ kcal/mole — 48

(3) Entropy

$S_{298}^\circ = 13.0$ eu — 27, 48

b. Chemical reactions and reaction rates — 50

(1) Oxygen – no reaction

(2) Nitrogen – no reaction

(3) Water – forms $Sr(OH)_2$

(4) Inorganic acids – soluble

(5) $CO_2$ – reacts to form $SrCO_3$

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 w with iron, lead, and uranium shielding are given in Figs. 7-10 for a SrO matrix. These sources require significant shielding because of the high energy of some of the photons from the bremsstrahlung radiation. — 4

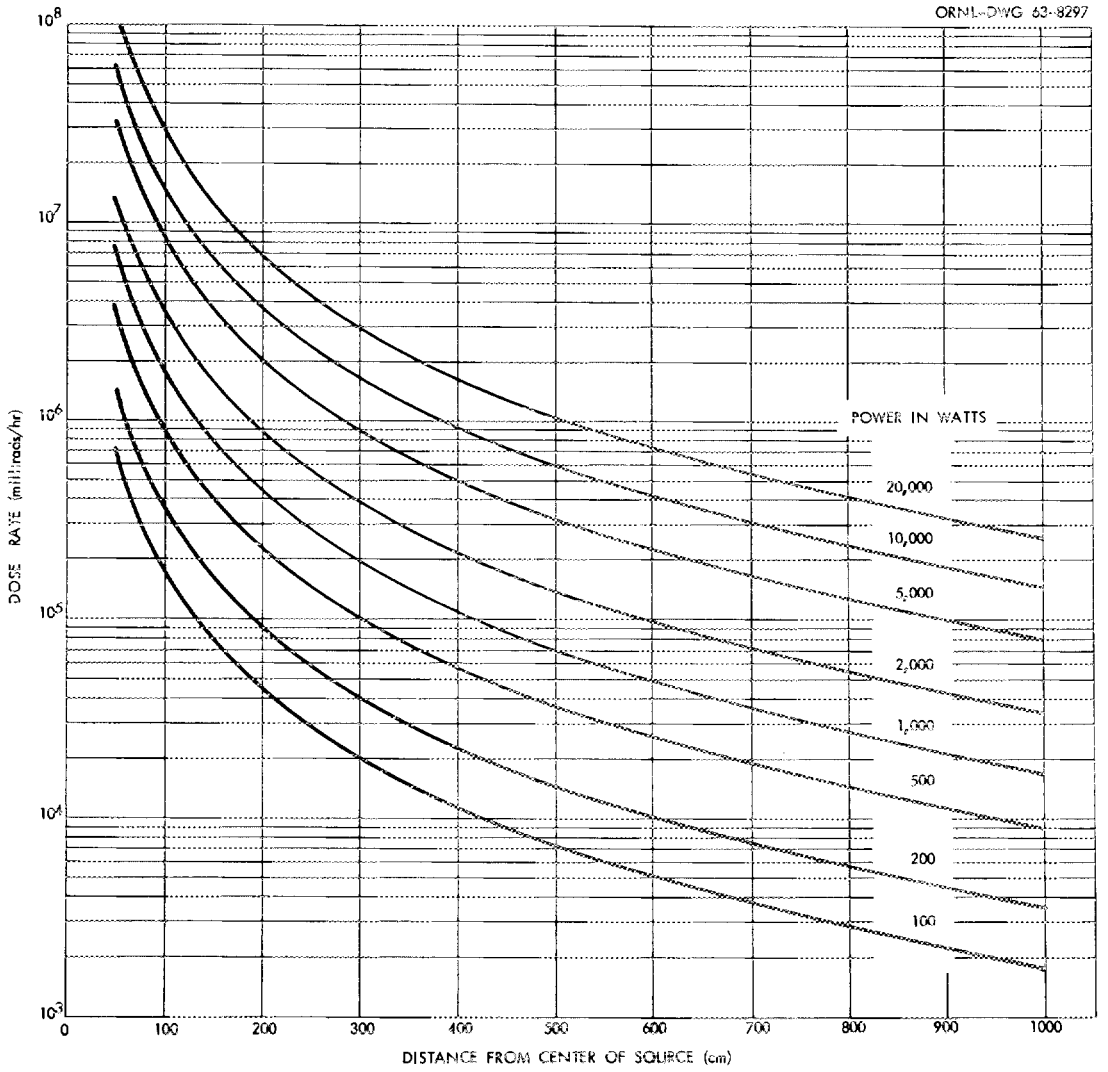


Fig. 7. Bremsstrahlung Dose Rates from Unshielded Isotopic Power Sources of Strontium-90 (Strontium Oxide) as a Function of Distance from Center of Source.

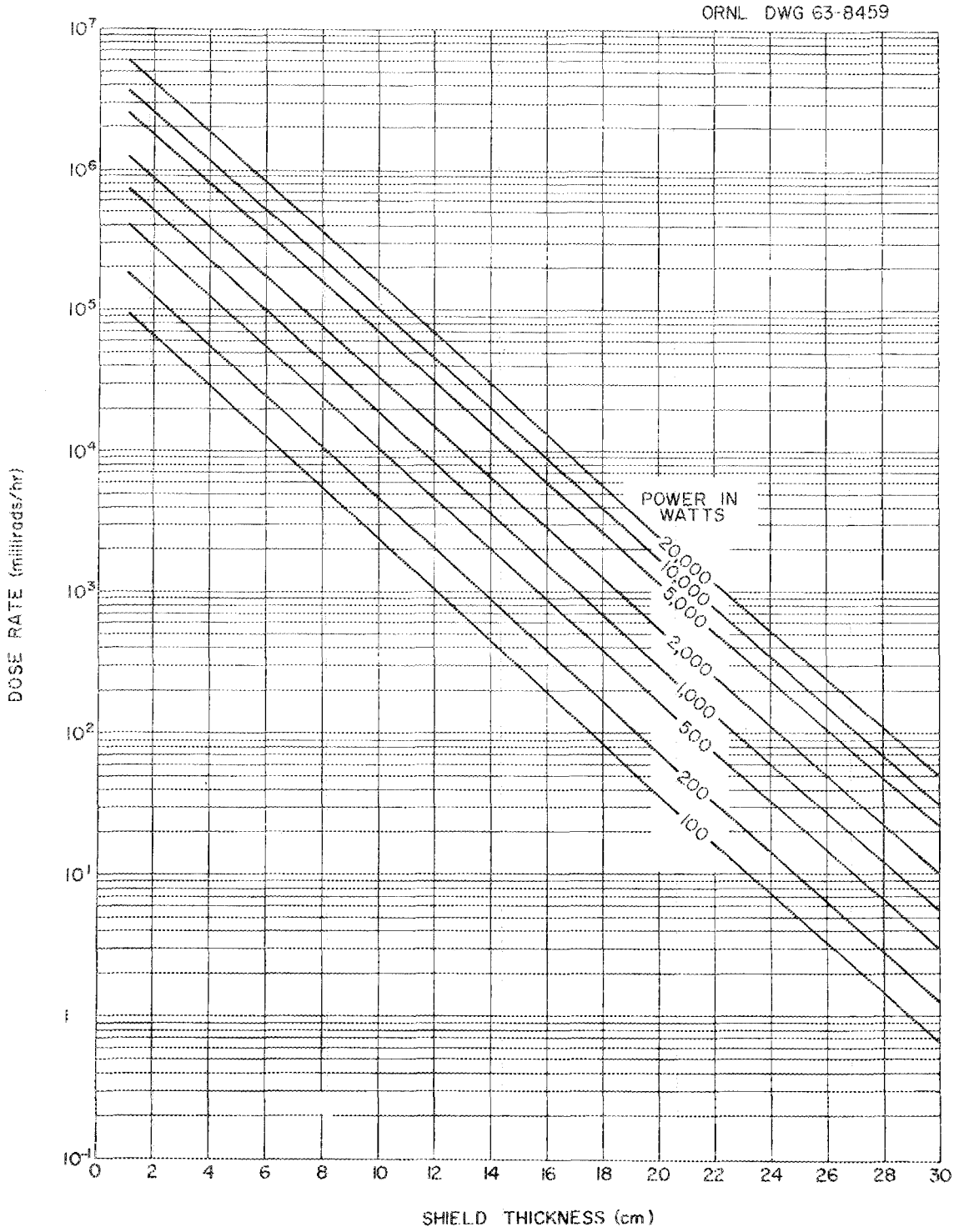


Fig. 8. Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

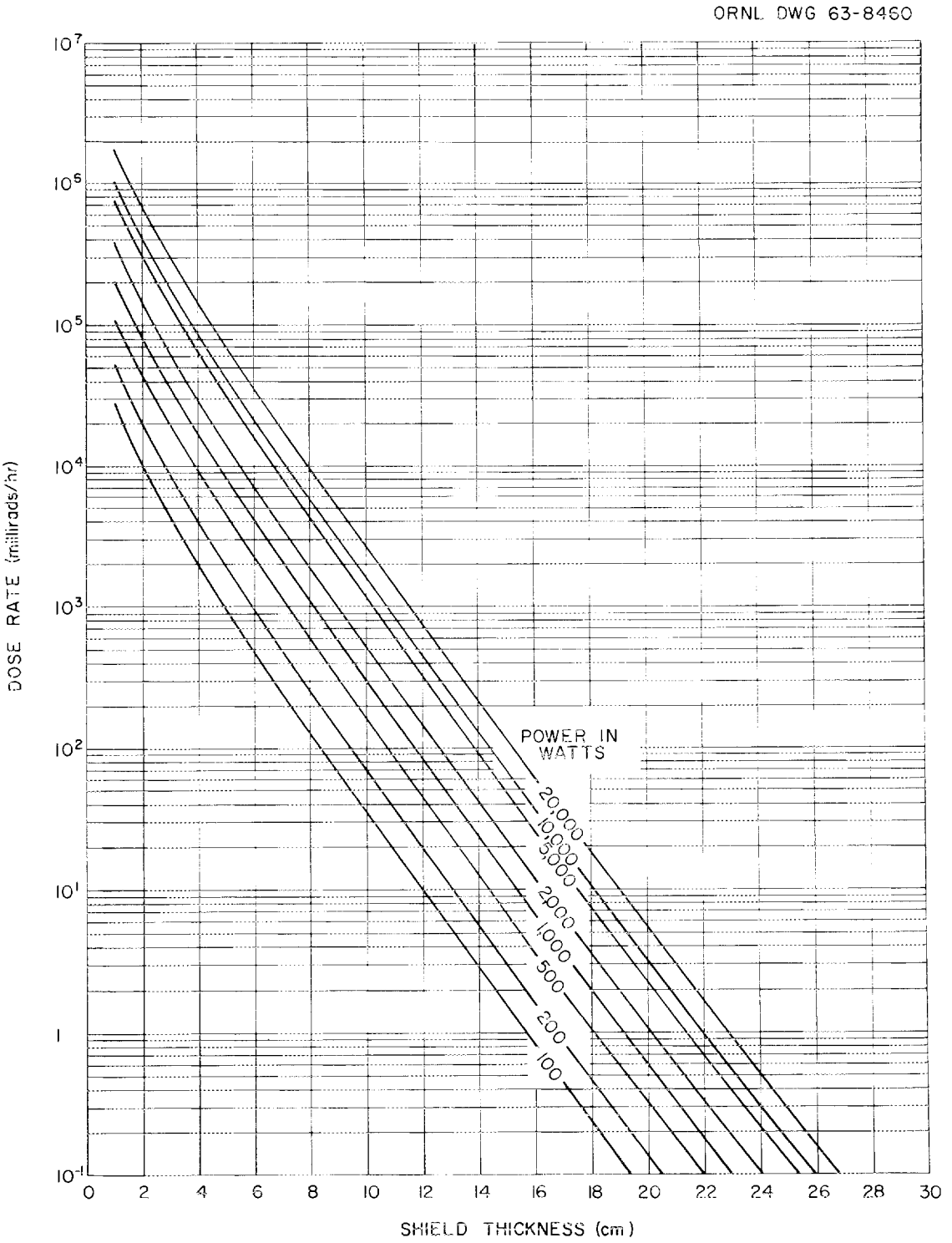


Fig. 9. Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

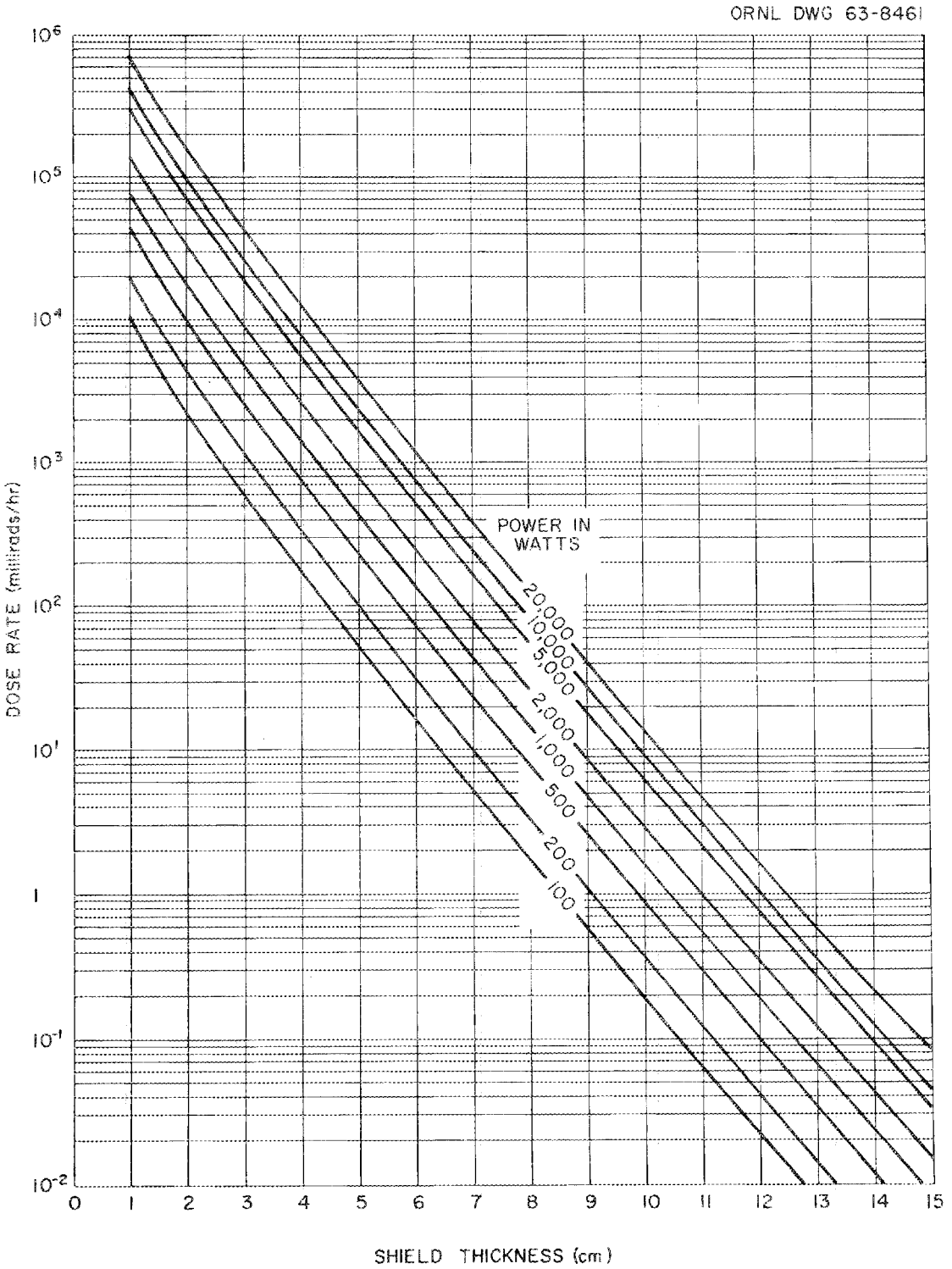


Fig. 10. Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Source of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.

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, wt % | Minimum, wt % |
|---|---|---|
| Sr | 97 | 92 |
| Ca | 5 | 2 |
| Ba | 2 | 0.5 |
| Mg | 2 | 0 |

One gram of $^{90}Sr$ will produce an average of 0.0232 g of $^{90}Zr$ after one year's decay.

(2) Average chemical composition

| Cation | Metal, wt % | Metal fluoride ($MF_2$), wt % |
|---|---|---|
| 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 70.10%.

The strontium metal content of average $SrF_2$ is 65.5%.

The as-processed $SrF_2$ will contain 36.0% $^{90}Sr$. 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. 0.360 w/g of pure $SrF_2$ (38.6% $^{90}Sr$ metal)
0.336 w/g of average $SrF_2$ (36.0% $^{90}Sr$ metal)

It is assumed that there are 139 Ci/g of $^{90}Sr$ and 148.9 Ci of $^{90}Sr$ per thermal watt.

b. 53.7 Ci of $^{90}Sr$ per gram of pure $SrF_2$ (38.6% $^{90}Sr$ metal)
50.0 Ci of $^{90}Sr$ per gram of average $SrF_2$ (36.0% $^{90}Sr$ metal)

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

STRONTIUM FLUORIDE ($SrF_2$) — REFERENCE COLUMN

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 inactive $SrF_2$ test specimens exposed for 19 months at 925°C gave the following results. 36

| Encapsulating material | Penetration, in. Maximum | Average |
|---|---|---|
| Simulated $SrF_2$ fuel[a] | | |
| 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[b] | | |
| Haynes 25 | 0.0015 | 0.0008 |
| Ta liner in Haynes 25 | Complete penetration of Ta liner | |
| Hastelloy C | 0.0007 | 0.0003 |
| Hastelloy N | 0.0028 | 0.0011 |
| Hastelloy X | 0.0055 | 0.0011 |

[a]1 wt % Ca, 0.5 wt % Fe.
[b]$SrF_2$ plus 2-1/2 wt % Zr as $ZrO_2$.

Also see Section I.B.5.

6. Thermophysical Properties

a. Density 51

4.29 g/cm$^3$ for pure $SrF_2$

4.20 g/cm$^3$ for average $SrF_2$

b. Coefficient of thermal expansion

$\alpha/°C = 15.72 \times 10^{-6} - 0.63 \times 10^{-8}t + 1.17 \times 10^{-10}t^2$ 52

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

STRONTIUM FLUORIDE ($SrF_2$)

REFERENCE COLUMN

c. Specific heat and enthalpy

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

$0.125 + 5.57 \times 10^{-5}T$ — 43

(T is in °K)

(2) Enthalpy in cal/mole

$H_T - H_{298} = 15.7T + 3.5 \times 10^{-3}T^2 - 4980$ — 43

(T is in °K)

d. Temperatures of phase transformations

(1) Melting point

1463°C — 53

(2) Boiling point

2477°C — 43

e. Latent heats of phase transformations

| | | |
|---|---|---|
| ΔH fusion | 4.3 kcal/mole | 43 |
| ΔH vaporization | 71 kcal/mole | 43 |

f. Vapor pressure

| Vapor pressure, torr | Temperature, °C | |
|---|---|---|
| 8.5 | 1822 | 20 |
| 15.0 | 1880 | |
| 25.7 | 1927 | |
| 31.0 | 1959 | |

g. Thermal conductivity

| Thermal conductivity, cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C | |
|---|---|---|
| 0.0120 | 20 | 54 |
| 0.0055 | 300 | |
| 0.0030 | 725 | |

h. Thermal diffusivity

| 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 $g/cm^3$.

STRONTIUM FLUORIDE ($SrF_2$) — REFERENCE COLUMN

i. Viscosity

Log $\eta = 0.781 + 436/T$ — 55

($\eta$ is in centipoises and T is temperature in °K)

j. Surface tension

184 dyn/cm — 56

k. Total hemispherical emittance

l. Spectral emissivity

A value of 0.9 can be assumed. — 18

m. Crystallography

Cubic: a = 5.781 Å — 51

n. Solubilities

0.0009 mole/liter in water 18°C — 20

o. Diffusion rates

7. Mechanical Properties

a. Hardness, moh

$H_M = 3.5$ — 20

b. Crush strength

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

$\Delta H_f^\circ = -290.3$ kcal/mole — 48

(2) Free energy of formation

$\Delta F_f^\circ = -277.2$ kcal/mole — 48

(3) Entropy

$S_{298}^\circ = 20.5$ eu — 43

b. Chemical reactions and reaction rates — 50

(1) Nitrogen — no reaction

(2) Water — slightly soluble

(3) Inorganic acids — insoluble

STRONTIUM FLUORIDE ($SrF_2$)

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, wt % | Minimum, wt % |
|---|---|---|
| Sr | 97 | 92 |
| Ca | 5 | 2 |
| Ba | 2 | 0.5 |
| Mg | 2 | 0 |

One gram of $^{90}Sr$ will produce an average of 0.0232 g of $^{90}Zr$ after one year's decay.

(2) Average chemical composition

| Cation | Metal, wt % | Orthotitanate, wt % |
|---|---|---|
| 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 61.42%.

The strontium metal content of average $Sr_2TiO_4$ is 57.24%.

The as-processed $Sr_2TiO_4$ will contain 31.5% $^{90}Sr$. 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 as compared to the bremsstrahlung radiation.

### 2. Specific Power

2, 4, 5

a. 0.315 w/g of pure $Sr_2TiO_4$ (33.8% $^{90}Sr$ metal)
0.294 w/g of average $Sr_2TiO_4$ (31.5% $^{90}Sr$ metal)

It is assumed that there are 139 Ci/g of $^{90}Sr$ and 148.9 Ci of $^{90}Sr$ per thermal watt.

b. 47.0 Ci of $^{90}Sr$ per gram of pure $Sr_2TiO_4$ (33.8% $^{90}Sr$ metal)
43.8 Ci of $^{90}Sr$ per gram of average $Sr_2TiO_4$ (31.5% $^{90}Sr$ metal)

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

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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

See Section I.B.5.

6. Thermophysical Properties

a. Density

4.99 g/cm$^3$ for pure $Sr_2TiO_4$ 57

4.93 g/cm$^3$ for average $Sr_2TiO_4$ (hot pressed) 33

b. Coefficient of thermal expansion

The values of mean linear coefficient of expansion for $SrTiO_3$ and SrO are given in Section I.B.6.b. and I.C.6.b., respectively. The values shown below for $Sr_2TiO_4$ are taken to be an average of those for $SrTiO_3$ and SrO. 26

| Mean linear coefficient of expansion, 1/°C | Temperature interval, °C |
|---|---|
| $10.9 \times 10^{-6}$ | 0-100 |
| $10.8 \times 10^{-6}$ | 0-200 |
| $10.9 \times 10^{-6}$ | 0-300 |
| $11.0 \times 10^{-6}$ | 0-400 |
| $11.0 \times 10^{-6}$ | 0-500 |
| $11.1 \times 10^{-6}$ | 0-600 |
| $11.1 \times 10^{-6}$ | 0-700 |
| $11.2 \times 10^{-6}$ | 0-800 |
| $11.3 \times 10^{-6}$ | 0-900 |
| $11.3 \times 10^{-6}$ | 0-1000 |
| $11.4 \times 10^{-6}$ | 0-1100 |
| $11.5 \times 10^{-6}$ | 0-1200 |
| $11.7 \times 10^{-6}$ | 0-1300 |
| $11.7 \times 10^{-6}$ | 0-1400 |

c. Specific heat and enthalpy

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

$0.134 + 1.34 \times 10^{-5}T - 1.63 \times 10^{3}T^{-2}$ 28

(T is in °K; temperature range 298-1800°K)

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(2) Enthalpy in cal/mole

$$H_T - H_{298} = 38.45T + 1.92 \times 10^{-3}T^2 + 4.67 \times 10^5 T^{-1} - 13{,}201$$ 28

(T is in °K; temperature range 298-1800°K)

d. Temperatures of phase transformations

(1) Melting point

1860 ± 20°C 58

(2) Boiling point

2500-3000°C 10

(3) $\alpha$-$Sr_2TiO_4$ converts to $\beta$-$Sr_2TiO_4$ at 1600°C 29

e. Latent heats of phase transformations

$\Delta H$ fusion (not available)

$\Delta H$ vaporization 71 kcal/mole 12

(calculated from Trouton's rule)

f. Vapor pressure

g. Thermal conductivity

(1) $SrO:TiO_2 = 2.00$ 30

The following equation was derived from data by a method of least mean squares:

$$1/k = 110.26 + 0.0268T \quad (°K)$$

where k is the thermal conductivity in cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$. The data covered the range 350 to 900°C. Useful range of the equation is 200 to 1400°C.

| Thermal conductivity,[a] cal $cm^{-1}$ $sec^{-1}$ $°C^{-1}$ | Temperature, °C |
|---|---|
| 0.0081 ± 0.0007 | 200 |
| 0.0078 ± 0.0004 | 400 |
| 0.0075 ± 0.0002 | 600 |
| 0.0072 ± 0.0004 | 800 |
| 0.0069 ± 0.0006 | 1000 |
| 0.0067 ± 0.0008 | 1200 |
| 0.0065 ± 0.0009 | 1400 |

[a]Determined on theoretically dense pellets of stoichiometric $Sr_2TiO_4$ with a composition of 65.56 wt % SrO, 2.47 wt % BaO, 3.10 wt % CaO, 0.37 wt % MgO, and 28.50 wt % $TiO_2$ simulating a freshly prepared Hanford product.

(2) Thermal conductivity of various $SrO-TiO_2$ compositions are given in Section I.B.6.g.(2). 30, 31

h. Thermal diffusivity

| Thermal diffusivity,[a] $cm^2/sec$ | Temperature, °C |
|---|---|
| 0.0124 | 200 |
| 0.0114 | 400 |
| 0.0106 | 600 |
| 0.0099 | 800 |
| 0.0094 | 1000 |
| 0.0089 | 1200 |
| 0.0085 | 1400 |

[a]These values were calculated 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

m. Crystallography

Tetragonal, body-centered

a = 3.88 Å  c = 12.60 Å 57

n. Solubilities 59

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

| Days | Micrograms of fuel per ml of dissolver solution | | | |
|---|---|---|---|---|
| | Deionized 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 |

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n. Solubilities (continued)

| Days | Micrograms of fuel per ml of dissolver solution: Deionized 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.$^2$ — 35 ($CaTiO_3$)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation

$\Delta H_f^\circ = -545.6$ kcal/mole — 37, 38

(calculated from available data)

(2) Free energy of formation

$\Delta F_f^\circ = -518.2$ kcal/mole — 37

(calculated from available data)

(3) Entropy

$S_{298}^\circ = 38.0 \pm 0.3$ cal °C$^{-1}$ mole$^{-1}$ — 60

b. Chemical reactions and reaction rates — 61

(1) Oxygen — no reaction

(2) Nitrogen — No reaction

(3) Water — decomposes

(4) Inorganic acids — soluble

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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 w with iron, lead, and uranium shielding are given in Figs. 3-6 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

## II. APPENDIX

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

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

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

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

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