Strontium-90 Fluoride Data Sheet

by
H. T. Fullam

October 1977

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RICHLAND, WASHINGTON 99352

ABSTRACT

This report presents a compilation of available data and appropriate literature references on the properties of $^{90}\text{SrF}_2$ and nonradioactive SrF_2 . It represents an updating of one section of the Strontium-90 Data Sheets (ORNL-4358, March 1969) prepared by S. J. Rimshaw and E. E. Ketchen of the Oak Ridge National Laboratory.

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STRONTIUM-90 FLUORIDE DATA SHEET

H. T. Fullam

1.0 INTRODUCTION

A significant portion of the heat released by the spent fuel from nuclear reactors results from the decay of the fission product ^{90}Sr and its decay daughter ^{90}Y . Because of its relative abundance, moderately long half-life and heat output, ^{90}Sr is a candidate fuel for radioisotope-fueled power generating systems to be used in terrestrial applications. The Energy Research and Development Administration (ERDA) and its predecessor, the Atomic Energy Commission (AEC), have sponsored extensive programs at the Pacific Northwest Laboratory (PNL), the Martin Company, and the Oak Ridge National Laboratory (ORNL) to develop ^{90}Sr -fueled isotopic heat sources.

The fission product strontium in spent reactor fuels consists of a mixture of stable and radioactive strontium isotopes. The isotopic composition of the strontium is influenced by several factors but depends primarily on the time since discharge of the fuel from the reactor. Typically the fission product strontium is recovered for use from the high-level fission product waste stream generated by reprocessing of the spent fuel using the Purex process.(1) Except for the ^{90}Sr , the radioactive strontium isotopes in the fission product strontium have relatively short half-lives and will normally have decayed to low levels by the time the strontium is recovered from the reprocessing wastes. As a result the recovered fission product strontium will usually consist of a mixture of the radioactive ^{90}Sr and several stable strontium isotopes. Even though the stable isotopes normally make up 45% or more of the fission product strontium it is typically referred to as ^{90}Sr , and compounds prepared from fission product strontium are referred to as ^{90}Sr compounds (e.g., $^{90}\text{SrTiO}_3$, $^{90}\text{SrF}_2$).

To date, terrestrial applications for ^{90}Sr -fueled heat sources have used strontium titanate (SrTiO_3) or strontium orthotitanate (Sr_2TiO_4) as the fuel form (one source used ^{90}SrO as the fuel form). For most applications the ^{90}Sr was recovered at Hanford from wastes generated by reprocessing of production reactor or dual purpose reactor fuels. Up to the present time no significant quantities of strontium have been recovered from commercial power reactor fuels in the United States. The strontium recovered at Hanford was shipped to the Oak Ridge National Laboratory (ORNL) or the Martin Company for conversion to the desired fuel form. ORNL and the Martin Company have prepared essentially all of the strontium-90 titanates produced in this country for heat source applications. However, production of ^{90}Sr compounds by the Martin Company was halted several years ago.

Because of waste management considerations all of the strontium in the stored high-level wastes at Hanford is being recovered from the wastes and converted to strontium fluoride. The strontium fluoride is doubly encapsulated and stored in water-filled basins on the Hanford Reservation. Strontium recovery takes place in B-Plant, while the fluoride preparation, encapsulation and storage take place in the Waste Encapsulation and Storage Facilities (WESF). These facilities were operated for ERDA initially by the Atlantic Richfield Hanford Co. (ARHCO) and are currently operated by Rockwell International.

Once the strontium in the Hanford wastes is converted to SrF_2 , ORNL will no longer have a source of ^{90}Sr for production of the strontium titanates. ORNL has already stopped routine production of the titanates, and the equipment used for their preparation has been largely dismantled. The quantities of the two titanates available from ORNL have been reduced to negligible levels as of the date of this document. Therefore the only major domestic source of ^{90}Sr available for use in heat source and other possible applications is the encapsulated $^{90}\text{SrF}_2$ stored at WESF.

The use of $^{90}\text{SrF}_2$ as an isotopic heat source fuel will require qualification testing and licensing of the $^{90}\text{SrF}_2$ fuel form. An ERDA-sponsored program has been under way at PNL for several years to develop the technology needed to permit licensing of $^{90}\text{SrF}_2$ -fueled heat sources. The objective of this document is to compile in a single source all pertinent data developed at PNL and elsewhere on $^{90}\text{SrF}_2$ to assist potential users in developing and licensing $^{90}\text{SrF}_2$ fueled heat sources for power conversion and thermal applications. Data on the molecular structure, electronic structure, optical properties, etc. of $^{90}\text{SrF}_2$, which are not pertinent to its use as a heat source fuel, have not been included in the data sheet.

This data sheet represents an updating of one section of the Strontium-90 Data Sheets prepared by ORNL.⁽²⁾ The presentation of the data follows the format for other radionuclide data sheets recommended by the former AEC-Division of Isotopes Development. However the scope has been expanded to include information on the preparation of $^{90}\text{SrF}_2$. Since WESF is the only available domestic source of $^{90}\text{SrF}_2$, much of the data presented in the report is for WESF-produced $^{90}\text{SrF}_2$, or nonradioactive SrF_2 containing similar impurities. This data sheet will be updated periodically as additional data become available.

2.0 PREPARATION OF $^{90}\text{SrF}_2$

Strontium fluoride is most easily prepared by precipitation from aqueous solution. The addition of fluoride to an aqueous solution containing 0.5 M strontium ion will precipitate in excess of 99% of the strontium as strontium fluoride.

The fluoride can be added as a soluble solid (e.g., NaF) or fluoride ion in solution. The pH of the solution can be varied over a fairly wide range without affecting the yield of SrF_2 to any marked degree. However, an initial pH of 8-10 is preferred since many impurities will precipitate in this pH range and can be removed by filtration or settling before the SrF_2 is precipitated.

The wet precipitate can be dried by heating without significant hydrolysis. The SrF_2 must be heated to at least 800°C to remove residual traces of moisture. Strontium fluoride fired at 1100°C in air or an inert atmosphere for several hours normally contains less than 50 ppm of oxygen as water or oxide. The strontium fluoride is not hygroscopic.

2.1 WESF FLOWSHEET FOR THE PREPARATION OF $^{90}\text{SrF}_2$

At Hanford spent fuel from the reactors is reprocessed using the Purex process. The ^{90}Sr and other fission products from the spent fuel exit the Purex process in the high-level acid waste stream which is neutralized and stored in tanks. The simplified flowsheet for recovery of the strontium from the fuel reprocessing waste and its purification is shown in Figure 1. The flowsheet for conversion of the strontium to strontium fluoride and subsequent encapsulation of the SrF_2 is shown in Figure 2. The strontium recovery and purification take place in B-Plant, while the fluoride conversion and encapsulation take place in the Waste Encapsulation and Storage Facilities (WESF). Both facilities are operated by Rockwell International.

In the $^{90}\text{SrF}_2$ process the strontium is recovered from current Purex acid waste (CAW) or Purex acid sludge (PAS) by solvent extraction. The extractant used is di-2-ethylhexylphosphoric acid (HDEHP) and tributyl phosphate (TBP) in normal paraffin hydrocarbon (NPH). The strontium is stripped from the organic phase using dilute nitric acid and purified using a series of sulfate and hydroxide precipitation steps. The purified strontium is stored in a dilute nitric acid solution until it is converted to SrF_2 .

All steps in the fluoride conversion and encapsulation process are batch operations. A volume of aqueous feed solution containing 3-5 kg of strontium is neutralized to pH 8-9 with sodium hydroxide solution. Solid sodium fluoride is added to the solution to precipitate SrF_2 . The resulting slurry is digested at approximately 80°C for one hour with air sparging and is then filtered. The filter cake is washed with water and fired at approximately 1100°C in argon for several hours. After cooling, the SrF_2 is pulverized to minus 1/2 in. granules and loaded into a Hastelloy Alloy C-276 capsule by impact consolidation, which is essentially a cold step-pressing operation. The capsule is closed by tungsten inert gas (TIG) welding a lid in place; it is leak checked and decontaminated. The cleaned capsule is sealed in an outer capsule of 316 L stainless steel by TIG welding. The weld integrity of the outer capsule is checked using ultra-sonic techniques. After weighing and calorimetry to determine the heat output, the capsule is stored in a water-filled basin.

Figure 1. Simplified Flowsheet for Strontium Recovery and Purification

Figure 2. WESF Flowsheet for Preparation and Encapsulation of $^{90}\text{SrF}_2$

2.2 WESF $^{90}\text{SrF}_2$ STORAGE CAPSULE

At the present time the encapsulated $^{90}\text{SrF}_2$ stored at WESF represents the only major domestic source of ^{90}Sr . The ^{90}Sr isotopic content of the SrF_2 currently produced at WESF can vary from approximately 55% to as low as 25%-30% depending on the age of the strontium. Pertinent data for a typical WESF storage capsule containing SrF_2 having an initial ^{90}Sr isotopic content of 55% are given in Figure 3. The heat output, power density and activity of the capsules will vary from the nominal values listed depending on the initial ^{90}Sr content and will decrease with time as the ^{90}Sr decays.

3.0 PROPERTIES OF STRONTIUM FLUORIDE

Data that have been reported in the literature on the properties of strontium fluoride are summarized in the following sections. Some of the data were obtained using $^{90}\text{SrF}_2$, but most were obtained using nonradioactive SrF_2 . The data obtained with $^{90}\text{SrF}_2$ are so indicated. Some properties of SrF_2 were calculated using theoretical techniques or estimated from data on similar compounds. The calculated or estimated values are indicated as such.

The quality of the SrF_2 used in making the property measurements is included when available. In the PNL studies three grades of nonradioactive SrF_2 were used for most property measurements. They were:

- Pure SrF_2 (<0.1% total impurities)
- Commercial SrF_2 (0.5% total impurities)
- WESF-Grade SrF_2 (~5% impurities similar to those found in WESF-produced $^{90}\text{SrF}_2$).

WESF-produced $^{90}\text{SrF}_2$, or $^{90}\text{SrF}_2$ produced at PNL using the WESF flowsheet and ^{90}Sr solution from ARHCO, was used for property measurements where the radioactivity was expected to affect the results obtained (i.e., dissolution rate, compatibility).

3.1 HALF-LIFE

^{90}Sr - 28.6 years⁽³⁾

^{89}Sr - 50.5 days⁽⁴⁾

^{91}Sr - 9.5 hours⁽⁴⁾

^{90}Y - 64.1 hours⁽³⁾

STRONTIUM FLUORIDE

1. AMOUNT ~ 2.8 kg/CAPSULE
2. CHEMICAL PURITY $\sim 95\%$
3. ^{90}Sr ISOTOPIC CONTENT $\sim 55\%$
4. BULK DENSITY $\sim 70\%$ OF THEORETICAL DENSITY
5. ACTIVITY $\sim 140,000$ Ci/CAPSULE
6. HEAT LOAD ~ 960 W/CAPSULE
7. POWER DENSITY ~ 1.0 w/cm³

CAPSULE DATA

	<u>INNER CAPSULE</u>	<u>OUTER CAPSULE</u>
1. MATERIAL	HASTELLOY C-276	316L STAINLESS STEEL (a)
2. INNER DIAMETER	2.01"	2.39"
3. OUTER DIAMETER	2.25"	2.63"
4. TOTAL LENGTH	19.05"	20.10"

(a) HASTELLOY C-276 WAS USED FOR THE OUTER CAPSULE
DURING THE EARLY STAGES OF THE WESF OPERATION

Figure 3. Typical Data (At Time of Capsule Loading) for a
WESF $^{90}\text{SrF}_2$ Storage Capsule

3.2 COMPOSITION

3.2.1 Isotopic Composition

The isotopic composition of fission product strontium is influenced by a number of factors but will depend primarily on the time since the strontium was discharged from the reactor. Unintentional additions of natural strontium during fuel reprocessing and strontium recovery will also have some effect on the isotopic composition. Because of its relatively short half-life, any ^{91}Sr initially present in the discharged fuel will have decayed to a negligible level by the time the strontium is recovered from the waste. The calculated activity and atomic ratios for ^{89}Sr - ^{90}Sr as a function of time since reactor discharge for an enriched uranium power reactor fuel are shown below. The $^{89}\text{Sr}/^{90}\text{Sr}$ ratio decreases by a factor of 2 with every 50 3/4 days of cooling.

Calculated Ratios of $^{89}\text{Sr}/^{90}\text{Sr}$ as a Function of Time Since Reactor Discharge for an Enriched Uranium Fuel (3.4% ^{235}U initial) - 30,000 MWD/T Burnup at 20 MW/T(5)

Cooling Time (days)	Activity Ratio $^{89}\text{Sr}/^{90}\text{Sr}$	Atomic Ratio $^{89}\text{Sr}/^{90}\text{Sr}$
Discharge	6.89	3.39×10^{-2}
90	2.01	9.90×10^{-3}
180	0.585	2.89×10^{-3}
365	0.046	2.29×10^{-4}
1825	9.6×10^{-11}	2.12×10^{-11}
3650	0	0

A typical analysis of fission product strontium recovered from Hanford wastes is shown below. The waste had aged sufficiently at the time of strontium recovery that the ^{89}Sr had decayed to a nondetectable level. A part of the stable strontium isotopes resulted from unintentional additions of small amounts of natural strontium with various chemical streams during the processing operations.

Typical Isotopic Analysis of Fission Product Strontium Recovered From Hanford Wastes(6)

Isotope	Atomic %
^{90}Sr	55.10
^{89}Sr	43.80
^{87}Sr	0.40
^{86}Sr	0.57
^{84}Sr	0.10

3.2.2 Radiochemical Composition

The radiochemical purity of fission product strontium will depend primarily on the time since discharge from the reactor and on the effectiveness of the purification procedures used in strontium recovery. The principal radiochemical impurities which may be present in fission product strontium include the following:

Isotope	$t_{1/2}$ (4)	Isotope	$t_{1/2}$ (4)
^{91}Y	58.6 d	^{134}Cs	2.06 y
^{95}Zr	65.5 d	^{137}Cs	30.1 y
^{95}Nb	35.1 d	$^{137\text{m}}\text{Ba}$	2.55 m
^{106}Ru	369 d	^{144}Ce	284 d
^{106}Rh	2.18 h	^{144}Pr	17.3 m

Strontium recovered from Hanford wastes has been reported to contain up to 0.03% of the total activity as ^{144}Ce and 0.003% as ^{137}Cs . Analysis of strontium fluoride produced at WESF shows the only measurable activity other than ^{90}Sr - ^{90}Y is ^{137}Cs . WESF $^{90}\text{SrF}_2$, which was about 18 months old at the time of analysis, contained approximately 2.8×10^{-5} Ci of ^{137}Cs per Ci of ^{90}Sr . (7)

The WESF-produced SrF_2 will contain ^{90}Y which is the decay daughter of ^{90}Sr . Once secular equilibrium is established, the $^{90}\text{Y}/^{90}\text{Sr}$ atomic ratio is 2.56×10^{-1} .

3.2.3 Chemical Composition

The strontium fluoride produced at WESF will contain substantial quantities of cation impurities and much lesser amounts of anion impurities. The impurity concentrations can vary over a considerable range. Strontium recovered from different waste tanks will, in general, contain the same kinds of impurities, but the concentrations may vary. Since the procedures for purifying the strontium are only partially effective, the impurity concentrations of the $^{90}\text{SrF}_2$ product will vary with the source of the strontium. Corrosion of process equipment, especially in the fluoride firing operation, will also contribute to the impurities in the WESF $^{90}\text{SrF}_2$. Some product nonhomogeneity will result from the corrosion of process equipment. The impurities normally found in WESF-produced $^{90}\text{SrF}_2$ and their probable concentration ranges are presented below:

Typical Impurities Found in WESF-Produced $^{90}\text{SrF}_2$ and Their Probable Concentration Ranges⁽⁶⁾

Component	wt%	Component	wt%
Sr	66 (nominal)	Mn	<0.1
F	30 (nominal)	Na	1-4
		Ni	<0.1
Al	< 0.5	Pb	<0.2
Ba	0.1-2.0	RE(a)	<2.0
Ca	0.1-2.0	Si	<0.02
Cd	<0.1	Zr(b)	Variable
Cr	<0.2	H	<0.01
Cu	<0.01	O	<0.05
Fe	<0.1	NO_3^-	<0.05
K	<0.01	SO_4^{2-}	<0.01
Mg	0.05-0.5		

(a) RE - Rare Earth Elements

(b) Decay product - will increase as ^{90}Sr decays

WESF produced $^{90}\text{SrF}_2$ usually contains about 95% SrF_2 and 5% impurity fluorides. A typical batch analysis is shown below.

Typical Analysis of Fuel Grade WESF $^{90}\text{SrF}_2$ ⁽⁸⁾

Impurity	wt%	Impurity	wt%
Al	0.29	Mg	0.090
Ba	1.06	Mn	0.0042
Ca	0.39	Na	1.67
Cd	0.014	Ni	0.016
Cr	0.012	Pb	0.022
Fe	0.024	Zr	0.20

3.3 DECAY SCHEME ^{90}Sr Decay (3)

The chemical species resulting from the decay of the ^{90}Sr in SrF_2 have not been identified experimentally. The $^{90}\text{SrF}_2$ should decay to the difluoride of stable ^{90}Zr .

Zirconium difluoride has been reported in the literature⁽⁹⁾ but is said to disproportionate at elevated temperatures to zirconium tetrafluoride and zirconium metal powder.

Any ZrF_2 formed as a decay product in a $^{90}\text{SrF}_2$ heat source should disproportionate at source operating temperatures, but this has not been demonstrated experimentally. The possibility also exists that the ZrF_2 could react with the SrF_2 , or impurity fluorides present, to form complex fluorides.

^{89}Sr Decay⁽¹⁰⁾ 3.4 SPECIFIC ACTIVITY^(11,12)

a. ^{90}Sr (100% Basis)

139 Ci/g

149 Ci/W(t)

0.933 W(t)/g

b. Pure SrF_2 (70.1% Sr, 55% ^{90}Sr Isotopic Content)

53.6 Ci/g

0.360 W(t)/g

c. WESF SrF_2 (95% SrF_2 , 55% ^{90}Sr Isotopic Content)

50.9 Ci/g

0.342 W(t)/g

1.02 W(t)/cm³ (at 70% of theoretical density)

The heat output of the $^{90}\text{SrF}_2$ will decrease with time as the ^{90}Sr decays. The following table shows this relationship for WESF $^{90}\text{SrF}_2$ of 95% chemical purity and having an initial ^{90}Sr isotopic content of 55%.

The Decrease In Heat Output of WESF $^{90}\text{SrF}_2$ ^(a) With Time				
Time yr	^{90}Sr Isotopic	Activity Ci/g	Heat Output	
	Content %		w(t)/g	w(t)/cm ³ (b)
0	55.0	50.9	0.342	1.02
1	54.4	49.7	0.334	0.991
2	53.8	48.5	0.326	0.968
5	52.0	45.1	0.303	0.899
10	49.0	39.9	0.268	0.795
20	42.9	31.3	0.211	0.626
28.6	37.9	25.4	0.171	0.508
57.2	23.4	12.7	0.0855	0.254

(a) WESF $^{90}\text{SrF}_2$ of 95% chemical purity

(b) $^{90}\text{SrF}_2$ compacted to 70% of theoretical density

3.5 RADIATION

a. Alpha Particles

None

b. Beta Particles^(3,12,13)

Nuclide	Max. E Mev	Ave. E Mev	Abundance %	W/kCi	Particles w-sec
^{90}Sr	0.546	0.196	100	1.16	5.51×10^{12}
^{90}Y	2.279	0.937	100	5.55	5.51×10^{12}
Total Power				6.71	

c. Gamma

None

d. Bremsstrahlung^(12,13)

The high-energy bremsstrahlung photons produced from ^{90}Sr and ^{90}Y in a SrF_2 matrix have not been determined. However Arnold⁽¹²⁾ at ORNL has calculated the bremsstrahlung photons for SrO and SrTiO_3 matrices and the data are presented in the tables on pages 13-16. The bremsstrahlung photons from a SrF_2 matrix should lie between those for SrO and SrTiO_3 but closer to SrO .

Sources containing ^{90}Sr - ^{90}Y activities require slightly more shielding than ^{137}Cs - $^{137\text{m}}\text{Ba}$ sources because of the high energy bremsstrahlung radiation from ^{90}Y which emits a 2.279 Mev beta particle.

e. Neutrons

None

Production of Bremsstrahlung Photons
from Strontium-90 Beta in Strontium Oxide Matrix (12)

	Maximum beta-particle energy	0.545 Mev
	Average beta-particle energy	0.201 Mev
Bremsstrahlung Energy Group, Mev	Photons per Beta Particle	Photons w-1 sec-1
0.020 $\pm$ 0.01	1.378×10^{-2}	7.58×10^{10}
0.040 $\pm$ 0.01	5.523×10^{-3}	3.04×10^{10}
0.060 $\pm$ 0.01	2.998×10^{-3}	1.65×10^{10}
0.080 $\pm$ 0.01	1.841×10^{-3}	1.01×10^{10}
0.100 $\pm$ 0.01	1.208×10^{-3}	0.66×10^{10}
0.120 $\pm$ 0.01	8.239×10^{-4}	0.45×10^{10}
0.140 $\pm$ 0.01	5.759×10^{-4}	3.17×10^9
0.160 $\pm$ 0.01	4.086×10^{-4}	2.25×10^9
0.180 $\pm$ 0.01	2.923×10^{-4}	1.61×10^9
0.200 $\pm$ 0.01	2.099×10^{-4}	1.15×10^9
0.220 $\pm$ 0.01	1.505×10^{-4}	0.83×10^9
0.240 $\pm$ 0.01	1.074×10^{-4}	0.59×10^9
0.260 $\pm$ 0.01	7.604×10^{-5}	0.42×10^9
0.280 $\pm$ 0.01	5.315×10^{-5}	2.92×10^8
0.300 $\pm$ 0.01	3.654×10^{-5}	2.01×10^8
0.320 $\pm$ 0.01	2.458×10^{-5}	1.35×10^8
0.340 $\pm$ 0.01	1.609×10^{-5}	0.88×10^8
0.360 $\pm$ 0.01	1.016×10^{-5}	0.56×10^8
0.380 $\pm$ 0.01	6.135×10^{-6}	3.37×10^7
0.400 $\pm$ 0.01	3.491×10^{-6}	1.92×10^7
0.420 $\pm$ 0.01	1.835×10^{-6}	1.01×10^7
0.440 $\pm$ 0.01	8.638×10^{-7}	0.48×10^7
0.460 $\pm$ 0.01	3.456×10^{-7}	1.90×10^6
0.480 $\pm$ 0.01	1.065×10^{-7}	5.86×10^5
0.500 $\pm$ 0.01	2.007×10^{-8}	1.10×10^5
0.520 $\pm$ 0.01	1.000×10^{-9}	5.50×10^3
0.540 $\pm$ 0.01	0.000	
Total bremsstrahlung energy, Mev/beta particle 1.411×10^{-3}		

Production of Bremsstrahlung Photons
from Yttrium-90 Beta in Strontium Oxide Matrix⁽¹²⁾

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 $w^{-1} \text{ sec}^{-1}$
0.100 $\pm$ 0.05	6.152×10^{-2}	3.38×10^{11}
0.200 $\pm$ 0.05	2.415×10^{-2}	1.33×10^{11}
0.300 $\pm$ 0.05	1.281×10^{-2}	0.70×10^{11}
0.400 $\pm$ 0.05	7.674×10^{-3}	4.22×10^{10}
0.500 $\pm$ 0.05	4.894×10^{-3}	2.69×10^{10}
0.600 $\pm$ 0.05	3.234×10^{-3}	1.78×10^{10}
0.700 $\pm$ 0.05	2.181×10^{-3}	1.20×10^{10}
0.800 $\pm$ 0.05	1.485×10^{-3}	8.17×10^9
0.900 $\pm$ 0.05	1.014×10^{-3}	5.58×10^9
1.000 $\pm$ 0.05	6.887×10^{-4}	3.79×10^9
1.100 $\pm$ 0.05	4.630×10^{-4}	2.55×10^9
1.200 $\pm$ 0.05	3.000×10^{-4}	1.65×10^9
1.300 $\pm$ 0.05	1.973×10^{-4}	1.09×10^9
1.400 $\pm$ 0.05	1.231×10^{-4}	0.68×10^9
1.500 $\pm$ 0.05	7.337×10^{-5}	4.04×10^8
1.600 $\pm$ 0.05	4.117×10^{-5}	2.26×10^8
1.700 $\pm$ 0.05	2.125×10^{-5}	1.17×10^8
1.800 $\pm$ 0.05	9.740×10^{-6}	5.36×10^7
1.900 $\pm$ 0.05	3.728×10^{-6}	2.05×10^7
2.000 $\pm$ 0.05	1.058×10^{-6}	5.82×10^6
2.100 $\pm$ 0.05	1.670×10^{-7}	9.19×10^5
2.200 $\pm$ 0.05	4.768×10^{-9}	2.62×10^4
Total bremsstrahlung energy, Mev/beta particle		2.814×10^{-2}

Production of Bremsstrahlung Photons
from Strontium-90 Beta in Strontium Titanate Matrix⁽¹²⁾

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

Total bremsstrahlung energy, Mev/beta particle 9.924×10^{-4}

Production of Bremsstrahlung Photons
from Yttrium-90 Beta in Strontium Titanate Matrix⁽¹²⁾

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

3.6 SHIELDING DATA⁽¹²⁾

Shielding calculations for $^{90}\text{SrF}_2$ sources have not been carried out. Arnold⁽¹²⁾ at ORNL has calculated the bremsstrahlung dose rates for ^{90}Sr sources having SrO and SrTiO_3 matrices. The calculated dose rates for unshielded and shielded sources of various sizes are presented in Figures 4 - 11. Shielding requirements for $^{90}\text{SrF}_2$ sources are expected to be intermediate between those of equivalent sized ^{90}SrO and $^{90}\text{SrTiO}_3$ sources, but closer to those of ^{90}SrO . For example, Arnold's calculations show that 500 watt sources of ^{90}SrO and $^{90}\text{SrTiO}_3$ would require about $14\frac{1}{2}$ cm. and $13\frac{1}{2}$ cm. of lead shielding respectively to reduce the dose rate to 10 millirad/hr at a distance of 100 cm. A $^{90}\text{SrF}_2$ source of the same size would probably require between 14 - $14\frac{1}{2}$ cm. of lead shielding to attain the same dose rate. The ^{90}Sr sources require substantial shielding because of the high-energy bremsstrahlung radiation resulting from ^{90}Y decay.

Figure 4. Bremsstrahlung Dose Rates from Unshielded Isotopic Power Sources of Strontium-90 (Strontium Oxide) as a Function of Distance from Center of Source.⁽¹²⁾

Figure 5. Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm. (12)

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Figure 6. Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm. (12)

Figure 7. Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Source of Strontium-90 (Strontium Oxide). Center of source to dose point separation distance = 100 cm.(12)

Figure 8. Bremsstrahlung Dose Rates from Unshielded Isotopic Power Sources of Strontium-90 (Strontium Titanate) as a Function of Distance from Center of Source. (12)

Figure 9. Bremsstrahlung Dose Rates from Iron-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate), Center of source to dose point separation distance = 100 cm.(12)

Figure 10. Bremsstrahlung Dose Rates from Lead-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). (12)
Center of source to dose point separation distance = 100 cm.

Figure 11. Bremsstrahlung Dose Rates from Uranium-Shielded Isotopic Power Sources of Strontium-90 (Strontium Titanate). Center of source to dose point separation distance = 100 cm.(12)

3.7 BIOLOGICAL TOLERANCES^(14,15,16,17)

The ^{89}Sr and ^{90}Sr tolerances recommended by the International Commission on Radiological Protection are presented below.

Maximum Permissible Body-Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure^(14,15)

Radionuclide	Organ of Reference (Critical Organ underscored)	Maximum Permissible Burden in Total Body $q(\mu\text{Ci})$	Maximum Permissible Concentration, $\mu\text{Ci}/\text{cm}^3$			
			For 40-Hr Week		For 168-Hr Week	
			Water	Air	Water	Air
^{89}Sr $^{38}_{38}$	(Sol) <u>Bone</u>	4	3×10^{-4}	3×10^{-8}	1×10^{-4}	1×10^{-8}
	GI (LLI)		1×10^{-3}	3×10^{-7}	4×10^{-4}	9×10^{-8}
	β^- Total Body	40	2×10^{-3}	2×10^{-7}	7×10^{-4}	6×10^{-8}
	(Insol) <u>Lung</u>			4×10^{-8}		1×10^{-8}
^{90}Sr $^{38}_{38}$	GI (LLI)		8×10^{-4}	1×10^{-7}	3×10^{-4}	5×10^{-8}
	(Sol) <u>Bone</u>	2.0	1×10^{-5}	1×10^{-9}	4×10^{-6}	4×10^{-10}
	GI (LLI)		1×10^{-3}	3×10^{-7}	5×10^{-4}	1×10^{-7}
	β^- Total Body	3.0	2×10^{-5}	2×10^{-9}	7×10^{-6}	7×10^{-10}
	(Insol) <u>Lung</u>			5×10^{-9}		2×10^{-9}
	GI (LII)		1×10^{-3}	2×10^{-7}	4×10^{-4}	6×10^{-8}

The abbreviations GI and LII refer to the gastrointestinal tract and lower large intestine respectively.

The maximum permissible concentrations for ^{89}Sr and ^{90}Sr in restricted and unrestricted areas as defined in 10CFR Part 20⁽¹⁶⁾ and ERDA-MC-0524⁽¹⁷⁾ are presented below:

Maximum Permissible Concentrations for ^{89}Sr and ^{90}Sr in Air and Water Above Natural Background⁽¹⁶⁾

Radionuclide	Maximum Permissible Concentration, $\mu\text{Ci}/\text{ml}$			
	Restricted Area ^(a)		Unrestricted Area	
	Water	Air	Water	Air
^{89}Sr $^{38}_{38}$	(Sol) 3×10^{-4}	3×10^{-8}	3×10^{-6}	3×10^{-10}
	(Insol) 8×10^{-4}	4×10^{-8}	3×10^{-5}	1×10^{-9}
^{90}Sr $^{38}_{38}$	(Sol) 1×10^{-5}	1×10^{-9}	3×10^{-7}	3×10^{-11}
	(Insol) 1×10^{-3}	5×10^{-9}	4×10^{-5}	2×10^{-10}

^(a) Based on a 40-hr exposure in any period of seven consecutive days.

The radiation exposure limits for individuals in restricted and unrestricted areas as defined in ERDA-MC-0524⁽¹⁷⁾ are presented below:

Exposure Limits for Individuals in Restricted Areas⁽¹⁷⁾

Type of Exposure	Exposure Period	Dose Equivalent [Dose or Dose Commitment (rem)] ^(a)
Whole body, head and trunk, gonads, lens of the eye ^(b) , red bone marrow, active blood forming organs.	Year	5 ^(c)
	Calendar Quarter	3
Unlimited areas of the skin (except hands and forearms). Other organs, tissues, and organ systems (except bone).	Year	15
	Calendar Quarter	5
Bone.	Year	30
	Calendar Quarter	10
Forearms. ^(d)	Year	30
	Calendar Quarter	10
Hands ^(d) and feet.	Year	75
	Calendar Quarter	25

^(a) To meet the above dose commitment standards, operations must be conducted in such a manner that it would be unlikely that an individual would assimilate in a critical organ, by inhalation, ingestion, or absorption, a quantity of radionuclide(s) that could commit the individual to an organ dose which exceeds the limits specified in the above table.

^(b) A beta exposure below an average energy of 700 Kev will not penetrate the lens of the eye; therefore, the applicable limit for these energies would be that for the skin (15 rem/year).

^(c) In special cases with the approval of the Director, Division of Operational Safety, a worker may exceed 5 rem/year provided his average exposure per year since age 18 will not exceed 5 rem per year.

^(d) All reasonable effort shall be made to keep exposures of forearms and hands to the general limit for the skin.

Exposure Limits for Individuals in Unrestricted Areas⁽¹⁷⁾

<u>Type of Exposure</u>	<u>Annual Dose Equivalent^(a) or Dose Commitment (rem)</u>	
	<u>Based on dose to individuals at points of maximum probable exposure</u>	<u>Based on an average dose to a suitable sample of the exposed population</u>
Whole body, gonads, or bone marrow	0.5	0.17
Other organs	1.5	0.5

(a) In keeping with ERDA policy on lowest practicable exposure, as expressed in Chapter 0524-012, exposures to the public shall be limited to as small a fraction of the respective annual dose limits as is practicable.

3.8 CRITICAL MASS

The radioactive strontium isotopes and ⁹⁰Y are not fissionable.

3.9 THERMOPHYSICAL PROPERTIES

3.9.1 Density

Pure SrF₂⁽¹⁸⁾

$$\rho = 4.29 \text{ g/cm}^3 \text{ (at } 25^\circ\text{C)}$$

WESF-Grade SrF₂ (calculated value)

$$\rho = 4.24 \text{ g/cm}^3 \text{ (at } 25^\circ\text{C)}$$

3.9.2 Thermal Expansion⁽¹⁹⁾

The thermal expansion of pure SrF₂ and WESF-Grade SrF₂ was measured over a temperature range of 50°-700°C. The thermal expansion coefficient α was essentially constant over the temperature range studied.

<u>Grade of SrF₂</u>	<u>Temperature °C</u>	<u>Linear Thermal Expansion Coefficient (α), cm/cm-°C</u>
Pure SrF ₂	50 - 700	2.13×10^{-5}
WESF-Grade SrF ₂	50 - 700	2.19×10^{-5}

3.9.3 Specific Heat^(19,20,21,22)

The specific heat of pure SrF_2 has been determined experimentally by various investigators over a temperature range of 100° to 2126°K . The specific heat of WESF-Grade SrF_2 was measured over a temperature range of 320° - 710°K . The experimentally measured values are presented below:

The Specific Heat of Pure SrF_2 and WESF-Grade SrF_2

Temperature $^\circ\text{K}$	Specific Heat (C_p), cal/g- $^\circ\text{C}$			
	Pure SrF_2 (21)	Pure SrF_2 (20,22)	Pure SrF_2 (19)	WESF-Grade SrF_2 (19)
0	0			
100	0.0698			
200	0.1173			
298	0.1332		[0.1307]	[0.1361]
320			0.1340	0.1395
360			0.1384	0.1442
400			0.1417	0.1477
440			0.1443	0.1504
480			0.1468	0.1526
520			0.1491	0.1537
560			0.1510	0.1537
600			0.1510	0.1537
700			0.1510	0.1537
800		0.1540		
900		0.1567		
1000		0.1632		
1100		0.1716		
1200		0.1847		
1300		0.2070		
1400		0.2738		
1500		0.2945		
1600		0.2396		
1700		0.2165		
1800		0.2042		
1900		0.1954		
2000		0.1895		
2100		0.1859		

[] Extrapolated values

3.9.4 Debye Temperature⁽²³⁾

$$\Theta_D = 420^\circ\text{K (estimated value)}$$

3.9.5 Enthalpy

The enthalpies, or heat contents, of pure SrF_2 and WESF-Grade SrF_2 were calculated from the specific heat data given in Section 3.9.3 using the equation

$$H_t - H_{298} = \int_{298}^t C_p dt$$

The average molecular weight of the WESF-Grade SrF_2 was assumed to be 124.5.

Enthalpy of Pure SrF_2 and WESF-Grade SrF_2

Temperature °K	$H_t - H_{298}$, cal/g mole	
	Pure SrF_2	WESF-Grade SrF_2
298	0	0
400	1,750	1,810
500	3,570	3,690
600	5,460	5,600
700	7,360	7,520
800	9,260	9,400
900	11,220	
1,000	13,230	
1,100	15,320	
1,200	17,560	
1,300	19,990	
1,400	22,920	
1,500	26,800	
1,600	30,080	
1,700	32,930	
1,800	35,560	
1,900	39,060	
2,000	40,480	
2,100	42,830	

3.9.6 Phase Transitions

a. Solid Phase Transitions^(20,22,23)

SrF₂ is reported to undergo a phase transition between 1421° and 1484°K. The phase transition has not been verified by X-ray diffraction measurements; however, the transition appears to be a second order transition similar to that observed with other alkaline earth halides having the calcium fluoride structure.⁽²³⁾

b. Melting Point

A range of values has been reported in the literature for the melting point of SrF₂. Recently reported values for pure SrF₂ are given below:

<u>Source</u>	<u>Melting Point °K</u>
Efremova and Matizen (22)	1750 ± 2
Kojima, et al. (24)	1746 ± 1
Petit and Delbove (25)	1735
Porter and Brown (26)	1736 ± 5
Average	1742 °K

Additions of impurities to the SrF₂ will reduce the melting point. The SrF₂-NaF system, for example, exhibits a minimum melting point of 856°C.⁽²⁷⁾ Differential thermal analysis of WESF-Grade SrF₂ shows the existence of a low melting phase having a melting point of 851° ± 5°C.⁽²⁸⁾ At temperatures up to 1100°C the amount of liquid phase present appears to be very small (<1%).

c. Boiling Point⁽²⁰⁾

$$T_b = 2759^\circ\text{K}$$

3.9.7 Latent Heats of Phase Transitions

a. Solid Phase Transition⁽²⁰⁾

$$\Delta H_t \approx 0$$

b. Melting⁽²⁰⁾

$$\Delta H_m = 7.09 \pm 0.15 \text{ kcal/mol}$$

c. Boiling⁽²⁰⁾

$$\Delta H_v = 76.4 \text{ kcal/mol}$$

3.9.8 Vapor Pressure⁽²⁹⁾

Temperature °C	Vapor Pressure Torr
1822	8.5
1880	15.0
1927	25.7
1959	31.0

3.9.9 Thermal Diffusivity⁽¹⁹⁾

The thermal diffusivities of pure SrF_2 and WESF-Grade SrF_2 were measured over a temperature range of 50°-850°C using a pulsed laser technique.

Temperature °C	Thermal Diffusivity (α), cm^2/sec	
	Pure SrF_2	WESF-Grade SrF_2
25	[0.0283]	[0.0249]
50	0.0255	0.0230
150	0.0174	0.0173
250	0.0133	0.0135
350	0.0110	0.0112
450	0.0091	0.0096
550	0.0075	0.0084
650	0.0064	0.0074
750	0.0056	0.0066
850	0.0049	0.0059

[] Extrapolated values

3.9.10 Thermal Conductivity

The thermal conductivities of pure SrF_2 and WESF-Grade SrF_2 were calculated from the thermal diffusivity values given in Section 3.9.9 using the equation

$$\lambda = \alpha \cdot C_p \cdot \rho$$

where λ is the thermal conductivity in cal/cm-sec-°C

α is the thermal diffusivity in cm^2/sec

C_p is the specific heat in cal/g-°C

ρ is the density in g/cm^3 .

The values of C_p used in calculating λ are given in Section 3.9.3. The density values were calculated using the thermal expansion coefficients given in Section 3.9.2.

Temperature °C	Thermal Conductivity (λ), cal/cm-sec-°C	
	Pure SrF_2	WESF-Grade SrF_2
25	0.0160	0.0144
50	0.0147	0.0136
150	0.0106	0.0109
250	0.0084	0.0087
350	0.0071	0.0072
450	0.0058	0.0062
550	0.0048	0.0055
650	0.0042	0.0049
750	0.0038	0.0045
850	0.0035	0.0042

3.9.11 Ionic Conductivity⁽³⁰⁾

Pure SrF_2 (Polycrystalline and molten)

Figure 12. The logarithm of the conductivity σ as a function of the reciprocal temperature. T_m is the melting point.

3.9.12 Viscosity⁽²⁾

$$\log \mu = 0.781 + 436/T$$

where μ is the fluid viscosity in centipoises
 T is the temperature in $^{\circ}\text{K}$.

3.9.13 Surface Tension⁽³¹⁾

$$\gamma = 670 - 0.3T \text{ erg/cm}^2$$

where T is the temperature in $^{\circ}\text{C}$.

3.9.14 Total Hemispherical Emittance

No value reported.

3.9.15 Spectral Emissivity⁽²⁾

A value of 0.9 is recommended.

3.9.16 Crystallography⁽³²⁾Face centered cubic - C1 (CaF₂) type

$$a^{\circ} = 5.7996 \text{ \AA}$$

A - B distance $2.51 \text{ \AA}$ 3.9.17 Solubility in Aqueous Media⁽³³⁾a. Pure SrF₂Solubility of Pure SrF₂ in Demineralized Water^(a)

Temperature °C	Solubility g/l	Solubility Product K _{sp}
4	0.133	4.7×10^{-9}
23	0.135	5.1×10^{-9}
35	0.143	5.8×10^{-9}
50	0.157	7.7×10^{-9}

- (a) Demineralized water having a resistivity of 2 megohms

Solubility of Pure SrF₂ in Natural Seawater

Temperature °C	Equilibrium Sr Conc. <u>M</u>	Equilibrium F Conc. <u>M</u>	SrF ₂ Dissolved ^(a) g/l
4	0.00115	0.00227	0.114
23	0.00119	0.00255	0.149
35	0.00129	0.00243	0.150
50	0.00139	0.00268	0.163

- (a) Calculated from the equilibrium Sr and F concentrations after correcting for the initial Sr and F concentrations of the natural seawater.

b. WESF-Grade SrF_2

Experimental studies show that soluble impurities in WESF-Grade SrF_2 have a significant effect on the solubility of the SrF_2 in demineralized water, both by the common ion effect and by their effect on the ionic strength of the solution. However, the impurities have little effect on the solubility of the SrF_2 in seawater.

The Effect of Impurities on the Solubility of
Strontium Fluoride in Aqueous Media at 23°C

Grade of SrF_2 (a)	SrF_2 Dissolved, g/l	
	Demineralized Water (b)	Natural Seawater (c)
Pure SrF_2	0.135	0.149
Commercial SrF_2	0.0749	0.144
WESF-Grade SrF_2	0.0138	0.141

(a) 15 grams of solid SrF_2 added per liter of water

(b) calculated from the equilibrium Sr concentration

(c) calculated from the equilibrium Sr concentration after correcting for the initial Sr concentration of the seawater.

3.9.18 Dissolution Behavior⁽³³⁾

The dissolution rate of strontium fluoride in aqueous media is influenced by several factors including:

- the surface area of the SrF_2
- the thermal history of the SrF_2
- the impurity content of the SrF_2
- the composition of the dissolving medium and
- the temperature of the dissolving medium.

The surface area and thermal history of the SrF_2 are interrelated, and the relationship is highly dependent on the impurity content of the fluoride.

It was not possible to measure the surface area of the $^{90}\text{SrF}_2$, and the dissolution rates for $^{90}\text{SrF}_2$ were reported on the basis of contained strontium (μgSr dissolved/hr-g Sr initially present). Since the surface area of $^{90}\text{SrF}_2$ is not known, direct comparisons of the dissolution rates of $^{90}\text{SrF}_2$ and nonradioactive SrF_2 are difficult. However the experimental data show the dissolution rate of $^{90}\text{SrF}_2$ in aqueous media is much greater than that of non-radioactive SrF_2 of similar composition and thermal history. Results of a large number of tests with various grades of SrF_2 show the average dissolution rate of SrF_2 in demineralized water is about three times greater than in natural seawater. Although direct comparisons are difficult, SrF_2 appears to dissolve at a more rapid rate than SrTiO_3 and at a slower rate than Sr_2TiO_4 .

Typical dissolution rate values for various grades of $^{90}\text{SrF}_2$ and nonradioactive SrF_2 are given below:

Dissolution Rate of Nonradioactive SrF_2
in Aqueous Media at 24°C

Grade of SrF_2 Tested	Surface Area cm^2/g	Dissolution Rate $\mu\text{g Sr}$ Dissolved/hr-g Sr Initially Present	
		Demineralized Water	Natural Seawater
Pure SrF_2 Fired at 1100°C for 96 hr	440	320 ± 60	120 ± 36
Pure SrF_2 Fired at 800°C for 240 hr	510	660 ± 140	290 ± 82
WESF-Grade SrF_2 Fired at 1100°C for 1 hr	440	130 ± 24	75 ± 12
WESF-Grade SrF_2 Fired at 1100°C for 240 hr	140	32 ± 7	24 ± 6
WESF-Grade SrF_2 Fired at 800°C for 240 hr	510	360 ± 28	130 ± 12
WESF-Grade SrF_2 Fired at 800°C for 440 hr	290	62 ± 7	36 ± 4

Dissolution Rate of $^{90}\text{SrF}_2$ in Aqueous Media at 30°C (a)

Grade of $^{90}\text{SrF}_2$ Tested	Dissolution Rate	
	$\mu\text{g Sr Dissolved/hr-g Sr Initially Present}$ Demineralized Water	Natural Seawater
WESF-Produced $^{90}\text{SrF}_2$	442 ± 48	298 ± 25
WESF-Grade $^{90}\text{SrF}_2$ (b)	1630 ± 260	270 ± 50

(a) The surface area of $^{90}\text{SrF}_2$ could not be measured, and the dissolution rates are reported on the basis of contained strontium.

(b) Prepared by PNL using WESF flowsheet and ^{90}Sr feed solution from ARHCO.

The Effect of Temperature on the Dissolution
Rate of SrF_2 (a)

Temperature $^\circ\text{C}$	Dissolution Rate	
	$\mu\text{g Sr Dissolved/hr-g Sr Initially Present}$ Demineralized Water	Natural Seawater
3	73	32
9	76	44
24	130	75
34	250	
35		100
42	300	130
61	680	
81	1900	
90	2600	

(a) WESF-Grade SrF_2 fired at 1100°C for 1 hour. Surface Area = $440 \text{ cm}^2/\text{g}$

3.9.19 Infrared Spectrum (34)

The infrared spectrum obtained with a single crystal of high-purity SrF_2 is shown in Figure 13.

Figure 13. Infrared Transmission of High Purity SrF_2 Single Crystal⁽³⁴⁾

3.10 MECHANICAL PROPERTIES

3.10.1 Hardness (pure SrF_2)

Moh hardness⁽²⁹⁾

$$H_m = 3.5$$

Knoop Hardness - Single Crystal

Unoriented Specimen⁽³⁴⁾

$$K_{hn} = 140 \text{ kg/mm}^2$$

Oriented Specimen⁽³⁵⁾

Knoop Hardness Number in Several Crystallographic Directions For SrF_2 (Values in parentheses are normalized with respect to $\langle 100 \rangle$)

Direction	Knoop Hardness Number
Slip mode	$\{100\} \langle 110 \rangle$
$\langle 100 \rangle$	154 (1.0)
$\langle 210 \rangle$	143 (0.93)
$\langle 110 \rangle$	140 (0.91)
$\langle 211 \rangle$	135 (0.87)
$\langle 111 \rangle$	126 (0.81)

3.10.2 Modulus of Rupture (pure SrF_2)⁽³⁶⁾

6100 psi

3.11 CHEMICAL PROPERTIES3.11.1 Thermodynamic Properties⁽²⁰⁾Selected Thermodynamic Functions for SrF_2

Temperature °K	S° eu	$-(G^\circ - H_{298})/T$ cal/mol-°K	$-\Delta H_f^\circ$ kcal/mol	$-\Delta G_f^\circ$ kcal/mol	Log Kp
0	0	Infinite	290.4	290.4	Infinite
100	5.02	32.91	291.1	286.9	627.0
200	13.32	21.11	291.1	282.7	308.9
298	19.63	19.63	290.9	278.6	204.2
400	24.72	20.30	290.6	274.4	149.9
500	28.77	21.60	290.3	270.4	118.2
600	32.17	23.09	290.0	266.5	97.06
700	35.10	24.60	289.7	262.6	81.98
800	37.66	26.08	289.5	258.7	70.68
900	39.96	27.49	289.5	254.9	61.89
1000	42.07	28.85	289.3	251.0	54.86
1100	44.07	30.14	290.9	247.1	49.09
1200	46.01	31.38	290.4	243.1	44.28
1300	47.96	32.58	289.7	239.2	40.21
1400	50.13	33.76	288.6	235.4	36.74
1500	52.80	34.94	286.4	231.6	33.75
1600	54.92	36.12	284.9	228.0	31.15
1700	56.65	37.28	316.4	223.6	28.75
1800	58.15	38.40	315.2	218.2	26.49
1900	59.51	39.47	314.1	212.8	24.48
2000	60.75	40.51	313.1	207.5	22.68
2100	61.90	41.50	312.2	202.3	21.05
2200	62.98	42.45	311.3	197.0	19.58

3.11.2 Chemical Reactions

- a. Oxygen - No reaction
- b. Nitrogen - No reaction
- c. Water - Slightly soluble (see Sections 3.9.17 and 3.9.18)
- d. Hydrochloric Acid - Dissolves in boiling 6N HCl
- e. Nitric Acid - Dissolves in hot 2-6 M HNO₃
- f. Sulfuric Acid - Reacts with hot concentrated H₂SO₄
- g. Containment Materials - See Section 3.14.

3.12 COMPACTION CHARACTERISTICS

3.12.1 Hot Pressing^(7,37)

A limited amount of work at ARHCO and PNL indicates that SrF₂ can be compacted to greater than 92% of theoretical density by hot pressing at 750°-800°C and 5000 psi using graphite or metal dies.

3.12.2 Cold Pressing⁽³⁸⁾

Strontium fluoride is readily compacted to moderately high densities using cold pressing techniques. Rockwell International uses pneumatic impaction, which is essentially a cold pressing operation, to obtain a SrF₂ density of 70%-75% of theoretical density in the WESF storage capsule. Figure 14 shows the densities obtained when three grades of SrF₂ were cold pressed into cylindrical pellets having a length-to-diameter ratio of approximately 0.5. The temperature at which the SrF₂ is fired affects the density which can be obtained by cold pressing (see Figure 15). The particle size of the SrF₂ appears to have only a small effect on the density which can be obtained by cold pressing as shown below:

The Effect of Particle Size on the Cold Pressing
of Commercial SrF_2 Fired at 1100°C for 84 Hours and Crushed

Size Fraction (U.S. Standard Sieve)	Compacted Density, % of theoretical density	
	11.1 tons/sq in.	34.0 tons/sq in.
- 20 + 70	78	88
- 70 + 100	78	89
-100 + 140	80	89
-140 + 200	78	87
-200 + 230	75	87
-230 + 325	76	86
-325	75	85
Combined Fractions	78	87

Figure 14. Density of Cold Pressed Pellets as a Function of Applied Pressure for Three Grades of SrF_2 Which Had Been Fired at 1100°C for 16 Hours and Crushed to a -20 Mesh Powder

Figure 15. The Effect of Firing Temperature on the Cold Pressing of Commercial Strontium Fluoride

3.13 SINTERING CHARACTERISTICS^(33,39)

Because of its relatively low melting point, strontium fluoride compacted to less than theoretical density will sinter and agglomerate when held at the temperatures expected in an operating $^{90}\text{SrF}_2$ heat source. The presence of impurities in the SrF_2 , which can result in the formation of low melting phases (see Section 3.9.6) will increase the tendency for agglomeration to occur. How the surface area of freshly prepared SrF_2 decreases when the SrF_2 is fired at various temperatures for extended periods of time is shown in the table on page 43.

Since the standard WESF $^{90}\text{SrF}_2$ capsule contains strontium fluoride compacted to approximately 70% of theoretical density, additional sintering and agglomeration of the SrF_2 could occur during heat source service. This could produce changes in the distribution of the SrF_2 in the capsule during use and possibly affect: (a) $^{90}\text{SrF}_2$ -clad compatibility and, (b) the heat flow pattern in the capsule.

Time At Temp. (hrs)	Surface Area, cm ² /g of SrF ₂					
	600°C		800°C		1100°C	
	Pure SrF ₂	WESF-Grade SrF ₂	Pure SrF ₂	WESF-Grade SrF ₂	Pure SrF ₂	WESF-Grade SrF ₂
0	2550	2700	2550	2700	2550	2700
0.5		2280		820		380
1	2420	2000	1250	970	860	460
2	2320	1850	1210		810	520
4	2130	1740	1150	1030	730	380
8	1950	1650	1080	950	650	380
24	1660	1530	920	830	520	370
48	1650					
72		1410		540		230
96	1530		680		420	
240	1490	1230	510	510	390	140
480	1450					
1500	1470		540	470	360	130
4400				480		

3.14 COMPATIBILITY WITH CONTAINMENT MATERIALS^(6,40-44)

A number of tests have been carried out, or are currently under way, at PNL to evaluate the compatibility of ⁹⁰SrF₂ and nonradioactive SrF₂ with potential containment materials at elevated temperatures. In the tests a specimen of the material being evaluated was contacted with SrF₂ in a sealed container of the same material, as shown in Figure 16. The test capsules were sealed in protective jackets of Inconel 600 and then heated at 600°-1100°C for the required times. After testing, the specimens were analyzed by metallographic techniques, scanning electron microscopy and electron microprobe analysis.

Compatibility data obtained to date with both ⁹⁰SrF₂ and nonradioactive SrF₂ indicate that impurities in the strontium fluoride are the major cause of metal attack. Therefore, the exposed metal surface-to-SrF₂ volume ratio (S/V) of the test capsule is an important parameter in evaluating SrF₂-clad compatibility. In general, decreasing the S/V ratio results in increased attack of the containment material. Various size capsules were used in the compatibility tests to give S/V ratios of 4.5, 2.5 and 0.9 cm⁻¹. The WESF ⁹⁰SrF₂ storage capsule has an S/V ratio of approximately 0.85 cm⁻¹.

NOTES:

1. CAPSULE, LID, AND TEST SPECIMEN ARE SAME MATERIAL
2. SrF_2 COMPACTED TO $\sim 75\%$ OF THEORETICAL DENSITY
3. THREE CAPSULE SIZES USED TO GIVE EXPOSED METAL SURFACE-TO-FUEL VOLUME RATIOS (S/V) OF 0.9, 2.5, AND 4.5 cm^{-1}

Figure 16. Capsule Design Used in the SrF_2 Compatibility Tests

Many containment materials when exposed to strontium fluoride at elevated temperatures suffer two distinctly different types of attack which have been designated as: a) chemical attack and, b) changes in microstructure. Chemical attack is defined as attack which can be directly attributed to reaction of the containment material with the strontium fluoride or contained impurities and includes such mechanisms as metal dissolution, selective leaching of alloy components, intergranular attack, subsurface void formation and pitting. Changes in microstructure are defined as those instances where a containment material exhibits areas in which the morphology differs from that of the bulk of the specimen or from control samples tested without fluoride present. The microstructural change usually consists of one or more of the following: marked changes in grain size, the disappearance of normal alloy precipitates, and the formation of abnormal precipitates.

3.14.1 Preliminary Screening Tests^(6,43)

Two sets of screening tests were carried out at 800°-1100°C to evaluate the compatibility of $^{90}\text{SrF}_2$ and nonradioactive SrF_2 with a large number of potential containment materials. The first set of tests was restricted to containment materials that could be adapted for use in the WESF operation and included seven nickel or cobalt-base superalloys and two refractory metals. The test capsules were limited to a single S/V ratio of 4.5 cm⁻¹. Four grades of strontium fluoride were tested with each containment material: (1) high purity nonradioactive SrF_2 , (2) high purity $^{90}\text{SrF}_2$, (3) WESF-Grade $^{90}\text{SrF}_2$, and (4) high purity nonradioactive SrF_2 with controlled levels of added impurities. The two refractory metals tested, tungsten and TZM, exhibited very good compatibility with all grades of SrF_2 , whereas the seven superalloys suffered varying degrees of attack. In the case of the superalloys, both the extent of attack and the attack mechanisms varied with temperature, time, and composition of the strontium fluoride. The results of the tests are summarized in the Tables on pages 46-47, and a detailed discussion of the tests and additional test results are provided in Reference 6.

A second set of screening tests was carried out at 800°C using non-radioactive SrF_2 containing impurities similar to those found in WESF $^{90}\text{SrF}_2$. Thirty-two containment materials were evaluated including precious metals, refractory metals and base metal alloys. Selection of the materials to be tested was based on potential compatibility with SrF_2 , and without regard to other factors such as cost, availability, fabricability and mechanical properties. The test capsules were limited to a single S/V ratio of 4.5 cm⁻¹. A summary of the test results is given in the Table on page 48 and a detailed discussion of the tests is provided in Reference 43. The precious metals iridium and Ir-0.3% W alloy and rhenium exhibited excellent compatibility with the SrF_2 at 800°C, while the other materials tested suffered varying degrees of attack. In general, metal attack did not increase appreciably with increasing exposure time. The metal attack is apparently due primarily to impurities in the SrF_2 and the impurities are consumed in a relatively short period of time.

3.14.2 Long-Term Tests⁽⁴⁰⁻⁴²⁾

Based on the results of the preliminary screening tests, three containment materials were selected for long-term testing with WESF-produced $^{90}\text{SrF}_2$: Hastelloy C-276, Haynes Alloy 25 and TZM.

Summary of the Results Obtained in the Screening Tests
With High-Purity Nonradioactive SrF_2 (a)(6)

Material Tested	Test Temperature (C°)	Depth of Metal Affected, mils			
		Chemical Attack		Change in Microstructure	
		1500 hr	4400 hr	1500 hr	4400 hr
Hastelloy C-276	800	1	2	1	1
	1000	4	7	1	2
	1100	6	8	0	2
Hastelloy X	800	1	<1	2	2
	1000	1	1	2	1
	1100	2	1	1	4
Hastelloy N	800	1	4	2	5
	1000	3	3	5	5
	1100	<1	1	5	6
Haynes Alloy 25	800	<<1	1	<1	<1
	1000	<<1	1	<1	1
	1100	<<1	1	1	2
Haynes Alloy 188	800	2	1	2	2
	1000	2	3	0	0
	1100	2	4	1	1
Inconel 600	800	0	<1	3	6
	1000	<1	<1	5	7
	1100	<1	1	0	4
Inconel 625	800	1	1	1	2
	1000	3	3	4	4
	1100	2	3	0	0
TZM	800	0	0	0	<1
	1000	0	0	0	<1
	1100	0	0	0	<1
Tungsten	800	0	0	0	<1
	1000	0	0	0	<1
	1100	0	0	0	<1

(a) The SrF_2 contained <0.1% total impurities.

Summary of the Results Obtained in the Screening
Tests With WESF-Grade $^{90}\text{SrF}_2$ (a)(6)

Material Tested	Test Temperature (C°)	Depth of Metal Affected, mils			
		Chemical Attack		Change in Microstructure	
		1500 hr	4400 hr	1500 hr	4400 hr
Hastelloy C-276	800	2	2	3	3
	1000	2	3	5	8
	1100	3	3	5	6
Hastelloy X	800	1	3	4	4
	1000	1	1	6	4
	1100	3	3	6	10
Hastelloy N	800	4	6	7	6
	1000	7	9	20	12
	1100	6	---	8	---
Haynes Alloy 25	800	1	1	2	2
	1000	1	1	2	3
	1100	1	2	2	2
Haynes Alloy 188	800	1	2	2	4
	1000	3	4	7	10
	1100	1	2	8	5
Inconel 600	800	1	3	4	11
	1000	1	2	8	14
	1100	2	2	7	12
Inconel 625	800	1	4	4	8
	1000	2	5	20	18
	1100	4	5	18	14
TZM	800	<1	<1	0	0
	1000	<1	<1	1	0
	1100	<1	<1	0	0
Tungsten	800	0	0	0	0
	1000	0	<1	0	0
	1100	1	<1	0	0

(a) The $^{90}\text{SrF}_2$ was prepared by PNL using the WESF flowsheet and contained ~ 4.5% cation impurities.

Summary of the Results Obtained in the Screening Tests With WESF-Grade Nonradioactive SrF_2 (a)(43)

Containment Material	Depth of Metal Affected, mils			
	Chemical Attack		Change in Microstructure	
	1500 hr	4400 hr	1500 hr	4400 hr
Hastelloy C-276	3	3	7	5
Haynes Alloy 25	2	1	3	2
TZM	<1	<1	0	<1
Hastelloy C-4	5	4	12	13
Hastelloy S	7	3	15	12
Hastelloy B	4	4	15	11
Hastelloy B-2	10	6	18	18
Haynes Alloy 556	5	5	6	7
Inconel 617	7	8	14	14
Inconel 671	25	20	25	20
Incoloy 800	8	7	0	0
René 41	10	11	14	13
Udimet 700	>25	>25	0	>25
Monel 400	5	6	8	6
Nickel 200	7	8	10	8
Ingot Iron	3	4	0	7
Ductile Cast Iron	CR ^(b)	CR	X ^(c)	X
316L SS	6	22	0	0
JS 777	6	5	7	6
Copper	>25	>25	0	0
Titanium	>25	>25	X	X
Hafnialloy 2525 ^(d)	>25	CR	X	X
Molybdenum	2	<1	0	<1
Niobium	3	2	2	2
Ta-10% W	10	2	0	0
Mo-50% Re	2	1	0	0
W-26% Re	2	1	0	0
Rhenium	<1	<1	0	0
Iridium	0	<<1	0	0
Ir-0.3% W	0	<<1	0	0
Platinum	>25	>25	X	X
Gold	>15	>15	X	X

(a) The SrF_2 contained impurities similar to those found in WESF-produced $^{90}\text{SrF}_2$

(b) CR - Complete Reaction

(c) X - Could not be estimated because of extensive chemical attack

(d) Hafnialloy 2525 is a hafnium base developmental alloy containing 0.25% Pt and 0.25% Pd

The tests are being carried out at 600°, 800° and 1000°C and will be of 1000, 6000, 12,000, 20,000 and 30,000 hr duration. Similar tests are under way with nonradioactive SrF_2 containing impurities similar to those found in WESF-produced $^{90}\text{SrF}_2$. Tensile and Charpy V-notch impact specimens are included in the tests to determine the effects of fluoride attack on the mechanical properties of the three materials. Various size capsules were used to give S/V ratios of 4.5, 2.5 and 0.9 cm^{-1} . The 1000 hr tests have been completed and the results obtained with $^{90}\text{SrF}_2$ are summarized in the Table on page 50. The TZM specimens suffered less attack than the two superalloys; but all three materials suffered greater attack than was observed in the screening tests. The increased attack is attributed to the impurities in the WESF $^{90}\text{SrF}_2$. The additions of ZrF_4 and Zr metal to the $^{90}\text{SrF}_2$ to simulate decay product buildup produced a marked decrease in metal attack.

Summary of Results From the 1000 Hr Tests with WESF-
Produced $^{90}\text{SrF}_2$ (40-42)

Containment Material	Temperature °C	S/V Ratio ^(a) cm ⁻¹	Depth of Metal Affected, mils	
			Chemical Attack	Change in Microstructure
Hastelloy C-276	600	4.5	3	5
	600	2.5	10	12
	600 ^(b)	4.5	1	2
	800	4.5	7	12
	800	2.5	30	35
	800 ^(b)	4.5	2	5
	1000	4.5	10	15
	1000	2.5	12	15
	1000 ^(b)	4.5	3	7
Haynes Alloy 25	600	4.5	2	0
	600	2.5	2	0
	600 ^(b)	4.5	<<1	0
	800	4.5	5	10
	800	2.5	18	10
	800 ^(b)	4.5	2	5
	1000	4.5	7	9
	1000	2.5	10	12
	1000 ^(b)	4.5	5	3
TZM	600	4.5	2	0
	600	2.5	3	0
	600 ^(b)	4.5	1	0
	800	4.5	2	0
	800	2.5	3	0
	800 ^(b)	4.5	1	0
	1000	4.5	2	0
	1000	2.5	2	0
	1000 ^(b)	4.5	1	0

^(a) S/V - The exposed metal surface-to- $^{90}\text{SrF}_2$ volume ratio of the test capsule

^(b) Zr metal powder and ZrF_4 added to the $^{90}\text{SrF}_2$ to simulate 10 yr ^{90}Sr decay

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