149
8-30-73
DR 305

ORNL-4910

34567

CURIUM DATA SHEETS

T. A. Butler

E. E. Ketchen

J. R. DiStefano

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy \$5.45; Microfiche \$0.95

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL-4910

UC-33 - Nuclear Propulsion Systems
and Aerospace Safety

Contract No. W-7405-eng-26

ISOTOPES DEVELOPMENT CENTER

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

CURIUM DATA SHEETS

T. A. Butler
Isotopes Division

E. E. Ketchen
Isotopes Division

J. R. DiStefano
Metals and Ceramics Division

AUGUST 1973

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

100-100000

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

100

page blank

CONTENTS

	<u>Page</u>
A. CURIUM SESQUIOXIDE (Cm_2O_3)	1
1. Composition	1
2. Specific Power and Power Density	2
3. Radiation	2
4. Critical Mass	6
5. Compatibility	7
6. Thermophysical Properties	12
7. Mechanical Properties	17
8. Chemical Properties	18
9. Biological Tolerances	18
10. Shielding Data	19
B. CURIUM-244 METAL	23
1. Composition	23
2. Specific Power	23
3. Radiation	23
4. Critical Mass	23
5. Compatibility	24
6. Thermophysical Properties	24
7. Mechanical Properties	26
8. Chemical Properties	27
9. Biological Tolerances	27
10. Shielding Data	27
C. CURIUM OXYSULFIDE ($\text{Cm}_2\text{O}_2\text{S}$)	28
1. Composition	28
2. Specific Power	28
3. Radiation	28
4. Critical Mass	28
5. Compatibility	28
6. Thermophysical Properties	29
7. Mechanical Properties	30
8. Chemical Properties	30
9. Biological Tolerances	31
10. Shielding Data	31

	<u>Page</u>
D. CURIUM FLUORIDE (CmF_3)	32
1. Composition	32
2. Specific Power Density	32
3. Radiation	32
4. Critical Mass	32
5. Compatibility	32
6. Thermophysical Properties	32
7. Mechanical Properties	34
8. Chemical Properties	34
9. Biological Tolerances	35
10. Shielding Data	35
REFERENCES	36

CURIUM-244 DATA SHEETS

T. A. Butler
E. E. Ketchen
J. R. DiStefano

A. CURIUM SESQUIOXIDE (Cm_2O_3)

^{244}Cm half-life:¹ 18.12 years

1. Composition

a. Radionuclidic abundance

The isotopic composition of ^{244}Cm products recovered from wastes generated by the processing of spent power reactor fuels is chosen as representative of the most probable fuel form for the next decade. The calculated isotopic composition is based on spent Diablo Canyon reference fuel as typical for a light-water reactor.²

<u>Isotopic Composition of Curium Product^a</u>		
<u>Isotopic Mass</u>	<u>Wt %</u>	<u>Half-life (y)</u>
243	0.25	32.
244	91.77	18.12
245	7.16	8265.
246	0.82	4655.

^aFive years after reactor discharge. The ^{242}Cm (half-life, 0.446 y) content (0.015 wt %) contributes <1% to the total heat output and is neglected along with minor amounts of ^{247}Cm and ^{248}Cm .

b. Radiochemical purity³

The ^{244}Cm product will contain small amounts of fission products that are not removed in the chemical separations process. The gamma activities of the fission product impurities can be calculated and are tabulated in the table in Section A.3.c. (p. 4) in the column labeled "From Impurities." Almost all of the gamma rays above 1 MeV are from ^{144}Pr and $^{152-154}\text{Eu}$, and those below 1 MeV are primarily from ^{95}Zr - ^{95}Nb , ^{144}Ce , ^{106}Rh , and ^{103}Ru - ^{103}Rh . In addition, fission products will also be formed by the spontaneous fission of the ^{244}Cm and ^{252}Cf , which is present at an estimated maximum of 4×10^{-5} wt % of the ^{244}Cm . The gamma activities from these spontaneous fission products are tabulated under the columns labeled "From Fission Products of ^{244}Cm and ^{252}Cf ." Americium-243 and ^{252}Cf which are formed in the reactor irradiation process are removed during chemical processing except for an estimated 0.5 wt % ^{243}Am and $<4 \times 10^{-5}$ wt % ^{252}Cf in the ^{244}Cm product.

c. Chemical purity⁴

The following elemental impurity limits were set as objectives for the ²⁴⁴Cm process by Savannah River Plant during the CY 1968-1969 campaign:

<u>Elemental Impurities</u>	<u>Maximum Wt % of Cm</u>
Li + Na + K (total)	0.1
Si + Zn (total)	0.1
Fe + Cr + Ni (total)	0.2
²⁴⁰ Pu	a
Any other single impurity (except Am, Pu, Zr)	0.2
Total of all impurities (except Am, Pu, Zr)	1.0
Total of all impurities (except Pu)	3.0

^aPlutonium-240 as a decay product of ²⁴⁴Cm will be present in amounts increasing with time following chemical processing and should be taken into account.

d. Phase composition of various curium oxides⁵⁻⁹

CmO _{2.00}	CmO _{1.52-1.62} (C-type)
CmO _{1.81}	CmO _{1.50} (B- and A-type)
CmO _{1.71} (Cm ₇ O ₁₂)	

2. Specific Power and Power Density^{1,10-12}

- a. 2.58 W/g of 100% chemically pure ²⁴⁴Cm₂O₃ (100% ²⁴⁴Cm isotope)
 2.37 W/g of 100% chemically pure ²⁴⁴Cm₂O₃^a
 2.30 W/g of 97% chemically pure ²⁴⁴Cm₂O₃^a
- b. Specific power values are based on 80.9 Ci/g of ²⁴⁴Cm (100%) isotope and 35.0 W/kCi of ²⁴⁴Cm (2.83 W/g of ²⁴⁴Cm).
- c. Power density of 100% pure Cm₂O₃^a is 27.66 W/cm³ at 100% density (11.67 g/cm³).

^aIsotopic composition of curium as given in Section A.1.a.

3. Radiationa. Alpha particles^{1,10-12}

Nuclide	Max E (MeV)	Av E (MeV)	Abundance (%)	W/kCi	Particles W ⁻¹ sec ⁻¹
²⁴⁴ Cm	5.801	5.801	76.7	35.0	0.804 × 10 ¹²
	5.759	5.759	23.3		0.244 × 10 ¹²

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

Volume of Helium ^a (cm ³ of He per g of ²⁴⁴ Cm)	Time	
	Years	Half-lives
6.15	1.8	0.1
11.8	3.6	0.2
17.3	5.4	0.3
22.1	7.2	0.4
26.9	9.1	0.5
31.2	10.9	0.6
35.3	12.7	0.7
39.1	14.5	0.8
42.6	16.3	0.9
45.9	18.1	1.0
59.3	27.1	1.5
68.9	36.2	2.0
80.3	54.3	3.0
86.1	72.4	4.0
88.9	90.5	5.0
91.7	181.0	10.0

^aStandard conditions.

b. Beta particles

None

c. Gamma³

The significant gamma emissions of product-grade ²⁴⁴Cm are listed in the following table. The gamma emissions result from the following:

- (1) Decay of curium nuclides and of ²⁴³Am (based on 0.25 wt % ²⁴³Cm, 91.77 wt % ²⁴⁴Cm, and 0.5 wt % ²⁴³Am).
- (2) Spontaneous fission of ²⁴⁴Cm and ²⁵²Cf (based on a maximum of 4×10^{-5} wt % ²⁵²Cf).
- (3) Decay of fission products resulting from the spontaneous fission of ²⁴⁴Cm and ²⁵²Cf.
- (4) Decay of fission products formed in the irradiation process and not removed in the chemical separation process.

Significant Gamma Rays of Curium-244 Product

Energy (MeV)	Abundance (photons per sec per W of ^{244}Cm product)								Total
	From Decay of Nuclides			From Spontaneous Fission		From Fission Products of		From Impu- rities	
	^{243}Cm	^{244}Cm	^{243}Am	^{244}Cm	^{252}Cf	^{244}Cm	^{252}Cf		
0.0-0.5	3.6×10^5	2.5×10^8	1.0×10^7	4.1×10^6	4.9×10^5	2.2×10^6	1.9×10^5	2.2×10^7	2.8×10^8
0.5-1.0	—	2.2×10^6	—	2.6×10^6	2.5×10^5	6.7×10^6	6.0×10^5	7.5×10^6	2.0×10^7
1.0-2.0	—	—	—	1.9×10^6	1.8×10^5	1.5×10^6	1.3×10^5	1.1×10^6	4.8×10^6
2.0-3.0	—	—	—	6.0×10^5	4.9×10^4	6.0×10^5	5.2×10^2	3.7×10^5	1.6×10^6
3.0-4.0	—	—	—	1.8×10^5	1.3×10^4	—	—	—	1.9×10^5
4.0-5.0	—	—	—	6.0×10^4	3.7×10^3	—	—	—	6.4×10^4
5.0-6.0	—	—	—	3.3×10^4	1.0×10^3	—	—	—	3.4×10^4
6.0-7.0	—	—	—	5.6×10^3	1.5×10^2	—	—	—	5.8×10^3

d. Bremsstrahlung

Negligible

e. Neutrons

- 4.04×10^6 n/sec.W of ^{244}Cm from spontaneous fission (half-life for spontaneous fission is 1.34×10^7 years).¹⁰⁻¹²
- 1.51×10^5 n/sec.W of ^{244}Cm from (α ,n) reaction on oxygen in Cm_2O_3 .¹⁰
- 2.9×10^4 n/sec.W of ^{244}Cm due to spontaneous fission of ^{246}Cm (0.82%) from a spontaneous fission half-life of 1.66×10^7 years and 3.08 neutrons/fission.¹²⁻¹⁴
- 3.5×10^5 n/sec.W of ^{244}Cm from estimated maximum of ^{252}Cf content of 4×10^{-5} wt %.¹⁰
- The energy distribution of spontaneous fission neutrons from ^{244}Cm is given in the table on page 5.³
- The energy distribution of neutrons occurring as a result of the interaction of fast alpha particles from ^{244}Cm decay with oxygen atoms in Cm_2O_3 is given in the table on page 6.³

Energy Distribution of Spontaneous
Fission Neutrons from Curium-244

Energy (MeV)	Abundance (n/sec.W of ^{244}Cm)
0.3-0.4	1.51×10^5
0.4-0.6	3.13×10^5
0.6-0.8	3.20×10^5
0.8-1.0	2.77×10^5
1.0-1.2	2.84×10^5
1.2-1.4	2.80×10^5
1.4-1.6	2.44×10^5
1.6-1.8	2.19×10^5
1.8-2.0	1.98×10^5
2.0-2.2	1.80×10^5
2.2-2.4	1.65×10^5
2.4-2.6	1.58×10^5
2.6-2.8	1.30×10^5
2.8-3.0	1.08×10^5
3.0-3.2	1.01×10^5
3.2-3.4	0.97×10^5
3.4-3.6	0.93×10^5
3.6-3.8	0.75×10^5
3.8-4.0	0.79×10^5
4.0-4.4	1.04×10^5
4.4-4.8	0.86×10^5
4.8-5.2	0.65×10^5
5.2-5.6	0.50×10^5
5.6-6.0	0.40×10^5
6.0-6.4	2.95×10^4
6.4-6.8	2.12×10^4
6.8-7.2	1.47×10^4
7.2-7.6	1.12×10^4
7.6-8.0	0.90×10^4
8.0-8.8	1.01×10^4
8.8-9.6	2.95×10^3
9.6-10.4	3.1×10^3
10.4-11.2	2.05×10^3
11.2-12.8	1.40×10^3

Neutrons from (α ,n) Reactions with Oxygen

Energy (MeV)	Abundance (n/sec.W of ^{244}Cm)
0.2	1.62×10^2
0.4	0.68×10^3
0.6	0.83×10^3
0.8	1.69×10^3
1.0	2.70×10^3
1.2	0.43×10^4
1.4	0.61×10^4
1.6	0.83×10^4
1.8	1.01×10^4
2.0	1.19×10^4
2.2	1.33×10^4
2.4	1.40×10^4
2.6	1.40×10^4
2.8	1.37×10^4
3.0	1.22×10^4
3.2	1.01×10^4
3.4	0.79×10^4
3.6	0.50×10^4
3.8	3.02×10^3
4.0	2.01×10^3
4.2	1.37×10^3
4.4	0.86×10^3
4.6	0.72×10^2

4. Critical Mass¹⁵

The critical mass of unreflected and reflected spheres of $^{244}\text{Cm}_2\text{O}_3$ has been calculated by C. W. Craven, Jr., at ORNL using the cross-section data available as of November 1965. The results, shown in the following table, agree within 10% of the results obtained in a replacement experiment at Los Alamos. The critical mass equation used is:

$$M_c = 2370/\rho^2 \quad (\text{kg})$$

where ρ = density of Cm_2O_3 .

Calculated Critical Mass of $^{244}\text{Cm}_2\text{O}_3$

Core		Reflector		Critical Mass (kg)	Critical Radius (cm)
Mixture	Density (g/cm ³)	Mixture	Thickness (cm)		
Cm_2O_3 ^a	10.60	Bare	-	21.1	7.8031
Cm_2O_3	9.01	Bare	-	29.2	9.1803
Cm_2O_3	10.60	Au-H ₂ O	4.0-15.0	11.9	6.4540
Cm_2O_3	10.60	Au-H ₂ O	2.0-7.5	13.5	6.7188
Cm_2O_3	10.60	Au-H ₂ O	0.5-2.0	16.5	7.1966

^aAssumed composition: 98.07 wt % ^{244}Cm and 1.93 wt % ^{241}Pu .

5. Compatibility

The compatibility of $^{244}\text{Cm}_2\text{O}_3$ with potential container materials has been studied at 750, 1250, 1650, 1800, 1850, and 2000°C for times up to 12,000 hr. In all of these tests, a $^{244}\text{Cm}_2\text{O}_3$ hot-pressed pellet was heated to the desired temperature while in contact with a specimen of the test material in a sealed capsule of the same material. Components from the system were then evaluated by metallographic, autoradiographic, or electron-beam microprobe techniques.

a. Tests at 750°C¹⁶

The following metals and alloys have been evaluated with $^{244}\text{Cm}_2\text{O}_3$ for 1000 and 10,000 hr at 750°C: Ni, Ni-10% Cr, Ni-7% Cr-16% Mo-5% Fe (Hastelloy N), Ni-20% Cr, Ni-16% Cr-16% Mo-6% Fe-3% W (Hastelloy C), Co-10% Cr, and Co-20% Cr-15% W-10% Ni (Haynes alloy No. 25).

In general, the results indicated good compatibility between $^{244}\text{Cm}_2\text{O}_3$ and all the materials tested. Metallographic observations are summarized in the table on page 8. Only Hastelloy N of the three commercial alloys showed any evidence of attack after 10,000 hr.

b. Tests at 1250°C¹⁷

The following materials were tested with $^{244}\text{Cm}_2\text{O}_3$ for 1000 and 10,000 hr at 1250°C: Nb, Nb-1% Zr, Ta, Ta-10% W, W, Mo, V, and Zr. After 10,000 hr, all materials except zirconium showed only limited reaction with $^{244}\text{Cm}_2\text{O}_3$ in the form of subsurface voids or intergranular penetration to <2 mils. Zirconium (both the specimen and capsule) completely reacted with $^{244}\text{Cm}_2\text{O}_3$ to form a compound of the type $\text{Zr}_x\text{Cm}_y\text{O}_z$ or Zr_xCm_y . Results from these tests are summarized in second table on page 8.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 750°C

Material	1,000-hr Test	10,000-hr Test
Nickel	Heavy porosity in grain boundaries of specimen, end plug, and capsule wall to maximum depth of 25 mils.	Specimen unaffected; end plug had heavy precipitation or void formation to 0.5 mil.
Ni-10% Cr	Surface reaction zone to maximum depth of 0.5 mil. Slight surface roughening.	Surface reaction zone to maximum depth of 0.5 mil. Some large voids in reaction zone.
Ni-20% Cr	Surface reaction zone to maximum depth of 0.5 mil. Slight surface roughening.	Surface reaction zone to maximum depth of 0.5 mil. Surface roughening.
Hastelloy N	Unaffected.	Surface reaction zone to maximum depth of 0.1 mil.
Hastelloy C	Surface roughening.	Unaffected.
Co-10% Cr	Surface roughening.	Surface roughening and slight attack to maximum depth of <0.5 mil.
Haynes 25	Very slight surface roughening.	Unaffected.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1250°C

Material	1,000-hr Test	10,000-hr Test
Nb	Not examined.	Intergranular penetration and subsurface voids to maximum depth of ~2 mils. Surface roughening.
Nb-1% Zr	Not examined.	Intergranular penetration and subsurface voids to <2 mils.
Ta	Not examined.	Intergranular penetration and subsurface voids to maximum depth of <2 mils. Surface roughening.
Ta-10% W	Not examined.	Subsurface voids to depth of <1 mil.
Mo	Not examined.	Intergranular penetration and subsurface voids to maximum depth of 1.5 mils. Surface roughening.
V	Not examined.	Intergranular penetration and subsurface voids to depth of <2 mils. Surface roughening.
Zr	Not examined.	Complete reaction with Cm_2O_3 .

c. Tests at 1650°C¹⁸

The following materials were tested with $^{244}\text{Cm}_2\text{O}_3$ for 1000 and 10,000 hr at 1650°C: Ta, Ta-10% W, T-111, Mo, TZM, W, and W-26% Re. After 10,000 hr severe attack in the form of intergranular penetration and subsurface voids occurred in Ta-10% W and T-111. An autoradiograph of the Ta-10% W capsule showed that it was completely penetrated by ^{244}Cm (or $^{244}\text{Cm}_2\text{O}_3$) and evidence

of ^{244}Cm was found outside the capsule. The grain boundaries of T-111 (up to 30 mils) contained a phase rich in both ^{244}Cm and hafnium. The remaining materials, Ta, Mo, TZM, W, and W-26% Re, showed <1 mil attack, primarily along grain boundaries or as subsurface precipitate or void formation.

The crystal structure of the $^{244}\text{Cm}_2\text{O}_3$ used in these tests was the monoclinic B-type. When heated above 1600°C , it transforms reversibly to the hexagonal A-type. Metallographic examination of the $^{244}\text{Cm}_2\text{O}_3$ pellets indicated a well defined grain structure with a high degree of twinning (characteristic of a phase transformation during cooling) and some coalescing of voids, especially at grain boundary intersections. Grain size varied and was smaller in samples exposed to tantalum or tantalum alloys, indicating some dissolution which may have inhibited grain growth. Little redistribution of $^{244}\text{Cm}_2\text{O}_3$ occurred after 1000 hr, but more occurred after 10,000 hr. The results of the 1650°C test are summarized in the following table.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1650°C

Material	1,000-hr Test	10,000-hr Test
Ta	Widmanstätten precipitate distributed throughout. Diffusion zone at surface of $^{244}\text{Cm}_2\text{O}_3$. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening and metallic particles in $^{244}\text{Cm}_2\text{O}_3$ indicating dissolution of Ta. Few subsurface voids at <1 mil in Ta. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
Ta-10% W	Grain boundary penetration to 1-2 mils. Metallic particles in $^{244}\text{Cm}_2\text{O}_3$. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Complete penetration of capsule by $^{244}\text{Cm}_2\text{O}_3$. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
T-111	Grain boundary penetration to 5-10 mils. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Grain boundary penetration to 30 mils. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
Mo	Grain boundary penetration and subsurface voids to <1 mil. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening. Large subsurface voids to 1-2 mils. Slight redistribution of $^{244}\text{Cm}_2\text{O}_3$.
TZM	Very slight attack (<0.1 mil). No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening. Few subsurface voids to 1-2 mils. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
W	Voids or precipitation along grain boundaries to <0.5 mil. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Heavy surface roughening and some tungsten mass transfer. Few subsurface voids (1-2 mils). Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
W-26% Re	Not tested.	Slight surface roughening. Large subsurface voids to <0.5 mil. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.

d. Tests at 1800°C^{19,20}

The following materials were exposed to $^{244}\text{Cm}_2\text{O}_3$ for 12,000 hr at 1800°C: Mo, Mo-46% Re, W, W-25% Re, and W-18% Mo-35% Re. Results were characterized by surface roughening (~3 mils or less, generally) and subsurface voids to 3 mils (10 mils for W-25% Re). Curia appeared to show a two-phase structure which could indicate loss of oxygen through the capsule wall. Results of these tests are summarized in the following table.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1800°C

Material	Summary of Results for 12,000-hr Test
Mo	Heavy surface roughening and metallic particles in $^{244}\text{Cm}_2\text{O}_3$ indicating dissolution of molybdenum. Large subsurface voids (1-3 mils). No definite grain structure to $^{244}\text{Cm}_2\text{O}_3$, but many large voids and a two-color grey pattern.
Mo-46% Re	Medium-sized subsurface voids to <1 mil. Less cracking and voids in $^{244}\text{Cm}_2\text{O}_3$ compared with above.
W	Not examined.
W-25% Re	Heavy surface roughening. Large subsurface voids to 2-3 mils. Deep cracks (10-15 mils) in corner of capsule bottom, probably as a result of coalesced voids along grain boundaries.
W-18% Mo-35% Re	Heavy surface roughening and medium-to-large subsurface voids to depth of approximately 3 mils.

e. Tests at 1850°C¹⁸

The following materials were tested with $^{244}\text{Cm}_2\text{O}_3$ for 1000, 5000, and 10,000 hr at 1850°C: Ta, Ta-10% W, T-111, Mo, TZM, W, and W-26% Re. Results were characterized by surface dissolution and subsurface voids in the metal specimens. Mass transfer of metallic elements and redistribution of $^{244}\text{Cm}_2\text{O}_3$ were typical in the longer time.

Curia exposed to tantalum or tantalum alloys appeared to have been liquid during tests indicating the formation of a low melting phase. The alloys W-26% Re and TZM appeared to show the best overall resistance to attack. In none of the tests did the $^{244}\text{Cm}_2\text{O}_3$ have a definite grain structure and very often a two-phase structure was observed. Results are summarized in the following table.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1850°C

Material	1,000-hr Test	5,000-hr Test	10,000-hr Test
Ta	Very shallow subsurface voids (<1 mil). Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening. Shallow subsurface voids. Mass transfer of Ta. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test results except increased mass transfer of Ta.
Ta-10% W	Very shallow subsurface voids (<1 mil). Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Slight surface roughening and few subsurface voids. Mass transfer of Ta. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test results except increased evidence of mass transfer.
T-111	Few subsurface voids (1 mil). Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening and mass transfer. Specimen joined to capsule in some areas. Few subsurface voids. Complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test results.
Mo	Grain boundary penetration and subsurface voids to <1 mil. Very slight redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening and mass transfer. Large subsurface voids to 1-2 mils. Few metallic particles in $^{244}\text{Cm}_2\text{O}_3$. Slight redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test except longer subsurface voids and complete redistribution of $^{244}\text{Cm}_2\text{O}_3$.
TZM	Surface roughening and subsurface voids to <1 mil. Slight redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening and mass transfer. Subsurface voids to 1-2 mils. Slight redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test results.
W	Surface roughening and metallic particles in $^{244}\text{Cm}_2\text{O}_3$. Very small grain boundary. Subsurface voids to <0.5 mil. No redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Increased surface roughening and mass transfer. Grain boundary subsurface voids to 1 mil. Redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test except increased mass transfer and larger subsurface voids.
W-26% Re	Very slight surface attack, primarily along grain boundaries (0.1 mil). Redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Surface roughening and subsurface voids to <1 mil. Redistribution of $^{244}\text{Cm}_2\text{O}_3$.	Same as 5000-hr test results.

f. Tests at 2000°C¹⁹⁻²¹

The following materials were tested with $^{244}\text{Cm}_2\text{O}_3$ for 1000 and 10,000 hr at 2000°C: Mo, Mo-46% Re, W, W-25% Re, W-18% Mo-35% Re, and Re. Results were characterized by surface roughening, mass transfer, and subsurface voids in the metallic components. Rhenium and Mo-46% Re appeared to show the best overall resistance to attack in the tests examined. Results are summarized in the following table.

Summary of Metallographic Examination of
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 2000°C

Material	1,000-hr Test	10,000-hr Test
Mo	Surface roughening. Grain boundary attack to 2 mils. Metallic particles in $^{244}\text{Cm}_2\text{O}_3$.	Not examined.
Mo-46% Re	Subsurface precipitate or voids to <1 mil.	Surface roughening and large subsurface voids to 1 mil. Two-phase $^{244}\text{Cm}_2\text{O}_3$ structure.
W	Heavy grain boundary attack and/or subsurface void formation to 10 mils.	Not examined.
W-25% Re	Subsurface void formation to <1 mil.	Heavy surface roughening. Large subsurface voids to 1-2 mils. $^{244}\text{Cm}_2\text{O}_3$ penetration to 5 mils. Two-phase $^{244}\text{Cm}_2\text{O}_3$ structure.
W-18% Mo-35% Re	Subsurface void formation to <1 mil.	Not examined.
Re	Subsurface void formation to <1 mil.	Not examined.

6. Thermophysical Properties

a. Density (calculated from lattice parameters)^{7,9}

C-type (bcc)	10.70 g/cm ³ at room temperature
B-type (monoclinic)	11.67 g/cm ³ at room temperature
B-type (monoclinic)	10.9 g/cm ³ at 1600°C
A-type (hex)	11.4 g/cm ³ at 1640°C

b. Coefficient of thermal expansion⁹

B-type (monoclinic) Cm_2O_3

Thermal Expansion of Monoclinic B-Type Cm_2O_3 .
Volume expansion is approximately linear to
1000°C with a coefficient of $28.8 \times 10^{-6}/^\circ\text{C}$.

c. Specific heat and enthalpy

(1) Specific heat in cal/g.°C

(2) Enthalpy

d. Temperatures of phase transformations

(1) Phase transitions^{6,7,9,22}

- C-type Cm_2O_3 (bcc) transforms irreversibly to B-type Cm_2O_3 (monoclinic) between 800–1300°C depending on degree of crystallinity of cubic form.

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

- A-type Cm_2O_3 (hexagonal) transforms reversibly to H-type Cm_2O_3 (hexagonal) at $2000 \pm 20^\circ\text{C}$.

(2) Melting point²²⁻²⁴

- $2265 \pm 20^\circ\text{C}$

- 2180°C (production oxide)

(3) Boiling point⁶

- $3700 \pm 200^\circ\text{C}$

(4) Thermogravimetric analytical work on the decomposition of CmO_2 to Cm_2O_3 at SRL confirmed previous work at ORNL and indicated some variations from earlier SRL results. Stable oxide phases and temperature ranges of stability in various atmospheres are:^{5,6,8,9,22}

Phase	Type	Composition	Range of Stability in ($^\circ\text{C}$)		
			Oxygen	Helium	4% H_2 -96% He
CmO_2		$\text{CmO}_{2.0}$	<380	<400	<250
Delta		$\text{CmO}_{1.81}$	445-480	Unstable	Unstable
Cm_7O_{12}		$\text{CmO}_{1.71}$	500-700	450-520	Unstable
Cm_2O_3	C	$\text{CmO}_{1.62-1.52}$	700-800	600-900	530-750
Cm_2O_3	B	$\text{CmO}_{1.50}$	{ <250 520-1600	<950	<850
Cm_2O_3	A	$\text{CmO}_{1.50}$		>1600	<2000

The range of stability of curium oxide compounds in oxygen, helium, and 4% H_2 -96% He is only qualitative and the references should be consulted for further details.

e. Latent heats of phase transformations⁶

ΔH fusion 29 kcal/mole (Richard's rule)

ΔH° vaporization 133.0 ± 2.7 kcal/mole of gas
between 1600 and 2250°C

f. Vapor pressure⁶

$$\log_{10} P_E \text{ (atm)} = (7.32 \pm 0.26) - [(29,050 \pm 590)/T \text{ (°K)}]$$

at 1800–2600°K where P_E is an artificial pressure of $\text{Cm}_2\text{O}_3(\text{g})$. The vapor species in the vaporization reaction have not been identified, but the most prominent are believed to be $\text{CmO}(\text{g})$ and $\text{O}(\text{g})$. P_E is related to the actual vapor pressure P_T as follows:

$$P_T = 2[(M_{\text{CmO}}/M_{\text{Cm}_2\text{O}_3})^{1/2} + (M_{\text{O}}/M_{\text{Cm}_2\text{O}_3})^{1/2}]P_E = 1.567 P_E$$

where M = moles of the designated species.

g. Thermal conductivity²⁵

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

$$1/K = 37.795 + 0.01659 T$$

where K at theoretical density is in $\text{W/cm.}^\circ\text{C}$ and T is in $^\circ\text{K}$. The data covered the range of 500–1100°C. The useful range of the equation is 200–1400°C.

Thermal Conductivity (W/cm.°C)	Temperature (°C)
0.02193 ± 0.00326	200
0.02043 ± 0.00193	400
0.01914 ± 0.00101	600
0.01880 ± 0.00043	800
0.01698 ± 0.00048	1000
0.01608 ± 0.00084	1200
0.01526 ± 0.00118	1400

h. Thermal diffusivity²²

Thermal Diffusivity (cm ² /sec)	Temperature (°C)	Density (g/cm ³)
0.00516	100	11.05
0.00505	200	11.02
0.00495	300	11.00
0.00485	400	10.97
0.00476	500	10.94
0.00467	600	10.91
0.00458	700	10.88
0.00450	800	10.85
0.00442	900	10.81
0.00434	1000	10.77
0.00427	1100	10.73
0.00419	1200	10.68
0.00412	1300	10.62
0.00406	1400	10.56

The following equation was derived from these data:

$$\alpha = (0.0404T + 190)^{-1}$$

where α is thermal diffusivity in cm²/sec and T is in °C.

i. Viscosity

j. Surface Tension

k. Total hemispherical emittance

l. Spectral emissivity²⁶

• 0.20 to 0.50 (for ThO₂)

The precise value is a function of the roughness of the material surface, the presence of impurities, and the effects of radiation.

m. Crystallography

- (1) Cubic, related to fcc structure of CmO₂, possibly CmO_{1.81}, obtained on heating at 450°C in oxygen.
 $a = 5.435 \pm 0.001$ Å at room temperature.⁹

- (2) Rhombohedral cell with $a = 6.677 \pm 0.004 \text{ \AA}$ and $\alpha = 99.52 \pm 0.007^\circ$ with composition of $\text{CmO}_{1.76}$ obtained by thermal reduction in oxygen at 475°C .⁹
- (3) Cubic with superstructure, related to bcc structure of C-type Cm_2O_3 , $5.459 \text{ \AA}$ with composition of $\text{CmO}_{1.72}$ obtained in oxygen at 700°C .⁹
- (4) Body-centered cubic, C-type rare-earth oxide structure with variable lattice parameter, produced by reducing CmO_2 .⁷ $a = 10.922 \pm 0.001$ ($\text{CmO}_{1.64}$) to 10.997 ± 0.003 ($\text{CmO}_{1.52}$) at room temperature.
- (5) Monoclinic B-type Cm_2O_3 produced irreversibly by heating C-type Cm_2O_3 in a reducing or helium atmosphere 800 – 1300°C , composition $\text{CmO}_{1.50}$.⁹ $a = 14.276 \pm 0.008 \text{ \AA}$, $b = 3.656 \pm 0.001 \text{ \AA}$, $c = 8.913 \pm 0.004 \text{ \AA}$, and $\beta = 100.39 \pm 0.03^\circ$.
- (6) Hexagonal, A-type rare-earth oxide structure, obtained by reversible transformation or reaction of B-type Cm_2O_3 on noble metals on heating at 1600°C .⁹ $a = 3.845 \pm 0.005 \text{ \AA}$ at 1650°C on iridium in 4% H_2 –96% He and $c = 6.092 \pm 0.005 \text{ \AA}$ at 1650°C on iridium in 4% H_2 –96% He.

n. Solubilities²⁴

The solubility in air-saturated sea water is $3.4 \pm 1.4 \times 10^{-3}$ mg/liter. The maximum solubility was reached in a few hours and remained constant up to 1032 hr.

The solubility in air-saturated distilled water is $9.06 \times 10^{-4} t^{1.913}$ where t is time in hours. The solubility continued to increase until the experiment was terminated at 1032 hr. The pH of the solution decreased up to the end and could have accounted for the solubility increase. The increase in acidity may have been due to the formation of a nitrogen acid or sulfuric acid in combination with radiation. Air containing N_2 and traces of SO_2 was bubbled through the water to maintain a saturated solution.

o. Diffusion Rates^{27,28}

The average concentration of helium (C_{av}) within a monoclinic B-type $^{244}\text{Cm}_2\text{O}_3$ solid body, as derived from a spherical model, is given by

$$C_{\text{av}} = P/15 D' \quad (\text{cm}^3/\text{cm}^3)$$

where P is the rate of helium generation within the body and D' is the effective steady-state diffusion-release parameter. At

temperature below 1620°C, the diffusion parameter, D' , is controlled by two processes which are additive and is obtained by adding values calculated from

$$D' = 7.87 \times 10^{-4} \exp (-16,248/RT^{\circ}\text{K}), \text{ predominate } <1300^{\circ}\text{C}, \text{ and}$$

$$D' = 68.0 \exp (-53,080/RT^{\circ}\text{K}), \text{ predominate } 1300\text{--}1620^{\circ}\text{C}.$$

At temperatures above 1620°C the diffusion parameter is significantly different, presumably due to formation of the hexagonal A-type structure, and is given by

$$D' = 4.65 \times 10^7 \exp (-102,730/RT^{\circ}\text{K}), \text{ predominate } >1620^{\circ}\text{C}.$$

The diffusion parameter, D' , is independent of the geometry of the fuel form. The results of steady-state helium release determinations from 700 to 1800°C are shown in the following figure.

Helium Diffusion Parameter in $^{244}\text{Cm}_2\text{O}_3$ as a Function of Reciprocal Absolute Temperature.

7. Mechanical Properties

a. Hardness

b. Crush strength²⁹

1900 kg/cm² (for CeO₂)

8. Chemical Properties

a. Heat and free energy of formation, entropy

(1) Heat of formation^{30,31}

<u>Phase</u>	<u>$-\Delta H_f^\circ$ (298°K), kcal/mole</u>
CmO _{1.50}	215 ± 7 (est)
CmO _{1.71}	218 ± 10 (est)
CmO _{1.83}	225 ± 10 (est)
CmO _{2.00}	236 ± 8 (est)

(2) Free energy of formation of CmO_{1.50}³⁰

$$\Delta G_f^\circ (298^\circ\text{K}) = -205 \pm 7 \text{ kcal/mole (calc)}$$

(3) Entropy of CmO_{1.50}³²

$$S_{298}^\circ = 19.2 \text{ eu (est)}$$

b. Chemical reactions and reaction rates^{7,9}

(1) Oxidation of B-type Cm₂O₃ in oxygen (1 atm)

While C-type Cm₂O₃ oxidizes slowly at room temperature in an atmosphere containing oxygen, the B-type Cm₂O₃ does not oxidize below 250°C. Both forms of Cm₂O₃ oxidize readily between 250 and 520°C to form CmO_{1.71} or CmO₂. The CmO₂ is the more stable product below 360°C and CmO_{1.71} is the more stable oxidation product above 360°C. While the C-type curium oxide can accommodate excess oxygen above 520°C, the B-type Cm₂O₃ resists oxidation above 520°C. Large compacts of B-type Cm₂O₃ may have enough self-heating to remain above 520°C and hence could be resistant to further oxidation.

(2) Nitrogen — no reaction³³

(3) Water — possible hydration reaction³³

(4) Inorganic acids — soluble in acids³³

9. Biological Tolerances³⁴

Maximum permissible body burdens and maximum permissible concentrations of ²⁴⁴Cm in air and water are shown in the following table.

Maximum Permissible Body Burdens and Maximum Permissible Concentrations
for Radionuclides in Air and in Water for Occupational Exposure^{3,4}

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

^aThe abbreviations GI and LLI refer to the gastrointestinal tract and lower large intestine, respectively.

10. Shielding Data¹⁰

Gamma dose rates with water, iron, lead, and uranium shielding are given in Figs. 1-5 for ²⁴⁴Cm power sources of 100, 200, 500, 1000, 2000, 5000, 10,000, and 20,000 W. Neutron dose rates with water shielding are given in Fig. 6. Neutron dose rates on shielding with Be, CH, CH₂, or LiH can be estimated by using Fig. 6 in conjunction with Fig. 7.

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

Fig. 2. Gamma Dose Rates from Iron-Shielded Isotopic Power Sources of ^{244}Cm . Center of source to dose point separation distance is 100 cm.

Fig. 3. Gamma Dose Rates from Water-Shielded Isotopic Power Sources of ^{244}Cm . Center of source to dose point separation distance is 100 cm.

Fig. 4. Gamma Dose Rates from Lead-Shielded Isotopic Power Sources of ^{244}Cm . Center of source to dose point separation distance is 100 cm.

Fig. 5. Gamma Dose Rates from Uranium-Shielded Isotopic Power Sources of ^{244}Cm . Center of source to dose point separation distance is 100 cm.

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

Fig. 7. Fast Neutron Dose Rate (Multiplied by 4πr²) in Various Materials as a Function of Penetration Depth from a Unit Point Isotropic Fission Source.

B. CURIUM-244 METAL1. Composition

- a. Radionuclidic abundance — See Section A.1.a.
- b. Radiochemical purity — See Section A.1.b.
- c. Chemical purity — See Section A.1.c.

2. Specific Power^{1,10-12,35}

- a. 2.83 W/g of ^{244}Cm (100% ^{244}Cm isotope).
 2.60 W/g of pure curium element (91.77% ^{244}Cm plus curium isotopic abundances given in Section A.1.a).
 2.52 W/g of curium product (97% chemically pure, see Section A.1.c).
- b. Specific power values are based on 80.93 Ci/g of ^{244}Cm (100%) and 34.97 W/kCi of ^{244}Cm .
- c. Power density is 35.1 W/cm³ of chemically pure curium element (91.77% ^{244}Cm plus curium isotopic abundances given in Section A.1.a) and 34.0 W/g of curium product (97% chemically pure, see Section A.1.c).

3. Radiation

See Section A.3.

4. Critical Mass^{36,37}

The critical radii and masses of ^{244}Cm metal have been calculated at BNWL.

Density (g/cm ³)	H/M	k_{∞}	Bare Critical		Water Reflected ^a Critical		Steel Reflected ^a Critical	
			Radius (cm)	Mass (kg)	Radius (cm)	Mass (kg)	Radius (cm)	Mass (kg)
13.5	0	2.4552	7.430	23.20	7.303	22.02	6.31	14.21
10.872	0.5	1.7440	10.667	55.27	10.466	52.21	—	—
9.055	1.0	1.3993	15.727	147.54	15.432	139.39	—	—
7.758	1.5	1.1747	25.813	558.92	—	—	22.817	368.025
6.787	2.0	1.0143	102.825	30,907.43	—	—	—	—

^a20-cm reflector.

5. Compatibility^{35,38,39}

- Severe interaction of curium with tantalum container when in contact for 10 min at 950°C.
- Molten curium dissolves appreciable amount of tantalum.
- Extensive solubility in tungsten at temperatures up to 1795°C.
- Interaction at melting point of curium with tungsten is low.

6. Thermophysical Propertiesa. Density^{35,40}13.51 g/cm³ of metal12.66 g/cm³ of high-temperature formb. Coefficient of thermal expansion⁴¹ $\alpha_a = 7.5 \times 10^{-6}/^{\circ}\text{C}$ (for Am) $\alpha_c = 6.2 \times 10^{-6}/^{\circ}\text{C}$ (for Am)c. Specific heat and enthalpy⁴²

(1) Specific heat

<u>Specific Heat</u> <u>(cal/g.°C)</u>	<u>Temperature</u> <u>(°K)</u>
0.0265	300
0.0264	400
0.0262	500
0.0259	600
0.0257	700
0.0255	800
0.0253	900
0.0251	1000
0.0250	1100
0.0249	1200
0.0248	1300
0.0246	1400
0.0245	1500
0.0244	1600
0.0242	1700
0.0241	1800
0.0240	1900
0.0238	2000

(2) Enthalpy⁴²

$H_T^\circ - H_{298}^\circ$ (kcal/gfw)	Temperature (°K)
0.0119	300
0.6514	400
1.2860	500
1.9150	600
2.5384	700
3.1566	800
3.7703	900
4.3799	1000
4.9859	1100
5.5885	1200
6.1880	1300
6.7843	1400
7.3774	1500
7.9674	1600
8.5541	1700
9.1377	1800
9.7180	1900
10.2952	2000

d. Temperatures of phase transformations

(1) Melting point^{35,38}

1340 ± 40°C

1350 ± 60°C

(2) Boiling point³⁹

3525 ± 130°C

e. Latent heats of phase transformations³⁹ ΔH fusion 3.5 kcal/mole (Richard's rule) $\Delta H_{600^\circ K}^\circ$ vaporization 82.6 ± 2.7 kcal/molef. Vapor pressure³⁹ $\log_{10} P = 4.74 \pm 0.37 [(18,060 \pm 589)/T]$

(T is in °K and P is in atm)

g. Thermal conductivity⁴³

0.1 W/cm.°K at 300°K (est)

h. Thermal diffusivity

0.0668 cm²/sec at 26°C

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

i. Viscosity⁴⁴

4.76 centipoises at 1340°C (calc)

j. Surface tension⁴⁵

1300 dyn/cm (for U)

k. Total hemispherical emittance⁴⁶

0.37 at 89°C (for Pu)

l. Spectral emissivity²⁶

0.55 (for Er)

A higher value of 0.9 can be assumed if the metal surface is oxidized or if impurities are present.

m. Crystallography³⁵

Double hexagonal close packed, $a = 3.496 \pm 0.003 \text{ \AA}$ and
 $c = 11.331 \pm 0.005 \text{ \AA}$

n. Solubilities³³

Reacts strongly with water

o. Diffusion rates

7. Mechanical Properties⁴⁷

a. Hardness

Vicker's 97.7 (for Dy)

b. Crush strength

7741 kg/cm² (for Tm)

8. Chemical Properties

a. Heat and free energy of formation, entropy

- (1) Heat of formation - Zero, by definition of standard state
- (2) Free energy of formation - Zero, by definition of standard state
- (3) Entropy⁴⁸ - $S_{298}^{\circ} = 18 \text{ cal/}^{\circ}\text{C.mole}$ (est)

b. Chemical reactions and reaction rates

- (1) Oxygen at room temperature - slow³⁵
- (2) Oxygen at elevated temperature - fast^{36,37}
- (3) Nitrogen at room temperature - very slow⁴⁹
- (4) Nitrogen at elevated temperature - slow⁴⁹
- (5) Water at room temperature - fast³³
- (6) Hydrogen at room temperature - slow³³
- (7) Hydrogen at elevated temperature - fast³³
- (8) 1 N HCl at 25°C - rapid⁵⁰

9. Biological Tolerances

Maximum permissible body burden and maximum permissible concentrations of ^{244}Cm in air and in water are given under Section A.9.

10. Shielding Data

The dose rates are given under Section A.10.

C. CURIUM OXYSULFIDE ($\text{Cm}_2\text{O}_2\text{S}$)

1. Composition

- a. Radionuclidic abundance — See Section A.1.a.
- b. Radiochemical purity — See Section A.1.b.
- c. Chemical purity — See Section A.1.c.

2. Specific Power^{1,10-12}

- a. 2.30 W/g of 100% pure $\text{Cm}_2\text{O}_2\text{S}^a$
2.23 W/g of 97% pure $\text{Cm}_2\text{O}_2\text{S}^a$
- b. Specific power values are based on 80.93 Ci/g of ^{244}Cm and 34.97 W/kCi of ^{244}Cm .
- c. Power density
22.9 W/cm³ of pure $\text{Cm}_2\text{O}_2\text{S}^a$
22.2 W/cm³ of 97% $\text{Cm}_2\text{O}_2\text{S}^a$

^aIsotopic curium composition in Section A.1.

3. Radiation

The radiation is given under Section A.3.

4. Critical Mass

See Section A.4.

5. Compatibility⁵¹

Compatibility tests of $^{244}\text{Cm}_2\text{O}_2\text{S}$ with materials of containment have not been conducted; however, qualitative data are available for $\text{Ce}_2\text{O}_2\text{S}$ in contact with superalloys and refractory metals which are expected to be indicative of the $^{244}\text{Cm}_2\text{O}_2\text{S}$. The superalloys Hastelloy X, Haynes alloy No. 25, Ni-o-nel, and N-155 were tested at 1000°C for 1000 hr. The results showed only slight reaction in all cases except N-155 which showed major reaction. The refractory metals Mo, Ta, W, and TZM alloy were tested at both 1000°C and 1850°C for 1000 hr. In the 1000°C tests, tungsten showed no reaction and Mo, Ta, and TZM only slight reaction. At 1850°C, molybdenum and tungsten showed slight reaction and tantalum a major reaction; TZM was not tested.

- 9.95 g/cm³ (for Pu₂O₂S)

- Volume expansion is approximately linear to 1000°C with a coefficient of $28.8 \times 10^{-8}/^{\circ}\text{C}$. (for Cm_2O_3)

- (1) Specific heat in cal/g.°C

$$(3.62 \times 10^{-2}) + (2.83 \times 10^{-5} \text{ T}) \text{ (}^\circ\text{K)} \text{ (for Am}_2\text{O}_3\text{)}$$

- $$H_T - H_{298} = 20 T + (7.8 \times 10^{-3} T^2) - 6.657 \text{ (for Am}_2\text{O}_3\text{)}$$

- (1) Melting point⁵⁴

2000°C (for $\text{Ce}_2\text{O}_2\text{S}$)

- $$3700 \pm 200^\circ\text{C} \text{ (for } \text{Cm}_2\text{O}_3\text{)}$$

- $$\Delta H_{\text{fusion}} \quad 29 \text{ kcal/mole (for } \text{Cm}_2\text{O}_3\text{)}$$

[illegible]

- g. Thermal conductivity

Values for the thermal conductivity of curium oxysulfide have not been derived but probably are in the same order of magnitude as the values for Cm_2O_3 which are given in Section A.6.g.

- Values for the thermal diffusivity of curium oxysulfide have not been derived but probably are in the same order of magnitude as the values of Cm_2O_3 which are given in Section A.6.h.

- i. Viscosity
- j. Surface tension
- k. Total hemispherical emittance
- l. Spectral emissivity²⁶

0.20 to 0.57 (for ThO₂)

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

- m. Crystallography⁵² (for Pu₂O₂S)

Hexagonal, $a = 3.927 \text{ \AA}$ and $c = 6.769 \text{ \AA}$. The cell constants should be slightly smaller for Cm₂O₂S due to the actinide contraction.

- n. Solubilities⁵⁵

- (1) Soluble in strong acids (Ce₂O₂S)
- (2) Insoluble in acetic acid (Ce₂O₂S)

- o. Diffusion rates

7. Mechanical Properties

- a. Hardness
- b. Crush strength

8. Chemical Properties

- a. Heat and free energy of formation, entropy

- (1) Heat of formation⁵⁴

$$\Delta H_f^\circ = -430 \text{ kcal/mole (approximated by Ce}_2\text{O}_2\text{S)}$$

- (2) Free energy of formation⁵⁴

$$\Delta G_f^\circ = -414 \text{ kcal/mole (calculated by } \Delta G_f^\circ = \Delta H_f^\circ - T\Delta S_f^\circ)$$

- (3) Entropy⁵⁶

$$S_{298}^\circ = 34.3 \text{ eu (calculated by Latimer's method)}$$

b. Chemical reactions and reaction rates⁵⁵

- (1) Air at room temperature — slow
- (2) Air at elevated temperature — fast
- (3) Water at room temperature — no reaction
- (4) Inorganic acids at room temperature — reacts

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given in the $^{244}\text{Cm}_2\text{O}_3$ form, Section A.9.

10. Shielding Data

The radiation dose rates are given under the $^{244}\text{Cm}_2\text{O}_3$ form, Section A.10.

D. CURIUM FLUORIDE (CmF₃)

1. Composition

- a. Radionuclidic abundance -- See Section A.1.a.
- b. Radiochemical purity -- See Section A.1.b.
- c. Chemical purity -- See Section A.1.c.

2. Specific Power and Power Density^{1,10-12,57}

- a. 2.11 W/g of 100% pure CmF₃^a
2.04 W/g of 97% pure CmF₃^a
- b. Specific power values are based on 80.93 Ci of ²⁴⁴Cm (100%)
and 34.97 W/kCi of ²⁴⁴Cm.
- c. Power density
20.8 W/cm³ of 100% pure CmF₃^a
20.1 W/cm³ of 97% pure CmF₃^a

^aIsotopic curium composition given in Section A.1.

3. Radiation

The radiation is given under Section A.3.

4. Critical Mass

The critical mass is given under Section A.4.

5. Compatibility⁵¹

Compatibility tests of ²⁴⁴CmF₃ with materials of containment have not been conducted; however, qualitative data are available for CeF₃ in contact with superalloys and refractory metals which are expected to be indicative of the ²⁴⁴CmF₃. The superalloys Hastelloy X, Haynes alloy No. 25, Ni-o-nel, and N-155 and the refractory metals Mo, Nb, Ta, and W were tested at 1000°C for 1000 hr. The results showed no reaction with the metals with the exception of Hastelloy C and tungsten which showed only a slight reaction.

6. Thermophysical Properties

- a. Density⁵⁷
9.85 g/cm³

- b. Coefficient of thermal expansion⁵⁸ (for BaF₂)

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

(t is in °C with a temperature range of 26-296°C)

- c. Specific heat and enthalpy⁵³ (for AmF₃)

- (1) Specific heat in cal/g.°C

$$(7.21 \times 10^{-2}) + (2.06 \times 10^{-5} T) \quad (^\circ\text{K})$$

- (2) Enthalpy in cal/mole

$$H_T - H_{298} = 21.7 T + (3.1 \times 10^{-3} T^2) - 6746$$

(estimated from other actinide data)

- d. Temperatures of phase transformations

- (1) Melting point⁵⁹

1406°C

- (2) Boiling point⁶⁰

2330°C This value is the average of the boiling points of LaF₃, CeF₃, and PrF₃.

- e. Latent heats of phase transformations⁵³ (for AmF₃)

ΔH fusion 13 kcal/mole

ΔH vaporization 66 kcal/mole

- f. Vapor pressure⁶¹ (for AmF₃)

Vapor Pressure (torr)	Temperature (°C)
5.07×10^{-7}	853
7.18×10^{-6}	943
1.486×10^{-4}	1033
1.725×10^{-3}	1141
5.820×10^{-3}	1196

- g. Thermal conductivity⁶² (for BaF₂)

Thermal Conductivity (W/cm.°C)	Temperature (°C)
0.124	0
0.105	100

h. Thermal diffusivity

Thermal Diffusivity (cm ² /sec)	Temperature (°C)
0.0379	0
0.0319	100

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

i. Viscosity⁶³ (for BaCl₂)

$$\eta = 1.643 \times 10^{-3} \exp (-20,030/RT) \text{ antipoise}$$

j. Surface tension⁶⁴ (for UF₄)

$$\sigma = 447 - (19.2 \times 10^{-2} T) \text{ (°K) dynes/cm}$$

k. Total hemispherical emittance

A value of 0.9 can be assumed.

l. Spectral emissivity

m. Crystallography⁵⁷

Hexagonal, LaF₃-type, space group P6₃/mmc, a = 4.041 ± 0.001 Å and c = 7.179 ± 0.002 Å.

n. Solubilities

o. Diffusion rates

7. Mechanical Properties

a. Hardness

b. Crush strength

8. Chemical Propertiesa. Heat and free energy of formation, entropy⁴⁸

(1) Heat of formation

$$\Delta H_f^\circ = -357 \text{ kcal/mole (estimated from other actinide data)}$$

(2) Free energy of formation

$$\Delta G_f^\circ = -339 \text{ kcal/mole}$$

(3) Entropy

$$S_{298}^{\circ} = 29 \text{ eu}$$

b. Chemical Reactions and reaction rates³³

- (1) Air at room temperature — no reaction
- (2) Air at elevated temperature — forms oxyfluoride
- (3) Nitrogen — no reaction
- (4) Water — insoluble
- (5) Inorganic acids — insoluble in weak inorganic acid

9. Biological Tolerances

Maximum permissible body burdens and maximum permissible concentrations of ^{244}Cm in air and in water are given under Section A.9.

10. Shielding Data

The dose rates are given under Section A.10.

REFERENCES

1. W. J. Kerrigan and R. S. Dorsett, "Calorimetric Measurement of Alpha Half-life of ^{244}Cm ," *J. Inorg. Nucl. Chem.* 34, 3603-6 (1972).
2. ORNL Staff, *Siting of Fuel Reprocessing Plants and Waste Management Facilities*, ORNL-4451, Oak Ridge National Laboratory (July 1971).
3. D. H. Stoddard, *Radiation Properties of ^{244}Cm Produced for Isotopic Power Generators*, DP-939, Savannah River Laboratory (November 1964).
4. Private communication, R. L. Folger, Savannah River Laboratory, to E. Lamb, Oak Ridge National Laboratory, Dec. 20, 1967.
5. J. C. Posey, P. R. Kuehn, and R. E. McHenry, "The Influence of Temperature and Oxygen Pressure on the Composition of Curium Oxide," presented at the 150th Meeting of the American Chemical Society, Atlantic City, N. J., 1969.
6. P. K. Smith and D. E. Peterson, "High-Temperature Evaporation and Thermodynamic Properties of Cm_2O_3 ," *J. Chem. Physics* 52(10), 4963-72 (1970).
7. W. C. Mosley, Jr., "B-Type $^{244}\text{Cm}_2\text{O}_3$ - A Candidate Isotopic Power Fuel," *Abstracts of Papers, 155th National Meeting, American Chemical Society, San Francisco, California, April 1968*, Abstract No. 0-173.
8. T. D. Chikalla and L. Eyring, "The Curium-Oxygen System," *J. Inorg. Nucl. Chem.* 31, 85-93 (1969).
9. W. C. Mosley, "Phases and Transformations in the Curium-Oxygen System," *J. Inorg. Nucl. Chem.* 34, 539-55 (1972).
10. E. D. Arnold, *Handbook of Shielding Requirements and Radiation Characteristics of Isotopic Power Sources for Terrestrial, Marine and Space Applications*, ORNL-3576, Oak Ridge National Laboratory (April 1964).
11. *Nucl. Data Sheets* B3, 19-20 (May 1969).
12. D. Metla, H. Diamond, R. F. Barnes, J. Milsted, J. Grey, Jr., D. L. Henderson, and C. M. Stevens, "Nuclear Constants of Nine Transplutonium Nuclides," *J. Inorg. Nucl. Chem.* 27, 33-39 (1965).
13. L. J. King, J. E. Bigelow, and E. D. Collins, *Transuranium Processing Plant Semiannual Report of Production, Status and Plans for Period Ending June 30, 1972*, ORNL-4833, Oak Ridge National Laboratory (January 1973).
14. *Nucl. Data Sheets* B3, 46 (1969).

15. R. A. Robinson, *et al.*, *Brayton-Cycle Radioisotope Heat Source Design Study (Conceptual Design), Phase I Report*, ORNL-TM-1691-dec., Oak Ridge National Laboratory (August 1967), pp. 107-13.
16. E. Lamb, *ORNL Isotopic Power Fuels Quarterly Report for Period Ending December 31, 1972*, ORNL-4857, Oak Ridge National Laboratory.
17. J. R. DiStefano and K. H. Lin, "Compatibility of Refractory Metals with $^{244}\text{Cm}_2\text{O}_3$," *Nuclear Technology* (to be published July 1973).
18. J. R. DiStefano and K. H. Lin, *Compatibility of Curium Oxide with Refractory Metals at 1650°C and 1850°C*, ORNL-4773, Oak Ridge National Laboratory (April 1972).
19. J. L. Andelin and J. D. Watrous, *Plutonia/Curia Compatibility Testing, April-June 1971, Quarterly Report No. 11*, MDC-G3124, Donald W. Douglas Laboratories (July 1971).
20. J. L. Andelin and J. D. Watrous, *Plutonia/Curia Compatibility Testing, January-March 1971, Quarterly Report No. 14*, MDC-G3142, Donald W. Douglas Laboratories (April 1972).
21. J. L. Andelin and J. D. Watrous, *Plutonia/Curia Compatibility Testing, January-March 1971, Quarterly Report No. 10*, MDC-G2055, Donald W. Douglas Laboratories (April 1971).
22. R. L. Gibby, *et al.*, "The Thermal Diffusivity, Thermal Conductivity, and Transformation Temperatures of Curium Sesquioxide," *J. Nucl. Mater.* 34, 299-306 (1970).
23. P. K. Smith, "Melting Point of Cm_2O_3 ," *J. Inorg. Nucl. Chem.* 31, 241-5 (1969).
24. R. E. McHenry, "Curium-244 — A Radioisotopic Power Fuel," EN/IB26 from Second International Symposium on Power from Radioisotopes, Madrid, Spain, 1972.
25. E. E. Ketchen, *Thermal Conductivity of Cm_2O_3* , ORNL-TM-2915, Oak Ridge National Laboratory (April 1970).
26. R. C. Weast, S. M. Selby, and C. D. Hodgman, *Handbook of Chemistry and Physics*, 45th Ed., The Chemical Rubber Company, Cleveland, Ohio, 1954.
27. P. Angelini, *Helium Release from $^{244}\text{Cm}_2\text{O}_3$* , ORNL-4785, Oak Ridge National Laboratory (in publication).
28. P. Angelini, *et al.*, *Helium Release in $^{238}\text{PuO}_2$ Microspheres*, ORNL-4507, Oak Ridge National Laboratory (March 1970).
29. J. R. Hague, *et al.* (eds.), *Refractory Ceramics for Aerospace*, American Ceramic Society, Columbus, Ohio, 1964.

30. Private communication, P. K. Smith, Savannah River Laboratory, to S. J. Rimshaw, Oak Ridge National Laboratory, July 25, 1968.
31. W. R. McDonell, *et al.*, *Curium-244 for Radioisotopic Heat Sources - Savannah River Laboratory*, DP-1066, Vol. II, Savannah River Laboratory (May 1966), pp. 111-28.
32. E. F. Westrum, Jr., and Fredrik Gronvold, "Thermochemical Data of Actinide Element Chalcogenides," in *Thermodynamics of Nuclear Materials*, International Atomic Energy Agency, Vienna, 1962, p. 28.
33. Private communication, J. L. Burnett, Oak Ridge National Laboratory, November 1965.
34. U. S. Department of Commerce, National Bureau of Standards, *Maximum Permissible Body Burdens and Maximum Permissible Concentrations in Air and in Water for Occupational Exposure*, Handbook 69 (June 5, 1959).
35. B. B. Cunningham and J. C. Wallman, "Crystal Structure and Melting Point of Curium Metal," *J. Inorg. Nucl. Chem.* 26, 271-5 (1964).
36. L. C. Schmid, *et al.*, *Reactor Physics Quarterly Report - October, November, December 1969*, BNWL-1304, Pacific Northwest Laboratories (February 1970).
37. H. K. Clark, "Critical Masses of Fissile Transplutonium Isotopes," *Trans. Am. Nucl. Soc.* 12, 886 (1969).
38. I. D. Eubank and M. C. Thompson, "Preparation of Curium Metal," *Inorg. Nucl. Chem. Letters* 5, 187-91 (1969).
39. P. K. Smith, *et al.*, "Vapor Pressure and Crystal Structure of Curium Metal," *J. of Chem. Physics* 30, 5066-76 (1969).
40. R. D. Baybarz and H. L. Adair, "Preparation of the High Temperature Form of Curium Metal," *J. Inorg. Nucl. Chem.* 34, 3127-30 (1972).
41. D. B. McWhan, B. B. Cunningham, and J. C. Wallman, "Crystal Structure, Thermal Expansion, and Melting Point of Americium Metal," *J. Inorg. Nucl. Chem.* 24, 1025-38 (1962).
42. R. C. Feber and C. C. Herrick, *Ideal Gas Thermodynamic Functions of Lanthanide and Actinide Elements*, LA-3184, Los Alamos Scientific Laboratory (Feb. 5, 1965).
43. C. Y. Ho, R. W. Powell, and P. E. Liley, "Thermal Conductivity of the Elements," *J. Phy. Chem. Ref. Data* 1(2), 279-421 (1972).
44. A. V. Grosse, "The Viscosity of Liquid Metals and an Empirical Relationship Between Their Activation Energy of Viscosity and Their Melting Points," *J. Inorg. Nucl. Chem.* 23, 333-39 (1961).

45. O. Flint, *Surface Tension of Liquid Metals* (a review), British Rpt. AERE-M-1479, Atomic Energy Research Establishment (November 1964).
46. R. N. Karlsson, *The Total Hemispherical Emittance of Polished and Oxidized Alpha Plutonium*, RFP-616, The Dow Chemical Company (July 1965).
47. T. Lyman, ed., *Metals Handbook, Vol. 1, Properties and Selection of Metals*, 8th Ed., American Society for Metals, Metals Park, Novelty, Ohio, 1961.
48. B. B. Cunningham, "Compounds of the Actinides," in *Preparative Inorganic Reactions*, Vol. 3, W. J. Jolly (ed.), Interscience Publishers, New York, 1966, pp. 79-121.
49. R. M. Dell and M. Allbutt, *The Nitrides of Uranium, Thorium, and Plutonium. A Review of Present Knowledge*, British Rpt. AERE-R-4253, Atomic Energy Research Establishment (March 1963).
50. J. C. Wallmann, *et al.*, "The Heat of Solution of Curium Metal and the Heats of Formation of $^{+3}\text{Cm}(\text{aq.})$ and $\text{CmCl}_3(\text{c})$," *J. Inorg. Nucl. Chem.* 29, 2097-99 (1967).
51. W. D. Box and R. S. Crouse, *Compatibility Tests for Selection of Radioisotopic Heat Source Compounds*, ORNL-4298, Oak Ridge National Laboratory (December 1968).
52. W. H. Zachariasen, "Crystal Chemical Studies of the 5-f Series of Elements, VII. The Crystal Structure of $\text{Ce}_2\text{O}_2\text{S}$, $\text{La}_2\text{O}_2\text{S}$, and $\text{Pu}_2\text{O}_2\text{S}$," *Acta Cryst.* 2 60-2 (1949).
53. A. Glassner, *The Thermochemical Properties of the Oxides, Fluorides, and Chlorides to 2500°K*, ANL-5750, Argonne National Laboratory (1957).
54. E. D. Eastman, *et al.*, "Preparation and Properties of the Oxide-Sulfides of Cerium, Zirconium, Thorium, and Uranium," *J. Am. Chem. Soc.* 73, 3896-9 (1951).
55. G. V. Samsonov and S. V. Radzikovskaya, "The Chemistry of Rare Earth and Actinide Sulfides," *Russian Chemical Reviews* 30, 28-41 (1961).
56. W. Latimer, *Oxidation Potentials*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1952.
57. L. B. Asprey, T. K. Keenan, and F. H. Kruse, "Crystal Structures of the Trifluorides, Trichlorides, Tribromides, and Triiodides of Americium and Curium," *J. Inorg. Chem.* 4(7), 985-6 (1965).

58. D. B. Sirdeshmukh and V. T. Desphande, "Temperature Variation of the Lattice Constants and the Coefficients of Thermal Expansion of Some Fluoride Type Crystals," *Indian J. Pure Appl. Phys.* 2(12), 405-7 (1964).
59. J. Burnett, "Melting Points of CmF_3 and AmF_3 ," *J. Inorg. Nucl. Chem.* 28, 2454-6 (1966).
60. J. A. Gibson, *et al.*, *The Properties of the Rare Earth Metals and Compounds*, Battelle Memorial Institute, Columbus, Ohio, May 1959.
61. S. C. Carnigler and B. B. Cunningham, "Vapor Pressures of Americium Trifluoride and Plutonium Trifluoride, Heats and Free Energies of Sublimation," *J. Am. Chem. Soc.* 77, 1451-3 (1955).
62. K. A. McCarthy and S. S. Ballard, "Thermal Conductivity of Eight Halide Crystals in the Temperature Range 220°K to 390°K," *J. Appl. Phys.* 31(8), 1410-2 (1960).
63. G. J. Janz, *et al.*, *Molten Salt Data*, Technical Bulletin Series, Rensselaer Polytechnic Institute, Troy, N. Y., July 1964.
64. A. D. Kirshenbaum and J. A. Cahill, "Surface Tension of Liquid Uranium and Thorium Tetrafluorides and a Discussion on the Relationship Between the Surface Tension and Critical Temperature of Salts," *J. Phys. Chem.* 70, 3037-41 (1966).

ORNL-4910
UC-33 -- Nuclear Propulsion Systems
and Aerospace Safety

INTERNAL DISTRIBUTION

1. Biology Library	83. O. L. Keller
2-4. Central Research Library	84-85. E. E. Ketchen
5-6. ORNL - Y-12 Technical Library	86. E. H. Kobisk
Document Reference Section	87-91. E. Lamb
7-41. Laboratory Records Department	92. R. E. Leuze
42. Laboratory Records, ORNL R.C.	93. H. C. McCurdy
43. G. M. Adamson, Jr.	94. H. F. McDuffie
44. P. Angelini	95. R. G. Niemeyer
45-47. P. S. Baker	96-100. C. L. Ottinger
48. R. D. Baybarz	101. J. J. Pinajian
49. E. E. Beauchamp	102. J. K. Poggenburg
50. J. E. Bigelow	103. J. C. Posey
51. F. T. Binford	104. D. W. Ramey
52-71. T. A. Butler	105. R. A. Robinson
72. F. N. Case	106. A. F. Rupp
73. C. E. Clifford	107. R. W. Schaich
74. F. L. Culler	108. J. R. Sites
75. J. E. Cunningham	109. M. J. Skinner
76. J. R. DiStefano	110. D. B. Trauger
77. R. G. Donnelly	111. W. E. Unger
78. C. Feldman	112. A. M. Weinberg
79. D. E. Ferguson	113. R. C. Weir
80. J. H. Gillette	114. J. C. White
81. K. W. Haff	115. A. Zucker
82. H. Inouye	

EXTERNAL DISTRIBUTION

116. E. L. Alpen, Pacific Northwest Laboratories, P. O. Box 999, Richland, Washington 99352
117. R. D. Baker, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, New Mexico 87544
118. F. P. Baranowski, AEC, Division of Production and Materials Management, Washington, D. C. 20545
119. M. Bell, TRW Systems, One Space Park, Redondo Park, California 90278
120. Linda Benker, Thermo Electron Corporation, P. O. Box 482, Waltham, Maryland 02154
121. P. E. Brown, General Electric Company, Missile and Space Division, P. O. Box 8555, Philadelphia, Pennsylvania 19101
122. H. C. Carney, Jr., Gulf Energy and Environmental Services, P. O. Box 81608, San Diego, California 92138
123. R. T. Carpenter, AEC, Division of Space Nuclear Systems, Washington, D. C. 20545
124. W. T. Cave, Mound Laboratory, P. O. Box 32, Miamisburg, Ohio 45342
125. Commander, Naval Undersea Research and Development Center, Attention: Technical Library, Code 133, San Diego, California 92132

126. D. Couchman, Nuclear Utilities Services Corporation
127. G. R. Crane, Headquarters AFSC (XRTS), Andrews Air Force Base, Maryland 20331
128. G. P. Dix, AEC, Division of Space Nuclear Systems, Washington, D. C. 20545
129. R. A. DuVal, AEC, San Francisco Operations Office, 2111 Bancroft Way, Berkeley, California 94704
130. R. English, NASA, Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135
131. T. P. Fleming, Naval Facilities Engineering Command, Nuclear Power Division, Department of the Navy, Code 042, Washington, D. C. 20390
132. R. K. Flitcraft, Mound Laboratory, P. O. Box 32, Miamisburg, Ohio 45342
- 133-135. E. E. Fowler, Division of Applied Technology, AEC, Washington, D. C. 20545
136. L. Frank, Weinber Associates, Inc., 107 Industry Lane, Cockeysville, Maryland 21030
137. D. S. Gabriel, AEC, Division of Space Nuclear Systems, Washington, D. C. 20545
- 138-152. N. Goldenberg, AEC, Division of Space Nuclear Systems, Washington, D. C. 20545
153. M. Goldman, AEC, Division of Biomedical and Environmental Research, Washington, D. C. 20545
154. E. Gritton, Rand Corporation, 1700 Main Street, Santa Monica, California 90406
155. R. C. Hamilton, IDA - Room 19, 400 Army-Navy Drive, Arlington, Virginia 22202
156. W. J. Haubach, AEC, Division of Physical Research, Washington, D. C. 20545
157. M. G. Hegarty, Radio Corporation of America, Electronic Components and Devices, 415 South 5th Street, Harrison, New Jersey 07029
158. R. E. Hopkins, U.S. Army Mobility Equipment R&D Center, Fort Belvoir, Virginia 22060
159. J. H. Jarrett, Pacific Northwest Laboratories, P. O. Box 999, Richland, Washington 99352
160. I. Jones, TRW Systems, One Space Park, Redondo Beach, California 90278
161. T. B. Kerr, NASA Headquarters, Code RY, Washington, D. C. 20546
162. F. E. Kruesi, Savannah River Laboratory, Drawer E, Aiken, S. C. 29801
163. J. A. Lieberman, AEC, Division of Reactor Development and Technology, Washington, D. C. 20545
164. G. Linkous, Teledyne-Isotopes, Inc., Nuclear Systems Division, 110 W. Timonium Road, Timonium, Maryland 21093
165. W. A. McDonald, Teledyne-Isotopes, Inc., Nuclear Systems Division, 110 W. Timonium Road, Timonium, Maryland 21093
166. W. E. Mott, AEC, Division of Biomedical and Environmental Research, Washington, D. C. 20545
167. W. G. Parker, Westinghouse Astronuclear Laboratory, P. O. Box 10864, Pittsburgh, Pennsylvania 15236
168. W. E. Osmeyer, Teledyne Isotopes Energy Systems Division, 110 W. Timonium Road, Timonium, Maryland 21093
169. N. C. Ostrander, Rand Corporation, 1700 Main Street, Santa Monica, California 90406

170. F. K. Pittman, AEC, Division of Waste Management and Transportation, Washington, D. C. 20545
171. A. M. Platt, Pacific Northwest Laboratories, P. O. Box 999, Richland, Washington 99352
172. T. A. Nemzek, Division of Reactor Development and Technology, AEC, Washington, D. C. 20545
173. R. Schafer, General Electric Company, P. O. Box 8661, Bldg. CC-F8, Philadelphia, Pennsylvania 19101
174. J. A. Swartout, Union Carbide Corporation, 270 Park Avenue, New York, New York 10017
175. H. H. VanTuyl, Pacific Northwest Laboratories, P. O. Box 999, Richland, Washington 99352
176. R. L. Wainwright, Dayton Area Office, AEC, P. O. Box 66, Miamisburg, Ohio 45342
177. AEC, Savannah River Operations Office, P. O. Box A, Aiken, South Carolina 29802
178. General Electric Company, MSD, P. O. Box 8661, Philadelphia, Pennsylvania 19101
179. General Electric Company, Vallecitos Atomic Laboratory, P. O. Box 846, Pleasonton, California 94566
180. NASA, Goddard Space Flight Center, Greenbelt, Maryland 20700
181. NASA, Langley Research Center, Langley Station, Hampton, Virginia 23365
182. NASA, Manned Spacecraft Center, Houston, Texas 77058
183. NASA, Marshall Space Flight Center, Alabama 35812
184. Navy Space Systems Activity, Attn: R. V. Silverman, Code 40, Air Force Unit Post Office, Los Angeles, California 90045
185. Teledyne Isotopes, Inc., 110 W. Timonium Road, Timonium, Maryland 21093
186. Research and Technical Support Division, AEC , ORO
187. Richland Operations Office, AEC, P. O. Box 550, Richland, Washington 99352
188. Patent Office, AEC, ORO
- 189-336. Given distribution as shown in TID-4500 under Nuclear Propulsion Systems and Aerospace Safety category (25 copies — NTIS)