**Compatibility of $^{244}\text{Cm}_2\text{O}_3$ With Containment
Materials for Electric Power
Generator Systems**

J. R. DiStefano

MASTER

OAK RIDGE NATIONAL LABORATORY

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METALS AND CERAMICS DIVISION

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FOR ELECTRIC POWER GENERATOR SYSTEMS

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ABSTRACT

Curium-244 sesquioxide has many properties that makes it attractive as a heat source in electric power generator systems. Current radioisotopic thermoelectric generator designs generally specify fuel-containing interface temperatures from 800–1400°C. Results of compatibility tests of $^{244}\text{Cm}_2\text{O}_3$ with a variety of materials are reported. Test conditions included 5000 hr at 900 and 1400°C, 2500 hr at 1100°C, and static helium and dynamic vacuum environments. Materials included graphite, ThO_2 , superalloys, noble metals, and refractory metals.

INTRODUCTION

Reliable electric power generators are needed for orbiting satellites, remote weather stations, ocean buoys, as well as other applications where maintenance would be difficult. A radioisotopic heat source coupled to a thermionic-, thermoelectric-, or thermomechanical-conversion system is one method of providing electrical power for such applications. Curium-244 is particularly useful as a heat source where high power density to achieve high temperatures is required or where reductions in system size and weight are desirable. The lack of availability of ^{244}Cm has limited its use in systems constructed thus far. However, ^{244}Cm occurs with other rare-earth fission products in the high-activity waste of nuclear electric power generating stations that use ^{238}U or ^{239}Pu . Recovery of ^{244}Cm from power reactor fuel processing waste has now been successfully demonstrated on residues from the reprocessing of the Shippingport reactor blanket fuel elements.¹ With increased construction of nuclear power generating stations planned, it is expected that significant quantities of ^{244}Cm will be available during the next decade.

The use of radioisotopes as heat sources requires the development of fuel forms having suitable physical and chemical properties. Some of the important properties of several radioisotopes that have been considered or used in heat source applications are shown in Table 1. Note

¹*Report on the Availability and Cost of Curium-244 from Reactor Fuel Reprocessing Waste*, General Electric Co., Document No. 74S04209 (February 15, 1974), p. 1–3.

Table 1. Radionuclides for Isotopic Power Generator Applications

Radionuclide	Principal Type of Activity	Half-Life (Years)	Fuel Form	Active Isotope in Fuel (%)	Power of Fuel Form (W/g)	Power Density of Fuel Form (W/cm ³)
²¹⁰ Po	Alpha	0.38	Metal	95	134	1210
²³⁸ Pu	Alpha	87.4	PuO ₂	70	0.39	3.9
²⁴² Cm	Alpha, neutron	0.45	Cm ₂ O ₃	82	98	882
²⁴⁴ Cm	Alpha, neutron	18.1	Cm ₂ O ₃	86	2.45	27.0
⁶⁰ Co	Beta, gamma	5.2	Metal	10	1.74	15.8
⁹⁰ Sr	Beta	28	SrTiO ₃	23	0.22	1.01
¹³⁷ Cs	Beta, gamma	30	CsCl	28	0.12	0.38
¹⁴⁴ Ce	Beta, gamma	0.78	Ce ₂ O ₃	3.8	1.0	6.2
¹⁴⁷ Pm	Beta	2.6	Pm ₂ O ₃	82	0.27	1.8

that ²⁴⁴Cm₂O₃ has a relatively high power density (~27 W/cm³) as compared with fuel forms of the other long-lived radioisotopes listed.

Current radioisotope thermoelectric generator (RTG) designs specify fuel container interface temperatures ranging from 800–1400°C. The purpose of this work was to evaluate the compatibility of several potential container materials with ²⁴⁴Cm₂O₃ under conditions that simulate those in an RTG.

EXPERIMENTAL DESIGN

The test system used to conduct these studies is shown in Fig. 1. The inner-capsule assembly contains a ²⁴⁴Cm₂O₃ hot-pressed pellet sandwiched between two cylindrical disk specimens of the same material as the capsule. The inner capsule has welded top and bottom end plugs, but the top end plug has a small hole (0.005 in. in diameter) to vent the inner-capsule assembly to an environment of either static helium or dynamic vacuum. Many RTG designs for space applications utilize a graphite shell around the primary fuel capsule. In order to determine if graphite would have any effect on primary fuel-container compatibility or contribute to mass transport in the system, one group of inner-capsule assemblies was tested inside graphite capsules, while a second group was not. Tables 2 and 3 list the material and the test conditions. Iridium and graphite were tested at three temperatures. Testing of the other materials was limited to those temperatures where melting point, mechanical strength, or chemical reactivity with the environment would not prohibit their use. Unfueled control tests as shown in Table 2 were conducted for comparison with specimens exposed to Cm₂O₃.

ORNL-DWG 73-1116

Fig. 1. Compatibility Test System. Couples exposed together in the same test system are referred to as a "set."

Table 2. Potential Containment Materials Tested
with $^{244}\text{Cm}_2\text{O}_3$

Material ^a	Set Numbers (see Table 3 and Fig. 1)	
	$^{244}\text{Cm}_2\text{O}_3$ Compatibility Tests	Unfueled Control Tests
Iridium	1,2,3,4,5,6,7,8,9,10	2,6,7,10
Graphite	1,4,5,7,10	1,3,6,7,10
Platinum	1,2,3,4,5,6	2,3
Hf-105 ^b	1,2	1,2
Hastelloy C-276 ^c	1,2	1,2
Haynes alloy No. 25 ^d	1,2	1,2
Haynes alloy No. 188 ^e	1,2	1,2
ThO ₂	1,2	1
Pt-20% Rh	1,2	1,2
Pt-2608 ^f	1,2	1,2
Pt-2608M ^g	3,4,5,6	3
Pt ₃ Ir	3,4,5,6	3,6
Molybdenum	7,8,9,10	7,10
Mo-46% Re	7,8,9,10	10
Tantalum	7,8,9,10	7,10
T-111 ^h	7,8,9,10	7,10
Tungsten	7,8,9,10	7,10
W-26% Re	7,8,9,10	7,10

^aInner capsule and disk specimen.

^bHf-1% Pt-0.5% Pd.

^cNi-15% Cr-16% Mo-5% Fe-4% Fe.

^dCo-20% Cr-15% W-10% Ni-3% Fe.

^eCo-22% Cr-22% Ni-14% W-1.5% Fe-0.75% Mn.

^fPt-26% Rh-8% W.

^gPt-26% Rh-8% W-0.5% Ti.

^hTa-8% W-2% Hf.

Table 3. Components and Conditions for $^{244}\text{Cm}_2\text{O}_3$ Compatibility Tests and Unfueled Control Tests

Set	Temperature (°C)	Time (hr)	Intermediate Capsule	Capsule Holder	Atmosphere	Outer Container
1	900	5000	None	Al ₂ O ₃	Helium	Hastelloy X
2	900	5000	Graphite	Graphite	Helium	Hastelloy X
3	1100	2500	Graphite	Graphite	Helium	Tantalum
4	1100	2500	None	Al ₂ O ₃	Vacuum	Tantalum
5	1100	2500	None	Al ₂ O ₃	Helium	Tantalum
6	1100	2500	Graphite	Graphite	Vacuum	Tantalum
7	1400	5000	Graphite	Graphite	Helium	Tantalum
8	1400	5000	None	BeO	Vacuum	Tantalum
9	1400	5000	None	BeO	Helium	Tantalum
10	1400	5000	Graphite	Graphite	Vacuum	Tantalum

MATERIALS

Primary Container Capsules and Specimens

All the metal or alloy test components were prepared from arc-melted or electron-beam starting stock. Materials were procured as follows:

Material	Source
Ir-Pt, Pt-20% Rh, Pt-2608, Pt-2608M, Pt ₃ Ir	Casting and Forming Laboratory, Metals and Ceramics Division, ORNL
ThO ₂	Ceramics Laboratory, Metals and Ceramics Division, ORNL
Hf-1% Pt-0.5% Pd	TRW, Inc., Redondo Beach, California
Graphite, Hastelloy C-276, Haynes alloy No. 25, Haynes alloy No. 188, Mo, Mo-46% Re, Ta, T-111, W, W-26% Re	Commercial vendors

All metallic inner-capsule components were cleaned, dye-penetrant inspected for defects, and then heat treated according to the schedule shown in Table 4. The purpose of heat treating was to provide a recrystallized microstructure that ensures a more uniform starting material which is easier to evaluate in post-test examination.

Table 4. Annealing Conditions for Metallic Inner-Capsule Components

Material	Temperature (°C)	Time (hr)
<u>Argon (Air Cool)</u>		
Haynes alloy No. 25	1100	1
Haynes alloy No. 188	1100	1
Hastelloy C-276	1100	1
<u>Vacuum</u>		
Hafnialloy 105	900	1
Platinum	1200	0.5
Pt-20% Rh	1200	0.5
Pt-26% Rh-8% W	1400	1
Pt-26% Rh-8% W-0.5% Hf	1400	1
Iridium	1500	1
Pt ₃ Ir	1500	1
Tantalum	1500	1
T-111	1500	1
Molybdenum	1500	1
Mo-46% Re	1500	1
Tungsten	1500	1
W-26% Re	1500	1

A number of dye-penetrant-defect indications were noted on the iridium capsule bodies, particularly in the counterbored recess for the end plug. The capsule bodies had been formed from rod by gun drilling and then honing. The counterbored areas were not honed and therefore were rougher in texture. Although all of the inner-diameter indications were confined to the counterbored area, the outer-diameter surfaces exhibited longitudinal scratches or pits in several areas. However, helium-leak tests of these capsules indicated they were all leak-tight.

The following procedures were used for cleaning and outgassing all graphite components prior to test:

1. ultrasonically cleaned in alcohol,
2. dried by heating to 190°C for 16 hr in air furnace,
3. heated to 1200°C for 2 hr in vacuum,
4. temperature raised to 2100°C for 7 min, and
5. stored in argon atmosphere.

Curium Oxide

Curium-244 source material ($^{244}\text{CmO}_{2.0}$) was obtained from Savannah River Laboratory (SRL) production batch 18. Radiochemical analysis for ^{244}Cm and ^{240}Pu are shown in Table 5.

Table 5. Radiochemical Analysis of Batch SRL-18 Curium Oxide

Sample	Weight (mg)	Contents, mg/g			
		^{244}Cm	^{240}Pu	Total Cm ^a	Total Pu ^a
Cm18-2	13.57	638	99.1	676.4	99.1
Cm18-3	10.66	626	99.5	663.7	99.5
Cm18-4	15.88	628	102.4	665.8	102.4
Average		630.7	100.3	668.6	100.3
Adjusted Average ^b		738	115.8	771.8	115.8

^aBased on 94.32% abundance of ^{244}Cm and >99% abundance of ^{240}Pu .

^bBased on assumption of incomplete sample transfer.

Five determinations of contaminants in batch SRL-18 curium oxide were made at ORNL and one by SRL, which was supplied with the batch shipment. From these assays, the values shown in Table 6 were taken as representative of the oxide used in the pellet fabrication.

Curium-244 sesquioxide was prepared by first calcining $^{244}\text{CmO}_2$ at 1000°C in vacuum for 4 hr. The $^{244}\text{Cm}_2\text{O}_3$ powder was then transferred

Table 6. Impurities in Batch SRL-18 Curium Oxide

Element	Concentration (ppm)	Element	Concentration (ppm)
Aluminum	15	Lead	20
Arsenic	<10	Platinum	1000
Boron	<5	Silicon	300
Barium	<10	Strontium	<10
Calcium	130	Tantalum	100
Niobium	<10	Titanium	<15
Cadmium	<10	Tungsten	400
Cobalt	<5	Zinc	100
Chromium	400	Zirconium	400
Copper	100	Americium	7500
Iron	2000	Yttrium	30
Iridium	100	Bromine	<10
Potassium	<5	Chlorine	20
Magnesium	<10	Fluorine	10
Manganese	15	Sulfur	15
Molybdenum	100	Lanthanum	15
Sodium	<10	Cerium	30
Nickel	150	Other rare earths	100

into graphite dies (argon atmosphere) in a hot press, and the press chamber evacuated to ~200 torr. After slowly heating to 1450°C, a pressure of 4000 psi was applied for 1 hr. The press was then allowed to cool for 30 min at 200 torr before it was cooled further by an argon gas stream. The completed $^{244}\text{Cm}_2\text{O}_3$ pellets were then heated to 1000°C while the oxygen content of the argon was increased to ~2000 ppm. These conditions were maintained for 4 hr to oxidize any residual carbon from the pellet surfaces. Oxygen content of the argon was then reduced to <100 ppm and the pellets cooled to cell temperature. Finally, the pellet surfaces were polished on a diamond-impregnated steel plate to obtain uniform surface finishes.

One typical pellet was selected for examination prior to testing. Bulk density was calculated from averaged measurements of diameter, thickness, and weight as shown in Table 7. The density was 76.4% of theoretical based on a maximum value of 11.7 g/cm³ for β -type Cm_2O_3 calculated from x-ray diffraction data. The top surface temperature of the pellet when resting on a thermally insulated surface was measured by a thermocouple to be 110°C. The specific power was determined by calorimetry to be 2.06 W/g; thus the power and power density of the pellet was 0.6 W and 18.4 W/cm³, respectively.

Optical microscopy of a cross section of the pellet indicated areas of variable density and considerable void volume, which would be anticipated from the density measurement. Characterization by x-ray diffraction

Table 7. Typical Size of (Description) of $^{244}\text{Cm}_2\text{O}_3$ Pellet
Prior to Testing

Dimensions, in.		Weight (g)	Volume (cm^3)	Density (g/cm^3)
Thickness	Diameter			
0.0796	0.1783	0.2915	0.03257	8.9502
0.0797	0.1782	0.2915	0.03257	8.9490
0.0798	0.1784	0.2915	0.03269	8.9178
0.0797	0.1784	0.2915	0.03265	8.9289
Av 0.0797	0.1783	0.2915	0.03262	8.9365

did not show peaks that could be identified with any curium or plutonium oxides, and electron-beam microprobe analysis of the polished surface of the pellet indicated the presence of Al, Fe, and Ca in addition to Cm.

TEST ASSEMBLY AND DISASSEMBLY

The inner-capsule components were inserted in a hot cell under argon atmosphere (<150 ppm O_2). After welding, the inner capsules were transferred to an adjacent argon-atmosphere cell where they were enclosed in an outer capsule (Hastelloy X or tantalum). Those couples to be tested in dynamic vacuum were also sealed in the secondary capsule under argon, but immediately prior to being loaded into the test furnace, the upper end cap was punctured. The other unvented couples, which were run under a static helium atmosphere, were inserted into secondary capsules having an open 1/4-in.-OD tube protruding from the top end plug (nickel tube from Hastelloy X and tantalum tube from the tantalum end plug). This tube allowed the container to be evacuated and backfilled with helium. With the helium line still attached, the protruding tube was first crimped closed and then pinched off as near the end as possible. The pinched end of the tube was then sealed by tungsten-arc welding. Sealing of these secondary capsules with an internal helium pressure of 1 atm provided positive assurance that the surrounding atmosphere was helium.

The 10 secondary capsules containing the 67 compatibility couples were visually examined and photographed through a Kollmorgan periscope. The appearance of the welds on the secondary capsules was satisfactory, although there were some areas of roll-over and indentations. A helium-leak test of the individual secondary capsules in an evacuated chamber indicated that all were sealed. The outer capsules for the 1100 and 1400°C tests were transferred to argon-atmosphere glove boxes attached to Brew vacuum furnaces, and the outer capsules containing the couples for exposure to dynamic vacuum were penetrated. Outer capsules for the 900°C tests were transferred to a standard air furnace to be heated for the required period.

To preserve the integrity of the after-test interface between the specimen and $^{244}\text{Cm}_2\text{O}_3$, the capsule assemblies were maintained in a vertical position following loading. Upon completion of the test, each set of capsule assemblies was transferred to the High Radiation Level Examination Laboratory (HRLEL) for examination. There the outer protective containers were removed by making a transverse cut through the capsule wall using an Al_2O_3 resinoid-reinforced cutoff wheel. A similar transverse cut was made to remove the top end plug of the inner capsule.

Whenever possible the top specimen was removed and submitted for oxygen analysis. An epoxy material was then poured into the inner capsule to immobilize the specimen and pellet. Each capsule was mounted and then polished longitudinally until its approximate midplane was reached. At this point the capsule was photographed at $\sim 6\times$, and an autoradiograph² was made to show the ^{244}Cm distribution in the capsule. The capsule wall and specimen and fuel surfaces were examined to determine any changes in microstructure that occurred, and electron microprobe analysis was obtained on selected samples.

RESULTS OF 5000-hr TESTS AT 900°C

Chemistry

Results of analyses of test and control samples are summarized in Table 8. The top disk specimen from each of the $^{244}\text{Cm}_2\text{O}_3$ compatibility couples was removed and analyzed for oxygen. In the noble metal group only Pt-2608 (Pt-26% Rh-8% W) appeared to have picked up oxygen upon exposure to $^{244}\text{Cm}_2\text{O}_3$. Carbon analyses of control test specimens also indicated no appreciable increase in any of the noble metals. Significant oxygen increases also occurred in Hastelloy C-276 and Hafnalloys 105 (Hf-1% Pt-0.5% Pd), and in both cases oxygen pickup was greater where there was no intermediate graphite capsule. Hastelloy C-276, which initially contained 120 ppm C, showed a large uptake of carbon in the control test with a graphite intermediate capsule.

Microstructure

Metallographic and ceramographic results from sets 1 and 2 fuel tests are summarized in Table 9. In general, the noble metals (Figs. 2-5) and graphite (Fig. 6) were not significantly affected by the exposure to $^{244}\text{Cm}_2\text{O}_3$. Slight evidence of interaction between $^{244}\text{Cm}_2\text{O}_3$ and unalloyed platinum (Fig. 3) was noted in the form of surface roughening of the platinum specimen and a metallic layer on the $^{244}\text{Cm}_2\text{O}_3$. Control test results (Tables 10 and 11) also indicated very little or no effects on the structure of these materials in the absence of fuel. There was, however, a metallic layer on the graphite indicating that vapor species

²W. C. Mosley, "A Fission-Fragment Autoradiographic Technique for Detecting ^{244}Cm ," *Nucl. Appl.* 4: 42-46 (1968).

Table 8. Carbon and Oxygen Concentrations of Compatibility and Control Specimens from Tests at 900°C

Material	Carbon, ppm			Oxygen, ppm				
	Before Test	Control Test		Before Test	$^{244}\text{Cm}_2\text{O}_3$ Test		Control Test	
		Set 1	Set 2		Set 1	Set 2	Set 1	Set 2
Iridium	<10	a	10	<10	<10	<10	a	b
Platinum	<20	a	25	<10	<10	<10	a	20
Pt-20% Rh	<20	45	35	<10	<10	<10	12	15
Pt-2608	<20	30	25	<10	25	15	<10	<10
Haynes alloy No. 25	1120	865	815	40	85	85	b	b
Haynes alloy No. 188	1040	800	1265	90	85	75	b	b
Hastelloy C-276	120	135	1185	65	270	110	b	b
HF-105	10	35	35	75	680	260	105	95
ThO ₂	b	30	a	b	b	b	b	a
Graphite	b	b	b	<10	175	a	230	a

^aTest not run.^bSpecimen not analyzed.Table 9. Summary of Metallographic and Ceramographic Observations for Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ for 5000 hr at 900°C

Material	Set 1	Set 2
Platinum	Irregular surface on platinum. Metallic outer layer on Cm_2O_3 with dark and light gray sub-surface layers.	Slight surface roughening.
Pt-20% Rh	Slight surface roughening.	Slight surface roughening.
Pt-2608	No significant change.	No significant change.
Iridium	No significant change.	No significant change.
Haynes alloy No. 25	Very slight surface attack (~0.1 mil).	Surface roughening and some grain-boundary attack (~1-2 mils).
Haynes alloy No. 188	Grain-boundary attack (~1 mil).	Very slight surface roughening.
Hastelloy C-276	Grain-boundary attack (~2 mils).	Grain-boundary attack (~1 mil).
Hafnialloy 105	Surface roughening and very slight grain-boundary attack.	Dark gray layer on surface; some surface cracks.
ThO ₂	Irregular surface. Cm_2O_3 cracked.	Dark gray layer on surface; layer cracked in some areas.
Graphite	No significant change.

Fig. 2. Iridium- $^{244}Cm_2O_3$ After 5000 hr at 900°C.

Fig. 3. Platinum- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C.

Fig. 4. Pt-20% Rh- $^{244}Cm_2O_3$ After 5000 hr at 900°C.

Fig. 5. Pt-2608- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C.

HELIUM - Al_2O_3

Fig. 6. Graphite- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C .

Table 10. Summary of Results on Control Tests^a for
Set 1 $^{244}\text{Cm}_2\text{O}_3$ Compatibility Tests

Material	Visual Observations		Weight Change (g)
	Capsule	Specimen	
Hastelloy C-276	Gray-black-gold film on outer surface, especially on end touching Al_2O_3	Dull	0
Haynes alloy No. 188	Same as above, except gold film on top end not touching Al_2O_3	Dull	0
Haynes alloy No. 25	Same as Hastelloy C-276	Dull	0
Hafn alloy-105	Dull, alumina-colored layer on outside surface, gold-colored layer below	Dull, black on surface touching capsule bottom	-0.0021
Graphite	No change on outside, but metallic layer on inside	Metallic layer on all surfaces except bottom where in contact with graphite capsule	0
Pt-20% Rh	Slightly dull appearance on outside	Bright, except bottom surface touching capsule	0
Pt-2608	Same as above	Bright	0

^aTest conditions: 900°C, 5000 hr, static helium, Al_2O_3 capsule holder, Hastelloy X outer container, no $^{244}\text{Cm}_2\text{O}_3$ fuel or graphite.

Table 11. Summary of Results on Control Tests^a for
Set 2 $^{244}\text{Cm}_2\text{O}_3$ Compatibility Tests

Material	Visual Observations		Weight Change (g)
	Capsule	Specimen	
Hastelloy C-276	Gray-black layer on outer surface	Black	+0.0008
Haynes alloy No. 188	Same as above	Black	+0.0006
Haynes alloy No. 25	Light-gray layer on outer surface	Black	0
Hafn alloy-105	Gray-gold layer on outer surface	Dull, very light gold layer in some areas	0
ThO_2	Surface spotted gray-black-white	Same as capsule	0
Platinum	Etched appearance	Bright, but etched appearance	0
Pt-20% Rh	Bright	Dull	0
Pt-2608	Bright	Bright, one dark spot	0
Iridium	Bright	Bright	0

^aTest conditions: 900°C, 5000 hr, static helium, graphite intermediate capsule, graphite capsule holder, Hastelloy X outer container, no $^{244}\text{Cm}_2\text{O}_3$ fuel.

from the other materials had diffused through the vent hole and interacted with the graphite.

Approximately 1 to 2 mils of grain boundary attack occurred in fuel tests with superalloy specimens (Figs. 7-9). Results varied between sets 1 and 2, but there was no consistent difference. This indicates that surface contact between $^{244}\text{Cm}_2\text{O}_3$ and the superalloy specimen was probably more important than the presence or absence of graphite. Surface films were noted on the outer surfaces of the inner capsules in the control tests (Tables 10 and 11). In the absence of graphite the superalloy specimens in the control tests were relatively unaffected, and no weight changes were noted. When heated with graphite intermediate capsules, the superalloy specimens turned black and exhibited slight weight increases.

The alloy Hafnallo 105 (Hf-1% Pt-0.5% Pd) showed slight evidence of attack in the form of surface roughening and a few surface cracks (Fig. 10). The hardness of the specimen from fuel set 2 increased from 150 to 440 DPH near the Hafnallo 105- $^{244}\text{Cm}_2\text{O}_3$ interface. Chemical analysis of the top disk specimen had shown an oxygen increase to 260 ppm (compared with 680 ppm in the specimen from set 1) and the control specimen had indicated a slight increase in carbon to 55 ppm (Table 8). A thin surface layer (Fig. 10) was also visible on the Hafnallo 105 specimen in some areas.

No significant reaction was noted between ThO_2 and $^{244}\text{Cm}_2\text{O}_3$ (Fig. 11). There was a gray layer on the ThO_2 capsule wall opposite the $^{244}\text{Cm}_2\text{O}_3$ pellet and on the surface of the ThO_2 specimen that was in contact with the $^{244}\text{Cm}_2\text{O}_3$, but electron-beam microprobe analysis did not indicate the presence of curium in the layer. No layer was found on the ThO_2 from set 1, which did not include a graphite intermediate capsule.

Autoradiographs in Figs. 2-11 show the ^{244}Cm distribution in the inner capsule following test. Generally, the $^{244}\text{Cm}_2\text{O}_3$ was intact and no redistribution of ^{244}Cm was noted. In addition, vent holes in the capsule tops were clean indicating mass transfer effects in these systems were negligible.

RESULTS OF 2500-hr TESTS AT 1100°C

Chemistry

Only the noble metals and graphite were tested at 1100°C. In every set the platinum sample from the fuel tests could not be removed from the inner capsule assembly, and, therefore no oxygen analysis was made. Results of other capsules are shown in Table 12. In the fuel tests only Pt-2608M picked up oxygen. This alloy contains tungsten and titanium, both of which readily form oxides.

Fig. 7. Haynes Alloy No. 25- $^{244}Cm_2O_3$ After 5000 hr at 900°C.

Fig. 8. Haynes Alloy No. 188- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C.

Fig. 9. Hastelloy C-276- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C.

Fig. 10. $\text{Hf-105-}^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C .

HELIUM - GRAPHITE

HELIUM - Al_2O_3

Fig. 11. $\text{ThO}_2\text{-}^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 900°C .

Table 12. Oxygen Concentrations of Compatibility and Control Specimens from Tests at 1100°C

Material	Oxygen Concentration, ppm					
	Test Set 3	Control Set 3	Test			Control Set 6
			Set 4	Set 5	Set 6	
Iridium	<10	a	<10	<10	<10	<10
Platinum	b	<10	b	b	b	<10
Pt-2608M	107	<10	61	79	23	a
Pt ₃ Ir	33	<10	29	<10	<10	<10
Graphite	a	120	<10	<10	a	120

^aTest not run.

^bSpecimen could not be removed from inner capsule and, therefore, was not analyzed.

Microstructure

Results of examinations of fuel tests are summarized in Table 13 and those from control tests in Table 14. There was no visible interaction between graphite and $^{244}\text{Cm}_2\text{O}_3$ in either helium or vacuum (Fig. 12). Attack of iridium was less than 0.001 in. deep and occurred in only one (set 4: vacuum, Al_2O_3) of the four test conditions (Figs. 13 and 14). The alloys Pt-2608M and Pt₃Ir were attacked along grain boundaries, but generally to depths that were less than 0.002 in. (Figs. 15-18). Autoradiographs showed little or no curium redistribution and vent holes in the capsules were clean.

Unalloyed platinum reacted with Cm_2O_3 under all conditions (Figs. 19 and 20). Electron-beam microprobe data from one of the tests are summarized in Fig. 21. The reaction product is the area labeled "b" in the upper-left-hand picture. X-ray intensity data indicate that it contains 72% Pt and 14% Cm. If these data are normalized to 100% (i.e., assume no other constituents were present), the values would be 84% Pt-16% Cm. Stoichiometrically, this corresponds to a compound of the type CmPt_5 . In addition to the reaction product, there was a darker gray phase around the outer edge of $^{244}\text{Cm}_2\text{O}_3$ pellet as shown by the backscattered electron picture in the lower left of Fig. 21. However, x-ray intensity data indicated that it contained the same curium concentration as the bulk pellet.

Table 13. Summary of Microstructural Observations for Materials
Exposed to $^{244}\text{Cm}_2\text{O}_3$ for 2500 hr at 1100°C

Material	Set 3	Set 4	Set 5	Set 6
Iridium	No attack	<1 mil attack	No attack	No attack
Platinum	Significant reaction with $^{244}\text{Cm}_2\text{O}_3$ -corrosion product formed at interface	Same as Set 3	Same as Set 3	Same as Set 3
Pt-2608M	Grain-boundary attack to depths of 0.001-0.002 in.	Surface roughening and slight grain-boundary attack to depth of 0.001 in.	Grain-boundary attack to depth of 0.001 in.	Surface roughening
Pt ₃ Ir	Isolated areas of grain-boundary attack to depths of 0.001-0.003 in.	Very slight surface roughening and grain-boundary attack	Grain-boundary attack to depths of <0.001 in.	No attack
Graphite	Not included in Set 3	No attack	No attack	Not included in Set 6

Table 14. Summary of Results on Control Tests for Sets 3
and 6 $^{244}\text{Cm}_2\text{O}_3$ Compatibility Tests

Material	Visual Observations		Weight Changes, g	
	Set 3	Set 6	Set 3	Set 6
Iridium	a	Capsule and specimen bright	a	b
Platinum	Capsule and specimen had etched appearance	Capsule and specimen had etched appearance	0	+0.0003
Pt-2608M	Capsule and specimen bright	a	0	a
Pt ₃ Ir	Capsule and specimen bright	Capsule and specimen bright	0	0
Graphite	Unchanged	Unchanged	0	0

^aControl test not run.

^bSpecimen damaged when capsule was cut open.

Fig. 12. Graphite- $^{244}Cm_2O_3$ After 2500 hr at 1100°C.

Fig. 13. Iridium- $^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C .

Fig. 14. Iridium- $^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C .

Fig. 15. Pt-2608M- $^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C.

Fig. 16. Pt-2608M- $^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C.

Fig. 17. $\text{Pt}_3\text{Ir}-^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C .

Fig. 18. $\text{Pt}_3\text{Ir}-^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C .

Fig. 19. Platinum- $^{244}Cm_2O_3$ After 2500 hr at 1100°C.

Fig. 20. Platinum- $^{244}\text{Cm}_2\text{O}_3$ After 2500 hr at 1100°C .

Fig. 21. Electron Beam Scanning Images of Pt- $^{244}\text{Cm}_2\text{O}_3$ Reaction Product Formed After 2500 hr at 1100°C. Area A, 95% Cm-0 Pt; Area B, 72% Pt-14% Cm; Area C, 95% Cm-0 Pt; Area D, 100% Pt.

RESULTS OF 5000-hr TESTS AT 1400°C

Chemistry

Chemistry results on control and fuel test samples from sets 7, 8, 9, and 10 are summarized in Table 15. Carbon concentrations were measured in control test samples that were heat-treated inside capsules surrounded by graphite capsules (Fig. 1). Heavy carburization was found in molybdenum and Mo-46% Re alloys, and slight carburization in tantalum, T-111, and W-26% Re. Although carbon concentrations were not determined in specimens exposed to fuel, hardness measurements of 1150 and 1600 DPH were found in Mo-46% Re and W-26% Re, respectively, in the tests where there were graphite intermediate capsules.

Table 15. Carbon and Oxygen Concentrations of Compatibility and Control Samples from Tests at 1400°C

Material	Carbon ^a			Oxygen ^a						
	Before Test	Control Test		Before Test	²⁴⁴ Cm ₂ O ₃ Test				Control Test	
		Set 7	Set 10		Set 7	Set 8	Set 9	Set 10	Set 7	Set 10
Iridium	<10	20	4	50	175	20	85	30	250	b
Graphite	b	b	b	<10	c	b	c	3300	80	75
Molybdenum	40	1.4%	2.8%	60	b	b	600	b	10	b
Mo-46% Re	45	c	2.3%	40	b	b	65	b	c	b
Tantalum	20	1280	260	110	590	b	>1200 ^d	>1200 ^d	100	115
T-111	40	230	260	100	640	960	>2000 ^d	>2000 ^d	85	90
Tungsten	<10	50	10	70	15	110	70	40	b	b
W-26% Re	10	900	30	10	150	b	300	1000 ^d	b	b

^aConcentration in ppm except where noted.

^bSample not analyzed; in fuel tests top specimen could not be removed.

^cTest not run.

^dConcentration exceeded capacity of counter to record for that sample. ²⁴⁴Cm₂O₃ may have adhered to sample.

Results of oxygen analyses are difficult to interpret because there was not a clean separation of the specimen from the ²⁴⁴Cm₂O₃ pellet in several of the tests. During metallographic examination gray layers were noted on tantalum, T-111, and one W-26% Re specimen (see discussion below and Tables 16 and 17).

Microstructure

Results of metallographic examination of fuel tests are summarized in Tables 16 and 17. Iridium showed excellent resistance to ²⁴⁴Cm₂O₃

Table 16. Summary of Microstructural Observations on
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1400°C

Material	Set 7	Set 10
Iridium	Grain-boundary attack to depths of <0.5 mil. Few subsurface voids.	Grain-boundary attack to depths of <0.2 mil; precipitate in iridium near $^{244}\text{Cm}_2\text{O}_3$ interface.
Graphite	Top specimen could not be removed. Reacted with $^{244}\text{Cm}_2\text{O}_3$ 5 to 10 mils deep into graphite specimen. Possible formation of curium-oxycarbide.	Same as results from Set 7, except top specimen was removed for analysis.
Tantalum	Gray layer adhering to tantalum at $^{244}\text{Cm}_2\text{O}_3$ interface. Subsurface voids and/or grain-boundary attack to depths of <0.5 mil. White phase (carbide or oxide) in some grain boundaries.	Gray layer adhering to tantalum at $^{244}\text{Cm}_2\text{O}_3$ interface. Grain-boundary attack to depths of <0.5 mil.
T-111	Gray layer adhering to T-111 at $^{244}\text{Cm}_2\text{O}_3$ interface. Grain-boundary reaction phase to depths of 2-3 mils.	Gray phase adhering to T-111 at $^{244}\text{Cm}_2\text{O}_3$ interface. Grain-boundary phase to depths of 3-4 mils. Metallic particles in fuel. Partial disintegration of $^{244}\text{Cm}_2\text{O}_3$ pellet.
Molybdenum	Top specimen could not be removed; bonded to capsule wall. No significant attack by $^{244}\text{Cm}_2\text{O}_3$.	Top specimen could not be removed. Heavy subsurface void formation to depths of 1 mil. Disintegration of $^{244}\text{Cm}_2\text{O}_3$ pellet. Hard (>200 DPH) layer on inner surface of capsule.
Mo-46% Re	Top specimen could not be removed. Grain-boundary attack to depths of <0.5 mil.	Top specimen could not be removed. Heavy subsurface void formation to depths of 1 mil.
Tungsten	Slight grain-boundary attack to depths of <0.1 mil.	No significant attack.
W-26% Re	Slight grain-boundary attack to depths of <0.1 mil. Metallic particles in fuel.	Gray layer adhering to W-26% Re at $^{244}\text{Cm}_2\text{O}_3$ interface. Slight grain-boundary attack to depths of <0.1 mil. Metallic particles in fuel.

Table 17. Summary of Microstructural Observations on
Materials Exposed to $^{244}\text{Cm}_2\text{O}_3$ at 1400°C

Material	Set 8	Set 9
Iridium	Grain-boundary attack to depths of <0.5 mil. Complete disintegration of $^{244}\text{Cm}_2\text{O}_3$ pellet.	Grain-boundary attack to depths of <0.5 mil.
Tantalum	Top specimen could not be removed; bonded to capsule. Gray layer adhering to tantalum at $^{244}\text{Cm}_2\text{O}_3$ interface. Grain-boundary attack to depths of <0.5 mil.	Gray layer adhering to tantalum at $^{244}\text{Cm}_2\text{O}_3$ interface. Grain-boundary attack to depths of <0.5 mil.
T-111	Gray layer adhering to surface. Grain-boundary attack to depths of 3-4 mils. Metallic particles in fuel. Partial disintegration of $^{244}\text{Cm}_2\text{O}_3$ pellet.	Same as results for Set 8.
Molybdenum	Grain-boundary attack to depths of <0.1 mil. Complete disintegration of $^{244}\text{Cm}_2\text{O}_3$ pellet.	No significant attack.
Mo-46% Re	Top specimen could not be removed; bonded to capsule. Very slight surface roughening.	Slight grain-boundary attack to depths of <0.5 mil.
Tungsten	Top specimen could not be removed. Slight grain-boundary attack to depths of <0.1 mil.	No significant attack.
W-26% Re	Top specimen could not be removed; bonded to capsule. Slight $^{244}\text{Cm}_2\text{O}_3$ fuel distribution. Grain-boundary attack to depths of <0.1 mil.	Slight grain-boundary attack to depths of <0.1 mil.

attack (<0.5 mil) and no evidence of carburization (Figs. 22 and 23). There was no redistribution of $^{244}\text{Cm}_2\text{O}_3$ in the tests in helium, however, in one test in vacuum (Fig. 23) most of the original $^{244}\text{Cm}_2\text{O}_3$ was not present in the inner capsule. Control test results are given in Tables 18 and 19, and even the iridium capsule material that was in direct contact with the graphite remained bright and shiny.

Graphite, which had been unaffected by $^{244}\text{Cm}_2\text{O}_3$ at 900 and 1100°C , reacted at 1400°C as indicated by Fig. 24. A reaction product containing curium (possibly curium-oxycarbide) is visible at the graphite- $^{244}\text{Cm}_2\text{O}_3$ interface, and a significant portion of the graphite specimen (8 to 10 mils) has been consumed.

A gray layer (possibly $^{244}\text{Cm}_2\text{O}_3$) was found adhering to all the tantalum and T-111 specimens at the $^{244}\text{Cm}_2\text{O}_3$ -metal interface. Below this layer the tantalum (Figs. 25 and 26) exhibited subsurface voids to depths of less than 0.5 mil into the metal. In one specimen (Fig. 25) a massive white phase was observed in several grain boundaries. Grain-boundary

Fig. 22. Iridium- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C.

Fig. 23. Iridium- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C.

Table 18. Summary of Results on Control Tests^a for Set 7
²⁴⁴Cm₂O₃ Compatibility Tests

Material	Visual Observations		Weight Change (g)
	Capsule	Specimen	
Iridium	Shiny, etched	Bright, etched	Not obtained ^b
Graphite	Light gray	No change	0
Molybdenum	Bonded to graphite intermediate capsule, could not be separated	Etched but bright appearance	0
Tantalum	Dull on outer surface	Bright, large grains visible	0
T-111	Dull on outer surface	Dull	0
Tungsten	Shiny	Bright	Not obtained ^b
W-26% Re	Shiny	Dull to shiny	Not obtained ^b

^aTest conditions: 1400°C, 5000 hr, static helium, graphite intermediate capsule, graphite capsule holder, tantalum outer container, no ²⁴⁴Cm₂O₃ fuel.

^bSpecimen damaged when capsule was opened.

Table 19. Summary of Results on Control Tests^a for Set 10
²⁴⁴Cm₂O₃ Compatibility Tests

Material	Visual Observations		Weight Change (g)
	Capsule	Specimen	
Iridium	Bright, etched	Stuck to capsule; could not be removed. Shiny	Not obtained ^b
Graphite	Unchanged	Unchanged	0
Molybdenum	Bonded to graphite intermediate capsule. Inside surface irregular. Graphite appeared to have penetrated to inside. Capsule broken when we attempted to remove specimen — cleavage type fracture	Could not be removed; reacted with graphite and capsule	Not obtained ^b
Mo-46% Re	Bonded to graphite; could not be removed	Bright	+0.0014
Ta	Bonded to graphite; could not be removed	Bright	0
T-111	Shiny	Shiny	0
Tungsten	Bright	Bright	Not obtained ^b
W-26% Re	Dull to shiny	Shiny	0

^aTest conditions: 1400°C, 5000 hr, dynamic vacuum, graphite intermediate capsule, graphite capsule holder, tantalum outer container, no ²⁴⁴Cm₂O₃ fuel.

^bSpecimen damaged when capsule was opened.

Fig. 24. Graphite- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C .

Fig. 26. Tantalum- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C .

attack of T-111 (Figs. 27 and 28) proceeded to depths of 2-4 mils, and appeared as a gray colored corrosion product. Significantly only slight redistribution of $^{244}\text{Cm}_2\text{O}_3$ occurred in the tantalum tests, but significant redistribution occurred in the T-111 tests, especially those in vacuum. Results of previous tests of tantalum and Ta-10% W with $^{244}\text{Cm}_2\text{O}_3$ at 1250°C were similar except that the attack occurred to slightly less depths at the lower temperature.³

Both molybdenum specimens from fuel tests in which graphite was present (sets 7 and 10) could not be removed from the inner capsules. In the control tests the molybdenum container bonded to the graphite and in one case (set 10) the molybdenum specimen could not be removed even though it had not been in direct contact with graphite. In three of the four tests (Figs. 29 and 30) there was no significant attack of molybdenum by $^{244}\text{Cm}_2\text{O}_3$. Subsurface voids to depths of 1 mil were found in the specimen exposed to the vacuum-graphite conditions (Fig. 30) and there was a light colored surface layer that extended into the metal to depths of 5 mils or more along grain boundaries. Redistribution of $^{244}\text{Cm}_2\text{O}_3$ was significantly greater in the vacuum tests. However, there was no evidence of mass transfer in the vent holes.

The alloy Mo-46% Re behaved similarly to unalloyed molybdenum. Specimens could not be removed from tests involving either graphite or helium; and, except for the specimen from set 10, attack was limited to surface roughening or grain-boundary penetration that was less than 0.5 mil deep (Figs. 31 and 32). Heavy subsurface voids to depths of 1 mil (similar to unalloyed molybdenum) occurred in the specimen from set 10. Significant redistribution of $^{244}\text{Cm}_2\text{O}_3$ was noted in the graphite-vacuum test from set 10.

There was no significant attack of unalloyed tungsten in any of the tests at 1400°C. Grain boundary grooving to less than 0.1 mil was noted in specimens from sets 7 and 8, (Figs. 33 and 34) and the specimen from set 8 bonded to the capsule. The $^{244}\text{Cm}_2\text{O}_3$ redistribution was slight, even under the vacuum environment. Control test results indicated no significant interaction with carbon at this temperature.

Very similar results to unalloyed tungsten were found for W-26% Re alloy as shown in Tables 16 and 17, and Figs. 35 and 36. In two tests (sets 7 and 10) metal particles were noted in the fuel. In previous tests³ of this alloy at 1650 and 1850°C, these particles were identified as tungsten.

SUMMARY AND CONCLUSIONS

These experiments were conducted to (1) determine the materials having the best potential for containment of $^{244}\text{Cm}_2\text{O}_3$ in several temperature regimes (900, 1100, and 1400°C), (2) determine the effect of graphite on compatibility, and (3) determine whether mass transport would reduce the size of or plug a small vent hole (0.005 in. in diameter) in the system.

³J. R. DiStefano and K. H. Lin, "Compatibility of Refractory Metals with $^{244}\text{Cm}_2\text{O}_3$," *Nucl. Technol.* 19(7): 34-45 (1973).

Fig. 27. T-111- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C.

Fig. 28. T-111-²⁴⁴Cm₂O₃ After 5000 hr at 1400°C.

Fig. 29. Molybdenum- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C .

Fig. 30. Molybdenum- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C .

Fig. 31. Mo-46% Re- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C.

Fig. 32. Mo-46% Re- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C.

Fig. 33. Tungsten- $^{244}\text{Cm}_2\text{O}_3$ After 5000 hr at 1400°C .

Fig. 34. Tungsten-²⁴⁴Cm₂O₃ After 5000 hr at 1400°C.

HELIUM - BeO

HELIUM - GRAPHITE

Fig. 35. W-26% Re-²⁴⁴Cm₂O₃ After 5000 hr at 1400°C.

Fig. 36. W-26% Re-²⁴⁴Cm₂O₃ After 5000 hr at 1400°C.

Tests at 900°C

The $^{244}\text{Cm}_2\text{O}_3$ was tested with ten different materials and corrosion rates were small to negligible. Materials containing strong oxide formers did, however, pick up oxygen; and the alloy Hastelloy C-276 picked up carbon in a graphite system test. No other effects of graphite on compatibility were noted and vent holes were clean. There was no significant redistribution of $^{244}\text{Cm}_2\text{O}_3$. Noble metals and graphite were particularly inert under the test conditions. For RTG applications in this temperature range future tests should focus on evaluating combinations of materials proposed for actual systems to determine whether dissimilar metal interactions will occur.

Tests at 1100°C

Noble metals and graphite were selected for evaluation after 2500 hr. Of the materials tested only platinum was not satisfactory. Platinum reacted with $^{244}\text{Cm}_2\text{O}_3$ under all test conditions (vacuum or helium, graphite, or Al_2O_3) to form a compound believed to be Pt_5Cm . However, platinum containing 25% Ir (Pt_3Ir) or 26% Rh-8% W (Pt -2608) showed only slight evidence of attack. Graphite showed no evidence of attack by $^{244}\text{Cm}_2\text{O}_3$, and did not interact with any of the noble metals. The redistribution of $^{244}\text{Cm}_2\text{O}_3$ was slight and all vent holes were clean.

Tests at 1400°C

Graphite and iridium were the only materials tested at 1400°C that were also tested at 900 and 1100°C. Both were almost completely inert to $^{244}\text{Cm}_2\text{O}_3$ at the lower temperatures, but graphite reacted significantly at 1400°C. Iridium, along with tungsten and W-26% Re, showed little tendency to react at 1400°C in these simulated RTG systems. Molybdenum and Mo-46% Re showed good compatibility with $^{244}\text{Cm}_2\text{O}_3$, but significantly reacted with graphite.

Tantalum and the alloy T-111 (Ta-10% W-2% Hf) were also tested at 1400°C. Previously tantalum and Ta-10% W were tested with $^{244}\text{Cm}_2\text{O}_3$ at 1250°C, and all three materials at 1650 and 1850°C.⁴ At 1400 and 1650°C the tantalum alloys were attacked along grain boundaries while unalloyed tantalum was not. At 1250 and 1850°C there was very little evidence of grain-boundary attack in any of the materials. Because T-111 shows grain-boundary attack at 1400°C, it appears less suitable than tantalum as a container for $^{244}\text{Cm}_2\text{O}_3$. However, both tantalum and T-111 reacted with graphite indicating that neither would be satisfactory in systems where they would be in contact with graphite. Redistribution of $^{244}\text{Cm}_2\text{O}_3$ occurred in most of the 1400°C tests in vacuum. However, no evidence of mass transfer was noted in any of the vent holes examined.

These and other compatibility studies of $^{244}\text{Cm}_2\text{O}_3$ with various containment materials have indicated that several types of reactions occur:

⁴J. R. DiStefano and K. H. Lin, "Compatibility of Refractory Metals with $^{244}\text{Cm}_2\text{O}_3$," *Nucl. Technol.* 19(7): 34-45 (1973).

Reactions (1) and (2) involve oxidation of the metal component(s) of the system and the formation of substoichiometric curium sesquioxide. Reaction (2) might well occur in systems with tantalum or tantalum-hafnium alloys, which have a high affinity for oxygen. In the alloy T-111 a white, hafnium-rich phase has been identified in grain boundaries after exposure to $^{244}\text{Cm}_2\text{O}_3$ at 1400°C, which suggests reaction (1) could have occurred. There was no evidence that reactions of this type occurred at either 900 or 1100°C.

Reaction (3) has been found to occur between PuO_2 and platinum under reducing conditions.⁵ Under these conditions substoichiometric PuO_{2-x} may form resulting in a higher plutonium activity, which supports compound formation. The reaction does not occur under oxidizing conditions. Studies of Cm_2O_3 have been limited but Smith⁶ found no oxide lower than Cm_2O_3 after hydrogen reduction at 2000°C. The reaction between platinum and Cm_2O_3 occurred in helium or vacuum at 1100°C, and electron-beam microprobe data indicated the reaction product to contain platinum and curium, suggesting reactions (3) or (4) could have occurred. However, oxygen in the reaction product could not be determined. When the activity of platinum was lower, such as in Pt-2608 or Pt₃Ir, the reaction was eliminated at 1100°C.

Many of the materials exposed to $^{244}\text{Cm}_2\text{O}_3$ contain subsurface voids and/or evidence of grain-boundary attack. The voids may be diffusion or Kirkendall voids associated with chemical interactions such as described by reactions (1) through (4). In the 1400°C tests (and tests at higher temperatures⁴) we noted some smaller voids at discreet levels below the surface of the exposed metals or alloy. These may have been formed by the coalescence into bubble of helium atoms injected into the metal from the alpha decay of ^{244}Cm . Grain-boundary attack suggests some particular

⁵J. E. Selle, J. R. McDougal, and D. R. Shaeffer, *The Compatibility of Plutonium-238 Dioxide with Platinum and Platinum-Rhodium Alloys: Interim Report*, MLM-1684, Mound Laboratory, (Jan. 30, 1970).

⁶P. K. Smith and D. E. Peterson, *High-Temperature Evaporation and Thermodynamic Properties of Cm_2O_3* , DP-MS-67-110, Savannah River Laboratory, (October 1968).

element or phase is being dissolved by the $^{244}\text{Cm}_2\text{O}_3$. Although not well understood, reactions of this type have been reported in other metal-rare earth oxide systems.⁷⁻¹⁰

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⁷J. E. Selle, *A Summary of the Phase Diagrams and Compatibility of PuO_2 with Various Materials*, MLM-1589, Mound Laboratory, (April 21, 1969).

⁸D. R. Schaeffer, *The Compatibility of $^{238}\text{PuO}_2$ with Various Nickel and Cobalt Base Alloys*, MLM-1864, Mound Laboratory, (January 10, 1972).

⁹J. R. DiStefano, "Compatibility of Strontium Compounds with Superalloys at 900 and 1100°C," *Nucl. Technol.* 17(2): 127-42 (1973).

¹⁰J. R. DiStefano, *Compatibility of Eu_2O_3 with Type 316 Stainless Steel and Sodium*, ORNL-TM-4780 (January 1975).

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84. A. L. Mowery, Division of Space Nuclear Systems, ERDA
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91. B. J. Rock, Division of Space Nuclear Systems, ERDA
92. E. H. Sayell, General Electric Company
93. A. Schock, Fairchild Space and Electronics Company
94. C. O. Tarr, Division of Space Nuclear Systems, ERDA
95. N. R. Thielke, Division of Space Nuclear Systems, ERDA
96. R. H. Titran, Lewis Research Center
97. V. Truscello, Jet Propulsion Laboratory
98. D. R. Turno, Savannah River Laboratory
99. E. J. Wahlquist, Division of Space Nuclear Systems, ERDA
100. R. L. Wainwright, Dayton Area Office, ERDA
101. A. Wilbur, Ames Research Center, NASA
102. E. W. Williams, General Electric Company
103. Directorate of Nuclear Safety, Kirtland, AFB
104. Research and Technical Support Division, ERDA, ORO
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