663347

DP-1310

AEC RESEARCH AND DEVELOPMENT REPORT

SAVANNAH RIVER LABORATORY COBALT-60 POWER AND HEAT SOURCES

QUARTERLY PROGRESS REPORT

APRIL - JUNE 1972

[redacted]

Savannah River Laboratory

Aiken, South Carolina

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 $3.00; Microfiche $0.95

663347

DP-1310

UC-23, Radioisotope and Radiation Applications
UC-33, Propulsion Systems and Energy Conversion
(TID-4500, 59th Ed.)

SAVANNAH RIVER LABORATORY COBALT-60 POWER AND HEAT SOURCES

QUARTERLY PROGRESS REPORT

April-June 1972

Compiled by

C. L. Angerman

Published
August 1972

E. I. DU PONT DE NEMOURS & COMPANY
SAVANNAH RIVER LABORATORY
AIKEN, S. C. 29801

CONTRACT AT(07-2)-1 WITH THE
UNITED STATES ATOMIC ENERGY COMMISSION

PREFACE

This report is one in a series on the applied aspects of ^{60}Co that are under study at the Savannah River Laboratory (SRL). These reports are intended to present data that are useful to system designers and also to potential or active user agencies. The reports thus deal with the following subject areas of SRL programs:

1. Properties and reactions of ^{60}Co fuel forms useful or potentially useful as heat sources.

2. Information on the irradiation and postirradiation processing of these materials, when the information is relevant to their use as heat sources and is not in a sensitive area of production technology.

3. Development of design data directed toward the use of and manufacturing capability for isotopic heat sources.

This report contains principally data from work performed during the report period. Previous reports are listed in the Publications section.

SUMMARY

No detrimental effects of the compatibility or oxidation reactions were indicated by measurements of the hardnesses of these zones in superalloy capsules heated up to 20,000 hr at 1000°C. (p 3)

Satisfactory performance was demonstrated for 10,000 hr in vacuum at 1400°C with a W-25 wt % Re alloy capsule containing inactive Co metal wafers. (p 5)

Satisfactory encapsulation of inactive CoO wafers in iridium was prevented by previously undetected cracks in the as-machined capsule components and the as-received stock material. (p 8)

The Nickel 201 being used to fabricate the core of the WANL demonstration heat source exhibited satisfactory oxidation resistance in 2000-hr tests at 1000 and 1125°C. (p 12)

The thermoelectric generator fueled with ^{60}Co continued to operate satisfactorily after 16 months with an electrical output of 51.1 watts. (p 12)

CONTENTS

PROGRAM

The purpose of the Savannah River Laboratory (SRL) program on ^{60}Co is to provide data that will be required for designing, fabricating, and operating ^{60}Co heat sources. Primary emphasis is on selecting materials for encapsulating cobalt fuel forms and establishing temperature limits for operation of capsules in normal and accident environments. Development of specific heat source concepts is not at present included in the scope of the SRL program, but assistance is provided when required for the development and testing of demonstration units.

MATERIALS TECHNOLOGY AND DEVELOPMENT

CAPSULE MATERIALS FOR RADIOACTIVE COBALT

Corrosion in Marine Environments

Corrosion tests in sea water and bottom mud are continuing with samples of cobalt fuel forms and candidate capsule materials. The tests are being performed by the International Nickel Company at their Francis L. LaQue Corrosion Laboratory in Wrightsville Beach, N. C. Materials in test include bare and nickel-plated cobalt metal, CoO, $CoAl_2O_4$, $Co_{0.5}Mg_{0.5}O$, "Inconel"* 600, "Hastelloy"** C, "Hastelloy" X, "Haynes"** 25, "Haynes" 188, tungsten, tungsten-25 wt % rhenium (W-25 wt % Re) alloy, and samples cut from various inactive superalloy capsules that were previously heated for up to 22,500 hr at 1000°C. The effects of 61 days (1464 hr) exposure were described previously;[1] exposure for 5000 hr will be completed in July.

The lattice parameter of the CoO-MgO wafer exposed to seawater for 61 days was measured by X-ray diffraction. The value obtained corresponded to a composition of $Co_{0.6}Mg_{0.4}O$ instead of the $Co_{0.5}Mg_{0.5}O$ originally present. This result is consistent with the hypothesis that leaching of MgO from the solid solution wafers is the cause of the weight losses observed in seawater and fresh water corrosion tests of this compound.

* Trademark of International Nickel Co.
** Trademark of Cabot Corp.

Oxidation of Iridium

The oxidation of iridium, a candidate capsule material for ceramic cobalt compounds (CoO, $Co_{0.5}Mg_{0.5}O$, and $CoAl_2O_4$), was measured for comparison with literature data.[2] Two pieces of bar stock, one in the as-received condition and one with a weld bead around the edge on one side, were exposed to ambient furnace air at 1125°C for two 500-hr periods. The weight losses were the same for the two 500-hr periods, indicating that oxidation proceeded at the linear rate expected because iridium oxide is volatile. Volatilization occurred preferentially at the grain boundaries, producing 0.018-in. penetration in wrought metal but only 0.007-in. penetration in weld metal, Figure 1.

Measurement of the thickness of residual sound wrought metal showed that the total depth affected by oxidation was 0.048-in. after 1000 hr. This high rate indicates that iridium capsules would have to be protected from oxidation (by re-encapsulation in platinum or by coating the surface as is done for refractory metals) for safe use in a heat source, particularly under accident conditions. No additional oxidation tests are planned.

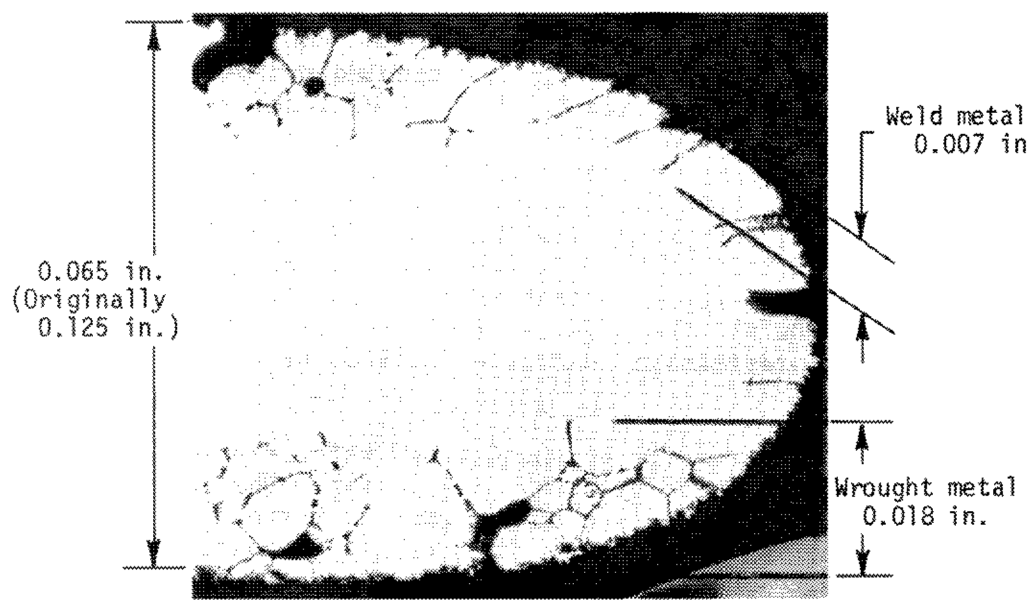

Fig. 1 IRIDIUM OXIDIZED 1000 hr AT 1125°C

CAPSULE FABRICATION AND TESTING

Heating Tests of Capsules with Unirradiated Cobalt Metal

Superalloy Capsules

The potential effect of compatibility and oxidation reactions on the strength of superalloys was assessed by measuring the Diamond Pyramid Hardness (DPH) of the reaction zones in "Hastelloy" C, "Hastelloy" X, and "Haynes" 25 capsules previously heated 20,000 hr at 1000°C and in an "Inconel" 600 capsule heated 10,000 hr at 1000°C. The reference hardnesses of the superalloys were measured by the averages of five indentations in the midplane of the capsule wall and in the center of the cap; no differences existed between the two regions. The hardness of the cobalt was measured by the average of ten indentations along the midplane of one cobalt wafer in each capsule. These data are compared in Table I with similar data from diffusion couples and other capsules heated at 1000°C for 168 hr and 1000 hr, respectively.

TABLE I

Diamond Pyramid Hardness of Cobalt and Superalloys after Heating at 1000°C

	Ave. Hardness (DPH), 1000-g load)			
	Couples	Capsules		
	168 hr	1000 hr	10,000 hr	20,000 hr
Cobalt metal	250	-	166	168
"Inconel" 600	-	165	125	-
"Hastelloy" C	-	286	-	311
"Hastelloy" X	175	-	-	191
"Haynes" 25	258	-	-	311

No detrimental effects of the reactions are indicated by the hardness data. Except for the apparent softening in the vicinity of the voids present in the compatibility zone, the hardness of this zone was intermediate between that of the superalloy and the cobalt. Reductions in hardness in the oxidation-affected zone varied from 10% for "Hastelloy" X to 25% for "Haynes" 25. These same trends were observed in the samples heated for shorter periods. The reductions in hardness of the cobalt and "Inconel" 600 with increased heating time are due to grain growth, while the increases in hardness of the "Hastelloys" and "Haynes" 25 are due to precipitation of alloy phases.

Heating tests at 850 to 1000°C are continuing toward 50,000 hr with seven superalloy capsules, Table II.

TABLE II

Summary of ^{59}Co Capsule Heating Tests

Capsule Material	Heating Time, hr	Heating Temp, °C	Wall, mils	No. of Capsules	Approx. Starting Date	Approx. Completion Date	Remarks
"Inconel" 600 (m.p. 1370°C)	1,000	850	50	1	12-66	2-67	Capsule intact
	5,000	850	50	1	12-66	7-67	Capsule intact
	10,000	850	50	1	12-66	1-68	Capsule intact
	10,000	850	95	1	7-67	9-68	Capsule intact
	50,000	850	95	1	7-67	3-73	Intact at 37,200 hr
	1,000	900	95	1	11-68	12-68	Capsule intact
	5,000	900	95	1	11-68	6-69	Capsule intact
	5,000[e]	900	95	1	3-69	10-69	Increased Co/capsule reaction
	10,000	900	95	1	11-68	1-70	Capsule intact
	20,000	900	95	1	11-68	5-71	Capsule intact
	10,000[e]	900	95	1	3-69	5-70	Increased Co/capsule reaction
	50,000	900	95	1	11-68	7-74	Intact at 27,400
	1,000	1,000	50	4	8-66	10-66	3 capsules intact; 1 capsule oxidized[b]
	5,000	1,000	50	1	4-67	11-67	Capsule intact
	1,000[a]	1,000	95	2	7-67	9-67	No severe oxidation of Co
	1,000[d]	1,000	95	1	2-68	4-68	No oxidation of Co or capsule
	5,000[d]	1,000	95	1	2-68	9-68	No oxidation of Co or capsule
	5,000	1,000	95	1	8-67	2-68	Capsule intact
	10,000	1,000	95	1	8-67	10-68	Capsule intact
	50,000	1,000	95	1	10-67	6-73	Intact at 39,400 hr
	10,000[d]	1,000	95	1	11-68	1-70	No oxidation of Co or capsule
"Hastelloy" C (m.p. 1270°C)	1,000	1,000	50	4	8-66	10-66	3 capsules intact; 1 capsule oxidized[b]
	5,000	1,000	95	1	10-67	5-68	Capsule intact
	10,000	1,000	95	1	10-67	12-68	Capsule intact
	50,000	1,000	95	1	10-67	6-73	Intact at 39,400 hr
	20,000	1,000	95	1	5-68	9-70	Capsule intact
TD Nickel (m.p. 1450°C)	1,000	850[c]	95	1	10-67	12-67	Capsule intact
	5,000	850	95	1	10-67	5-68	Capsule intact
	10,000	850	95	1	10-67	12-68	Capsule intact
	50,000	850	95	1	10-67	6-73	
	1,000	1,000	95	1	12-66	2-67	Capsule intact
	1,000[a]	1,000	95	2	10-67	12-67	No severe oxidation of Co
TD Nickel Chromium (m.p. 1430°C)	1,000[a]	1,000	95	2	10-67	12-67	Co near pinhole oxidized
	1,000	1,000	95	1	10-67	12-67	Capsule intact
	5,000	1,000	95	1	10-67	5-68	Capsule intact
	10,000	1,000	95	1	10-67	12-68	Capsule intact
	50,000	1,000	95	1	10-67	6-73	Intact at 39,400 hr
"Haynes" 25 (m.p. 1330°C)	10,000	850	95	1	11-68	1-70	Capsule intact
	1,000	1,000	95	1	10-67	12-67	Capsule intact
	5,000	1,000	95	1	10-67	5-68	Capsule intact
	5,000	1,000	95	1	5-68	12-68	Capsule intact
	10,000	1,000	95	1	10-67	12-68	Capsule intact
	29,300	1,000	95	1	10-67	11-70	Failed at 29,300 hr from oxidation
	20,000	1,000	95	1	5-68	9-70	Capsule intact
"Hastelloy" X (m.p. 1260°C)	1,000	1,000	50	1	4-67	6-67	Capsule intact
	5,000	1,000	50	1	4-67	11-67	Capsule intact
	5,000	1,000	95	2	2-68	9-68	Capsules intact
	10,000	1,000	95	1	2-68	4-69	Capsule intact
	50,000	1,000	95	1	2-68	10-73	Intact at 32,400 hr
	20,000	1,000	95	1	5-68	9-70	Capsule intact
	22,500	1,000	95	1	5-68	12-70	Capsule intact

[a] Two capsules, one not welded and one with drilled hole in wall, to test effects of capsule defects.
[b] Capsules reacted with fire-brick. See DP-1094, "SRL Isotopic Power and Heat Sources - Quarterly Progress Report," October-December 1966.
[c] Tests of TD Nickel at 850°C in flowing argon. [d] Internal atmosphere air instead of helium.
[e] Caustic residue on wafers.

Refractory Metal Capsules

Satisfactory performance was demonstrated with an inactive W-25 wt % Re alloy capsule heated 10,000 hr in vacuum at 1400°C, Table III. Nondestructive tests showed that the capsule was intact and the diameter increase was 0.001 in. The total width of the compatibility reaction zone was 0.068 in., including a 0.022-in.-wide intermetallic layer in the capsule wall and a 0.046-in.-wide zone of voids in the cobalt, Figure 2. Since it was heated in vacuum, there was no reaction zone on the exterior of the capsule.

TABLE III

^{59}Co – Refractory Metal Capsule Tests[a]

Capsule Material	Heating Time, hr	Heating Temp, °C	Approx. Starting Date	Approx. Completion Date	Welding Diameter, inch	Welding Technique	Remarks
Tungsten	1,000	1,200	9/70	4/71	0.745	TIG	Capsule intact
	10,000	1,200	9/70	7/72	0.745	TIG	
W-25 wt % Re	1,000	1,200	8/70	10/70	0.745	TIG	Capsule intact
	1,000	1,400	8/70	10/70	0.745	TIG	Capsule intact
	5,000	1,400	8/70	6/71	0.745	TIG	Capsule intact
→	10,000	1,400	8/70	3/72	0.745	TIG	Capsule intact

a. One capsule containing ~10 Co wafers 0.073 in. thick at each listed condition.
→ New information reported.

Comparison of these widths with those in other capsules previously heated 1000 and 5000 hr at 1400°C showed that the compatibility zone grew more slowly than observed in superalloys, Figure 3. The data predict that 0.035 in. of the wall would be affected after 50,000 hr at 1400°C. The increase in thickness was nearly proportional to the cube root of the heating time instead of the square root of time as observed with superalloys and predicted by diffusion theory. Departures from theory have been observed in many systems.[3,4] In the case of this capsule, the observed kinetics may result from the fact that the heating temperature is near the melting point of the cobalt but relatively low for the W-Re alloy; on the absolute temperature scale 0.95 T_m for cobalt and 0.50 T_m for the alloy.

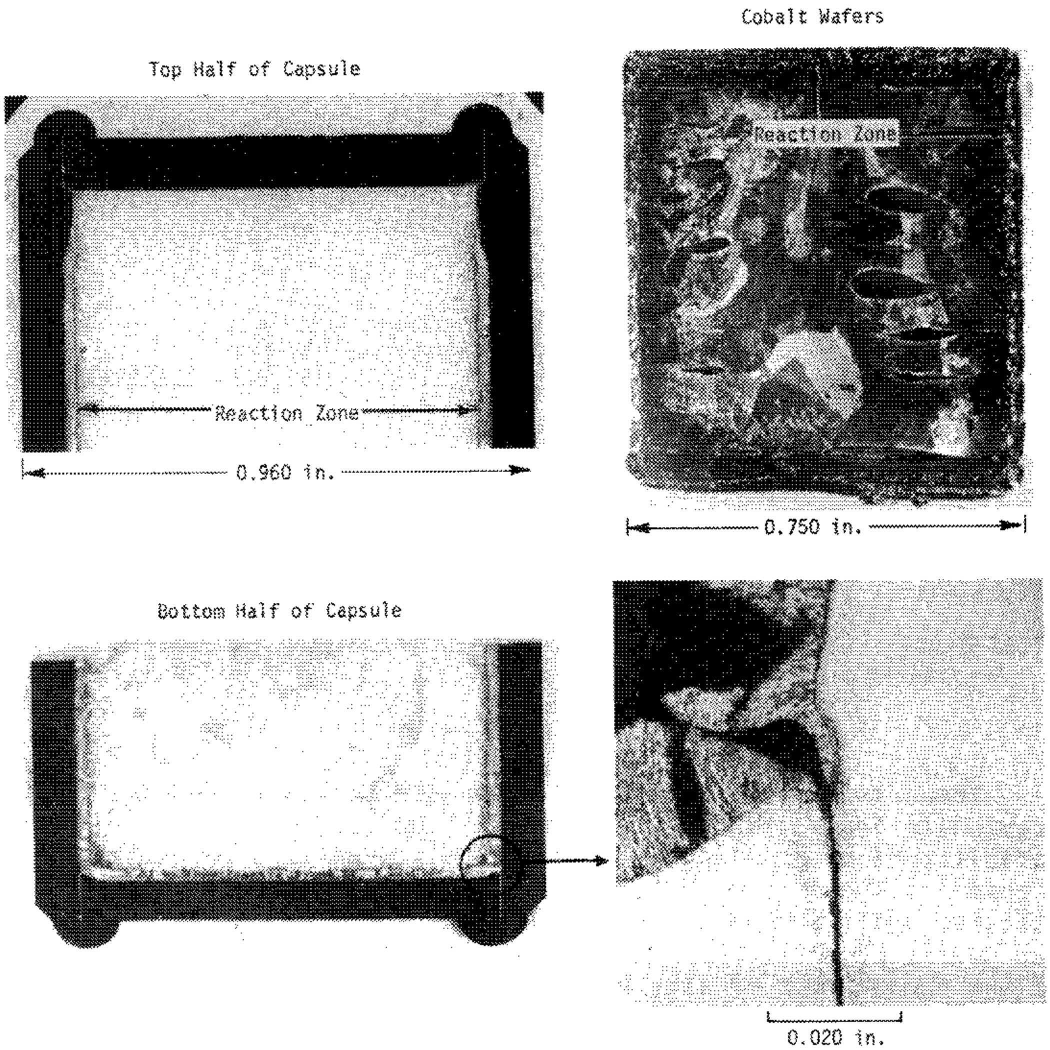

Fig. 2. W-Re ALLOY CAPSULE HEATED 10,000 hr AT 1400°C

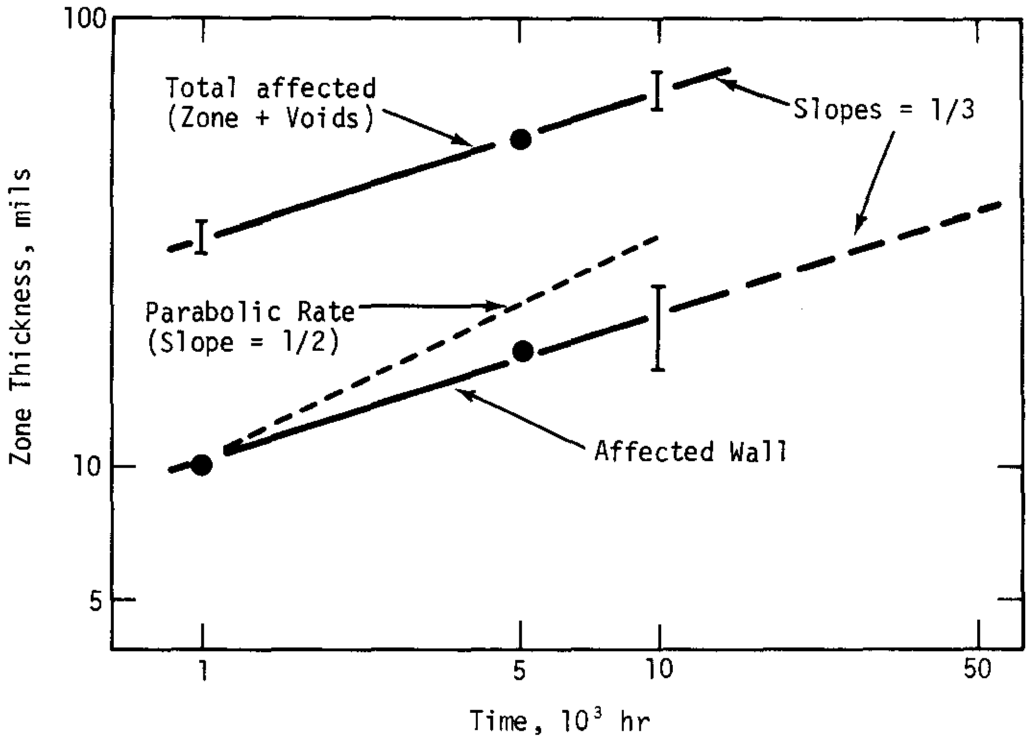

Fig. 3. GROWTH OF COMPATIBILITY ZONES IN W-Re CAPSULES AT 1400°C

A similar inactive tungsten capsule will attain a goal exposure of 10,000 hr at 1200°C in vacuum in July and will be examined.

Heating Tests of Capsules with Irradiated Cobalt Metal

Cobalt-60 Test Facility

Practice operation of the Cobalt Test Facility (CTF) is continuing with unirradiated materials. Modifications to the equipment are being made to improve safety and remote operability. Upon completion of this work, the five superalloy capsules currently in storage in the High Level Caves (HLC), Table IV, are scheduled to be transferred to the CTF and heating tests resumed toward goal exposures of 50,000 hr at 900 and 1000°C.

TABLE IV

Summary of ^{60}Co Capsule Heating Tests

Capsule Material	Heating Time, hr	Heating Temp, °C	Wall, mils	No. of Capsules	Activity Spec, Ci/g	Activity Total, Ci	Approx. Starting Date	Approx. Completion Date	Remarks
"Inconel" 600 (m.p. 1370°C)	130	850[a]	50	1	120	16,000	2-67	2-67	Swelled due to overheating
	1,000	∿900	50	1	100	5,000	4-67	6-67	Capsule intact
	5,000	∿900	50	1	150[b]	15,000	4-67	10-67	Capsule intact
	10,000	∿900	50	1	150[b]	15,000	4-67	6-68	Increased Co/capsule reaction
	11,000	∿900	50	1	150[b]	9,000	5-67	10-68	Increased Co/capsule reaction
	10,380	900	95	1	255[c]	36,500	2-68	8-69	Increased Co/capsule reaction
	19,460	900	95	1	288[c]	13,700	7-68	11-70	Capsule intact
	50,000	900	95	1	282[c]	13,400	7-68	4-74	In storage
	4,660	1,000	95	1	295[c]	14,000	9-68	4-69	Capsule intact
	9,380	1,000	95	1	288[c]	13,700	9-68	11-69	Capsule intact
	18,100	1,000	95	1	263[c]	12,500	9-68	3-71	Capsule intact
	50,000	1,000	95	1	255[c]	12,100	9-68	1-75	In storage
	9,740	850	95	2[e]	[d]	-	9-68	11-69	Capsule intact
"Hastelloy" C (m.p. 1270°C)	100	850	50	1	120	9,000	1-67	1-67	Capsule intact
	9,740	900	95	1	276[c]	13,100	7-68	8-69	Capsule intact
	9,650	1,000	95	1	282[c]	13,400	9-68	11-69	High He leak rate
	50,000	1,000	95	1	270[c]	12,800	9-68	1-75	In storage
"Haynes" 25 (m.p. 1330°C)	4,660	1,000	95	1	263[c]	12,500	9-68	4-69	Capsule intact
	9,650	1,000	95	1	288[c]	13,700	9-68	11-69	Capsule intact
	18,100	1,000	95	1	282[c]	13,400	9-68	3-71	Capsule intact
	50,000	1,000	95	1	295[c]	14,000	9-68	1-75	In storage
"Hastelloy" X (m.p. 1260°C)	4,660	1,000	95	1	250[c]	11,900	9-68	4-69	Capsule intact
	9,380	1,000	95	1	263[c]	12,500	9-68	11-69	Capsule intact
	18,360	1,000	95	1	263[c]	12,500	9-68	3-71	Capsule intact
	50,000	1,000	95	1	301[c]	14,300	9-68	1-75	In storage

a. Excursion to >1100°C for 3-6 hr.
b. Activity as of 2-67.
c. Activity as of 6-68.
d. Capsules contain ^{59}Co but heated along with ^{60}Co capsules.
e. One of these capsules was incorrectly identified during fabrication as "Haynes" 25.

Heating Tests of Capsules with Unirradiated Cobalt Compounds

Iridium Capsules

Encapsulation was begun of inactive ceramic wafers (CoO, $Co_{0.5}Mg_{0.5}O$, and $CoAl_2O_4$) in iridium. An iridium capsule containing CoO wafers (lowest melting point) was welded, Figure 4. Both welds appeared to be sound but leak tests indicated a leak through the cap at one end, Figure 5. Metallographic examination indicated that the CoO wafers had not been affected by the heat from the welding. Cracks were also found in both end caps outside the heat affected zones, Figure 6. These cracks were apparently the result of pre-existing defects, rather than stresses from welding, since die penetrant examination revealed similar cracks both in other machined capsule components and as-received stock material. Sound components, as selected by leak testing, will be assembled and welded in an attempt to produce sound capsules. Proposed capsule test program is given in Table V.

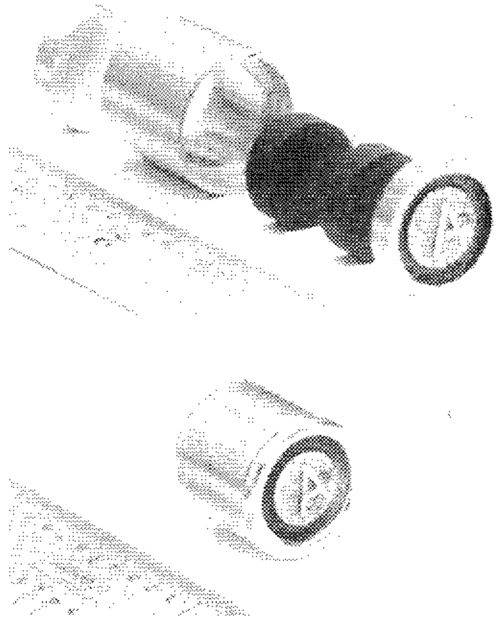

Fig. 4. IRIDIUM CAPSULE CONTAINING CoO WAFERS

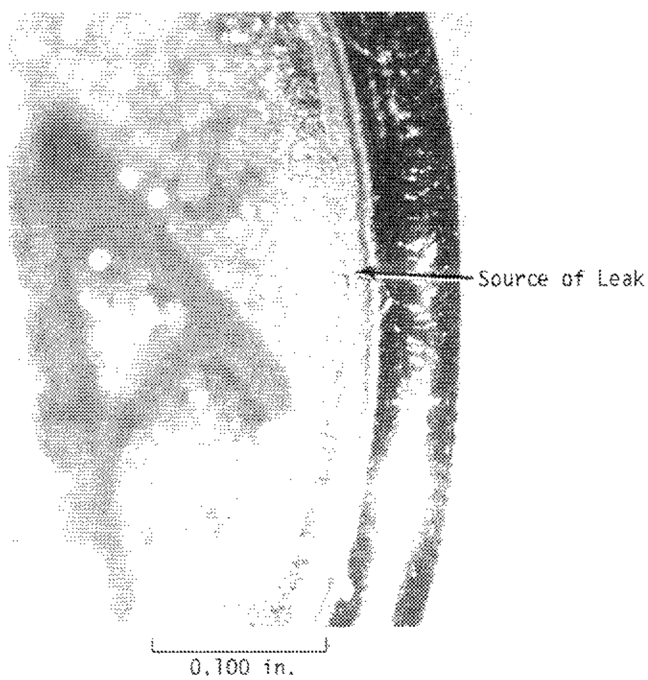

Fig. 5. SOURCE OF LEAK LOCATED BY BUBBLE TEST

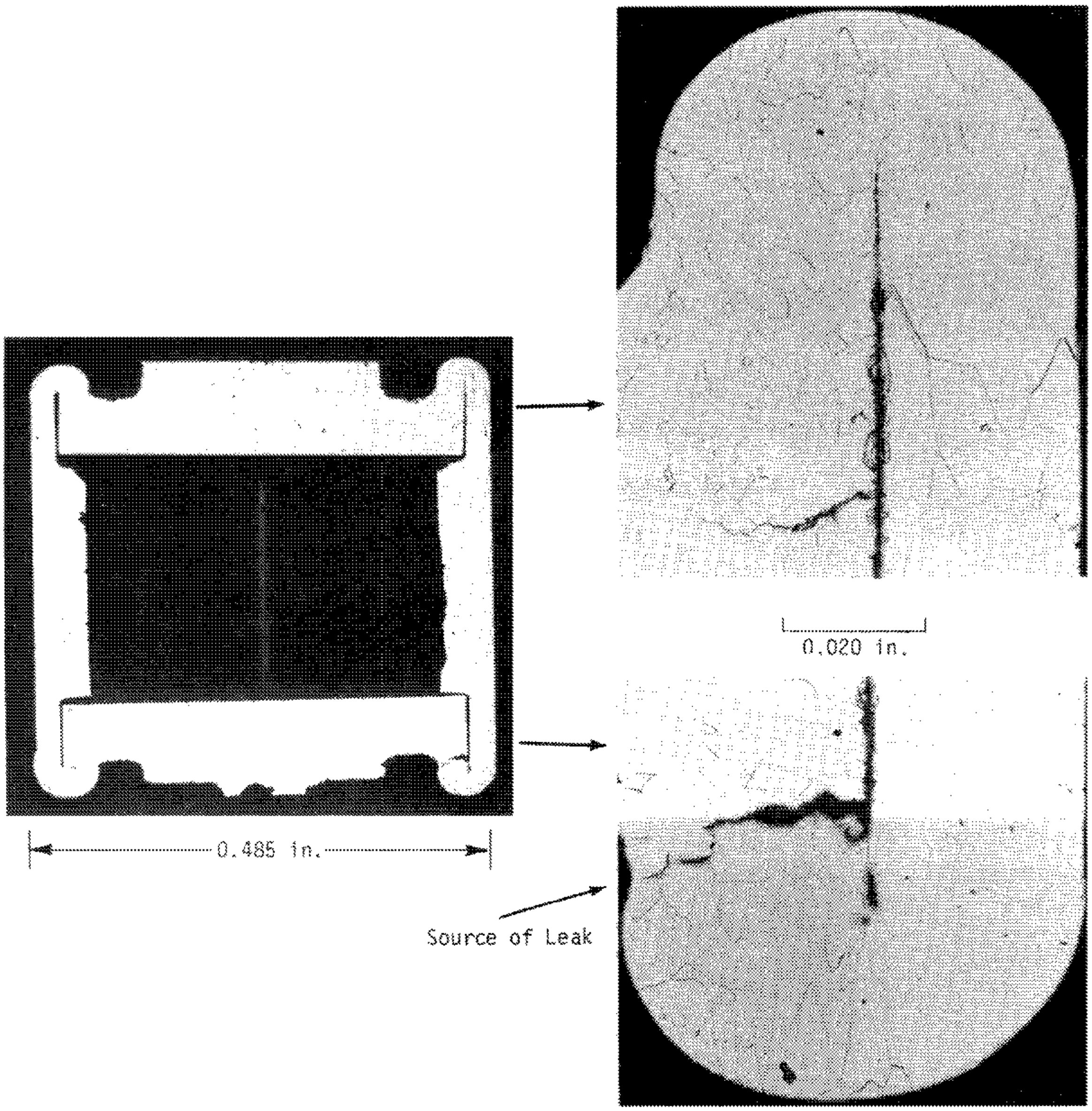

Fig. 6. WELDED IRIDIUM CAPSULE

TABLE V

^{59}Co Compound-Iridium Capsule Tests[a]

Fuel Compound	Time, hr	Temp, °C	Approx. Starting Date	Approx. Completion Date
CoO	1,000	1,600	8-72	10-72
	5,000	1,600	8-72	3-73
	10,000	1,600	10-72	12-74
$Co_{0.5}Mg_{0.5}O$	1,000	1,600	8-72	10-72
	5,000	1,600	8-72	3-73
	10,000	1,600	10-72	12-74
	1,000	2,000	8-72	10-72
	5,000	to be selected	10-72	5-73
	10,000	to be selected	10-72	12-74
$CoAl_2O_4$	1,000	1,600	8-72	10-72
	5,000	1,600	8-72	3-73
	10,000	1,600	10-72	12-74
	1,000	1,800	8-72	10-72
	5,000	to be selected	10-72	5-73
	10,000	to be selected	10-72	12-74

a. One capsule at each condition listed. Capsules will contain 2 wafers 0.354-in.-dia by 0.115-in. thick and will be sealed by TIG welding.

HEAT SOURCE DEMONSTRATION TESTS

WANL 30 kw(t) UNIT

SRL is providing the irradiated cobalt metal wafers as well as technical assistance in the program to design, fabricate, and test an experimental heat source containing 2 MCi (30 kw) of ^{60}Co. Westinghouse Astronuclear Laboratory is the contractor for this project.

Oxidation of Hastelloy X

Long-term oxidation of "Hastelloy" X is being measured on samples from the actual heat being used to fabricate the fuel capsules and fuel pins for the heat source. Exposure of one sample at 1000°C is continuing toward 10,000 hr; results of shorter-term tests were reported previously.[1]

Oxidation of Nickel 201

Long-term oxidation tests continued on samples from the actual heat of Nickel 201 being used to fabricate the core of the heat source. Tests for 2000 hr at 1000 and 1125°C were completed. The adherent scale formed at 1000°C was 0.015-in. thick and that formed at 1125°C was 0.035-in. thick. These values agree with those predicted by parabolic extrapolation of data from previous shorter-term tests. Tests are continuing for up to 10,000 hr at 1000°C and 3000 hr at 1125°C.

SRL THERMOELECTRIC GENERATOR

More than sixteen months of satisfactory operation were completed by the ^{60}Co-fueled thermoelectric generator. The measured electrical output after 500 days operation was 51.1 watts compared to an estimated 80.1 watts at the time of fueling in February, 1971. The panel-mounted ammeter used prior to June has been reading $\sim$5% high, so all power outputs reported to date have been adjusted accordingly. The rate of decrease in power output continues to be slightly greater than the square of the ^{60}Co decay, as discussed previously.[5]

^{60}Co LOAN PROGRAM

Because of the potential application of high-activity cobalt metal in heat sources, the AEC has established a loan program for the material. About 9 MCi (140 kw) of ^{60}Co at over 300 Ci/g Co are available for this program. Most of this material is in the form of 0.745-in.-dia wafers, plated with nickel. Individual companies or groups of companies are invited to participate by contacting the Savannah River Operations Office of the AEC. Moderate activities and amounts of ^{60}Co can be obtained commercially.

Radioactive cobalt metal shapes available under this loan program are listed in Table IV.

Table IV

^{60}Co Metal for Heat Source Development

(Activity as of 12/31/71)

	No. of Pieces	Wt of Co, g/piece	Avg Sp Activity, Ci/g Co	Total Activity, MCi	Total Power, kw(t)
Wafers, 0.040-in. thick					
0.745-in. dia.	2090	2.5	220	1.15	17.9
	3800	2.5	175	1.67	26.0
0.800-in. dia.	391	2.8	200	0.22	3.4
Wafers, 0.073-in. thick					
0.745-in. dia.	3080	4.5	410	5.71	89.0
	2360	4.5	310	3.25	50.6
	4560	4.5	175	3.60	56.0
Half-wafers, 0.073-in. thick					
1.00-in. dia.	682	4.1	260	0.74	11.5
1.25-in. dia.	434	6.4	260	0.73	11.3
1.49-in. dia.	620	9.1	260	1.48	23.1
Slabs,					
3.00 x 0.64 x 0.060-in. Ni-plated	93	16.6	200	0.31	4.8
2.96 x 0.735 x 0.092-in. SST-canned	93	13.5	200	0.25	3.9
3.00 x 0.740 x 0.072-in. SST-bonded	124	11.8	200	0.30	4.7
Total				19.4	302

SAVANNAH RIVER LABORATORY ^{60}Co PUBLICATIONS

QUARTERLY PROGRESS REPORTS

"Savannah River Laboratory Power and Heat Sources Quarterly Progress Report"

DP-1088	July - September 1966
DP-1094	October - December 1966
DP-1105-I	January - March 1967, Part I - Cobalt
DP-1120-I	April - June 1967, Part I - Cobalt
DP-1129-I	July - September 1967, Part I - Cobalt
DP-1143-I	October - December 1967, Part I - Cobalt
DP-1155-I	January - March 1968, Part I - Cobalt
DP-1169-I	April - June 1968, Part I - Cobalt
DP-1177-I	July - September 1968, Part I - Cobalt
DP-1192-I	October - December 1968, Part I - Cobalt
DP-1196-I	January - March 1969, Part I - Cobalt
DP-1206-I	April - June 1969, Part I - Cobalt
DP-1216	July - September 1969
DP-1226	October - December 1969
DP-1237	January - March 1970
DP-1247	April - June 1970
DP-1254	July - September 1970
DP-1267	October - December 1970
DP-1272	January - March 1971
DP-1279	April - June 1971
DP-1286	July - September 1971
DP-1293	October-December 1971
DP-1300	January-March 1972

TOPICAL REPORTS

DP-974	"^{60}Co Heat Sources for 10-60 kw(e) Generators" by A. H. Dexter, July 1965.
DP-1012	"Radioactive Cobalt for Heat Sources" by J. W. Joseph, H. F. Allen, C. L. Angerman, and A. H. Dexter, October 1965.
DP-1051 (Rev. 2)	"Properties of ^{60}Co and Cobalt Metal Fuel Forms", June 1968.
DP-1096	"Development of ^{60}Co Capsules for Heat Sources" by C. P. Ross, C. L. Angerman, and F. D. R. King, June 1967.
DP-1145	"Experimental ^{60}Co Heat Source Capsules" by J. P. Faraci, May 1968.

JOURNAL ARTICLES

A. H. Dexter, W. R. Cornman, and E. J. Hennelly. "The Advantages of ^{60}Co for Heat and Radiation Sources", *Nucl. Appl. 2(2)*, 99-101 (1966).

C. P. Ross. "Cobalt-60 for Power Sources", *Isotopes and Radiation Technology, 5(3)*, 185-94 (1968).

C. L. Angerman, F. D. R. King, J. P. Faraci, and A. E. Symonds. "^{60}Co Heat Source Encapsulation", *Nucl. Appl. 4(2)*, 88-95 (1968).

C. L. Angerman and J. P. Faraci. "Heating Tests of Encapsulated Cobalt Heat Sources", *Nuclear Metallurgy, Vol. 14, Symposium on Materials for Radio-Isotope Heat Sources,* D. E. Thomas, W. O. Harms, and R. T. Huntoon (Editors), American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, New York, pages 309-22 (1969).

J. A. Donovan and W. R. McDonell. "Cobalt-Rhenium Alloys for High Temperature ^{60}Co Heat Sources", *Trans. Amer. Nucl. Soc. 12(2)*,480-1 (1969).

P. K. Smith, P. E. McBeath, J. R. Keski, W. R. Kanne, Jr., and W. C. Mosley, "Cobalt-60 Oxides as Thermonic Fuels," *IEEE Conference Record of 1969 Thermonic Conversion Specialists Conference, October 21-23, 1969, Carmel, California.* 69 C 51-ED, pp 417-24, The Institute of Electrical and Electronics Engineer, Inc., New York (1969).

S. Mirshak, C. P. Ross, and V. Whatley. "Cobalt-60 for Heat and Power," *Chemical Engineering Progress Symposium Series No. 106 Application of Radioisotopes, Nuclear Engineering Part XXII, Vol. 66,* L. H. Meyer (ed.). American Institute of Chemical Engineers, New York, 7-15 (1970).

C. P. Ross. "AEC ^{60}Co Heat Source Programs." *Trans. Amer. Nucl. Soc. 13(2)*, 492-3 (1970).

D. T. Rankin, P. K. Smith, P. E. McBeath, W. R. Kanne, Jr., W. R. McDonell, and J. R. Keski. "Production and Properties of Refractory Forms of ^{60}Co for Isotopic Power Applications." *1971 Intersociety Energy Conversion Engineering Conference.* pp 751-760, Society of Automotive Engineers, Inc., New York (1971).

V. Whatley, C. P. Ross, P. E. McBeath, G. H. Parker, P. J. Chasko, and P. O. Tausom, "Demonstration Test of 90-Watt ^{60}Co-Fueled Thermoelectric Generator." *1971 Intersociety Energy Conversion Engineering Conference,* pp 787-792, Society of Automotive Engineers, Inc., New York (1971).

C. L. Angerman and C. P. Ross, "Performance of ^{60}Co Capsules at Heat Source Conditions." *1970 Intersociety Energy Conversion Engineering Conference, Vol. I.* pp 8-35 to 8-39. American Nuclear Society (1972).

REFERENCES

1. C. L. Angerman. *Savannah River Laboratory Cobalt-60 Power and Heat Sources Quarterly Progress Report. January-March, 1972.* USAEC Report DP-1300. E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, South Carolina 29801 (1972).

2. W. L. Phillips, Jr., "Oxidation of the Platinum Metals in Air," *Trans. ASM, 57,* 33 (1964).

3. B. Lustman and R. F. Mehl. "Rate of Growth of Intermediate Alloy Layers in Structurally Analogous Systems," *Trans. AIME, 147,* 369 (1942).

4. D. D. Van Horn. "Solid State Diffusion and the Motion of Phase Boundaries," *Trans. ASM, 51,* 185 (1959).

5. C. L. Angerman. *Savannah River Laboratory Cobalt-60 Power and Heat Sources Quarterly Progress Report. October-December, 1971.* USAEC Report DP-1293. E. I. du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina 29801 (1972).